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Lorenz M. Hilty
Bernard Aebischer *Editors*

ICT Innovations for Sustainability

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Foreword

This volume outlines the core concepts and methods of an emerging field of research and practice, ICT for Sustainability (ICT4S). Work in ICT4S clusters around twin pillars:

- Sustainability in ICT, making information and communication technologies themselves more sustainable;
- Sustainability by ICT, using information and communication technologies to encourage sustainable practices in society as a whole.

A central element of work in both realms is the inclusion of sustainability as a key criterion—to be optimized alongside traditional ones like quality, cost, and speed—in the design of systems.

This is a significant departure from prior practice. For most of history, material scarcity was the norm and economizing on human effort was the imperative. To thrive in the twenty-first century, we must move beyond habits honed in such a past and take into account that we live in a world of finite resources.

ICT4S calls for the adoption of a new calculus, one that incorporates sustainability from the outset by thinking hard, at the start of the design process, about how to reduce environmental impacts and ensure greater social fairness. This is a radical change from prior practice and at the heart of the ICT4S field.

The ICT industry is influential, and innovations pioneered within it in recent decades—venture funding of start-up companies, open innovation, crowdsourcing—have become widely adopted in other sectors. If a sustainability-based design approach can take hold in ICT, it may well diffuse broadly to other realms as well. Should that happen, it would represent a profound contribution by the pioneers of ICT4S.

This volume provides a solid intellectual framework for the field. In the introductory essay, Lorenz Hilty and Bernard Aebischer, co-organizers of the inaugural ICT4S conference held in 2013 in Zurich, cover a series of key concepts: they offer an inspiring and useful definition of sustainability (which laudably includes not only environmental but also social indicators); note the importance of ideas like substitutability, dematerialization, and the rebound effect; and point out the complex challenges associated with developing sustainability metrics. The chapter also recounts prior work in related fields and positions ICT4S within the context of earlier research.

Later chapters provide a broad variety of perspectives on Sustainability in ICT, with contributions that focus on every level, from the micro to the macro. Authors assess the environmental impact of software, semiconductors, end-user devices, servers, data centers, and the global Internet as a whole, examining the footprint of ongoing operations, as well as the material life cycle from mine to landfill.

Other chapters address aspects of Sustainability by ICT, with contributions on such topics as how technology-based tools may supplant, or augment, travel and print media; and the potential role of ICT in enabling sustainable supply chain management, the smart grid and green urban design; and how ICT might reshape household energy consumption patterns.

Most of the contributors to the volume are European, a reflection of Europe's leadership role in sustainability and the demographics of attendance at the inaugural ICT4S conference. One hopes future ICT4S conferences will see growing participation by researchers and practitioners from North America, the region with the largest per capita environmental footprint, and Asia, where the growth of consumption will be the greatest in the coming decades.

This book provides a strong foundation for the ICT4S community to continue its important work of building a sustainable future.

Cambridge, USA

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Bernard Aebischer is a pioneer in assessing the energy consumption of ICT. An energy analyst specializing in energy demand modeling, he has worked at ETH Zurich with Daniel Spreng since 1989 and at ETH Zurich's Centre for Energy Policy and Economics (CEPE) since its inception in 1999. On behalf of the Swiss Federal Office of Energy, he led the Competence Centre for ICT and Energy from 1994, incorporating it into CEPE, until his retirement in 2011. He is a recognized expert in ICT energy analysis and policy in Switzerland and the European Union.

Part I
Introduction

ICT for Sustainability: An Emerging Research Field

Lorenz M. Hilty and Bernard Aebischer

Abstract This introductory chapter provides definitions of sustainability, sustainable development, decoupling, and related terms; gives an overview of existing interdisciplinary research fields related to ICT for Sustainability, including Environmental Informatics, Computational Sustainability, Sustainable HCI, and Green ICT; introduces a conceptual framework to structure the effects of ICT on sustainability; and provides an overview of this book.

Keywords Sustainable use · Sustainable development · Technological substitution · Decoupling · Dematerialization · ICT4S

1 Introduction

This book is about using the transformational power of Information and Communication Technology (ICT) to develop more sustainable patterns of production and consumption. It grew out of a conference that the editors organized in Zurich in 2013: the first international conference on ICT for Sustainability,

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or ICT4S for short [1]. After publishing the proceedings [2], we felt the need for a book that brings together more systematically the fundamental ideas and methods of ICT for Sustainability as a field of study. This book, a joint effort by 47 authors, is the result.

As is to be expected, the book is only a first step. Many important aspects could not be covered, and efforts to generate consistent terminology and methodology are still in their infancy. We nevertheless hope that the reader will find inspiration and orientation in this exciting new field of research and innovation.

How can we harness ICT for the benefit of sustainability? Two things are essential:

1. To stop the growth of ICT's own footprint
2. To find ways to apply ICT as an enabler in order to reduce the footprint of production and consumption by society

So far, we have not defined "sustainability" or "footprint," but have relied on the reader's preconceptions. Section 2 will provide definitions of the basic concepts associated with ICT for Sustainability. In Sect. 3, we give an overview of other research fields related to ICT4S, such as Environmental Informatics, Computational Sustainability, Sustainable HCI, and Green ICT. Section 4 introduces a conceptual framework for structuring the effects of ICT. Finally, Sect. 5 provides an overview of the topics covered in this book.

2 What Is Sustainability?

2.1 Basic Definitions

We will first define "sustainable use" and then reconstruct the concept of "sustainable development" based on its original definition by the World Commission on Environment and Development (WCED).

Definition 1: Sustainable Use. To make *sustainable use of a system S with regard to a function F and a time horizon L* means to use *S* in a way that does not compromise its ability to fulfill *F* for a period *L*. In other words, a system is used sustainably if the user can sustain this use "long enough."

S may also be called a "resource" in the broadest sense of the term, and the process of fulfilling F can also be called a "service." We may think of *S* as being either a human-made or a natural system, or a combination of the two: a human-environment system.

This definition may appear rather formalistic at first sight. However, it is simply an attempt to make explicit what follows logically from the idea of using something for a purpose, and the everyday meaning of the adjective "sustainable", i.e., "able to be maintained at a certain rate or level" [3]. For instance, if we want to make sustainable use of a climbing rope, we simply avoid overloading it to the extent that it breaks.[1]

When H.C. von Carlowitz wrote his principles of sustainable forestry in 1713 [4],[2] the world was less complex than today. The function of a forest was to produce wood. His basic principle was simple: Do not cut more wood than will grow in the same period of time. Today, we are aware that forests have additional functions, such as filtering air and water, holding soil in place and preserving biodiversity, as well as protective and recreational functions. It follows that there is a variety of ideas on how to make sustainable use of a forest. Depending on the F that dominates our perspective and our interest, we may have different opinions on how to make sustainable use of a forest. Even worse, it may be unclear where exactly S begins and ends: Where should we draw the system boundary? Can S be meaningfully separated from the rest of the world?

Many controversies related to sustainability stem from the fact that people think of different systems and functions to be sustained, as well as different time horizons, and do not explicitly declare them when engaging in a discourse, when designing a technological artifact or developing a business model. Any theories or actions referring to sustainability should therefore answer Dobson's [5, p. 406] "principal organising question", namely:

> What is to be sustained?

Sustainable use, as we define it above, could be called a *relative* concept of sustainability. This is because its meaning depends on how system S, function F, and time horizon L are defined in context. It is a burden to the sustainability discourse that an increasing number of "sustainable x" terms (such as "sustainable management" or "sustainable software") are used without providing an explicit context in which S, F, and L are defined.

However, there is at least one "sustainable x" term that can be regarded as referring to an *absolute* concept of sustainability, as the context was set by the WCED in 1987 [6]: sustainable development. Below, we explicitly refer to this original definition of sustainable development and not to later variants.

Definition 2: Sustainable Development. "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [6]

This definition, also known as the "Brundtland definition," can be reformulated as "making sustainable use of our planet to maintain its function of fulfilling human needs." As a first glance, it therefore seems that sustainable development is

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[1] Assuming that we intend to use the rope for the next ten years, we can specify the parameters as follows: $S = \textit{rope}$, $F = \textit{securing a climber of up to 100}$ kg, $L = \textit{10}$ years.

[2] Carlowitz's book is usually cited as the origin of the word "nachhaltig," the counterpart of the English word "sustainable."

Table 1 Examples used in the text

Description	System S (resource)	Function F (service provided)	Time horizon L
Using a climbing rope	A rope	Securing a person	A decade
Sustainable forestry 1	A forest	Producing wood	Generations
Sustainable forestry 2	A forest	Preserving biodiversity	Generations
Sustainable forestry n	A forest	… (Any other function)	Generations
Sustainable development	*The planet*	*Meeting human needs*	*Generations*

just a special case of sustainable use, whereby $S = planet$, $F = fulfilling\ human\ needs$, and $L = several\ generations$ (Table 1).

However, there is a second element in the Brundtland definition that cannot be reduced to sustainable use: *distributive justice.* The WCED highlighted "the essential needs of the world's poor, to which overriding priority should be given" [7]. M. Christen points out that sustainable development "might best be conceptualised as an attempt to grant the right to a decent life to all living human beings *without* jeopardising the opportunity to live decently in *future*." Christen therefore revises Dobson's "principal organising question" in the following manner:

> What has to be guaranteed or safeguarded for every person, no matter whether she lives at present or in the future? [7]

It should be clear that no single product, process, policy, region, or technology can be "sustainable" in the sense of "sustainable development", as the latter concept has a global scope by definition.

Definition 3: Sustainability Indicator. A sustainability indicator is a measure that is used in a process of governance[3] to identify actions that are more beneficial to sustainability than others. In this definition, "sustainability" can be understood either as sustainable use (Definition 1) or as sustainable development (Definition 2). In the second case, there are two types of sustainability indicators:

- Resource-oriented indicators: They cover the "sustainable use of the planet" aspect of sustainable development. The term "footprint" has become a generic metaphor for resource-oriented sustainability indicators. *Carbon footprint* indicators estimate to what extent an activity uses the atmosphere's limited capacity to absorb greenhouse gases. The *ecological footprint* is an indicator trying to map any human impact onto a share of the carrying capacity of the planet. [9]

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[3] "Governance" is defined as "all processes of governing, whether undertaken by a government, market or network, whether over a family, tribe, formal or informal organization or territory and whether through laws, norms, power or language." [8].

- Well-being-oriented indicators: They cover the "fulfill human needs" aspect of sustainable development. As a basic indicator, Gross Domestic Product (GDP) is used. However, because "economic indicators such as GDP were never designed to be comprehensive measures of prosperity and well-being", additional indicators, known as "beyond-GDP indicators," are under discussion. [10]

It is important to understand that sustainable development (Definition 2) can only be quantified using indicators of both types; the idea is to fulfill human needs *and* make sustainable use of global resources.

Resource-oriented indicators reduce the complexity of deeply nested resource systems S to simple metrics. This is why any resource-oriented indicator—at least implicitly—relies on a *model* of the service-providing system. This model is used to estimate the impact of an action in terms of sustainability of use: The greater an unwanted impact on the resource, the less sustainable the action.

Established indicators are linked to specific *impact assessment methods* that prescribe how the data are collected and the models used to calculate the indicator for a specific case. Examples include the environmental impact assessment categories used in Life-Cycle Assessment (LCA).[4]

In engineering contexts, there is a tendency to focus on energy use or CO_2 emissions as central resource-oriented indicators. The terms "energy-efficient," "carbon-neutral," and "sustainable" are often used interchangeably. However, this is an oversimplification, for three reasons. First, the diffusion of energy-efficient technologies does not necessarily lead to an overall reduction of energy use: Efficient technologies can also stimulate the demand for the resource they use efficiently. This is known as Jeavons' paradox or the "rebound effect." Second, the production, use, and disposal of these technologies needs resources as well: When assessed from a life-cycle perspective, energy efficiency may look somewhat different. Third, although energy is crucial, the impact on other natural resources should also be included.

2.2 Classification of Resources and the Question of Substitutability

Resources can be classified in natural and human-made resources and in material and immaterial resources [14]. These two dimensions are orthogonal, in other words, all combinations are possible (Table 2). Furthermore, material natural resources can be renewable or non-renewable. A renewable resource can replenish

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[4] In several chapters of this book, the method of LCA is applied to estimate the environmental impacts of ICT goods and services: [11–13].

Table 2 Classification of resources and examples

	Material	Immaterial
Natural	*Renewable:* Wood *Non-renewable:* Minerals	Song of a bird Genetic information Climate regulation
Human-made	Machines Built environment Engineered materials	Literature Scientific knowledge Algorithms

if the rate at which it is used does not exceed its renewal rate. A non-renewable resource does not renew itself in meaningful human timeframes.

We will not introduce formal definitions of these resource categories here as they are defined more or less consistently in the literature. However, the distinction between "material" and "immaterial" resources deserves some clarification. UNEP's International Resource Panel introduced this useful distinction: A resource is called material if using it affects other uses of the resource. For example, a stone used to build a wall will no longer serve for other functions. By contrast, resources "whose use has no effect on the qualities that make them useful" are called immaterial. In this sense, "the shine of a star used by a captain to find his way" is an immaterial resource [14, p. 1].

Technological innovation leads to the diffusion of new technologies, which are then partially or fully *substituted* for older technologies or natural resources. Cars have replaced horse-drawn carriages, the computer has replaced the abacus, and LCD screens have recently replaced CRT screens. To express substitution in the terms we defined above, we can regard each technological product as a resource *S'* that may fulfill the same function *F* as a resource *S*. If this is the case, *S'* is obviously a potential substitute for *S*. Many controversies around sustainability are based on different beliefs about the future *substitutability* of resources. Below, we first define substitutability and then discuss an extended example.

Definition 4: Substitutability. If a function *F* provided by a system *S* can also be provided by *S'*, we say that *S'* is substitutable for *S*. Note that substitutability is a ternary relationship: *S'* is substitutable for *S* with regard to *F*.

Substitution is crucial with regard to non-renewable resources. Unless we assume, for example, that fossil energy sources are substitutable by renewables, transition to a sustainable use of energy must appear impossible.

Substitutability has implications for the actions to be taken to promote sustainability. If *S* can be substituted by an *S'* fulfilling *F* as well, there is no need to sustain *S*. What makes this concept hard to grapple with in political discourse is the fact that substitutability depends on future technological developments and discoveries, so it is impossible to know who is right today. An extreme technological optimist may believe that any limited material resource will become substitutable by some unlimited resource in due time, while a person thinking in an extremely precautionary way would not cut down a single tree as it might have some irreplaceable properties. Most people's beliefs are located somewhere between these two poles.

In fact, substitution is more complex as it can occur at different levels. An example will illustrate this idea. Bob wants to meet up with Jill, who lives on another continent. He may use an airline to travel to Jill's country. The airline needs planes, airport infrastructure, personnel, fuel, the atmosphere, stable weather conditions, and many other resources. For the aircraft to be built, materials must be extracted from the Earth's crust, people trained to build planes, power plants must generate electricity, and so on. The power plants, in turn, need fuel, they must be built, maintained, and so on. If Bob were to decide to have a virtual meeting with Jill instead, we would, of course, discover a similar structure of nested resource use.[5]

This example shows that there is usually a hierarchy (formally, a tree) of resources that provides a service. From an economic perspective, each node of the tree is a production process, whose input is resources provided by other processes. Thus, the airline produces the service of transporting Bob from A to B, the aircraft industry produces aircraft, and a refinery produces fuel. The overall system that produces the final service delivered to Bob is inconceivably complex, and we would probably never understand it in all detail if we tried.[6]

Given this hierarchy of resources that emerges when one asks how a specific service is produced, it is essential to understand that substitution can in principle occur at any level, as shown in Fig. 1:

- Bob could replace physical transport with an immersive telepresence technology that makes a virtual meeting with Jill sufficiently similar to a face-to-face meeting.
- He could replace air travel with a new means of transport, such as a vactrain traveling through evacuated tubes at five times the speed of sound with almost zero resistance.
- The airline could use a new type of aircraft that is extremely energy-efficient.
- The aircraft could use a new type of fuel, e.g., based on solar energy.
- CO_2 emissions to the atmosphere could be reversed by a new carbon sequestration technology.

People have different beliefs in substitutability depending on the level of the resource hierarchy. Some people tend to believe that we will still use planes

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[5] How to determine which alternative—flying or videoconferencing—is preferable from the perspective of sustainability is discussed in the chapter by Coroama et al. [13] in this volume.

[6] Fortunately, we do not need to. The market economy has an extremely useful feature that computer scientists refer to as "information hiding": You do not have to know what is behind an interface to make use of a module. In the same way, Bob does not have to understand how a plane is operated, the airline does not have to know how planes are built, and (in theory) nobody has to worry about where the energy comes from or how the environment deals with pollutants. However, market failures and the goal of distributive justice force us to strive for a deeper understanding of the dynamics of resource use.

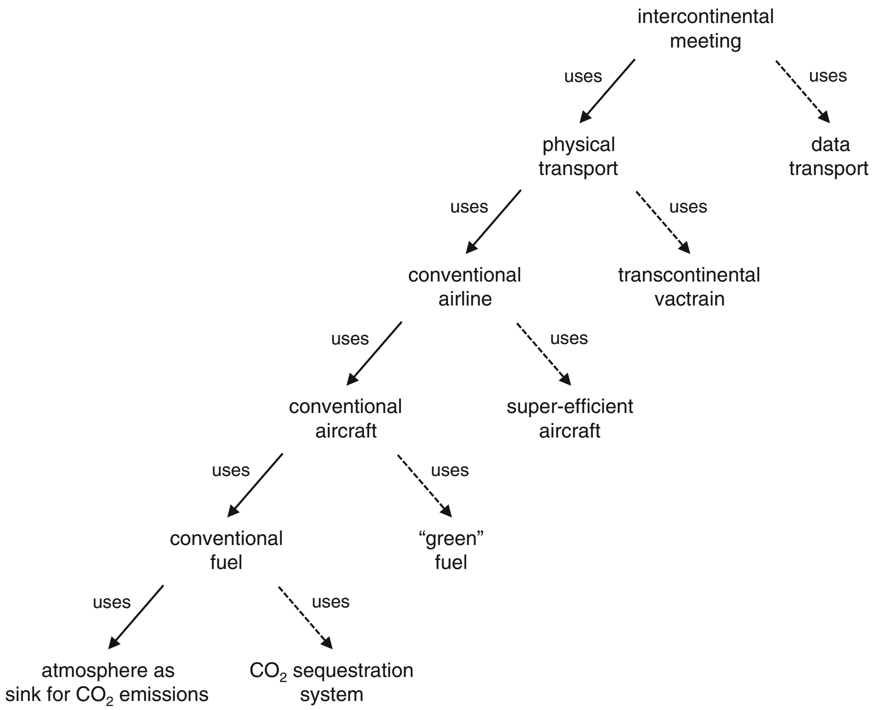

Fig. 1 A single branch of a resource-use hierarchy with potential substitutes at each level, indicated by *dotted arrows*

100 years from now, but with some substitutions at the lower levels. Others think that it is easier to change social practices—adopt new forms of virtual meetings—than to replace fossil fuels or solve the problem of greenhouse gas emissions.

An interesting question is what type of resource is at the bottom of the resource hierarchy. All human-made material resources are made from natural resources, abiotic or biotic, and even long-lasting human-made material resources need energy from the environment to be operated and maintained. No house can be built or repaired without using some form of energy; no food has ever been created without biomass as its raw material. Immaterial resources can be substituted for material ones only to a certain extent. All information needs a physical substrate; there is a theoretical minimum to the amount of energy used for information processing, known as Feynman’s limit.[7]

We depend on the resources that we take from the environment. Humankind has learned to transform this environment, which makes it debatable to which extent it should still be called the “natural environment.” There is, however, no reason to

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[7] See also the chapter by Aebischer and Hilty [15] in this volume.

assume that we could or should replace the basic *ecosystem services* provided by nature, which include the production of food and many raw materials, water and some forms of energy, as well as regulation services such as the purification of water and air, carbon sequestration, and climate regulation. These services, in turn, rely on supporting ecosystem services such as nutrient dispersal and cycling, seed dispersal and many others. The complexity of the global ecosystem is much greater than that of any human-made structure, and it can be regarded an ethical imperative that we should "sustain ecosystem services for all countries and generations to come." [16]

2.3 Is Sustainability a Question of Balance?

Sustainable development is commonly described with the help of a metaphor: finding a "balance" between the environment, economy, and society. This approach is also known as the "three-pillar model." It has become so common in the political discourse that critical reflection on it is often lacking.[8]

Yet this metaphorical description deserves critical examination. A balance can only exist between entities that are in principle independent but connected. This is frequently expressed by diagrams similar to the one shown in Fig. 2a, suggesting as it does that environment, economy, and society are entities that exist at the same ontological level and which are connected by overlapping areas.

With regard to the economy and society, this is a misconception. By definition, the economic system forms a part of society: It is hard to imagine economic activities outside human society.

With regard to the environment and society, the situation is different. It is not impossible to view human society as an entity that is at least in principle independent of its natural environment. However, this view suggests an extreme position regarding the substitutability of resources: We would have to assume that human-made capital can in principle substitute all natural resources.[9]

If, on the other hand, the three systems are regarded as nested—as shown in Fig. 2b—the idea of achieving a balance between them becomes impossible: By definition, there can be no balance between a part and a whole.

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[8] Indeed, there even exists a definition of "Computational Sustainability" built largely around this description (see Sect. 3.3).

[9] The normative implication of this position has been called "weak sustainability"—in contrast to "strong sustainability," which rejects the assumption that human-made capital can substitute all natural resources. The precautionary principle for dealing with uncertainty about technological risk implies a position of strong sustainability [17].

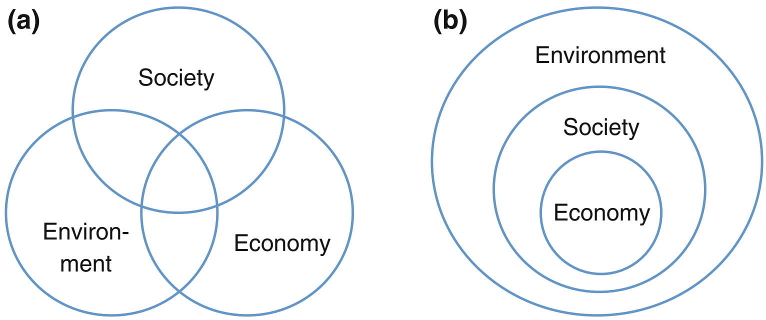

Fig. 2 Different views of the environment, society, and the economy; **a** a diagram frequently used to ilustrate the three-pillar model of sustainable development; **b** the nested model

2.4 Decoupling and Dematerialization

Comparing the global development of GDP with the extraction of natural material resources over the last century (Fig. 3) reveals two things [14]:

- The rate of resource extraction increased by a factor of 8.
- World GDP increased by a factor of 23.

This shows that the two indicators are "decoupled" to a certain degree. It also shows that the decoupling is not sufficient to bring resource extraction down, nor even to slow its growth. Below, we give a slightly generalized definition of decoupling.

Definition 5: Decoupling. Given two sustainability indicators I_1 and I_2, with I_1 being a well-being-oriented indicator and I_2 being a resource-oriented indicator (Definition 3), a process increasing the ratio I_1/I_2 over time is called *decoupling* I_1 *from* I_2.[10]

The quantity I_1/I_2 can itself be used as an indicator; it is called I_2 *productivity,* and its inverse I_2/I_1 is called I_2 *intensity.*

Decoupling obviously requires some substitution of resources at some level of the system.[11] To make a transition toward sustainable development possible, we must increase our understanding of technological substitution and focus on innovation that drives substitution in a sustainable direction.

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[10] The order in which the numerator and denominator are given varies, either as 'decoupling I_1 from I_2,' e.g., "decoupling GDP growth from resource use," [16] or as 'decoupling I_2 from I_1,' e.g., "decoupling natural resource use… from economic growth." [14].

[11] One might argue that there is an alternative way of decoupling, based on increasing the efficiency of production processes rather than on substitution. Increasing efficiency, however, can be regarded as substituting immaterial resources (information) for other resources. See also the chapter on interactions between information, energy, and time by D. Spreng [18] in this volume.

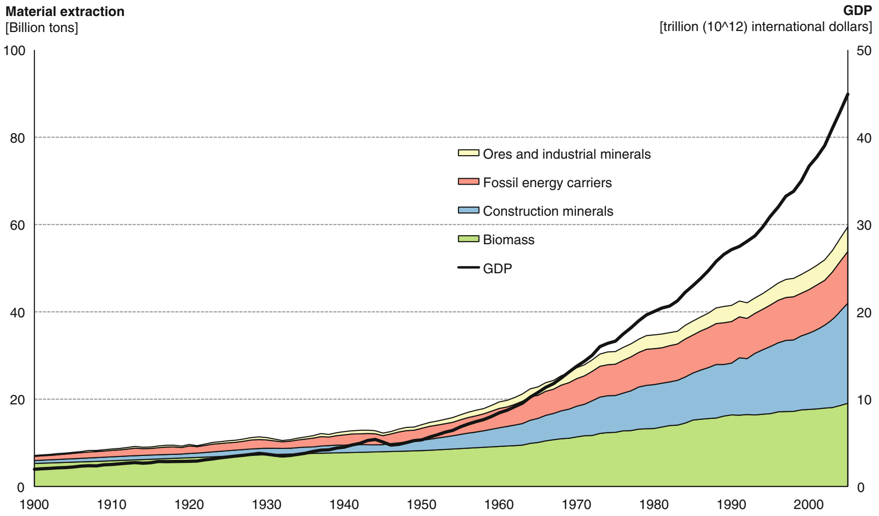

Fig. 3 Global material extraction in billion (10^9) tons and GDP in trillion (10^{12}) international dollars (*Source* [14, p. 11])

The special case of decoupling based on the substitution of immaterial resources for material resources is also known as *dematerialization*.

2.5 Distributive Justice

The use of global resources is not distributed equally throughout the world. One striking example is the use of the atmosphere as a sink of CO_2 and other greenhouse gases: Although people in all regions burn fossil fuels and practice agriculture (the two main reasons for greenhouse gas emissions), huge differences exist in per-capita emissions ([19], see Fig. 4).

In the long term, these differences will have to shrink for reasons of distributive justice. If global emissions are to be reduced for reasons of climate policy, it follows that dramatic dematerialization is needed in the currently high-emitting countries.

3 Related Research Fields

Several fields of applied research have been established to connect the two worlds of ICT and sustainability. Each of these fields is in itself an interdisciplinary combination of approaches, usually combining methods from disciplines of

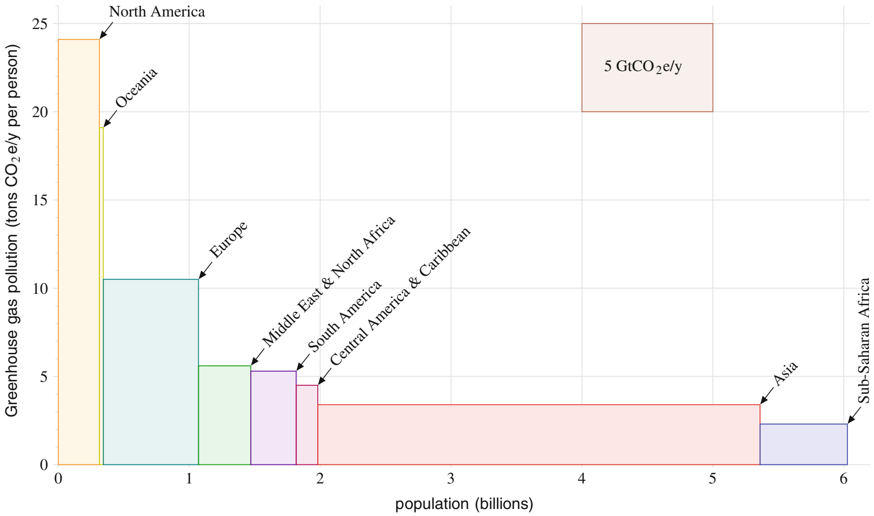

Fig. 4 Greenhouse gas emissions in tons of CO_2 equivalent per capita in the year 2000. The rectangular areas show the total annual emissions per region. This diagram includes all relevant greenhouse gases, not only CO_2 (*Source* [19, p. 12])

computing and communications with methods from environmental or social sciences. Below, we briefly introduce each field and then discuss how ICT4S relates to them. See Table 3 below for an overview.

3.1 Cybernetics as a Precursor

The idea of using computing power to make the world more sustainable is not new. The fourth Annual Symposium of the American Society for Cybernetics, held in Washington, D.C. in 1970, published its proceedings under the title “Cybernetics, Artificial Intelligence, and Ecology” [20]. It contained a vision of an automated air quality control system (Fig. 5) and boldly stated that “Knowledge acquisition is the answer to the ecological crisis!” “Model makers, system analysts, and those concerned with developing informational feedbacks” were encouraged to “help correcting environmental maladies.” [21] If published in the context of persuasive technology or eco-feedback systems today, this statement would not be unusual, although it could be criticized[12] for its simplistic approach; for the 1970s, it was remarkable.

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[12] See the chapter “Gamification and Sustainable Consumption”, which includes a critique of persuasive technologies, in this volume [71].

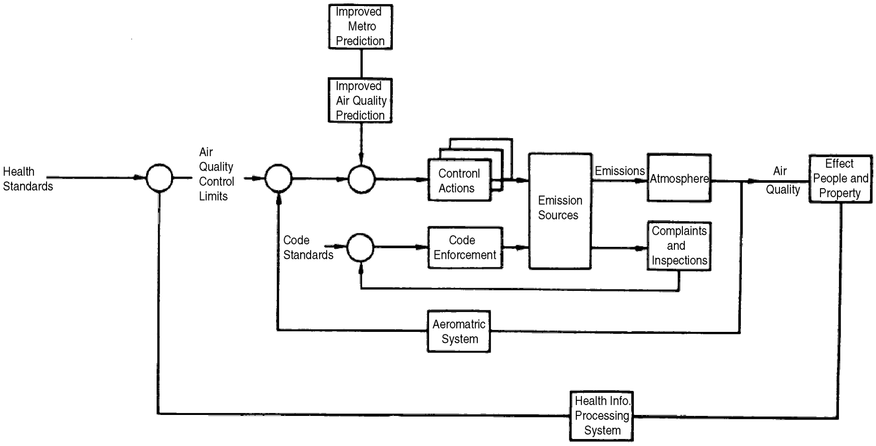

Fig. 5 Vision of an automated air quality control system from 1970. (*Source* [22])

3.2 Environmental Informatics

Environmental Informatics (EI) combines methods from the fields of Computer Science and Information Systems with problem-oriented knowledge from Environmental Science and Management. Similar to Health Informatics or Bioinformatics, EI emerged from the need to systematically meet domain-specific requirements to information processing: “The design of information processing systems for the appropriate utilization of environmental data is a big challenge for computer scientists […] The existing solutions often suffer from a narrowed, unidisciplinary view of the problem scope.” [23] This need became obvious in the early 1990s, when many public authorities started building up Environmental Information Systems (EIS). At that time, EI was focused on applications in the public sector. Private-sector applications emerged as a sub-field a few years later [24].

The first book entitled “Environmental Informatics” was edited in 1995 by Avouris and Page [25]. It lists six methods relevant for the field: modeling and simulation, knowledge-based systems, user interface design, computer graphics and visualization, artificial neural networks, and data integration. From today’s perspective, EI can best be described as a field that uses methods from Information Systems complemented by advanced simulation modeling techniques, and spatial data processing.

EI has sometimes also been called “E-Environment” [26]. Traditional environmental monitoring and new forms of ICT-based environmental metrics [27] can be regarded as part of EI.

The contribution of EI to sustainable development is the potential of shared data and understanding to create a consensus on environmental strategies and policies in the long term. Some authors today focus on the data-science aspects [28], while others put greater emphasis on transdisciplinary problem-solving and knowledge integration. The latter group includes one of the founding fathers of the field, B. Page. In his view, EI "analyses real-world problems in a given environmental domain and defines requirements for information processing. On the other hand, it introduces the problem-solving potential of Informatics methodology and tools into the environmental field" [29, p. 697].

The development of EI is documented in the proceedings of the three main conference series of the EI community: EnviroInfo, ISESS, and ITEE. The EI community is also connected to the International Environmental Modeling and Software Society and their bi-annual summit, iEMSs.[13]

ICT-ENSURE, the European Commission's support action for building a European Research Area in the field of "ICT for Environmental Sustainability" 2008–2010, has helped structure the field of EI [30].

3.3 Computational Sustainability

The field of Computational Sustainability (CompSust) is closely connected with the Institute for Computational Sustainability (ICS), which was founded in 2008 with support from an "Expeditions in Computing" grant from the U.S. National Science Foundation. [35]

CompSust is defined by ICS as "an interdisciplinary field that aims to apply techniques from computer science, information science, operations research, applied mathematics, and statistics for balancing environmental, economic, and societal needs for sustainable development." [35]

As described by C.P. Gomez, the aim of CompSust is to provide decision support for sustainable development policies, with a focus on "complex decisions about the management of natural resources. [...] Making such decisions optimally, or nearly optimally, presents significant computational challenges that will require the efforts of researchers in computing, information science, and related disciplines, even though environmental, economic, and societal issues are not usually studied in those disciplines." [36, p.5]

The contribution of CompSust is found in methods of dynamic modeling, constraint reasoning and optimization. It has also provided approaches using machine learning and statistical modeling. [36]

The phrase "balancing environmental, economic, and societal needs" occurs frequently in key documents describing CompSust (e.g., [35, 36]). However, it remains unclear which needs precisely are addressed, and what the assumed concept of balance is ([37], see also Sect. 2.3). The Brundtland definition (our Definition 2), to which the CompSust community also refers, addresses needs only

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[13] EnviroInfo: Environmental Informatics (since 1986) [31], ISESS: International Symposium on Environmental Software Systems (since 1995) [32], ITEE: International Conference on Information Technologies in Environmental Engineering (since 2000) [33], iEMSs: International Congress on Environmental Modelling and Software (since 2002) [34].

in one sense: as the basic human needs that all people, including those living in the future, have to be granted. “Balancing” seems to address this issue in some way, but without referring to an approach for dealing with the deeply normative issues connected to distributive justice. An algorithm that can resolve normative issues has yet to be invented.

3.4 Sustainable HCI

Sustainable HCI is a sub-field of Human-Computer Interaction (HCI) that focuses on the relationship between humans and technology in the context of sustainability. Sustainable HCI had its starting point in 2007, when E. Blevis first presented the concept of Sustainable Interaction Design (SID). Sustainability was considered a major criterion for the design of technology, as important in the design process as criteria such as usability or robustness [38]. SID considers not only the material aspects of a system’s design, but also the interaction throughout the life cycle of the system, taking into account how a system might be designed to encourage longer use, transfer of ownership, and responsible disposal at the end of life.

J. Mankoff et al. proposed a characterization of sustainability in interactive technologies according to the following categories:

- “Sustainability through design”: How can the design of technology and interactive systems support sustainable lifestyles or promote sustainable behavior?
- “Sustainability in design”: How can technology itself be designed such that its use is sustainable? [39]

Which concepts of sustainability are addressed here, given the definitions of Sect. 2? In the second case, the focus appears to be on the *sustainable use* (Definition 1) of the technological artifact itself. However, there seems to be a common assumption that the longevity of an artifact contributes to *sustainable development* (Definition 2) as well, in particular by saving materials and reducing waste.[14] In the first case, “sustainability through design”, the reference to lifestyles clearly suggests that sustainable development is addressed.

DiSalvo et al. [41] provide an empirical analysis of the emerging structure of Sustainable HCI research. They divide the field into five genres:

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[14] Although this assumption provides good guidance in many cases, it should not be taken for granted. Counterintuitive examples have been presented in LCA studies in other domains. For example, using a cotton shopping bag for ten shopping trips has a greater environmental impact than using ten plastic bags just once each [40].

- “Persuasive technology” stimulating desired (sustainable) behavior
- “Ambient awareness” systems making users aware of some aspect of the sustainability of their behavior, or qualities of the environment associated with issues of sustainability
- “Sustainable interaction design”
- “Formative user studies”
- “Pervasive and participatory sensing”

E. M. Huang [42] describes an “initial wave of research” in Sustainable HCI, having shown that “HCI can contribute to solutions to sustainability challenges,” but also that problems of sustainability cannot be “framed purely as problems for HCI or interaction design issues.” [16, 42] Based on this, she proposes building bridges to other fields: to existing bodies of environmental data (such as LCA data) and related theories, methods, and models; to environmental psychology (e.g., when designing eco-feedback systems); and, last but not least, to real-world situations such as negotiating with a municipality.

3.5 Green IT and Green ICT

We use the terms “Green IT” and “Green ICT” interchangeably. The first is more common, while the second is more consistent with this book’s terminology. We assume that digital convergence has amalgamated the technologies of computation and telecommunications to an extent that makes their separation obsolete in this context.

The term “Green IT” became popular after the publication of a Gartner report in 2007 [43] and was later joined by “Green Computing,” “Green Software,” “Green Software Engineering,” and “Green Information Systems (IS).”

S. Murugesan defined “Green IT” in 2008 as “the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems […] efficiently and effectively with minimal or no impact on the environment.” [44] He identifies the following focus areas [44, p. 26]:

- Design for environmental sustainability
- Energy-efficient computing
- Power management
- Data center design, layout, and location
- Server virtualization
- Responsible disposal and recycling
- Regulatory compliance
- Green metrics, assessment tools, and methodology
- Environment-related risk mitigation
- Use of renewable energy sources
- Eco-labeling of IT products

Besides these focus areas, he mentions two additional aspects:

- “Using IT for Environmental Sustainability […] by offering innovative modeling, simulation, and decision support tools”
- “Using IT to Create Green Awareness” through “tools such as environmental Web portals, blogs, wikis, and interactive simulations of the environmental impact of an activity” [44, pp. 32f]

The dichotomy between reducing the footprint of ICT itself and using ICT to support sustainability has also been called “Green in ICT” versus “Green by ICT” [45].

Q. Gu et al. develop a “Green Strategy Model” in the IT context that aims to “provide decision makers with the information needed to decide on whether to take green strategies and eventually how to align them with their business strategies” [46, p. 62]. This conceptual model differentiates between “green goals” (which an organization decides to achieve), “green actions” (which should help achieve a green goal), “action effects” (the ecological effects of the action with regard to the green goal), and the economic impacts of the action effects. Green actions are divided into two categories, “greening of IT” and “greening by IT” [46, p. 65].

In trying to cover both sides of the dichotomy, Green ICT is similar to Sustainable HCI. However, the implicit focus of Green ICT seems to be clearly on the “Green in ICT” part, if one considers the literature. Highly elaborated definitions and syllabi for Green ICT, such as the syllabus of the British Computer Society [47], do not include a “Green by ICT” aspect.

There are good reasons for this. Green ICT researchers seem to have created “Green by ICT” from scratch to fill a perceived gap in their field, apparently unaware that this area was already covered by other established fields. The first “additional aspect” mentioned by Murugesan and cited above, “Using IT for Environmental Sustainability…,” looks like a definition of EI or CompSust. The second aspect, “Using IT to Create Green Awareness,” is part of Persuasive Technologies and Ambient Awareness and thus covered by Sustainable HCI.

The field of Green Information Systems or Green IS [48] has been conceptualized by Loeser and Erek, for example. The field of IS is, as usual, differentiated from IT by including not only technical infrastructure but also the human activities within an organization. Green IS is attributed a higher transformation potential than “classical” Green ICT: “Green IS […] promise a much greater, organization-wide potential to measure, monitor, report and reduce the firm’s environmental footprint, but the transformation of the business with the help of Green IS requires a holistic long-term strategy.” Green IS strategy is defined as “the organizational perspective on the investment in, deployment, use and management of information systems (IS) in order to minimize the negative environmental impacts of IS, IS-enabled products and services, and business operations.” [48, p. 4]

Table 3 Overview of the research fields relating ICT to sustainability, their main methods, and intended contributions to sustainable development

Name of the field	Main methods	Contribution to sustainable development
Environmental Informatics	Information systems Modeling and simulation Spatial data processing	Monitoring the environment Understanding complex systems Data-sharing and consensus-building
Computational Sustainability	Modeling, optimization Constraint reasoning Machine learning, etc.	Decision support for the management of natural resources “Balancing” conflicting goals
Sustainable HCI	Empirical HCI methods Design research Methods from other fields	Longevity of devices Supporting sustainable lifestyle Promoting sustainable behavior
Green IT/ICT	IT management IT engineering Software engineering	Reducing the environmental impacts of ICT hardware and software (Green *by* ICT covered by other fields)
ICT for Sustainability	Assessment methods (LCA, TA, others) Empirical methods (incl. social sciences) Scenario-building Modeling and simulation	Reducing ICT-induced energy and material flows Enabling sustainable patterns of production and consumption Understanding and using ICT as a transformational technology

The software perspective of Green ICT is another important focus. A. Noureddine et al. [49] define Green IT from a software perspective as a “discipline concerned with the optimization of software solutions with regards to their energy consumption” [21, 49]. Their focus is on the environmental impacts caused by software, mainly CO_2 emissions related to power consumption. The approach conceptually includes energy models showing the energy use caused by software in hardware resources (in particular processors, working memory and hard disks), power monitoring at runtime, and the use of “power-aware information to adapt applications at runtime based on energy concerns.” [49, p. 27]

Both the software product and the processes of software engineering can be developed in the direction of sustainability (see the chapter by Naumann et al. [50] in this volume). A central question is how sustainability can be defined as a non-functional requirement [51].

3.6 ICT for Sustainability

Perhaps the clearest statement of what ICT for Sustainability (ICT4S) means, or should mean, is the preamble of the recommendations endorsed by the 200 participants of the first ICT4S conference held in Zurich in 2013. These recommendations are published under the title "How to Improve the Contribution of ICT to Sustainability" in the appendix of the proceedings [2]. The preamble reads:

> The transformational power of ICT can be used to make our patterns of production and consumption more sustainable. However, the history of technology has shown that increased energy efficiency does not automatically contribute to sustainable development. Only with targeted efforts on the part of politics, industry and consumers will it be possible to unleash the true potential of ICT to create a more sustainable society. [2, p. 284]

ICT4S was not originally intended as a research field. It began as a conference attended by experts from academia, industry and politics with a common aim: Harnessing this technology for sustainable development. For this reason, there are many overlaps between ICT4S and pre-existing fields. ICT4S can be subdivided into:

- Sustainability in ICT: Making ICT goods and services more sustainable over their whole life cycle, mainly by reducing the energy and material flows they invoke
- Sustainability by ICT: Creating, enabling, and encouraging sustainable patterns of production and consumption by means of ICT

Parts of the first aspect are covered by Green ICT, parts of the second by Sustainable HCI and EI. If there is something specific to ICT4S as a field, it is the critical perspective that challenges every technological solution by assessing its impact at the societal level: What is the effect of the solution on society at large – does it have a potential to contribute to sustainable development? In other words, sustainable development is seen a societal transformation, and technological impacts are interesting mainly for their transformational aspect.

The methods used in ICT4S are as varied as the disciplines contributing to it. Due to the critical perspective mentioned above, assessment methods such as LCA, approaches from Technology Assessment, and others are in use. Empirical methods from the social sciences are used to study the interactions between technology design and human behavior. Scenario methods and interdisciplinary approaches to modeling and simulation are employed to deal with complex dynamic systems.

ICT4S refers to sustainable development in the sense used by Brundtland, as defined in Sect. 2 (Definition 2).

3.7 Further Related Fields

A wide variety of other fields are also related to ICT4S, albeit less closely than the four areas presented in Sects. 3.2–3.5 above:

- ICT4D: ICT for Development, also known as "Development Informatics," is defined as "the application of information and communication technologies for international development." [52]
- ICT4EE: ICT for Energy Efficiency, a notion coined by the European Commission as an umbrella term for activities aimed at improving the energy efficiency in the ICT sector as well as "ways in which the ICT sector can lead to more energy efficiency in other sectors such as buildings, transport and energy." [53]
- Energy Informatics: This field is concerned with "the application of information technologies to integrate and optimize current energy assets such as energy sources, generating and distributing infrastructures, billing and monitoring systems, and consumers." [54]
- Sustainable Computing: This field is characterized in the journal of the same name as "making computing sustainable" and "computing for sustainability—use of computing to make the world a sustainable place"; it is thus similar to "Green in ICT" and "Green by ICT" as discussed above, but with a focus on algorithms. [55]
- Digital Sustainability: This term is used with various meanings. It may refer to the preservation of digital formats and content [56], to the use of media with low environmental impact [57], or to open access to information resources. [58]

3.8 ICT4S and Ethics

The normative aspects of ICT4S also connect this field to ethical aspects of computing. Historically, the discourse on the ethics of computing was initiated at the international level by IFIP TC9, IFIP's Technical Committee on ICT and Society, which still promotes this discussion. IFIP, the International Federation for Information Processing, was founded in 1960 under the auspices of UNESCO as the umbrella organization of the national computer societies. IFIP TC9 has continuously inspired, monitored, and framed the development of national ethics guidelines and codes of conduct for computer professionals in the national member societies [59].

A discourse analysis conducted by Lignovskaya [60] on the proceedings of the "Human Choice and Computers" (HCC) proceedings published by IFIP TC9 in the period 1974–2012 revealed a number of results regarding sustainability. First mentioned at the 1998 HCC conference, the relationship between sustainable development and the information society (or knowledge society) was discussed in

2002 and more broadly in the three succeeding conferences in 2002, 2006, and 2008. The 2012 proceedings show a surprisingly high frequency of "sustainable x" terms, in particular "sustainable innovation," "sustainable business," "sustainable growth," "sustainable computing," "sustainable consciousness," and "sustainable governance," whose relation to the concept of sustainable development is not always clear. The term "sustainable development" itself has almost vanished in the 2012 proceedings. A speculative interpretation of this observation is that the concept of sustainable development has been replaced by vague concepts of sustainability. The ICT4S community should therefore contribute clear ideas about the ethical aspects of sustainable development and the role of ICT in this context.

The results of the overall analysis, which are grouped around the ethical issues of autonomy and self-determination, responsibility, and distributive justice, are summarized in [61].

4 Toward a Conceptual Framework for ICT Impacts on Sustainability

A decade ago, the first author of this chapter was involved in a project by the European Commission's Institute for Prospective Technological Studies (IPTS) that aimed to estimate the positive and negative effects of the "informatization" of society on environmental indicators. The method employed was to develop a socio-economic model and so simulate various scenarios with a time horizon of 20 years. The most striking result of the simulations was that the *overall* impact of ICT on the environment was small, but it had substantial positive or negative impact in specific areas. For example, ICT applications for making freight transport more efficient *increased* the demand for transport (faster and cheaper transport stimulated demand), whereas utilizing the potential of ICT to dematerialize goods *reduced* the total demand for materials, which in turn reduced the demand for transport. Taken as a whole, such effects tended to cancel each other out.[15] [62]

The take-home message from the project was that the idea of ICT being either good or bad for the environment should be combated. Such simplistic beliefs are actually harmful, as they prevent the formation of policies that would systematically unleash the positive potential of ICT while inhibiting its negative potential. Targeted policies of this type can use ICT as a powerful tool to support the transition toward sustainability. One of the conclusions of the project team was that "It is […] essential to design policies that encourage environmentally

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[15] The ICT applications covered by the model were as follows: "e-business, virtual mobility (telework, teleshopping, virtual meetings), virtual goods (services partially replacing material goods), ICT in waste management, intelligent transport systems, ICT in energy supply, ICT in facility management, ICT in production process management." [65] See the chapter by Ahmadi Achachlouei and Hilty [66] in this volume for an update on the model.

advantageous areas of ICT application, while inhibiting applications that tend to increase the speed of resource consumption." [62, p. 61]

This is less surprising than it seems when one considers that ICT currently impacts on almost every aspect of production and consumption, in many different ways. The universality and ubiquity of ICT make it necessary to take a closer look at its interactions with sustainability. Any approach to systematically addressing ICT in the context of sustainability, be it from a research, policy-making or innovation perspective, requires a conceptual framework that answers the fundamental question: What types of ICT impacts should we be looking for?

There have been many attempts to define such frameworks, as documented in the annotated bibliography published in the annex of the ICT4S 2013 proceedings [63]. Below, we present our most recent proposal—the LES model (Sect. 4.2)—after describing some intermediate steps that led to it (Sect. 4.1).

4.1 The Three-Levels Model

Many authors differentiate between the first-, second- and third-order effects of ICT, a classification originally introduced by Berkhout and Hertin in a 2001 OECD report [64]:

1. "Direct environmental effects of the production and use of ICTs"
2. Indirect environmental impacts through the change of "production processes, products, and distribution systems"
3. Indirect environmental impacts "through impacts on life styles and value systems" [64, p. 2]

This framework has been re-used, re-interpreted and re-labeled many times [63]. Figure 6 shows how it can be combined with a second dimension that distinguishes positive from negative impacts, i.e., "ICT as part of the problem" from "ICT as part of the solution."[16] This matrix was published by the first author of this chapter in 2008 [67] and revised several times after that. It is intentionally normative, declaring some effects favorable for sustainability and others unfavorable. We discuss the possible downsides of such a normative approach in Sect. 4.2 below, and contrast it with a new approach that is purely descriptive.

The matrix contains different categories of ICT effects:

- Level 1 refers to the *direct effects* of the production, use and disposal of ICT, effects that can be assessed with a Life-Cycle Assessment (LCA) approach. In particular, this includes the demand for materials and energy throughout the whole life cycle. These effects are placed entirely on the negative side as they represent the cost of providing ICT services.

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[16] It is implicitly assumed that "the problem" here is the fact that sustainable development (Definition 2) does not currently exist.

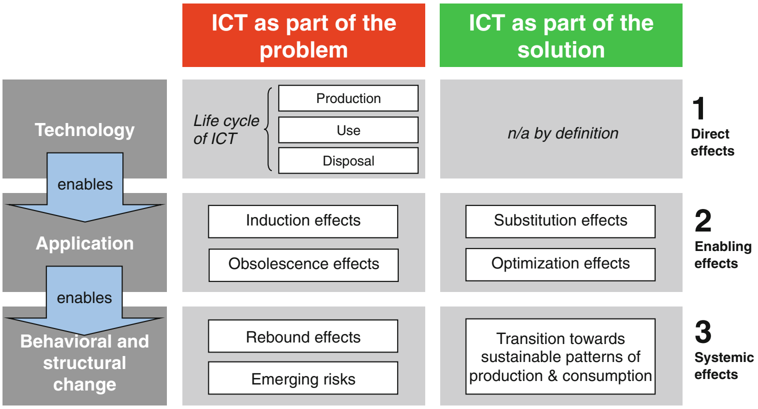

Fig. 6 A matrix of ICT effects, based on [67]

- Level 2 refers to the *enabling effects* of ICT services, or the effects of applying ICT. Two of them are attributed to the "problem" side, two to the "solution" side:
  - Induction effect: ICT stimulates the consumption of another resource (e.g., a printer stimulates the consumption of paper as it uses it faster than a typewriter).
  - Obsolescence effect: ICT can shorten the useful life of another resource due to incompatibility (e.g., a device that is no longer supported by software updates is rendered obsolete).
  - Substitution effect: The use of ICT replaces the use of another resource (e.g., an e-book reader can replace printed books, which is positive if it avoids the printing of a sufficiently large number of books).[17]
  - Optimization effect: The use of ICT reduces the use of another resource (e.g., less energy is used for heating in a smart home that knows where the people who live in it are located, which windows are open, what weather is forecast, etc.).
- Level 3 refers to the *systemic effects,* i.e. the long-term reaction of the dynamic socio-economic system to the availability of ICT services, including behavioral change (life styles) and economic structural change. On the negative side, rebound effects prevent the reduction of total material resource use despite decoupling (see Sect. 2.4) by converting efficiency improvements into additional consumption, and new risks may emerge, for example due to the vulnerability of ICT networks. On the positive side, ICT has the potential to support sustainable patterns of production and consumption.

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[17] For a detailed discussion of this example, see the chapter by Coroama et al. [13] in this volume.

Why is an induction effect not considered a rebound effect? The difference is one of perspective: An induction effect is the increase in the consumption of a specific resource as a consequence of applying ICT, viewed at the micro level. The rebound effect is the aggregated result of many processes interacting in a way that leads to increased consumption, viewed at the macro level. The same question could be asked with regard to substitution (or optimization) and sustainable production and consumption patterns.

The fact that these distinctions are not immediately clear reveals a weakness in the framework, namely that it mixes up levels of abstraction and categories of effects. If we understand Level 2 to be the economic micro-level—i.e., referring to substitutions and other ICT-related actions taking place in firms and private households—it is not determined what the aggregated effect of these actions will be at the macro-level. This is because the actions that we are describing in isolation are not actually isolated: In reality, they interact closely with each other via markets and other mechanisms of social coordination. The rebound effect is thus not an effect on the macro-level, but a concept related to the *relationship* between micro- and macro-level descriptions.

This criticism calls into question the whole idea of postulating normative categories of effects, at least at the micro-level. No substitution or optimization effect can be categorized as "sustainable" (or more precisely, conducive to sustainable development) a priori, as no induction or obsolescence effect can be considered "unsustainable" or harmful with regard to sustainable development a priori. Sustainable development (Definition 2) is defined on a global level, which implies that any analysis or assessment must ultimately take a macro-level perspective. Isolated actions cannot be considered part of the problem, nor part of the potential solution, unless there is a procedure in place for systematically assessing the macro-level impacts of micro-level actions.

4.2 The LES Model

The new model presented below builds on the matrix approach discussed above (Sect. 4.1), but with the following improvements:

- It avoids normative assumptions and tries to be purely descriptive.
- It connects better to production theory by reducing optimization to substitution.
- It connects better to the sociological structuration theory by using the dualism of action and structure.
- It can be extended, as it does not attempt to categorize all the possible effects of ICT.

We call our new model the "LES model," LES standing for the three levels of impact: Life-cycle impact, Enabling impact, and Structural impact. Structural impact represents the highest level of abstraction and thus comes at the top of the diagram (see Fig. 7). However, we shall describe the levels of impact starting with the lowest level first and moving upward.

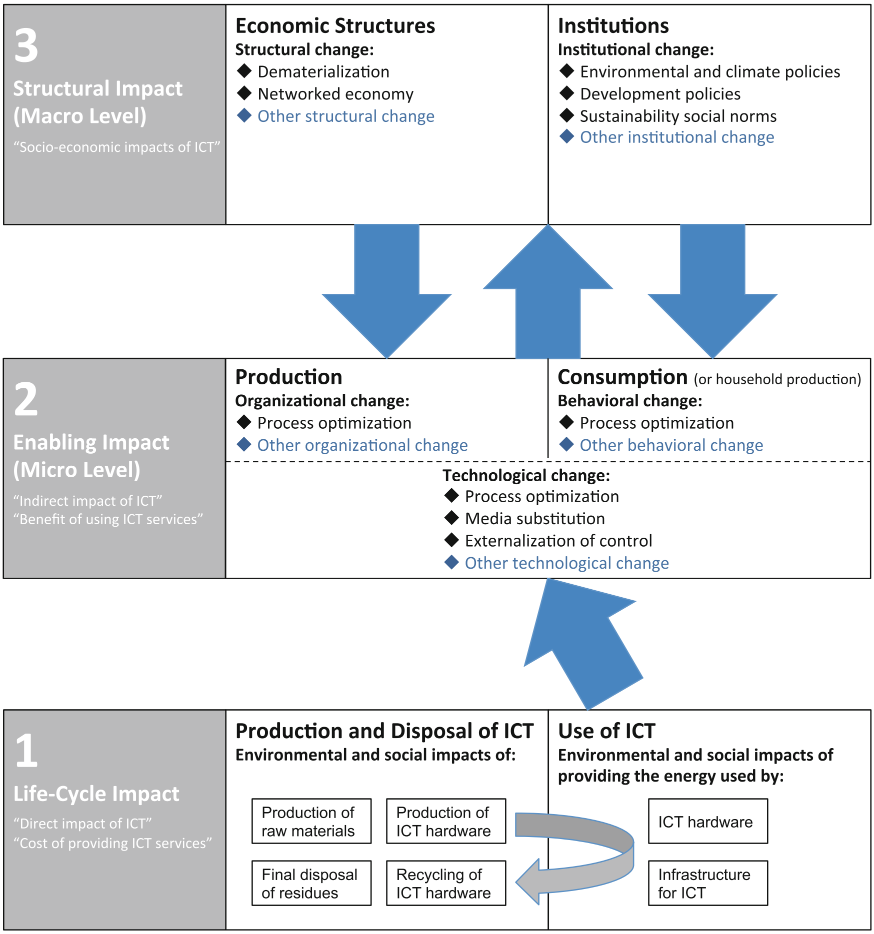

Fig. 7 The LES model

Level 1, Life-Cycle Impact. This refers to the effects caused by the physical actions needed to produce the raw materials for ICT hardware, to manufacture ICT hardware, to provide the electricity for using ICT systems (including the electricity for non-ICT infrastructures, such as cooling), to recycle ICT hardware, and finally to dispose of non-recycled waste. The total impact is then allocated to a functional unit of the service it produces during the use phase.

The method of choice for assessing life-cycle impacts is Life-Cycle Assessment (LCA). LCA connects the action of providing ICT to the use of natural resources. In some cases, it may be necessary to include an assessment of social impacts, for example the social impact of the mining activities required to produce the raw materials, or the social impact of informal recycling.

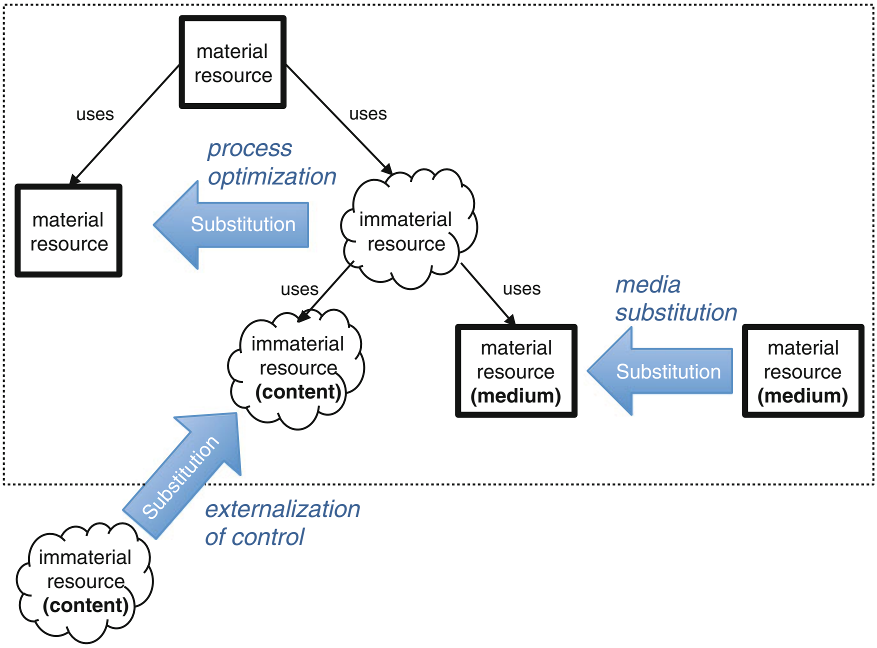

Fig. 8 Process optimization, media substitution, and externalization of control, explained as resource substitution: A material resource can be partially replaced by an immaterial resource (process optimization); the medium of an immaterial resource can be replaced by another medium (media substitution); and the content of an immaterial resource can be replaced by content provided from an external source (externalization of control)

In many practical cases, it may be sufficient simply to assess the energy consumption during the use phase in detail, and use default estimates for the production and end-of-life treatment.

Level 2, Enabling Impact. This refers to actions that are enabled by the application of ICT. In the context of sustainability, it is important to understand the effects of these actions on resource use. We therefore view all actions as processes of production or consumption. All impacts of ICT will be viewed as special types of substitution, thus linking the LES model to the definition of substitutability given further above (see Sect. 2.2, Definition 4).

The model differentiates between three types of enabling impact, each of which is based on substitution and can occur in both production and consumption: process optimization, media substitution, and externalization of control. Note that these three impacts occur in several places in the central part of Fig. 7.

These enabling impacts can be defined as special types of resource substitution in the following manner (see also Fig. 8):

- Process optimization as substituting an immaterial for a material resource
- Media substitution as substituting one material resource for another
- Externalization of control as substituting one immaterial resource for another

We discuss this in more detail below.

Process Optimization. All processes that have a purpose can be optimized by making use of information. Information is used to reduce the use of another resource by the process. This applies to production processes in businesses as well as to consumption by private households.[18] For example, a taxi driver may use a satellite navigation system to optimize the route taken when driving someone from A to B. If the driver of a private vehicle uses the same system to produce the same service for him- or herself, the optimization effect is essentially the same. In this sense, we may view process optimization as a category of enabling impact that applies to both production and consumption.

Process optimization is based, whether explicitly or implicitly, on an objective function that specifies the input resource that is to be minimized. According to production theory, this input resource may be labor, capital, or a natural resource (e.g., energy). Following the distinction between material and immaterial resources given in Sect. 2.2, these are all material resources. We can therefore view process optimization, which makes use of information, as *substituting immaterial for material resources*. At the same time, there may also be substitution between different material resources, depending on the objective function. The typical case here is industrial automation, which reduces labor at the cost of capital, energy, and information. However, it is also possible to substitute information for energy or time (without increasing energy use) within certain limits. Spreng's triangle, which describes the fundamental interactions between time, energy, and information, provides a basic framework for analyzing these substitutions (see [18], in this volume).[19]

Process optimization can occur either at a level where people are involved (e.g., organizational changes in production, behavioral changes in consumption) or at a purely technological level by making physical changes (see Fig. 7). For example, introducing sensors to control the lights in a building represents an optimization of the lighting process, one that does not involve organizational or behavioral change.

Media Substitution. As stated before, immaterial resources need a material resource as a substrate or *medium*. The prototypical enabling impact of ICT is the substitution of a digital electronic medium for the medium that was used previously. For example, public utilities may replace printed invoices sent by traditional mail with electronic invoices sent via the Internet. Although this is often referred to as "dematerialization," it actually involves *substituting one material resource with another material resource*. Whether this contributes to dematerialization as

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[18] Consumption processes are often similar to production processes, and can be viewed as "household production" (except for the last step, i.e., the consumption of the final good or service). For example, when baking a cake, a consumer transforms commodities purchased on the market into the final good, which is then consumed.

[19] Note that this terminology differs from that introduced in Sect. 4.1, which treats optimization and substitution as distinct concepts. In the LES model, process optimization is instead regarded as a special type of substitution.

we define it (i.e., as a special case of decoupling; see Sect. 2.4) is a question that requires systematic assessment in specific cases.[20]

Externalization of Control. Whenever a process requires information as one of its inputs, it is possible to externalize control over that process. If the information previously came from an internal source (i.e., from within the organization or household), this source can be replaced or complemented by an external source. Typically, this is enabled by a prior media substitution. For example, if a heating system is connected to the Internet, it can be controlled externally. This has the potential to lead to further optimizations (e.g., energy savings, remote maintenance), but also opens the door to possible misuse of data.

External control does not have to take place in real time. The distribution of software products has always represented a sort of external control over the system executing the software. In just the last few decades, update cycles have changed from years to days, and web-based applications are now close to real-time control.

Two effects of the "part of the problem" side of the matrix (Fig. 6), namely obsolescence and emerging risks, can be explained by the externalization of control. These two effects partially overlap:

- Obsolescence can occur if the provider of an external information resource has a monopoly on that resource and stops providing it; the customer's process is "no longer supported" and the capital attached to it devalued.[21]
- The fact that the external source of control can affect internal material resources creates the potential for misuse. In principle, external control can be used to create obsolescence by means of physical effects or for unwanted interference by third parties (as in the case of Stuxnet).
- The factual vulnerability of the ICT infrastructure creates risks for any system with external control.

Level 3, Structural Impact. The third level of the LES model refers to ICT impacts that lead to persistent changes observable at the macro level. Structures emerge from the entirety of actions at the micro level and, in turn, influence these actions. We focus here on two types of social structures: economic structures that emerge through the accumulation of capital, and institutions. Institutions, in the wider sense, include anything immaterial that shapes action, that is to say law, policies, social norms, and anything that can be regarded as the "rules of the game."

Structural Change. Structural change in general is any transition of economic structures. Two ongoing transitions connected to ICT are relevant for our discussion: dematerialization and the networked economy.

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[20] Examples of such assessments are given in the chapters by Coroama et al. [13] and by Hischier and Wäger [12] in this volume.

[21] Note that we are not claiming that this is the only mechanism that can promote obsolescence, but it is the one most likely to occur as an impact of ICT. This impact is not restricted to ICT devices but can also affect other products with embedded ICT (e.g., a blind control system).

We have defined dematerialization as a special case of decoupling (see Sect. 2.4). It can be viewed as a necessary but insufficient condition for sustainable development. In broad terms, dematerialization is the aggregate result of many process optimizations and media substitutions, moderated by rebound effects.

The networked economy is a new mode of production that has emerged with the appearance of the Internet and, in particular, Web 2.0 technologies. "The fundamental unit of such an economy is not the corporation but the individual. Tasks aren't assigned and controlled through a stable chain of management but rather are carried out autonomously by independent contractors." [68] This development may be relevant for sustainability in two ways. First, it may change the patterns of resource use in production in general. Second, it may be used specifically for projects aimed at contributing to sustainability—as in the case of MIT's Climate Co-Lab [69]—with the potential to tap the "wisdom of crowds." [70].

Institutions. To be relevant for sustainable development, institutional change usually involves environmental and development policies. These two types of policies are both crucial if society is to succeed in making sustainable use of the planet and meeting the needs of humanity.

ICT is indirectly involved in this through its key role in environmental monitoring and research, which shapes our view of the environment. ICT-based environmental information systems also support the implementation of environmental policies and regulations. In addition, ICT plays an important role in development, for example by providing people living in poverty who do not have bank accounts with alternative systems for carrying out financial transactions.

In a networked society, communication is more efficient and social norms evolve faster. This is conducive to the development of social norms related to sustainability, norms that are based on environmental and social awareness.

Extendability of the LES Model. The list of ICT impacts in the LES model is not intended to be exhaustive. Although we have tried to build the conceptual structure around a minimal set of basic concepts (material and immaterial resources, substitution, production, consumption, economic structure, institution), we are fully aware that, in reality, the world is more complex.

At Levels 2 and 3, where we could not draw upon an established methodology (unlike at Level 1), we have included "residual categories" at five different points:

- Level 2, other organizational change: Besides business process optimization, ICT can induce many organizational changes in production (e.g., flexible work patterns).
- Level 2, other behavioral change: This covers persuasive technologies, sustainable interaction design, and, more generally, research into social practices and lifestyles and their transformation.
- Level 2, other technological change: Some effects of ICT besides process optimization, media substitution, and externalization of control can potentially be implemented directly at the physical level.
- Level 3, other structural change: Economic structures may change in an ICT-based society in ways other than dematerialization and the network economy.

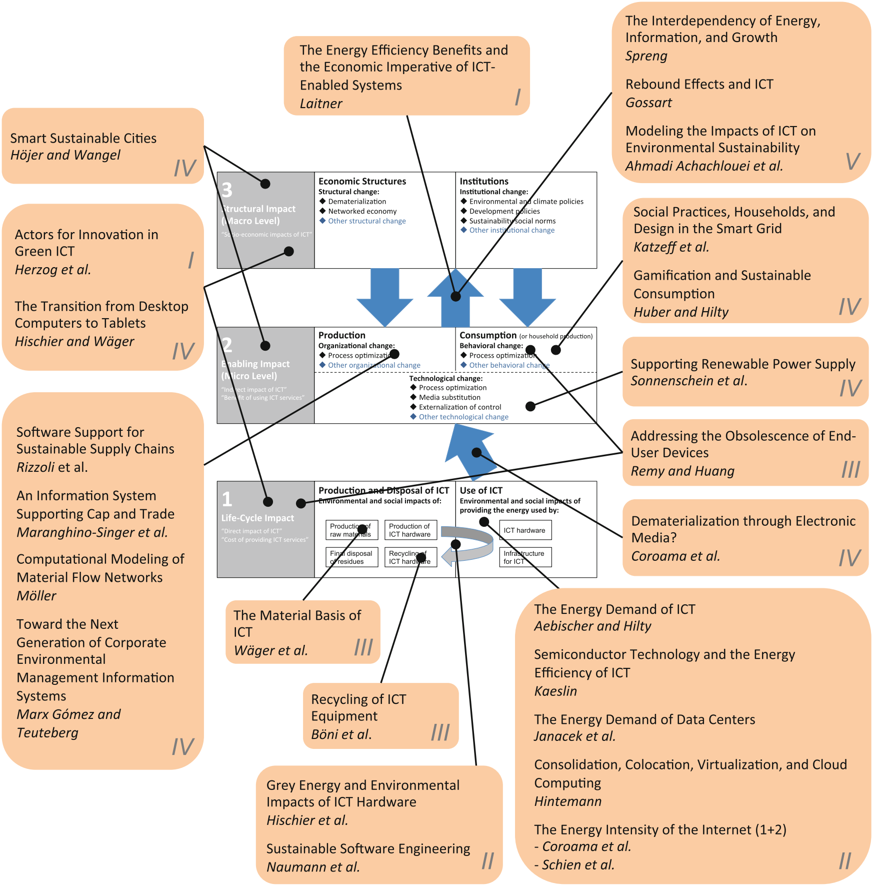

Fig. 9 The chapters of this book mapped onto the LES model (see Fig. 7 for a larger view of the model)

Issues such as intellectual property rights linked to media substitution may trigger a structural change in other directions.

- Level 3, other institutional change: Besides environmental policies, development policies, and social norms specifically connected to the issue of sustainability, many other institutional developments (e.g., ideological or religious developments) may be relevant for sustainable development.

5 Organization of This Book

This book is organized in five parts, as follows:

- Part I consists of three chapters introducing the topic of the book from different perspectives.

- Part II presents research into energy-related aspects of the ICT life cycle.
- Part III presents research into material aspects of the ICT life cycle.
- Part IV contains a collection of concepts, perspectives, and case studies on the enabling impact of ICT at the micro-level, including a number of assessments of aggregated effects.
- Part V consists of three chapters presenting frameworks and models for the link between the micro- and the macro-level.

In Fig. 9, we have attempted to map chapters to relevant parts of the LES model. Readers can use this map as a guide to identifying which chapters may be of greater interest to them. The map also reveals at least one "blind spot," Level 3: structural impact. Future research into ICT for sustainability should work more closely with the social sciences (including economics), so as to capture the full interaction between enabling impacts and the evolution of social structures.

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The Energy Efficiency Benefits and the Economic Imperative of ICT-Enabled Systems

John A. Skip Laitner

Abstract The global economy is not particularly energy-efficient. At current levels of consumption, we now waste about 86 % of the energy now used to maintain economic activity. This magnitude of waste imposes huge costs that constrain the robustness of the world economy. At the same time, however, there is an array of untapped cost-effective energy efficiency resources that can restore both energy and economic efficiency. Information and Communication Technologies (ICT) may be the key to unlocking that potential.

Keywords Information and communication technologies · Energy efficiency · Energy productivity

1 Introduction

In his speech "The American Scholar," philosopher Ralph Waldo Emerson noted an ancient oracle that said, "All things have two handles: beware of the wrong one" [1]. The continuing debate about ensuring an adequate supply of low-cost energy may be grabbing for the wrong handle. In a similar way, thinking about Information and Communication Technologies (ICT) merely as an emerging high tech market phenomenon may also be grabbing the wrong handle. It turns out that improvements in energy efficiency are critical drivers of a more robust and sustainable economy. At the same time, ICT devices, appliances, and networks may be the key to unlocking a more energy-efficient future.

All interactions of matter involve flows of energy. This is true whether they have to do with earthquakes, the movement of the planets, or the various biological and industrial processes at work anywhere in the world. Within the context of a

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regional or national economy, the assumption is that energy should be used as efficiently as possible. An industrial plant working two shifts a day 6 days a week for 50 weeks per year, for example, may require more than one million U.S. dollars (USD) per year in purchased energy if it is to maintain normal operations. An average American household may spend USD 2,000 or more per year for electricity and natural gas to heat, cool, and light the home as well as to power all of the appliances and devices within the house. And an over-the-road trucker may spend USD 1,500 on fuel to haul a load of freight 4,800 km from Quebec to Los Angeles. Regardless of either the scale or the kind of activity, a more energy-efficient operation can lower overall costs for the manufacturing plant, for the household, and for the trucker. The question is whether the annual energy bill savings are worth either the cost or the effort that might be necessary to become more energy-efficient?[1]

In one sense of the word, the global economy is hugely energy inefficient. At current levels of consumption, for example, the U.S. economy converts only 14 % of the total energy it uses into economic activity. This means that the United States is now wasting 86 % of its available energy resources [2].[2] With a similar level of energy intensity as the U.S. now maintains, the world economy is an anemic 14 % energy efficient. Drawing from the international energy statistics published by the U.S. Energy Information Administration (EIA) [4], the working estimate for Europe and Japan suggests that they are only marginally better at 18–20 % energy-efficient. That means, they continue to waste as much as 80–82 % of all the energy that that they consume.

Because of that very significant level of inefficiency around the world, many in the business and the policy community increasingly look to energy efficiency improvements as cost-effective investments to reduce waste and cut costs. One current example of this win–win opportunity is the advent of energy service companies (ESCO's) that save energy for clients, but at no upfront cost to the clients, while making a profit for themselves. As an example, the International Energy Agency (IEA) reports levels of ESCO spending that have grown from USD 1 billion in 2000 to USD 7 billion in 2011. This is an average annual growth rate of 20 %. Indeed, ESCOs are now active in close to 50 countries globally [5].

Perhaps more interesting, according to the IEA the annual routine investments for building and industry energy efficiency improvements are up to USD 300 billion globally in 2011. The IEA indicates this magnitude of annual spending on energy efficiency upgrades is at a scale that is similar to renewable energy and fossil fuel power sector investments. The reduced energy demand stemming from energy efficiency over the past decades is larger than any other single supply-side energy source for a significant share of IEA member countries. This, the IEA suggests, is driving energy efficiency to be our "first fuel" [5].

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[1] The mentioned examples of energy expenditures are derived from several calculations by the author.

[2] Laitner [2] builds on an updates work published by Ayres and War [3].

2 Historical Impact of Energy Efficiency

In many ways energy efficiency has been a continuing but also a seemingly invisible resource. Unlike a new power plant or a new oil well, we do not see energy efficiency immediately at work. A new car that uses 9.4 l per 100 km (25 miles per gallon), for example, may not seem all that much different than a car that requires only 4.7 l/100 km (50 miles per gallon). And yet, the first car may consume $\sim$250 gallons of gasoline to go 10,000 km in a single year while the second car, depending on how it is driven, may need only half that amount. In effect, energy efficiency in this example is the energy we do not use to travel 10,000 km per year. More broadly, energy efficiency may be thought of as the cost-effective investments in the energy we do not use either to produce some amount goods and services within the economy. Within that context we can ask how energy efficiency might compare to conventional energy resources.

Comparing economic activity over the period 1970 through 2010, the size of the global economy grew by about 3.9 times. Energy use, on the other hand, grew by only 2.4 times over that same period. In effect, the decoupling of economic growth and energy consumption was the result of increased energy productivity: in short, the ability to produce more goods and services, but doing so with less energy (and other resources). In a complementary analysis by the author, using a variety of IEA, EIA, and other available data, it appears that energy efficiency measures provided about one-half of the new demand for energy-related energy services over that 40-year time span. At the same time, analysis of 11 of the IEA member countries for which suitable data are available, indicates that between 1974 and 2010, energy efficiency was the single largest new energy resource that was brought online in that period (see Fig. 1).[3]

According to the IEA assessment, the avoided energy over the 36-year period was equal to 65 % of the total final consumption of energy in 2010. Over this time horizon, energy efficiency reduced growth in energy consumption to just 20 % of the 1974 levels. Said differently, without energy efficiency improvements, energy consumption would have increased by 93 %.

Having achieved these past gains, with an often ad hoc approach to energy efficiency improvements, there is compelling evidence to suggest that even greater energy productivity benefits can be achieved. Moreover, the evidence suggests that significant gains are not only possible, but they will be cost-effective as well. And as we shall see, ICT can be a critical part of the story.

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[3] The 11 countries are Australia, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Sweden, the United Kingdom and the United States. Estimated energy use is calculated on the basis of how much energy would have been required to deliver the actual levels of activity reported each year for all sub-sectors had 1974 levels of energy use per unit of output persisted. "Other" includes biofuels plus heat from geothermal, solar, co-generation and district heating. Co-generation refers to the combined production of heat and power.

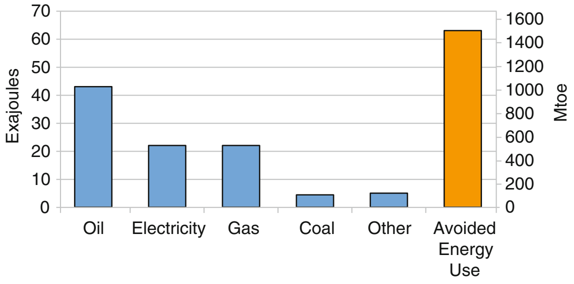

Fig. 1 The "first fuel": contribution of energy efficiency compared to other energy resources consumed in 2010 in 11 IEA member countries. *Source* IEA [5]

3 Cost-Effective Potential for Exploiting the Energy Efficiency Resource

Can the substantial investments that might be required in the more energy-efficient technologies save money for businesses and consumers? The *Efficient World Scenario* of the IEA *World Energy Outlook 2012* indicates that should policies remove market barriers and promote cost-effective energy efficiency measures, total primary energy supply could be reduced by an additional 900 million tonnes of oil (Mtoe) in 2020 beyond those reductions generated from current and announced policy interventions. This additional 900 Mtoe in avoided energy is equivalent to 7 % of 2010 global consumption, greater than the combined energy supply of Australia, Japan, Korea and New Zealand today. If achieved it would produce a corresponding reduction of USD 458 billion in consumer energy expenditures [6].

Lazard Asset Management [7] provides a detailed review of the various costs associated with electricity generation. They note, for instance, that meeting new energy demand by building new coal and nuclear power plants might cost an average of 6–15 cents per kWh of electricity generated. The costs for various renewable energy resources such as wind energy or photovoltaic energy systems (i.e. solar cells that convert sunlight directly into electricity) might range from 6 to 20 cents per kWh. In comparison, both Lazard and the American Council for an Energy-Efficient Economy (ACEEE) estimate a range of energy efficiency measures that might cost the equivalent of 3–5 cents per kWh of electricity service [8].

McKinsey and Company [9] in 2008 identified investments in energy efficiency that would generate at least a 10 % annual return. When spread out over time, McKinsey suggested a global energy efficiency market on the order of USD 170 billion per year with an average 17 % return. A subsequent McKinsey assessment stated that "energy efficiency offers a vast, low cost energy resource" in the United States [10]. If executed at scale, a holistic approach would yield energy savings worth more than USD 1,200 billion, well above the USD 520 billion needed through 2020 for upfront investment in energy efficiency measures. This is a sufficient cost-effective opportunity to reduce the nation's energy use in 2020 by roughly 23 % from business as usual projections—should the U.S. choose to invest in the more efficient use of its energy resources.

Such investments can deliver dramatic reductions in pollution. The Union of Concerned Scientists [11] recently published a detailed portfolio of technology and program options that would lower U.S. heat-trapping greenhouse gas emissions 56 % below 2005 levels in 2030. Their analysis indicated an annual USD 414 billion savings for U.S. households, vehicle owners, businesses, and industries by 2030. After subtracting out the annual USD 160 billion costs of the various policy and technology options, the net savings are on the order of USD 255 billion per year. Over the entire 2010 through 2030 study period, the net cumulative savings to consumers and businesses were calculated to be on the order of USD 1,700 billion under their recommended scenario (with all values in 2006 dollars).

More recently, Laitner et al. [12] documented an array of untapped, cost-effective energy efficiency resources roughly equivalent to 250 billion barrels of oil. That is a sufficient scale to enable the United States to cut total energy needs in half compared to business-as-usual projections for the year 2050. Capturing this energy efficiency resource could generate from 1.3 to 1.9 million jobs while saving all residential and business consumers a net USD 400 billion per year, or the equivalent of about USD 2,600 per household annually (in 2010 dollars).

At the international level, Copenhagen Economics [13] suggests that energy efficiency improvements in buildings alone, throughout the European Union, might lower total energy use by 8–12 % by 2030. This would require gross annual investments of 41 billion euros to 78 billion euros per year, but those investments would also deliver ongoing annual returns of 104 billion euros to 175 billion euros.

Pushing an innovation-led investment strategy, Nord-Pas de Calais, a former coal-mining and still heavy industrial region of 4 million people in northern France, accepted a Third Industrial Revolution Master Plan that, if successful, would reduce final energy use by as much as 60 % by 2050. As the plan laid it out, renewable energy technologies would power all remaining energy needs, also by 2050 [14]. The preliminary estimate of the total investment needed to drive the energy efficiency/renewable energy transition is on the order of 210 billion euros (in constant 2005 euros) over the period 2014–2050. This averages to a little more than 6 billion euros per year, or about 5 % of the region's GDP over that 37-year period. The substantial economic returns to Nord-Pas de Calais—including both the lower costs of energy and a more robust economy—would be about 1.7 times the total cost of the upfront investment. And the combination of investments and energy bill savings would generate an average 100,000 new jobs for that region with as many as 165,000 new jobs by 2050. In other words, the improved productivity, supported by the Third Industrial Revolution Master Plan, would measurably strengthen the region's overall economy.

There is a further aspect that merits a brief review—the non-energy benefits that typically accrue to energy efficiency investments. When energy efficiency measures are implemented in the industrial, commercial, or residential settings, several non-energy benefits such as maintenance cost savings and enhanced productivity benefits can often result—in addition to the anticipated energy savings. The magnitude of non-energy benefits from energy efficiency measures is significant. In one study of 52 industrial efficiency upgrades, all undertaken in separate industrial facilities across a number of different countries, Worrell et al. [15] found that the non-energy benefits were sufficiently large that they lowered the aggregate simple payback for energy efficiency projects from 4.2 years to 1.9 years.

Another study for 81 separate industrial energy efficiency projects showed that the simple payback from energy savings alone was less than 2 years, indicating annual returns higher than 50 %. When non-energy benefits were factored into the analysis, the simple payback fell to just under 1 year [16]. In residential buildings, non-energy benefits have been estimated to represent between 10 and 50 % of household energy savings [17]. Unfortunately, these non-energy benefits from energy efficiency measures are often omitted from conventional performance metrics. This leads, in turn, to overly modest payback calculations and an imperfect understanding of the full benefit of additional efficiency investments.

With this backdrop we can return to the report by Copenhagen Economics which actually decomposes the annual building energy efficiency benefits into a broader category of impacts. They include reduced air pollution, improved health benefits, and annual improvements of public finances as fewer long-term subsidies are needed. In fact, Copenhagen Economics actually broke down the economic returns—the previously referenced annual benefit to society of €104–175 billion in 2020—into those same three major categories: (i) €52–75 billion from lower energy bills, (ii) at least €9–12 billion from the co-benefits of reduced outlay on subsidies and reduced air pollution from energy production; and (iii) €42–88 billion in health benefits from improved indoor climate. If investments are continued after 2020, they noted, the annual benefits could be doubled by 2030.

4 The ICT Contribution

How might we think about the ICT-enabled contributions to the energy efficiency potential? First, we might simply step back and imagine how much easier it might be to move electrons around than to ship people or goods over long distances. Or to move information that can be acted, but using less energy. Hence, the more we can do to substitute the flow of information for goods that should lead to a reduction in the use of energy and materials. As an example, Cisco estimates there will be the very large sum of 830 exabytes of data that will flow through a variety of communication tools in 2014 [18]. Adding up all the incredibly light electrons that will be needed to hold all those bits of information in place, we might suggest a weight of only 3.4 millionths of an ounce. Yet, if we printed all of that information on paper, it might require, instead, more like 165 billion tons of paper.[4]

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[4] As a further insight, the 830 exabytes will be up significantly from 523 exabytes recorded in 2012, and heading for 1,448 exabytes or 1.4 zettabytes by 2017. That will translate into an average annual compound growth rate of 23 % over the period 2012–2017 [18].

Many of the assessments to date tend to focus on the direct energy requirements associated with different aspects of ICT-enabled systems. Coroama and Hilty [19], for example, provide a thoughtful overview of studies along these lines. As they properly note, assessing “the average energy intensity of Internet transmissions is a complex task that has been a controversial subject of discussion.” They document estimates published over the last decade “which diverge by up to four orders of magnitude—from 0.0064 to 136 kWh/GB” [19].[5]

Laitner et al. [22], on the other hand, note that energy intensity appears to be coming down as projected by the EIA’s *Annual Energy Outlook*. Looking at the year 2030, as an example, the *Annual Energy Outlook 2008* was forecasting that, in the United States, ICT-related activities might require 8.6 % of all electricity needs in that year. In the most recent 2014 projections, however, total demands in 2030 are down to just 2.8 %—even as total electricity consumption itself is now forecast to be 11 % lower than was previously estimated for 2030. The former reduction appears to be related to greater efficiencies in the equipment while the latter impact may be a greater rate of unexpected efficiency gains. That, of course, may well be driven, in turn, by the so-called substitution effect—or substituting the greater uses of electronics and ICT technologies and networks for primary energy.[6]

Evidence of this latter impact comes from a report sponsored by the Global-e Sustainability Initiative (GeSI). In 2012 Laitner, Partridge, and Vittore [23] explored the micro-level of energy efficiency associated with increased adoption of ICT and broadband services at the residential level. They examined eight consumer activities enabled by the development of broadband technology: telecommuting, use of the Internet as a primary news source, downloading video/music, online banking, online auctions/purchases, online education, use of digital photography, and use of e-mail. Assuming an upper end of reasonable adoption of all eight residential activities, the study found the U.S. could generate an annual net energy savings of about 336 million barrels of oil, equivalent to 2 % of total U.S. energy consumption. In a comparable finding, the five EU nations of France, Germany, Italy, Spain and the U.K would be able to save an annual net energy savings of 164 million barrels of oil, equivalent to 2 % of total energy consumption in those countries.[7]

While primarily focused on reducing greenhouse gas emissions, two complementary GeSI studies point the way to significant gains in energy efficiency. In 2008 the Global e-Sustainability Initiative (GeSI) demonstrated how ICT is making the world’s energy infrastructure more efficient and concluded that smart grids, buildings and transport along with travel substitution could reduce global

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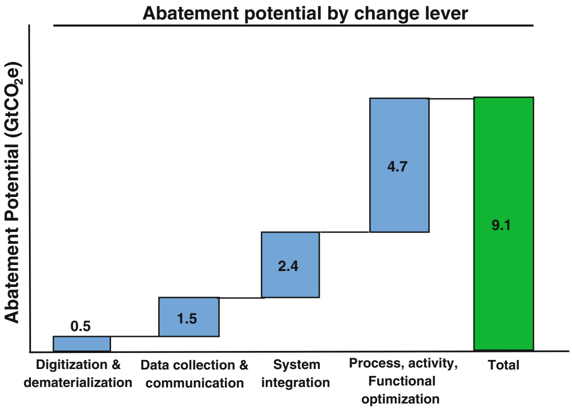
[5] An update on the state of research in Internet energy intensity is provided in two later chapters of this book [20, 21].

[6] The calculations in this paragraph exclude televisions and related equipment as among the ICT-related technologies.

[7] The emphasis here and elsewhere is on net energy savings. That is to say, the studies cited here reflect both the energy necessary to build, operate and maintain ICT-related technologies as well as the energy displaced by the use of those technologies.

Fig. 2 Mechanisms of greenhouse gas emissions reductions. *Source* GeSI 2012 [25]



carbon emissions by a net 15 % and save up to €600 billion by 2020 [24]. Most recently the GeSI *Smarter 2020* study found that the total abatement potential of ICT-enabled solutions in 2020 was about 9.1 gigatons of carbon dioxide equivalent ($GtCO_2e$), a savings of about 16.5 % of global GHG emissions by 2020. This is roughly equivalent as USD 1.9 trillion in gross energy and fuel savings and a savings of 21.6 billion barrels of oil [25]. Figure 2 shows the various mechanisms that helped achieve the overall savings.

Digitization and dematerialization, relying primarily on existing technologies that substitute or eliminate the need for a carbon intensive product, were shown to achieve 0.5 $GtCO_2e$. The use of social media and networking (data collection and communication) were shown to reduce emissions by 1.5 $GtCO_2e$.[8] Systems integration—primarily building or industrial management systems and the use of less-carbon intensive, renewable energy technologies—were shown to save 2.4 $GtCO_2e$ while the use of intelligent simulation, the automation of infrastructure, and industrial processes more broadly, were shown to save 4.7 $GtCO_2e$.

Using a top-down assessment, Laitner [28] reported that the deployment of semiconductor-enabled technologies since 1976 generated a sufficient energy productivity benefit across the entire U.S. economy to reduce total electricity consumption by 20 % compared to an economy without the benefit of those technologies. In other words, the family of semiconductor technologies now at work within the economy appears to have amplified the productivity of buildings and equipment, labor, and energy resources well beyond normally expected returns.

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[8] Related to the social media and networking mechanism is the role of consumer feedback. In a 2010 detailed review of 57 multi-continent studies over a 30-year period, Ehrhardt-Martinez et al. [26] showed that feedback initiatives—including real-time Web-based or in-home feedback devices and enhanced billing approaches–reduced individual household electricity consumption an average 4–12 %. Huber and Hilty [27] provide a brief overview of eco-feedback systems and related approaches in their chapter about gamification in this volume.

Although the impact of energy productivity has been significant, a further analysis indicated that a policy-driven semiconductor-enabled efficiency scenario (SEES) might stimulate an average annual investment of about USD 22.5 billion over the period from 2010 through 2030. More interesting, the findings also suggested an average electricity bill savings on the order of USD 61 billion during that same period of analysis. Even if the assessment includes program and administration costs necessary to drive that result, the net savings were still more than twice the total cost of the scenario. Perhaps an even more compelling outcome is the impact on employment. The working analysis suggested that, because energy-related expenditures are so much less labor intensive than almost all other consumer expenditures within the economy, the energy bill savings would support a net increase of about 553,000 jobs over that same 20-year period. This suggests an important additional benefit from the deployment of ICT-related technologies.

5 Overcoming Barriers to Improving Energy Efficiency

There is a range of market imperfections, market barriers, and real world behaviors that leaves substantial room for public policy to induce behavioral changes that produce economic benefits. One classic example is the misaligned incentive that exists for those living in rental units when the renter pays the energy bills but the landlord purchases the large appliances such as refrigerators and water heaters. In this case, the purchaser of the durable good does not reap the benefits of greater energy efficiency. The Market Advisory Committee of the California Air Resources Board [29] provides a nice short overview of key market failures.[9] A deeper exploration of the types of market barriers is beyond the scope of this paper, but others have done work to map this terrain [30–35].

The importance of reflecting policies that might be directed at market failures was explored, in part, by Hanson and Laitner. In one of the few top-down models that explicitly reflects both policies and behavioral changes as a complement to pricing signals, they found that the combination of both price and non-pricing policies (e.g., performance standards, eco-labeling, and product information more broadly)

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[9] Following are examples of three important market failures and suggested remedies: (1) step-change technology development in which there may be many uncertainties about appropriate technologies, as well as both market, and policy risks. Temporary incentives might be used to encourage companies to deploy new technologies at sufficient scale in ways that benefit the public good. Other remedies might include energy efficiency resource standards, energy or fuel performance standards and low-carbon fuel standards. (2) Fragmented supply chains—where economically rational investments (for example, energy efficiency in buildings) are not executed because of the complex supply chain. Examples of remedies are building codes or incentives for performance upgrades. (3) Consumer behavior where individuals have demonstrated high discount rates for investments in energy efficiency. Examples of remedies are vehicle and appliance efficiency standards and rebate programs [29].

actually resulted in a significantly greater level of energy efficiency gains and a lower carbon permit price to achieve the same level of emissions reductions [36].

One critical comment on the rebound effect may be appropriate at this point.[10] Lower energy prices and a positive income effect are likely to follow these energy efficiency improvements. These, in turn, may erode some of the net energy savings as lower prices and a slightly higher income encourage more energy use. But as Ehrhardt-Martinez and Laitner point out [38], this rebound effect is likely to be limited to 10–30 % of the initial energy savings in the short term. Moreover, just as we learn how to manage efficiency improvements, we can also learn over time how to mitigate the rebound effect with improved resource management strategies and people-centered energy initiatives. On balance, the net ICT energy savings and benefits are likely to remain significant—if we choose to pursue the full set of energy efficiency opportunities.

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[10] Gossart [37] provides an overview of the literature on rebound effects in an ICT context later in this volume.

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Actors for Innovation in Green IT

Christina Herzog, Laurent Lefèvre and Jean-Marc Pierson

Abstract Green IT is a mandatory process required for energy consumption reduction and sustainable development. Many actors are involved in the development and adoption of Green IT, ranging from individual persons to research groups, companies, governments, and countries. This chapter identifies actors for innovation in the field of Green IT, explores, and defines them. Their interactions are detailed and their influence on the Green IT landscape is pointed out. A definition of Green IT is given as a common understanding to form a basis for all further investigations of this sector. Then we detail the different actors of innovation in Green IT and outline their relationships to understand the keys for better development and adoption of Green IT.

Keywords Green IT · Standardization · Innovation

1 Introduction

Greening IT is a process required for reducing the consumption of energy and scarce materials used in IT. Green IT is a factor of innovation which can be considered as a large potential impacting contributor in terms of employment and societal improvements.

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This domain is being explored by a large number of academic and industrial research groups through the world. To be more impactive, it requires formalized links and support from various bodies (funding agencies, standardization bodies, technology transfer offices (TTO), etc.). It is crucial to understand the interactions between these entities in order to improve Green IT adoption and advancements. This chapter proposes to define the set of actors involved in innovation in Green IT: standardization bodies, influential groups, funding agencies, universities and academic research institutes, companies, technology transfer offices, and business angels.

We will explore involved actors using a standardized canvas which consists of defining the actors, giving some illustrative examples, analyzing the leverages for Green IT development and focusing on their potential for boosting it or slowing it down. This canvas will be also used for analyzing the links between selected actors in given scenarios.

While describing actors and their links in a formal model is fundamental, we have also investigated the implementation of such a model in a multi-agent system. We will briefly introduce this aspect so as to explain how the consideration of this chapter can be eventually concretized in a simulator.

The organization of this chapter is as follows: It will quickly revisit the definition of Green IT in Sect. 2. The formalized actors developing innovation in Green IT will be considered in Sect. 3, and in Sect. 4 actors supporting Green IT advances will be described. Section 5 will carefully select and analyze some scenarios in order to illustrate links and interactions between subsets of actors. Section 6 will present models for innovation and briefly describe our methodology for implementing a simulator of the complex system, and Sect. 7 will conclude this chapter.

2 Green IT

A large number of definitions of Green IT exist in the scientific and public press, in the scientific community, and in general discussions. These definitions take several aspects into account, such as optimizing cooling, optimizing server placement in data centers, shutting down unused devices from screens to complete servers, etc. They are more or less general. Some definitions also deal with economic aspects, while others focus mainly on energy management.

In our work, we use the life-cycle view given by Hilty [1]. Green IT must be involved in every phase, not only the use phase, but also production and end of life. Green IT helps to decrease the ecological damages which we all have to pay. Unfortunately the real costs for production and the “costs” for our environment are often not taken into account while we still will have to pay for them: hardware producing and recycling, with the societal aspects of people living in these areas where raw materials came from or are dismantled. Murugesan defines the field of green computing in [2] as “the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems—such as monitors, printers, storage devices, and networking and communication systems—efficiently and effectively with minimal or no impact on the environment". Many such slightly different definitions of Green IT exist due to the youth of this research field. Energy consumption awareness, the impacts of hardware production on the environment, recycling of IT equipment, etc. have become important public topics only during recent years. Previously, these issues were less discussed in IT and not at all in IT research.

Based on various definitions and motivations for Green IT, a basis for this work is stated: "Green IT is the effort to reduce resource consumption and environmental impact in IT. The reason for using Green IT may arise from economic, social, or ecological interests. Actions can affect the whole life cycle of IT—from construction via utilization through to disposal".

In the following, the actors for innovation in Green IT are considered, following the above definition. In some cases, actors may push more in the ecological dimension, some others in the economical dimension, and yet others in societal dimensions. It is idealistic (and not reasonable) to state that one actor drives in just one direction, hence every actor will have a mix of interests in Green IT, viewed from these three dimensions. These different interests may boost innovation differently.

3 Actors Developing Innovation in Green IT

As in any other technical or scientific field, many actors are involved in the development and adoption of Green IT. These actors are diverse by nature, by interest and motivation, and by means of changing the field. They span from individual persons (e.g., an activist, a researcher, a consultant), research groups in academia (research institutes, universities, academic research networks), companies (developing technologies, advising companies), groups of companies (influential and lobbying groups), governments (through public incentives, laws), to groups of governments (e.g., European Union).

All the actors interact in a kind of microcosm building and feeding each other, influencing and moving forward toward Green IT, at least toward their own view of Green IT. Before discussing their links in Sect. 4, we will oversee here some actors of innovation. The following actors may boost or slow down the development of innovation in Green IT, depending on different factors.

Formally, in this section we will detail some of the actors involved in the development of innovation in Green IT. The methodology we pursue is the following: We first define the actor, give some examples, and name the action leverages this actor can have in developing Green IT. We try to outline the boost this actor is giving to the field, or, conversely, the slowdown the actor may provoke.

In [3] we studied the similarities and differences between academia and industry related to 13 dimensions grouped in 3 categories: the process of research and innovation; the criteria of success and dissemination aspects; the organization. This section can therefore be seen as an extension of this preliminary work as well as its modeling.

We will explore involved actors through a standardized framework which consists in defining the actor (a), giving some examples (b), analyzing the leverages for Green IT development (c) and focusing on the potential boosting or slowing down features (d).

3.1 Standardization Bodies

(a) *Definition*. This section does not aim at giving a full global view of the Green IT standardization initiatives, but rather tries to outline the role and links between and among the standardization bodies [4, 5]. It is based on a study on the standardization bodies in the field of data center energy efficiency [6], complemented with newer developments in standardization efforts.

Standardization bodies can be categorized in two categories: (i) international formal standardization bodies (and their regional and national counterparts); (ii) influential groups and professional bodies. The section will describe category (i) in more detail. Category (ii) is described in the following section (Sect. 3.2).

In Fig. 1, one can see that the first providers of materials and tools that may make their way to actual standards are industry alliances, academic researchers, or both in collaborative projects. Some of the proposed ideas may be presented in one or several standardization bodies to eventually become standards. These standards can in turn be used by governments (at the national, federal, or European levels) as regulations in laws that must (and can) be enforced. Governments can use the materials directly as regulations, recommendations, or labels. While the process for formal standardization takes a long time since a consensus has to be achieved between all members (especially states), the direct link with governments is sometimes more efficient. Finally, it must be noted that some metrics, tools, and methods provided by industry and academia are used directly by final users and may become de facto standards. At the center of the figure is the certification authority whose role is to certify that the measurements claimed by suppliers of technologies actually follow the standards, the labels, or the recommendations.

(b) *Examples of Standardization Bodies*. The ISO (International Standardization Organization), the IEC (International Electrotechnical Commission), the IEEE-SA (Institute of Electrical and Electronics Engineers Standards Association) and the UN ITU (United Nations International Telecommunications Union) are three important bodies in the Green IT landscape.

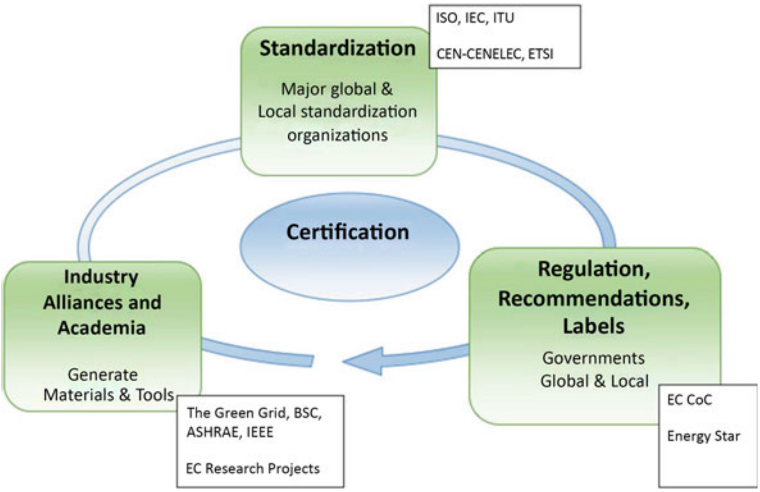

Fig. 1 Standardization stakeholders

(c) *Leverages for Green IT Development*. All three standardization bodies have activities in Green IT in general and in data center energy efficiency in particular. Their action lies in the development of standards, some individually, others in joint groups. The standards range from the design, the production, and the operation, to the recycling of IT services and materials. Some standards may be used directly by stakeholders or by states for regulation.

For instance, ISO 14064-1 is used for reporting on greenhouse gases and makes use of the GHG Protocol, while ISO 14101 addresses the environmental impact of an organization in general. Within IEC, Task Committee 111 is interested in environmental standardization for electrical and electronic products and systems. UN ITU-T Study Group 5 evaluates the effects of ICT on climate change and publishes guidelines for using ICT in an eco-friendly way. It is also responsible for studying design methodologies to reduce environmental effects. ITU-T L.1200 specifies the Direct Current interfaces while ITU-T L.1300 describes best practices to reduce negative impact of datacenters on climate.

Joint Technical Committees (JTC) are established between ISO and IEC in specific areas. JTC 1/SC 39 is the joint sub-committee on "Sustainability for and by Information Technology." The framework for describing metrics for energy efficiency is in flux and must be considered when developing new metrics for their standardization: standards 30134-1 (General Requirements and Definitions) and 30134-2 (Power-Usage Effectiveness, PUE).

At the regional level, concerning European standardization activities on data centers, ETSI (European Telecommunication Standard Institute) is responsible for the network, CENELEC (European Committee for Electrotechnical Standardisation) for the power infrastructure, CEN for IT management, ASHRAE for cooling (not EU-specific), and CEN/CENELEC for monitoring. The need for having joint and coordinated groups is obvious with so many different actors involved. The establishment of the Coordination Group on Green Data Centers (CEN-CENELEC-ETSI) helps to harmonize initiatives.

(d) *Boosting or slowing down*. Without a doubt, the role of standardization is globally, and in the long term, boosting the adoption of a technology and its dissemination throughout society. However, in the context of Green IT and IT in general, the duration of the standardization process is often not compatible with the pace of innovation. One such example is the TCP/IP protocol stack never standardized but de facto a standard. In Green IT, the same applies to PUE, which is still under development in standardization bodies, while already widely adopted (and sometimes misused) by industry.

3.2 Influential Groups

(a) *Definition*. Complementary to standardization bodies, some influential groups propose to enforce and influence development of Green IT by addressing the issue at various levels. Some are country-based, others interact at the global level. Some are purely industrial or academic, others are a mix of both. Some of these groups can be activated by governments, and some can also propose and defend some standards.

(b) *Examples*. The Green Grid is a non-profit organization, an open industry consortium of IT suppliers, end users, policy-makers, technology providers, and utility companies. Its aim is to unite global industry efforts, to create sets of metrics, and to develop educational tools. There is a strong link with the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), The Chartered Institute for IT (BCS), and the China Communications Standards Association (CCSA).

The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) is an organization within the IEEE developing global standards in a broad range of industries. IEEE-SA promotes its own standards for electronic products. In Green IT, it addresses desktop personal computers, laptops, and personal monitors. The standard covers environmental aspects of a product along the entire life cycle.

The GreenTouch initiative is devoted to exploring energy efficiency in networks. The main goal of this large academic and industrial consortium is to support an increase in network energy efficiency by a factor of 1,000 by 2015. This group explores all levels of technology and innovation associated with networks: wired and optical, wireless, routing and switching, services, etc.

(c) *Leverages for Green IT Development*. The influential groups can have a major impact on promoting and developing Green IT. By supporting collaborations and direct links between diversified partners, they enforce the promotion and dissemination of innovation.

(d) *Boosting or slowing down.* Like standardization bodies, influential groups have a large potential to boost Green IT development. But contrary to these bodies, with some disruptive supported approaches (like in GreenTouch), they bypass limitations due to long processes.

3.3 Universities/Academic Institutes

(a) *Definition.* Universities and academic institutes include the groups involved in the development of Green IT through academic research. These groups can be financially supported through a mix of international, European, national, regional, or private funding. Innovation in Green IT can come from permanent or temporary contributors: professors and assistant professors, researchers, postdocs, PhD, graduate, and undergraduate students, engineers.

(b) *Examples.* These actors include purely university research groups and groups at research institutes.

(c) *Leverages for Green IT development.* Academic researchers can have an excellent research overview due to their ongoing exchange with other academic research institutions. This overview allows them to connect various research ideas and to be up-to-date with new developments in research. Due to participation in conferences, collaboration in journals, and other activities together with researchers from other universities, a worldwide network of researchers exists. This community interacts on special issues of well-defined research. This specification leads to a very high level of scientific exchange producing new ideas with the possibility to prove easily whether it makes sense to continue in a particular direction, whether this direction can be considered useful or not, or if this idea has already been investigated—and if so, what are the existing but not yet published results.

(d) *Boosting or slowing down.* With some “freedom” in exploring new and disruptive fields, this actor can be a major contributor in boosting innovation in Green IT. But researchers may lack links to industry as they are not required to seek out cooperation with industry. This missing link may lead to the fact that the research work and results do not meet the demands of industry.

3.4 Companies

(a) *Definition.* A company can be defined as an “artificial person,” invisible, intangible, created by or under law, with a discrete legal entity, perpetual succession, and a company seal. It is an association of individuals (natural or legal persons or a combination of both). Company members share a common purpose, organizing their resources and skills to achieve a well-defined goal.

(b) *Examples*. In this set of actors, we find many different companies, from SMEs to large groups. Their potential influence is related to their size and importance in the field. Besides the large historic companies such as IBM, some newcomers concentrate especially on the field of Green IT (to differentiate their business value) and may become the next generation giant (or be bought by it).

(c) *Leverages for Green IT development*. A customer-company relationship always exists, meaning that the company is close to changes in society, the first one to get to know new trends, hypes, and interests. Companies may react quickly to these changes as a new hype also means a new market for them, hence new business/ profit to be made. A company may also create new hypes in proposing new technologies. This relationship holds the impact for developing innovations in Green IT. With society discussing "being green and greener," companies propose greener products with additional features, creating a new hype, which forces competitors to follow this direction and moreover inspires research institutions and funding agencies to take new directions.

(d) *Boosting or slowing down*. On the one hand, companies may boost innovation for Green IT, but on the other hand they also have the possibility to slow Green IT and innovation in general. As a rule, companies are interested in making money, doing business, and staying on the market. If an innovation could decrease their turnover or favor another brand, a company may protect an innovation with the aim of not bringing it to market.

In [3] the different approaches are presented and some are investigated more deeply to show the differences between academia and industry.

4 Actors Supporting Innovation for Green IT

4.1 Funding Agencies

(a) *Definition*. Funding Agencies are organizations providing the mechanisms in which financial incentives are provided to academia or industry individually, or both together. Innovations in Green IT are influenced by funding organizations, as they drive academia in certain directions of research when deciding the topics of open calls.

(b) *Examples*. The European Framework Program 7 and the new Horizon 2020, the French National Agency for Research, and the German FWF (Fonds zur Förderung der wissenschaftlichen Forschung) fall in this category. Countries may have dedicated agencies for Green aspects such the US EPA.

(c) *Leverages for Green IT development.* Before funding agencies publish an open call, experts are invited to give their ideas about new interesting research. Even at this stage, these experts are deciding the direction of research for the upcoming years, as these calls are in general fixed for at least one year. By using money as an incentive, the impact of such open calls on Green IT development is both direct (for the actors benefiting from the grants) and indirect (since these actors will have a societal and economic impact on their own).

(d) *Boosting or slowing down.* A difficulty arises from this situation in that new research ideas, social movements, and upcoming trends cannot be taken into account immediately. Additionally, the high administrative workload creates difficulties for organizations applying for funding. Identifying partners with whom to form a consortium according to the rules of the funding organization takes time, and consortia are not always formed by the requirements of the work packages, but more because partners are needed to respect the rules of the funding organization. Energy and money are wasted because rules for open calls are too strict, and organizations waste time due to burdensome administrative requirements instead of using this time for new research. The advantage of these funding organizations is that they group research ideas and that their research funds are rather large. Funding agencies provide grants for fundamental research, while other actors involved in the innovation process are interested in applied research.

The role of funding organizations will have to change to become a real booster for innovative research. This does not mean that the traditional role has to disappear, but rather that additional roles have to be created.

4.2 Technology Transfer Offices

(a) *Definition.* Technology transfer describes the formal process of transferring rights from scientific research to another party. The aim is to use and commercialize innovative research and results. These rights might be intellectual property (IP) in form of patents, copyrights, or any other form of IP, depending on the product or result of the research. This process involves invention disclosure, licensing, funded research, and also start-up ventures. Research may be sponsored in the form of milestone payments, and it may generate licensing royalties. Most academic and research institutions have now formalized their technology transfer policies. These policies do not always fit with the needs of industry, and TTOs have to find the best way to combine the two sets of interests. TTOs are the interface between industry and research institution. Figure 2 is describing the functioning of TTOs.

(b) *Examples.* In France, the government created a special company status names as SATT, for Technology Transfer. Some universities created their own TTO within this framework, like for instance TTT (Toulouse Technology Transfer).

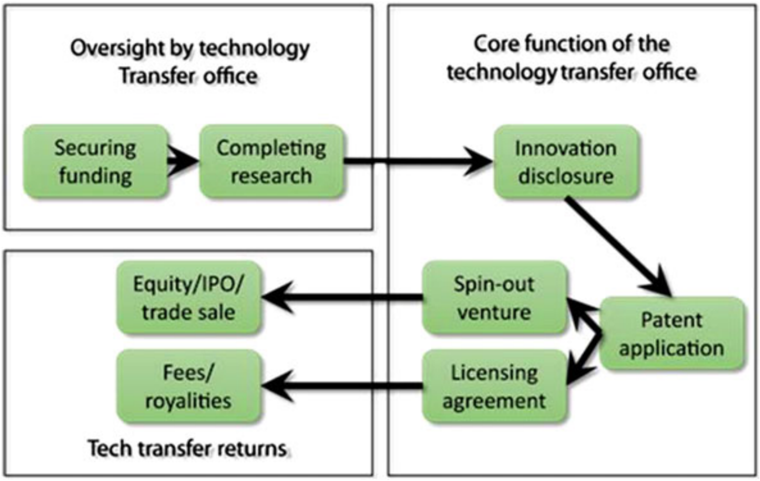

Fig. 2 Technology Transfer Offices' roles in innovation transfer

(c) *Leverages for Green IT development*. Technology transfer may be divided into 4 phases:

- The TTO has a relationship with the research institution. This relationship might be with one specific researcher, with the entire research staff, or with the whole institution. The TTO monitors ongoing research and provides links to commercial partners to fund ongoing research.
- Once the researcher files an invention disclosure with the institution, the TTO evaluates the commercial perspectives and possibilities. If the invention has potential, the TTO will pursue the patent application.
- Once the patent application is filed, the TTO will actively pursue commercial partners for license agreements or other forms of alliances.
- Fees and royalties emerging from commercialization will be paid. The TTO has the aim to become financially self-sufficient, but the research institution has different aims, such as societal benefit or enhancing its own reputation.

(d) *Boosting or slowing down*. TTOs boost new research, as they observe ongoing research as well as industry and the market and can quickly give feedback whether the research may be accepted on the market and meets the needs of industry. But TTOs are interested in financial independence, and it might be the case that they only see the financial return and not the innovation for society. Generally speaking, TTOs are rather new in some countries, and it remains to be seen whether they will become important actors.

4.3 Business Angels

(a) *Definition*. A business angel is an individual providing capital, but also knowledge and contact data, for a business start-up in a very early stage of its creation. Business angels are generally successful managers with more experience than the founder of a company.

(b) *Examples*. The World Business Angel Association is an international organization with the aim of promoting the idea of business angels and stimulating the exchange of knowledge and best practices in angel investing. This not-for-profit organization is based in Brussels and operates worldwide.

(c) *Leverages for Green IT development*. An obvious leverage of business angels is the money they invest in the Green IT start-up. Besides investing money, business angels also provide their knowledge of the field and their contacts. The start-up will have to pay back the sum invested. This may happen by exchanging convertible debts or ownership equity.

(d) *Boosting or slowing down*. Business Angels have a global overview of the industry in their field. If a start-up needs support in its early stages, business angels may help. They may provide contacts as well as financial support. Especially in Green IT, as a rather young research field, business angels are useful as they are experienced managers who know the markets, and potential partners find them trustworthy.

However, like all other actors, business angels have to be convinced of the idea in Green IT. If the business idea with the innovation were to fail, their reputation (or at least their credibility in the view of banks) would be damaged.

4.4 Governments

(a) *Definition*. At the national or international level, governments can certify, regulate, or enforce the usage of technologies, based on several factors. These factors can be related to Green IT and sustainability.

(b) *Examples*. The Energy Star program is a widely adopted means aimed at offering customers the possibility to buy more efficient products than required by law. In the US, the Department of Energy regularly monitors the compliance of the products with the Energy Star label, which was developed by the Environment Protection Agency (www.energystar.gov). The European Union Code of Conduct (EU CoC) is another such initiative. Its aim is to inform and foster the improvement of energy efficiency in the planning and operation of data centers. It is also a voluntary initiative to help design and operate data centers and to report on their power consumption.

(c) *Leverages for Green IT development*. So far, the above initiatives are not laws and thus cannot be enforced, and their impacts could be considered negligible, while they could help speed up the process of innovation transfer. However, the choice of governments to promote some standards or technologies even without introducing regulations has a direct impact on the visibility and attractiveness of these standards and technologies.

(d) *Boosting or slowing down*. Indirectly, these initiatives have impacts on Green IT development. Customers tend to choose the most efficient products; companies building energy-efficient products promote these labels in their marketing; data centers operating under the EU CoC advertise this fact, publicize their increase in energy efficiency, and use it as a commercial advantage. The direct and indirect social effect must therefore be included in this study.

5 Links and Interactions

As stated before, the different actors interact. These interactions can be of several kinds: between actors of the same group (e.g., between researchers) or between actors from different groups (e.g., researchers and companies). Formally, one should describe all the links between all the actors in Sects. 3 and 4 in detail and study them. We established eight actors, resulting in a potential for 28 links. We argue here that, among all these links, some have greater impacts on the development of Green IT than others, or have the potential to have stronger impacts if such links were to be established.

Following the method used in the previous sections, we detail in this section some of the links by defining them (which actors are involved, what is the nature or the object of the link, which metric could be used to assess the strength of this link), giving some examples, ascertaining what the leverages of this link are for developing innovation in Green IT, and what the impact of this link is for boosting or slowing down the process.

5.1 Link Between Universities

(a) *Definition*. This link is the most common one for researchers. Research is conducted in networks, and this link represents the actual joint research output. It can be assessed by the number of joint publications in Green IT, the number of regular visits, and the number of contracts in which two research groups collaborate. Also, PhD co-supervisions provide evidence of a stronger link.

(b) *Example*. The PhD candidate writing this chapter is co-supervised by and has produced some papers with both research groups. COST (European Cooperation in Science and Technology) Action IC0804 (www.cost804.org) and the new IC1305 are also examples of such networks in the field of energy efficiency in large-scale distributed systems (such as the cloud, HPC, networks, …) and ultrascale computing (up to the exascale).

(c) *Leverages of this link for Green IT*. Each research group in universities has some level of freedom to investigate particular topics, hence Green IT can be one of the topics selected. Also, some funding agencies may choose to favor Green IT if they already see some strong collaboration between partners and high-level publication results in the field. For instance, the COST office decides which actions to fund: The existence of the named funded networks has clearly furthered research in Green IT. Not to be forgotten is the intrinsic scientific reputation of each partner (leading to more or less strong commitment to collaborate).

(d) *Boosting or slowing down factors in Green IT*. While research groups have the capability to collaborate easily, it certainly furthers Green IT research when it is also their choice to do so. However, two factors may limit the impact of this link: The first is obviously the lack of money to hire staff or students to pursue or support the research, meaning that funding is not in line with ambition. The second is that a link may lose importance in one of the research groups independently of the partner, due to a new policy of the university or better opportunity or growing links in other fields: One cannot do everything and interests may change due to the above mentioned freedom.

5.2 Link Between University and Company

(a) *Definition*. This link is probably the oldest besides the one between universities. It is also one of the most controversial. The role of universities has changed during the last decade. Universities are becoming almost an industrial partner in collaborations, even if differences still exist, as explained in [3]. The link represents the contractual interaction between university and company and the value added to both partners through this (close) cooperation.

(b) *Example*. Numerous examples exist, but as these contracts are confidential, it is impossible to mention examples. Possible partners of universities in the field of (Green) IT are IBM, Microsoft, but also energy providers as well as major energy consumers or small SME interested in catching up with a new emerging market.

(c) *Leverages of this link for Green IT*. This link is important for each development in the field of Green IT. Companies are interested in new technologies in order to be the first one to enter the market and earn money. Cooperating with universities may be cheaper than having an research department of their own. However, many large groups already have research departments, some strongly linked with universities or employing former university staff (PhD students, for instance). For universities, it is an advantage to have links with industry: Industry may finance research by paying for students or by paying for results. Overall, it may be a win-win situation.

(d) *Boosting or slowing down*. This link depends is probably most strongly dependent on the contract(s) signed by partners, since they have different interests, as explained in [3]. These differences slow down the impact on Green IT, as it may take a long time to define common interests and goals. Also, links may weaken after the end of the contract, especially when university staff is frequently replaced due to limited contracts. Then, knowledge has to be built again almost from scratch, since only few permanent positions, which could provide for continuity, are available. This may change in the future, as the impact of the newly created TTOs will become apparent in some years. A company may also keep new technologies confidential if they represent a danger for the business. This case does not involve slowing down the innovation, but stopping it. In many cases, the interaction between industry and academia promotes innovation in Green IT.

5.3 Link Between Standardization Bodies and Influential Groups

(a) *Definition*. This link details the relationship existing between standardization bodies and influential groups. The metric for assessing this link can be the ratio of representatives from the various influential groups in each standardization body, in terms of absolute numbers and percentages. This will help to estimate their respective weights in the decision process.

(b) *Example*. One such example is the ISO/IEC Joint Technical Committees. Despite being open to members of the participating countries, there are only a few academic researchers in the formed working groups, for reasons outlined earlier: Motivations for researchers are linked to their scientific reputations and careers, and involvement in such bodies is not key for these. More specifically, the JTC1/39 group mentioned earlier is strongly linked with the GreenGrid in particular for defining the Power Usage Effectiveness (PUE), which was first described by the Green Grid in 2007. The definition of PUE was updated in 2012 [7] and is now being considered for standardization. There is only one academic out of 29 editors of and contributors to the Green Grid reference document, but 20 companies are represented. Only large IT-related groups are present in the list.

(c) *Leverages of this link toward Green IT*. As explained in 3.1 and 4.4, the impact of standardization and governments can be high. The stronger the link between influential groups and standardization bodies, the faster the development can be. Indeed, standardization activities suffer from a long process duration that cannot be followed by individuals, and only structured groups can actually influence decisions.

(d) *Boosting or slowing down.* Mostly driven by company-paid officers, standardization initiatives therefore reflect the interests of companies as well as member states trying to effectively promote their industries. One example involves the metrics for assessing the efficiency of data centers. Each country may participate in the final document for standardization (and eventually vote on it). However, it should be noted that the groups following this work are small in each country, and basically represent the same interests (sometimes they are even the same people). Other examples also discussed in the JTS1/39 group are WUE (Water Usage Effectiveness), CUE (Carbon Usage Effectiveness), and the more controversial GEC (Green Energy Coefficient). This latter promotes the use of green energy (which also has to be defined). Every country, protecting its industry, may behave differently with regard to these metrics. For instance, France's overwhelming electrical power source is nuclear. Data centers located in France benefit from a very good CUE value, but may have a bad GEC value compared to Canada, for instance, where power comes from mainly from hydroelectric plants. The choice of which standard may emerge for regulations (for instance, in EU directives and laws) is therefore a strategic issue for governments and industries.

5.4 Links Between TTOs and Universities

(a) *Definition.* This link is one of the most crucial if universities, researchers, or research groups want to commercialize innovations, results, and research. TTOs (should) monitor ongoing research carefully in order to identify important outcomes immediately. Important outcomes must be considered as to their industrial importance. This link represents the value of a university for industry.

(b) *Example.* Many universities now have a TTO, perhaps under a different name, as e.g., the project service office (PSB) at the University of Innsbruck. In France, the government created SATT, which has the same function as TTOs. As universities are mainly independent now, each may have a different contract with the relevant TTO.

(c) *Leverages of this link toward Green IT.* As TTOs are the interface between universities and industry, their influence on Green IT and new directions of research is rather high. TTOs are aware of new hypes in the industry and may therefore influence academic research due their relationship with the university. TTOs may give advice concerning the direction of the research, so it is their duty to discover new hypes on the markets and to encourage universities to strengthen research for industry.

(d) *Boosting or slowing down.* TTOs and their interaction with universities may boost as well as slow down innovation. The daily business of TTOs is to deal with contracts, Intellectual Properties, and research. Therefore, TTOs and their relationships with universities clearly boost innovations as administration takes less time and people working for the TTOs are up-to-date with research. In the best case, they were researchers before working for TTOs. A close relationship between TTOs and universities is clearly an advantage for collaborating with industry. On the other hand, a TTO is a third party joining, and what was previously a contract between two parties (industry and academia) is now a virtual contract between the TTO, industry, and the university. Even if TTOs represent the university they also have an interest in becoming financially independent. Their interest is to earn money by selling results, and this may slow down the smooth flow of interactions between industry and academia.

6 Models for Innovation

In this section, we outline first steps for modeling technology transfer between researchers and industry and its impact for society. Multi-agent systems (MAS) are well-suited for modeling the interactions in distributed environments, and aiming at optimizing a cost function, either for each individual, or for the community, or both. They have been successfully used in a variety of scenarios, including in Green IT where agents can be pieces of software moving between the physical hosts to find “greener” places, or conversely agents are the hosts trying to minimize their own ecological footprints.

The usage of MAS is not limited to computer science, and social science [8] uses MAS, for instance to model loose and hidden interactions, where non-expected behavior can emerge from a crowd. In this vein, the authors in [9] propose a survey of the usage of multi-agent systems for innovation diffusion. They show that the diffusion of innovations is a contagious process, driven by external influence such as mass media as well as by internal influence (word of mouth). The direct and indirect influences of the actors are derived in terms of mathematics and probability for anyone to adopt a technology. Then aggregate models are derived for communities of potential adopters. Showing the limits of aggregate models, they advocate for individual-level models of innovation diffusion. Agent-based models are shown to outperform aggregate models in a number of dimensions. Each agent is an autonomous decision-making entity interacting with others and its environment through a set of rules. Micro-level interactions between entities (the interactions described in Sect. 4) lead to macro-scale dynamics in an autonomic emergent manner. Thanks to this modeling, the global status of Green IT can be studied and compared for different scenarios of cooperation, funding, and influences between the partners.

We argue that it is feasible to model the innovation patterns in Green IT. In [4] we proposed a first step toward such a model. This study included four kinds of agents: Green IT researcher, IT researcher, general researcher, and society. Building on the methodology described in Sects. 3, 4, and 5, we can develop the agent-based model further.

In this section, we will detail some scenarios using some of the actors and links defined above.

Scenario 1 (*Direct collaboration*). A company contacts a university research group in order to start collaboration. This collaboration will be effective when the contract between the parties is signed, and the TTO acts as an intermediate for determining intellectual property rights, contract details, and the like. The agreement states the amount of money allocated by the company, this is the input of the model. The output of the model can be either a product, a patent, or some publications, depending on the agreement.

Scenario 2 (*Funded project*). This scenario includes four actors. A funding agency publishes a call for proposals in the Green IT area. A consortium is formed between one company and two universities. The chances of being funded are determined based on the quality of the consortium and the research project proposed. If the project is funded, its output will include both industry-related results and academic-related outputs, the effective output depending on the quality of the groups, the size of the company, the researchers' publication history, and other factors.

Scenario 3 (*Standardization activity*). This scenario involves four actors. A research group develops one metric for assessing the energy efficiency of data centers and tries to interact with the appropriate standardization body: This interaction depends on the body and number of academics participating. Then the metric is assessed in the standardization body where influential groups or companies may promote or conversely limit its diffusion, based on their own interests and strategies. Therefore, the interests of companies participating in influential groups and/or standardization bodies are needed for this scenario. The output of this scenario can be nil, or it can lead toward an effective standard in some timeframe, promoted eventually for regulation by a government. The duration of each interaction must therefore also be accounted for.

In these scenarios, different parameters are used as input or decisions patterns by the stakeholders. Building a statistical background from previous observed real-life interactions will help to determine the probabilities of the actors' behavior in general. For instance, in Scenario 1, the amount of money can be computed as the mean of previously observed contracts, and the output can be probabilistically determined as a percentage for each possible output (patent, product, publications, …). It is obvious that, when the model is set, we can observe the impact of increasing the amount of money in a collaboration (scenario 1), changing the grants allocated or the reputation of the partners (scenario 2), or the number of academics involved (scenario 3). The indirect output of one scenario must also be accounted for: For instance when a research group produces a new publication, it increases its societal impact (even though each individual publication may not have a high impact, the sum total of publications may well in the long term), its reputation, its future potential success in contracts, and so on.

Obtaining realistic input for the data at hand is one main difficulty of the modeling effort. Properly building the model requires deep knowledge and precise data analysis from various possible sources. We designed and circulated a survey for the research and industry communities in order to gather input for the models.

We are currently investigating some easy-to-understand metrics in order to assess the impacts of changes with regard to objective functions. These objective functions include a global Green IT innovation impact of each scenario (that can be computed from their outputs, with different weights associated to each output value) that could support decision-making: For instance, one could calculate the global impact of increasing participation in project calls, or the impact of raising funds in funding agencies for Green IT, and so on.

We started to implement the proposed model using the NetLogo framework (version 5) [10], which is widely used in the Agent-Based Modeling community. Even preliminary experiments with few actors showed us the strength and expressiveness of the associated language to properly describe the actors (agents, links) of the system, and the associated tools to calculate some key metrics and objectives to assess.

7 Conclusion and Future Work

In this chapter we analyzed the actors of innovation in Green IT, from the developments in research and technology to influential groups and standardization efforts. While many actors interact with each other, the interplay between them is an important aspect to be taken into consideration when trying to promote Green IT. The future of our work will be to complete the modeling of these actors in terms of agents in a multi-agent system, each actor being an agent pursuing its own interests and motivation, connected to others by a number of valuable links, and to determine quantitatively the main drivers or influential factors for a greener IT society.

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Part II
The Energy Cost of Information Processing

The Energy Demand of ICT: A Historical Perspective and Current Methodological Challenges

Bernard Aebischer and Lorenz M. Hilty

Abstract This chapter provides an overview of energy demand issues in the field of ICT with a focus on the history of measuring, modelling and regulating ICT electricity consumption and the resulting methodological challenges. While the energy efficiency of ICT hardware has been dramatically improving and will continue to improve for some decades, the overall energy used for ICT is still increasing. The growing demand for ICT devices and services outpaces the efficiency gains of individual devices. Worldwide per capita ICT electricity consumption exceeded 100 kWh/year in 2007 (a value which roughly doubles if entertainment equipment is included) and is further increasing. Methodological challenges include issues of data collection and modelling ICT devices and services, assessing the entire life cycle of ICT devices and infrastructures, accounting for embedded ICT, and assessing the effect of software on ICT energy consumption.

Keywords ICT energy consumption · ICT life cycle · Energy policy · Regulation · Standby power · Energy conversion · Green ICT · Green software

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1 Introduction

Since the first electronic computer was built in 1946, the energy needed for a computer operation has been halved about every 19 months through technological progress [1]. Yet today the energy consumption of digital ICT is an issue because the demand for ICT performance has increased even faster than its energy efficiency.

As an introduction to Part II of this book, The Energy Cost of Information Processing, this chapter describes the history of systematic research and political regulation of ICT's energy demand (Sect. 2). It draws on research at ETH Zurich, where the power demand of ICT devices has been researched since the 1980s, since 1994 in the framework of the Competence Centre for ICT and Energy (lead by the first author), which has been part of the newly founded Centre for Energy Policy and Economics (CEPE) since 1999. This perspective is supplemented by the experience of the second author, who launched the program Sustainability in the Information Society at Empa in 2001, which researches ecological and social issues surrounding ICT. Since 2004 these activities have continued at Empa's Technology and Society Lab.

Over the decades, methodological challenges have emerged in determining the energy consumption of ICT services, including problems of definition and modelling as well as assessing the effect of software on the hardware's energy consumption. We will describe and discuss these challenges in Sect. 3.

The issues discussed in this chapter are taken up in other chapters of this book, which discuss solutions based on the current state of research.

2 The History of ICT Energy Demand and Its Measurement

2.1 *Energy as a Key Topic Since the Early Beginnings of Computing*

Figure 1 shows how the number of computations a typical processor can perform per unit of energy has changed since the first electronic computer, ENIAC, in 1946. Roughly, this number has doubled every 1.57 years [1]. The unequaled[1]

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[1] For most technologies, the reduction in the energy needed per unit of delivered service) is on the order of a few percent per year. For lighting, the reduction rate since the candle and the gas light of 200 years ago until today's LED has been about 3.2 % per year; the reduction rates of household appliances in Switzerland between 1970 and 2000 were between 2.7 % per year for electric ovens and 5.9 % per year for freezers. For ICT, the mean improvement rate (CAGR) between 1950 and 2010 of the specific energy consumption (measured in kWh/computation) was much higher: between 36 and 39 % per year [2], corresponding roughly to a reduction by a factor of 100 in 10 years.

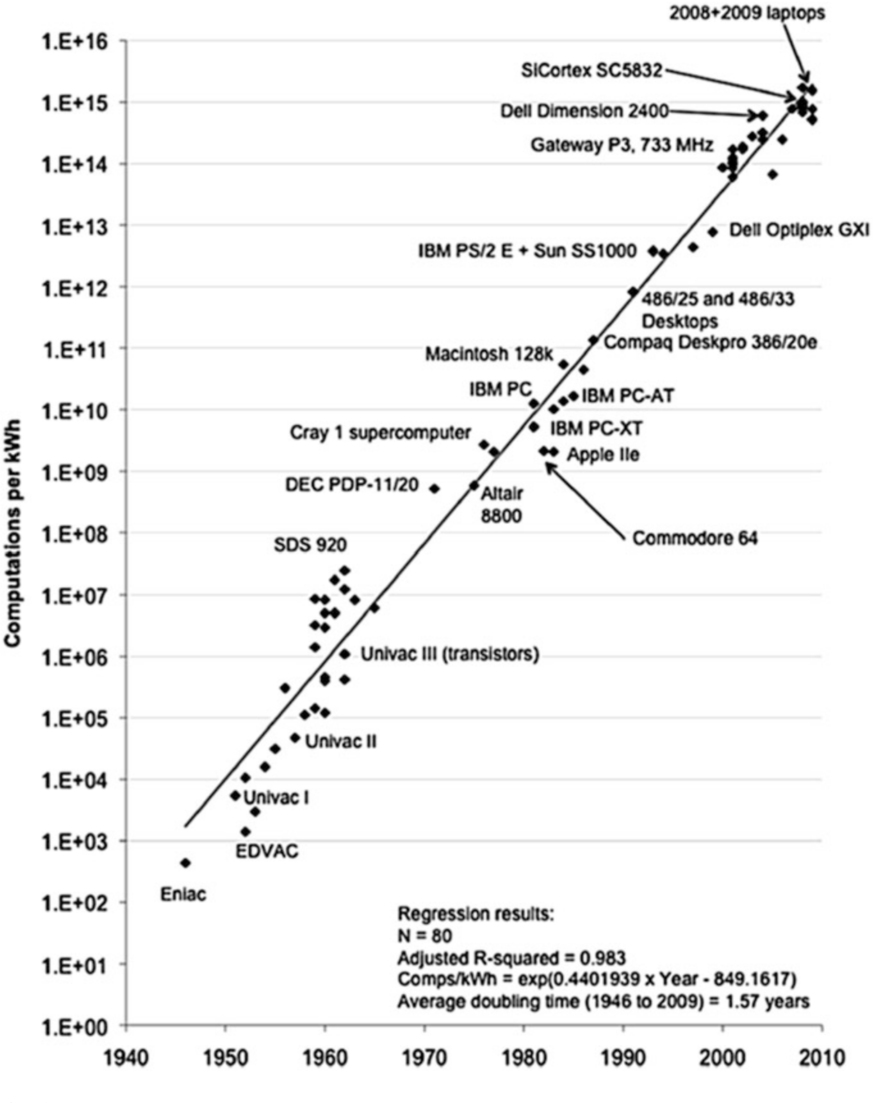

Fig. 1 Computing energy efficiency (in computations per kWh) from 1945 to 2010 (*Source* [1], reprinted with permission of IEEE Computer Society)

improvement in computing energy efficiency (if defined as computations per kilowatt-hour) has been *the* precondition for the extraordinary importance of ICT in today's society. Indeed, had the improvement rate been only half as large, but the diffusion of ICT unchanged, just Switzerland's (current) stock of installed computers would need more electricity than produced globally today.

It is not clear how long this trend of the past 60 years can be maintained before physical limits are reached. Assuming a constant improvement rate, the three-atom transistor, also known as "Feynman's limit," will be reached in 2041. However, there are reasons to assume that even smaller transistors can be built in the future [4]. Today's problem is not the physical limit, but the engineering feasibility discussed in [5]. A slowdown of the improvement rate of the computing energy efficiency would dramatically alter the projections of future computing capacity—or of ICT's future energy demand. In the so-called trend-scenario, EPA's projections [6] for data centers show an expected increase in electricity demand from 60 TWh/y in 2005 to 250 TWh/y in 2017. Absent continued technology improvement, the assumed increase in computing capacity would lead to almost five times as much electricity demand, i.e. 1,200 TWh/y [7].

Some insight into the physical and engineering innovations and improvements that lead to the fantastic progress in the past is offered in Kaeslin's chapter "Semiconductor Technology and the Energy Efficiency of ICT" in this volume [5]. There he also discusses possible ways to improve computing energy efficiency in the future.

One such means is miniaturization (called downscaling in microchip production). The observation that over the history of computing hardware, the number of transistors on integrated circuits doubles approximately every 2 years is known as "Moore's Law."

The overall impact of ICT on society was recognized early on by philosophers, historians, futurologists, economists and energy analysts. The impact on overall energy demand has usually not occupied a central place in these debates. The few projections of ICT's effects on total national energy demand published starting in the 1980s covered a spectrum between accelerated increase and substantial reduction.

- In 1983, Tokio Ohta warned that industrial robots and general-purpose computers could together account for 34 % of the total electricity demand in Japan [8]. Five years later, Uekusa predicted percentages of 8 % in 1990 and 11 % in 2000 (Fig. 34 in [9]). Besides direct electricity demand, Uekusa mentioned possible ripple effects and concluded: "Advancing 'informationization' … also has broad and crucial impacts on economic activities, corporate management, working modes, life-style, social systems, and energy … From an overall viewpoint, energy demand is thought to demonstrate strong vector toward increases" [9], p. 54 and p. 60f.
- In 1985 and 1986, William Walker discussed in two papers [10, 11] the possible consequences of ICT on the energy system. He emphasized the potential of ICT to increase energy efficiency:

> Information technology can affect energy consumption both directly and indirectly… Information technology will therefore be directly applied on an increasing scale to the task of reducing energy costs in the economy. But its capacities to raise simultaneously the productivity of all inputs to production will tend to increase energy efficiencies across the board; and the structural changes it initiates may have significant but largely unintended consequences for patterns and efficiencies of energy use [10, p. 465].

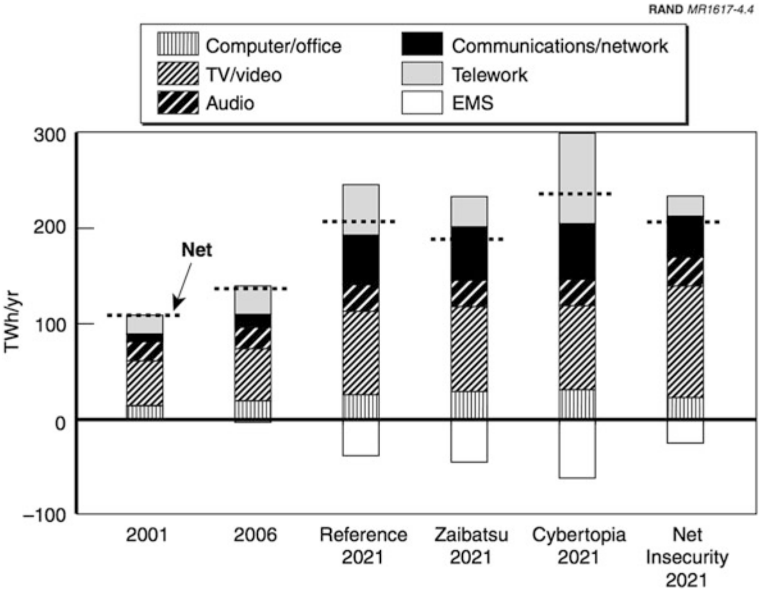

Fig. 2 ICT-driven electricity use in the residential, commercial, and industrial sectors, 2001–2021. Electricity savings (e.g., from EMSs) are shown as negative values. The "net" lines show the sum of the negative and positive components. (*Source* [15, Fig. 4.9, p. 73], reprinted with permission of RAND Corporation)

He concluded: "… the rate of growth of energy demand seems likely to remain below that of economic output, although how far below is again difficult to assess. Indeed, the possibility cannot be entirely ruled out that energy demand will fall with economic growth in advanced countries" [10, p. 475].

- In a bottom-up simulation of energy demand in Switzerland from 1985 to 2025, a scenario "communication technology" resulted in an energy demand in 2025 no higher than in 1985, whereas in the "business as usual" case, energy demand in 2025 was about 30 % higher than in 1985 [12]. This scenario calculation was based on a comprehensive description of a world in which ICT is purposefully used to save energy and natural resources [13] and on a techno-economic analysis of energy demand in the information society [14].
- Baer et al. [15] investigated in four scenarios the links between future ICT growth and electricity demand in the US. They estimated through 2020 the electricity demand of ICT equipment as well as electricity savings by ICT. They concluded that even large growth in the deployment and use of digital technologies will only modestly increase electricity consumption (Fig. 2).
- Laitner [16] published a moderately optimistic view regarding the impact of ICT on US energy consumption in 2003: "Although we may not yet be able to generalize about the future long-term energy needs associated with the information economy, the evidence points to continuing technical changes and the

growing substitution of knowledge for material resources. These interrelated trends will likely generate small decreases in energy intensity and reduce subsequent environmental impacts relative to many baseline projections." In a paper published in 2009 Laitner and colleagues evaluated a "semiconductor-enabled efficiency scenario" resulting in 2030 in 27 % less electricity consumed than in the reference case, and 11 % less than in the starting year 2007, even though the economy is assumed to grow by 70 % from 2009 to 2030. [17]. The current update of this estimate can be found in the chapter by Laitner [18] in this volume.
- Energy saving potentials by ICT have also been presented in more recent studies by the Global eSustainability Initiative (GeSI) [19, 20], and the American Council for an Energy Efficient Economy (ACEEE) [21]. The possible net energy savings[2] by ICT are typically estimated at 10–20 % of the world's energy consumption.
- "Spreng's Triangle" [22, 23] explained the spectrum of potential impacts of ICT on total energy demand using the idea that information can be substituted for time or for energy. For an update of Spreng's approach, see his Chapter [24] in this volume.

The effect of ICT on energy demand in other fields, also called an *indirect* or *enabling effect of ICT*, is certainly one of the most important impacts of ICT in the context of sustainability. It is further discussed in the following chapters of this volume:

- Höjer and Wangel [25] discuss the role of ICT in future cities, where it is interlinked with issues of transportation, mobility, and energy use in many ways.
- Sonnenschein et al. [26] provide insights into the enabling role of ICT for integrating renewable energy sources into the power grid.
- Katzeff and Wangel [27] discuss design issues related to the role of households as energy managers in a smart grid context.
- Huber and Hilty [28] discuss the role of ICT in motivating users to change behaviors in support of sustainable consumption.
- Maranghino et al. [29] introduce an information system supporting organization-internal cap-and-trade schemes for CO_2 emissions permits and other scarce resources.
- Gossart [30] provides a review of the literature on rebound effects counteracting ICT-induced progress in energy efficiency.

Although it has been argued that energy consumed by ICT and energy saved by ICT should be studied together (but for specific types of ICT, see [31]) in order to treat costs and benefit the same way, we will continue our analysis by focusing again on the cost side and the perception of it in research and policy.

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[2] Net energy savings are usually defined as the savings *enabled* by ICT (compared to a baseline) minus the energy *used* by ICT. There is no general rule for defining the baseline, which makes "net energy savings" a somewhat arbitrary concept. See also [32].

2.2 ICT Energy Demand as an Emerging Issue

After the two oil price shocks in 1973 and 1979, building codes were strengthened in many countries, and monitoring and auditing of energy consumption in buildings became a widely used practice. It was observed that despite important efficiency improvements in the traditional energy usages (HVAC, lighting), electricity consumption in many new commercial buildings was growing, which could be at least partly explained by the increased use of computers.

Utilities observed a fast growth of electricity demand in the commercial sector, and ICT was identified as one of the possible drivers for this growth:

> The rapid rise in service sector employment has driven up computer use, because the commercial sector is more computer-intensive than the manufacturing sector. Further, the fastest service sector growth has occurred in business-related services. For example, from 1977 to 1982, business-related services claimed the top six spots in the large and fast growing subsectors (over $10 billion in 1982 sales; more than 100 % growth). This is important because it is exactly these business-related services that are most likely to use computers. Historically, most growth in commercial sector electricity sales has come from new uses. Many of today's important uses began as small new loads, and computers may be the latest example [33].

Bottom-up Studies: Commercial Sector. At the annual conference of the American Council for an Energy Efficient Economy (ACEEE) in 1988, Norford et al. presented an estimation of electricity demand in the US by office equipment [34]. An improved and extended version of the paper was included in the proceedings of the "Electricity Conference" in Stockholm [35]. The authors analyzed the technical specifications and the use of office equipment, gathered statistical data on equipment installed and looked for potential energy savings. The main results of this study were the following:

- One important observation was the fact that the true electric load of a device was typically only 20–40 % of the nameplate rating. The latter is an indication of the load supported by the power supply. This fact—a 2–3 times over-dimensioning of the power supply—was later recognized as a main reason for the high energy losses in the power conversion of most ICT equipment (both for office and entertainment use).
- A surprise was the finding that office equipment other than computers (such as printers and copiers) consumed as much electricity as the PCs. It was also recognized that electricity consumption of equipment in standby mode was important and could be reduced by better software. Improvements in software were promulgated as one important way to reduce the energy demand of ICT equipment.
- In an outlook to 1995 (7 years ahead), they presented a steady increase of electricity consumption by office equipment in the commercial sector between 15 and 25 % per year [35]. This evaluation was further developed and presented a few years later in a 1991 report of the Lawrence Berkeley National Laboratory (LBNL) by Piette et al. [36].

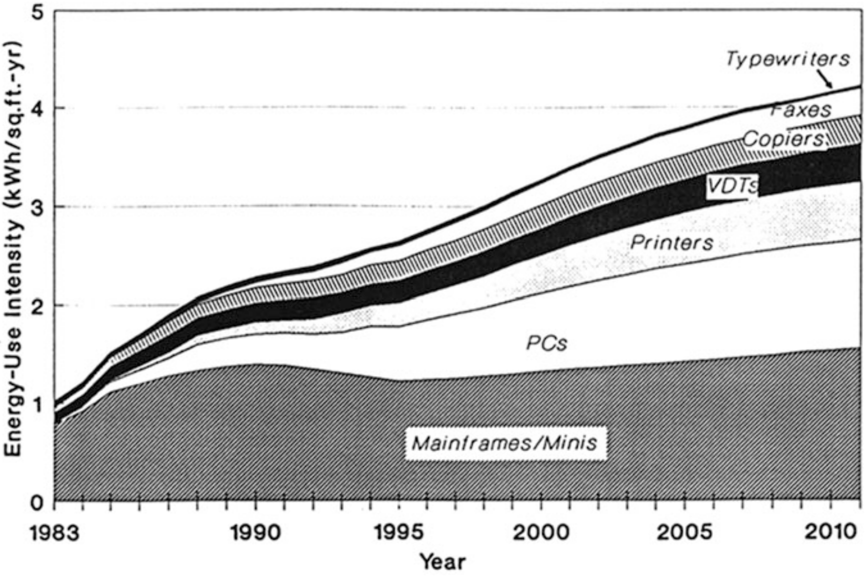

Fig. 3 Energy-use intensity (in kWh/ft^2 × year) of office equipment in US office buildings 1983–2010. (*Source* [35, Fig. 7, p. 44], reprinted with permission of Lawrence Berkley National Laboratory)

- The researchers did not overlook the enabling effects of ICT on energy savings but did not quantify this potential.

In 1991, Piette et al. expected electricity use intensity (EUI) of ICT in office buildings (defined in [36] as electricity consumption by ICT *per unit of floor area*)[3] to grow mainly due to the diffusion of PCs and other office equipment (copiers, printers) (Fig. 3). On the other hand, the EUI of central computers (mainframe and mini computers) was forecasted to stay more or less stable until 2010 and its share in EUI of total ICT would decline from almost 100 % to around 1/3 in less than 20 years. The EUI of all other ICT equipment was expected to grow from 1990 to 2010 by 200 % or 5.6 %/year. This implies that the total electricity demand of ICT in all office buildings (sectoral electricity demand) would grow even faster because the building stock would increase as well.

Piette et al. expected ICT electricity demand to grow in all commercial buildings (not only office buildings, but also hospitals, schools, and shopping centers), but at a slower pace than in office buildings. For the total commercial sector in the ”Pacific Gas and Electric” Service Territory (US), they estimated the growth of ICT electricity demand from 1989 to 2011 at between 125 and 235 % (or 3.7–5.6 % per year) [36].

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[3] This metric is defined on the level of final energy and does not include energy carriers other than electricity.

These first projections by Norford et al. and Piette et al. have to be regarded as parts of Business-As-Usual (BAU) scenarios, which assume that no technological breakthroughs or policy interventions would happen. However, both became reality shortly after these studies were published: Laptop computers and flat screens (mainly based on LCD technology) and the Energy Star Program and other policy interventions substantially reduced the energy demand of PCs and other office equipment. On the other hand, the triumphant adoption of the Internet drastically increased the demand for networking infrastructure, and the rapid diffusion of small servers changed the structure of central computing.

Bottom-up Studies: Household Sector. In the 1980s, energy analysts looked closely at the electricity consumption of household appliances. Entertainment electronics, telephone and office equipment were at that time included in a non-specific group of appliances termed “miscellaneous.” Electricity consumption by this group was observed to grow and expected to increase further.

Meier et al. [37] estimated in 1992 that televisions used about 3 % of total electricity consumption of households in the US. At that time computers were used in only 10–20 % of homes and their consumption was on the order of 0.2 % of total electricity use. In 1995 this fraction of computers was estimated at 0.3 % (3.3 TWh/y) and expected to reach 0.4 % (6.0 TWh/y) in 2010 [38]. This relatively modest electricity demand by computers was corrected on the basis of a 2005 survey of usage intensity of residential computers in the US by Roth et al. [39]: Electricity consumption by laptop and desktop computers in 2005 was now estimated at 22.5 TWh/y or 1.7 % of total residential electricity in the US.

Standby Losses and Inefficiencies in Power Conversion. These early studies were complemented, extended and enhanced by investigations in other places and other countries. In Europe, the “Electricity” Conference in Stockholm [35] acted as a catalyst for these kinds of studies. Politicians and civil society became interested in the field, which made funding available and boosted research. Most of the studies in the period from 1990 to 2005 were commissioned by government agencies and utilities. The results were usually published as research reports, i.e. as “grey literature.” Nevertheless, they were distributed widely and had a high impact worldwide. Many of these papers and reports can be found in the electronic literature database “IT and Energy Library” [40]. An overview of the activities in Europe and in the US was given by Aebischer and Roturier [41] and in less detail in [42]. Research activities in Switzerland are described in [43].

Understanding how and for what purpose energy is used in devices increased fast thanks to technical studies, surveys and measurement campaigns. The central message was simple (and has roughly remained true until today): A very large fraction of electricity is consumed while the equipment is idling and no service is delivered. “Reduction of Standby Losses” became in the 1990s the leitmotif for policy activities in the field of ICT (see Sect. 2.3 below). The ICT industry (both hardware and software producers) participated voluntarily in these activities. They had already tackled the problem for the market for mobile computers. The open questions were “how low” and “how fast.” The radical request of “1 Watt” standby power by Molinder in 1993 [44] is almost reality today, 20 years later. As an interim solution, accessory kits were proposed to power down computers, copiers, printers and fax machines.

A related question was the performance of the power supplies transforming the electric power down from 110 V or 230 V AC to typically 12 V and 5 V DC. The roughly 1 V level required by the processors is reached by DC-DC converters situated on the motherboard or even directly on the chip. After 1990 the traditional bulky and heavy transformers were hardly used in ICT equipment any more, except in the audio segment and for about 10 additional years in external power supplies. The new switch-mode power supplies might have been more efficient than the old transformers, but they were typically 2–3 times over-dimensioned for the standard configuration of a PC and for most other equipment. As a consequence, up to 50 % of the electricity was lost in the transformation chain from 110/230 V AV down to the 1 V DC level at the processor [45–47]. In the low power modes (e.g. standby), the losses could reach as high as 90 %. As long as no measures were taken at the level of the power supply, the standby power could therefore not be reduced substantially below the 30 W or 10 W level.

Furthermore, switching-mode power supplies generate so-called harmonic pollution, i.e. if the input signal is a pure sine wave, the output signal is distorted and composed beside the fundamental frequency by other harmonics (overtones). Harmonic pollution leads to an increase in total current and to a decrease in the quality of the electric current. The quality is described by the power factor, which is defined as the ratio of the real power flowing to the load to the apparent power in the circuit. The power factor is a dimensionless number between -1 and 1. In the early 1990s, the typical power factor for PCs and other office equipment was as low as 0.6 [48]. Because of the danger of fire due to the high electric current, insurance companies became concerned as well as government agencies and professional associations that were impelled to revise recommendations for the dimensioning of electric wiring in office buildings. First recommendations were formulated, and later voluntary standards were established to improve the power factor.

Reduction of standby losses, higher efficiency of power supplies and power factor correction were the three main measures considered by the Energy Star program and other energy efficiency programs for over 15 years, starting in 1992. These policies are discussed further in Sect. 2.3 “Energy Efficiency Policy” below.

Bulk Electricity Consumers. Until 1990, central computers (mainframes and so-called minis) dominated the electricity used for computing in US office buildings as shown in Fig. 3 above. An estimation of electricity use by different types of computers confirmed this observation in Switzerland: At about 50 % the mainframes were the largest electricity users; medium and small computer systems followed with 40 % and the personal computers’ share in 1988 was a modest 10 % of the total electricity demand of computers (Table 1).

Table 1 Electricity demand of computers in Switzerland in 1988, adapted from [49]

Type of computer	No. of devices	Power [kW]	Use [h/day]	Electricity demand [GWh/year]	Fraction of total (%)
Personal computer	900,000	0.125	3	120	11
Micro-system	12,200	2	6	50	4
Mini-system	18,100	5	6	190	17
Medium system	2,600	10	17	160	14
Mainframe	660	100	24	600	54
Total				1,120	100

In the city of Zurich, mainframes were at that time even more dominant because of the importance of the financial sector. In some companies, more than 50 % of the electricity was used by their in-house data center [50].

From this electricity used by data centers, typically 50 % or more was used by the central infrastructure—cooling, power transmission/transformation, and power security (UPS)—needed to run the computers. Additional losses for heat evacuation and power transformation occurred inside the machines, and finally only 25 % of the energy was typically available for calculations, transfer and storage of data [51]. Based on this analysis, a group of data center managers in Zurich introduced the indicator

$$K = electric\,power\,of\,IT/total\,electric\,power\,of\,data\,center$$

to compare the efficiency of the central infrastructure of their respective data centers [55, p. 75]. The inverse of this indicator corresponds to the Power Usage Effectiveness (PUE) proposed in 2009 [52] by the Green Grid and subsequently adopted worldwide as a measure of the energy efficiency of the infrastructure of a data center [53, 54].

Optimization of the cooling system in existing data centers and innovative solutions (e.g. free cooling) were demonstrated and resulted in electricity savings of up to 20 %, but greater relief came from the IT side. For a large Swiss bank, a new generation of computers together with completely new software led to electricity savings of 2/3 and to a reduction in floor area of more than 50 %—despite an increase in processing and storage capacity. But in this example, these tremendous savings in electricity demand in the early 1990s were compensated for after only a few years by new additional computers needed to cover the ever-increasing demand for processing power and storage capacity.

In these early years of the 1990s, the financial sector, research institutions and universities, a few industries and some governmental agencies were the only important users of large computers. Electricity demand of these machines was a concern for these organizations but was barely registered by policy makers or the general public. Less than 10 years later, the world of ICT in general and of data centers in particular had completely changed. The use of the Internet was expanding fast: E-mail, new emerging social media, and audio/video downloading/streaming became common activities. Small servers were popular; hosting became an interesting business case. Huge data centers with tens of thousands of servers were built and many others planned.

The projected power demand of the data centers planned in the Geneva region, for example, would have increased the electricity demand of the canton of Geneva by 20 %. This potential increase was in conflict with the cantonal government's energy plan to stabilize electricity consumption. Drastic efficiency improvements to the infrastructure of these data centers would have been necessary to slow down the increase; but this time relief came from the implosion of the "dot-com bubble" in March 2000. Only one of four planned data centers was built in Geneva. Similar events occurred worldwide.

But the improved understanding of electricity use in data centers, e.g. [55, 56], was not lost. Incentives for limiting the growth of electricity consumption in data centers were increasing. Fast growing heat density, rising electricity prices in some countries, and increasing pressure from utilities and governments (e.g., the US EPA's Report to Congress on Server and Data Center Energy Efficiency [6]) led to a revival of interest in that field [57]. Old ideas were taken up by new players, such as The Green Grid [58], and new approaches such as virtualization of servers were successfully promoted and supported by programs such as the European Code of Conduct for Data Centers [59], Energy Star in the US and the "CRC Energy Efficiency Scheme"[4] in the UK [60] (more in Sect. 2.3 below).

Despite these efforts, growing demand for communication and storage capacity led to a growing number of data centers and steadily increasing electricity consumption [3].

A technical overview of energy use in data centers is provided in the chapter by Schomaker et al. [61] in this volume. The chapter by Hintemann [62] highlights the changing structure of data centers and its impact on electricity demand.

From the end users' point of view, data centers are an element of the infrastructure needed to use services provided via the Internet. With the proliferation of the Internet and mobile devices, end-user equipment was no longer stand-alone equipment. In the early years, electricity was needed only for the end-user devices (PC). Today, communication networks and data centers providing content and services are essential parts of the computing environment and account for a significant part of the energy demand (for the network part, see the chapters by Coroama et al. [63] and Schien et al. [64] in this volume). And, as was earlier true for end-user equipment, standby losses in the mobile telecommunication networks and in switches, routers or servers in the Internet infrastructure are partly responsible for the energy consumption.

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[4] Formerly the Carbon Reduction Commitment, which is part of the UK government activities seeking to cut carbon emissions by 80 % of 1990 levels by 2050.

2.3 Energy Efficiency Policy

The news that ICT was an important driver of the growth of electricity demand made politicians think about regulating ICT equipment in the same way as household appliances. But ICT equipment is much more complex and heterogeneous than a refrigerator or a washing machine. Fast technical progress, evolving services, new types of equipment and global markets are reasons why standard setting was not an appropriate approach [65].

The finding that standby was a major energy consumer opened the way to an appropriate policy program. Electricity consumption in standby mode is (in most cases) useless, does not interfere with the specific service of the equipment and does not touch on technical characteristics of the equipment (e.g., specific energy of delivered service, capacity of equipment and chosen technology, e.g., desktop vs. laptop); reduction of standby losses is technically feasible (and already implemented in mobile equipment) and not too costly. Manufacturers agreed to collaborate. The reduction of "standby losses" (also called "vampire power" or "leaking electricity") was understandable to consumers and supported by public opinion. The questions were how (mandatory or voluntary; national or international/global), how fast and how ambitious?

In the US, the Energy Star Program, a voluntary program, was started as early as 1992. The required maximum standby power negotiated with industry was 30 watts for PCs. In a short time, the large majority of models on the market fulfilled the requirement. A major factor for the success of the program was the market power of the US federal administration. A 1993 Executive Order in the US directed all federal agencies to purchase only energy-efficient computers and office equipment that qualified for the Energy Star label [66]. In Switzerland, the E2000-Label was introduced on a voluntary basis in 1993. In this first year, the specification was very similar to the Energy Star, but it was conceived of as a dynamic program with annually strengthened requirements in order to signalize the best 25 % of models on the market. Similar programs were started in many countries [67–70].

In its early years, the Energy Star Program was not ambitious, but it demonstrated how to craft a successful voluntary program and became international, adopted by the EU and Canada in 2001; Japan in 2005; Australia, Taiwan and other countries at about the same time; and Switzerland in 2009. These new participants strengthened the supporters of a more ambitious program, and the requirement to get certified was more frequently adapted to market response. "Experience has shown that it is typically possible to achieve the necessary balance among principles by selecting efficiency levels reflective of the top 25 % of models available on the market when the specification goes into effect" [71, p. 2]. "As a general rule, product specifications will be reviewed for possible revision at least once every 3 years or when the market share of qualified products reaches about 35 %. For products that evolve rapidly in the market, such as displays, ENERGY STAR specifications are reviewed every 2 years" [71, p. 6].

Energy Star also tackled the problem of power conversion. The 80 PLUS initiative launched in the US in 2004 was adopted in 2006. Energy Star added 80 PLUS requirements to their then-upcoming Energy Star 4.0 computer specifications: The efficiency had to be at least 80 % (for a load between 20 and 100 %) and the power factor (cos phi) had to be 0.9 or higher. In 1992, The Energy Star Program started with PCs and monitors and has covered all major office equipment and TVs since 1998. In 2009, servers were integrated as well. The impact of the program is difficult to evaluate, since it is not known how the automatic power management (APM) essential in mobile devices would have been adopted in desktop computers and other equipment without political pressure. But Energy Star certainly accelerated the general adoption of APM, and a substantial fraction of the reduction of standby energy, estimated for computers and monitors at 32 TWh/y or 45 % of the actual electricity consumption by computers and monitors in the US 2012 [72, 73], can be attributed to the policy program.

The International Energy Agency (IEA) played an important role in propagating energy efficiency and in particular measures to reduce standby losses throughout all OECD countries [69, 74, 75].

On a global level, the World Summit on the Information Society [76] brought together representatives from governments at the highest level, participants of all relevant UN bodies and other international organizations, non-governmental organizations, private sector, civil society, and media to develop and foster a clear statement of political will and take concrete steps to establish the foundations for an information society for all [41, 42].

2.4 Trends in ICT Energy Demand Since the 1990s

In the mid-1990s, ICT was established as a relevant electricity consumer, and the explosive diffusion of the Internet around the turn of the millennium led to speculations of an excessive growth of future energy demand of ICT. Detailed bottom-up studies the world over showed that electricity demand of ICT was indeed growing, but in industrialized countries the growth rates were not expected to exceed 5 % and could possibly be dampened by policy measures. We compared results of three studies and the official outlook of the Department of Energy (DoE) in the US [39, 77–79] and two studies in Germany [80, 81]. We report on two indicators: the fraction of ICT electricity in sectoral electricity consumption and ICT electricity per capita.

The analysis was done separately for residential and commercial ICT. Residential ICT includes proper IT (e.g., PCs) as well as entertainment electronics[5] (e.g., TVs). Commercial ICT comprises all IT at work as well as the infrastructure

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[5] Roth et al. [39] do not include entertainment electronics. The corresponding data points (denoted by "TIAX_IT") are therefore not directly comparable with the other data.

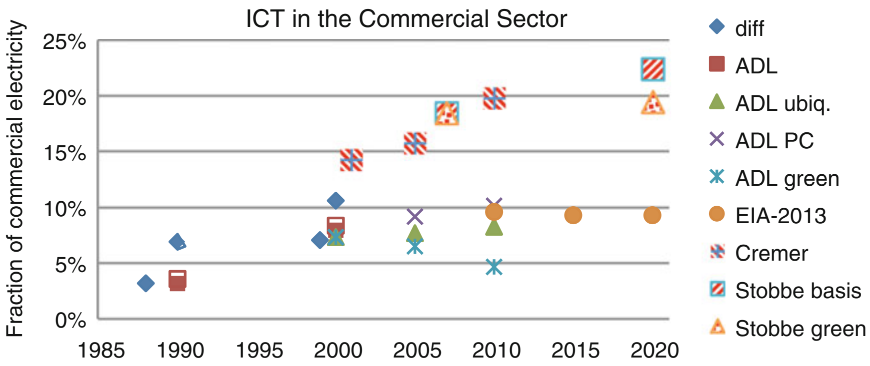

Fig. 4 Fraction of ICT electricity in the commercial sectors in the US and Germany. Data from different sources: *Data for the US* "diff" = [33, 82–84], all cited from [77, Figs. 2, 3, 4, 5]; "ADL" = [85]; "ADL ubiq", "ADL PC", and "ADL green" = [77, Figs. 2, 3]; "EIA_2013" = [79]. *Data for Germany* "Cremer" = [80]; "Stobbe basis" and "Stobbe green" = [81]

(data centers, networks) needed to run the networked end-use equipment at home and at work.

The fraction of ICT electricity steadily increased in both the residential and commercial sectors until 2010. For the US the official outlook of the Energy Information Administration (EIA) predicts a stabilization (by 2020) at about 10 % in the residential and the commercial sectors, corresponding to 7 % of total electricity demand [79]. In Germany, the fraction of ICT electricity is much higher and an increase to more than 25 % in the residential sector and to about 20 % in the commercial sector is expected by 2020. This corresponds to 12 % of total electricity demand in 2020. The important difference between the US and Germany is primarily due to a higher electricity consumption per capita in the US: In 2000, residential electricity consumption per capita in the US was 2.7 times as high as in Germany. The corresponding factors for the commercial sector and for the total electricity demand are 2.8 and 1.8. We conclude that the fraction of ICT electricity is not a good indicator for making comparisons between countries.

Using ICT electricity per capita as an indicator, the differences between the US and Germany disappear (this is clearly visible in Figs. 4 and 5). What remains is the uncertainty regarding the absolute level of the ICT electricity demand. But the trends in both residential and commercial ICT use are very similar in the American and in the German studies: steady growth to this day and more or less constant ICT electricity demand per capita of 0.8 MWh/y × cap[6] (0.35 MWh/y × cap for commercial and 0.45 MWh/y × cap for residential ICT) by 2020.

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[6] 0.8 MWh per year and capita is a relatively small fraction of the total electricity used in industrialized countries, but in many developing countries this would exceed the total consumption [42].

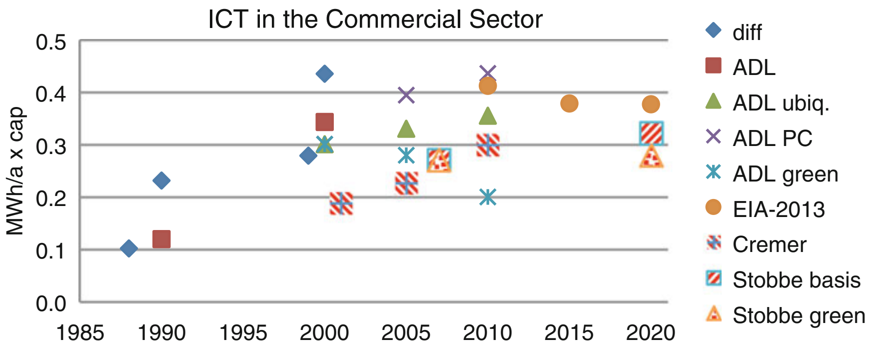

Fig. 5 ICT electricity per capita in the commercial sectors in the US and Germany. Data from different sources (see Fig. 4)

It is important to note that in the past and in the near future, growth in ICT electricity has been held down and is expected to be further dampened by:

- the reduction of standby losses of end-user equipment,
- improvements in the energy efficiency of the infrastructure of data centers and networks, and
- virtualization of servers in data centers.

These saving potentials are finite and ICT electricity demand may again increase faster in some years. This is particularly likely to happen should the rapid increase in the energy efficiency of computing come to an end.

A closer look at the evolution of ICT electricity in Germany (Fig. 6) reveals that residential end-user equipment is the largest consumer. TVs alone are responsible for roughly 50 % of this consumption. Within the commercial ICT, the electricity demand of the end-user equipment has declined slightly since 2001, whereas the infrastructure (data centers and networks) has become the dominant electricity consumer. It is interesting to note that standby losses are declining—even in absolute terms (Fig. 6).

An estimate of electricity consumption by ICT on the global level was provided by Malmodin et al. in 2010 [86] for 2007: 1,286 TWh/y or 0.19 MWh/y×cap (Fig. 7). The largest segment is entertainment and media equipment, which is dominated by TVs. The next largest is telecom/networks with almost ¾ of the electricity consumption by fixed telecom, IT end-user equipment (desktop and laptop computers), and finally data centers including the infrastructure (such as cooling) to run the servers.

Lannoo’s more recent estimations published in 2013 [87] for the same year do not include entertainment and media equipment. The results for the other segments do not differ significantly from Malmodin’s figures: slightly higher electricity consumption of data centers and lower consumption of telecom/networks and end-user equipment. On the other hand, telecom/networks are expected to grow much faster (10.1 %/year) than end-user equipment (5.2 %/year) and data centers (4.3 %/year).

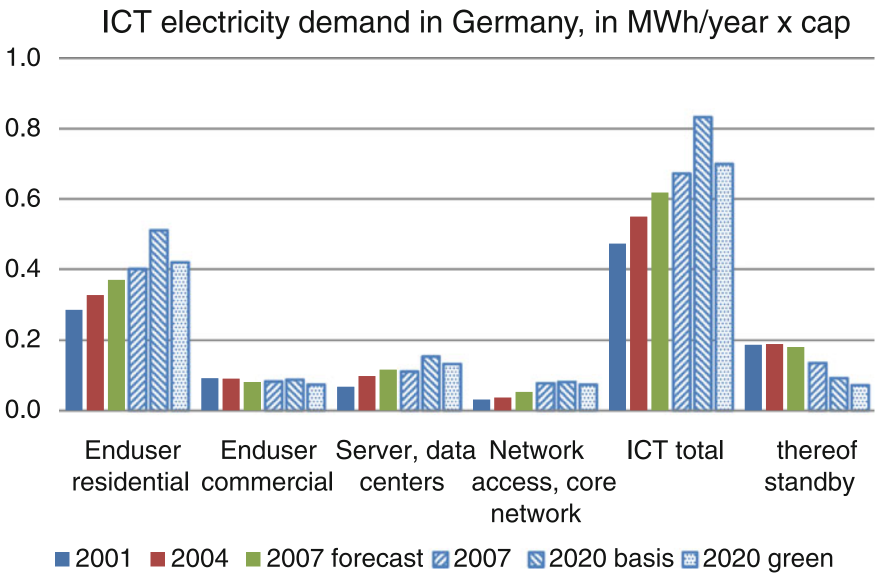

Fig. 6 ICT electricity demand per capita in Germany 2001–2020, estimated in 2009. (*Source* authors'chart based on data from [81])

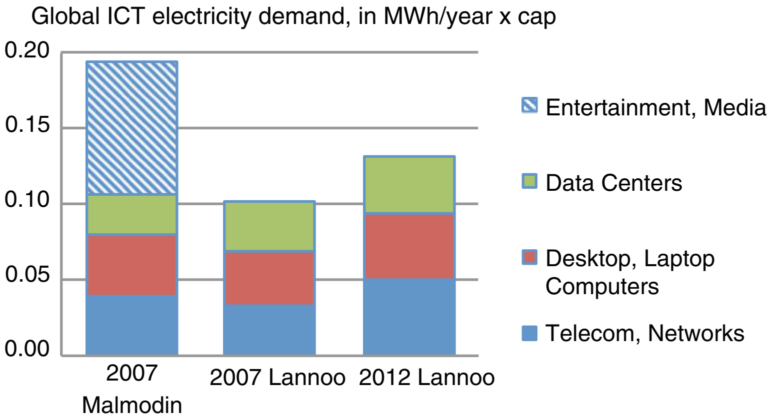

Fig. 7 Worldwide ICT electricity consumption per capita, in MWh/cap×year. (*Source* authors' chart based on data from Malmodin [86] and Lannoo [87])

Looking in detail at the electricity consumption of end-user equipment (Fig. 8), we can see that LCD screens surpass CRTs in electricity consumption in 2012, and electricity consumption of laptops has more than doubled in 5 years, whereas desktops have been roughly stable. Without these two structural changes, the electricity growth rate of end-user equipment would be at least 8.3 %/year (instead of 5.2 %/year).

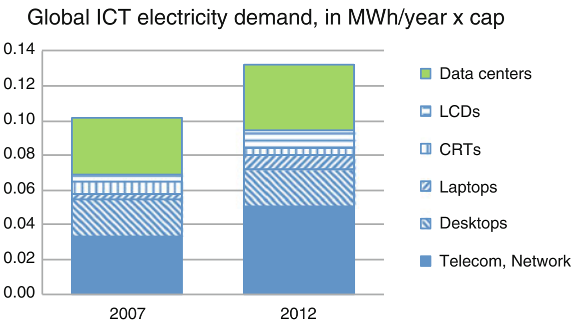

Fig. 8 Worldwide ICT electricity consumption per capita in still greater detail, in MWh/cap×year. (*Source* authors‘ chart based on data from [87])

For the effects of changing media use on energy consumption and CO_2 emissions, see also the chapter by Coroama et al. [88] in this volume.

2.5 *Energy Demand Throughout the Life Cycle of ICT Devices*

Thus far, we have focused on the energy demand of ICT devices during the *use phase*. The life cycle of an ICT device from cradle to grave, however, includes other phases that consume relevant amounts of energy as well, such as the *extraction of raw materials*, the *production* of the devices and the *end-of-life treatment* (recycling or final disposal) of the equipment after it has become obsolete. The method of Life Cycle Assessment (LCA) can be used to analyze all relevant environmental impacts of a product throughout its whole life cycle.

The first LCA studies of ICT devices were conducted in the 1990s. The primary energy demand for the production of a desktop PC was then estimated to be in the range of 10–12 GJ (2,778–3,333 kWh), which was more than that of an (analog) color TV set (2.8 GJ) and less than that of an average refrigerator (13 GJ) [89]. A study conducted by Grote in 1994 [90, 91] estimated the energy demand of the production of a PC to be much higher, namely 37.5 GJ. For technically more powerful workstations, a study done by the Microelectronics and Computer Technology Corporation (MCC) in 1993 estimated the production-related energy demand to be 25 GJ [92]. The two chapters by Hischier et al. [93, 94] in this volume provide detailed updates on LCA studies of desktop, laptop and tablet computers, including comparisons between production and use phase impact.

The communications aspect of ICT got the attention of LCA research much later. The first LCA studies on fixed line [95] and mobile telephone networks [96–100] were published after 2000.

In 2001, Empa started the 4-year research program “Sustainability in the Information Society” (SIS) which aimed to create a comprehensive picture of the effect of the ongoing “informatization” of society on sustainability, including positive and negative impacts. The program first focused on substitution effects, such as electronic media substituted for print media [101], or videoconferencing substituted for travel [102] and their counteracting induction and rebound effects [103]. The chapter by Coroama, Moberg, and Hilty [88] in this volume provides an update on the substitution of electronic for traditional media.

A part of the SIS program focused on the end-of-life phase of electronic devices, including a global perspective. An overview is provided in the chapter by Böni et al. [104] in this volume. An LCA study of e-waste recycling showed that the energy needed for industrial electronic waste recycling is clearly more than offset by avoided environmental impact, mainly due to the avoided primary production of the metals recovered [105].

Technology Assessment (TA) studies conducted in the SIS program (e.g., [106]) added a prospective part to the research on the effects of ICT on society and the environment. One result was that smaller, embedded ICT (such as RFID labels [107]) could in the future negatively affect established recycling processes, such as those of paper, plastics or textiles [108–111].

Although this chapter is written from an energy perspective, it is obvious that ICT is a field of technology closely related to material issues as well, both in its substitution potentials (e.g., replacing print media by electronic media) and through the raw materials needed to produce ICT devices. The latter aspect is covered in the chapter by Wäger et al. [112] in this volume.

2.6 The Influence of Software on the Hardware Life Cycle

The SIS research program at Empa also made an attempt to empirically investigate the influence of software products on the hardware life cycle. In 2003, a controlled experiment was conducted that confirmed that increasing processing power of PCs was overcompensated for by new software versions in terms of user productivity, at least for the basic tasks of file handling and text editing. New versions of operating systems and text processors not only forced users to buy new PCs because of their higher demand of computing power (and therefore shortened lifetime of hardware), they also increased the time users would spend at the machine to perform the same task as before [103, 113].

This trend, known as “software bloat”, came to a temporary halt with the emergence of small mobile devices, in particular smartphones and tablets—thanks to the limitation of the energy density of their batteries.

The mobile app has created a new paradigm for software design and distribution. Mobile apps are highly efficient, as they are reduced to the most important functions and because they are intended to run with limited hardware resources. At the same time, energy-consuming tasks are shifted from end-user devices to the cloud. The trend towards Web-based application software in combination with cloud computing has complex implications for the energy demand of ICT devices and services. This trend may enable end-user devices with low storage and processing capacities (even stationary devices, so-called thin clients) to become attractive because operations requiring large processing capacities can be carried out on the web server without burdening the client, and this can typically be a cloud-based service [114]. On the other hand, the energy consumption caused in the Internet and in data centers must be taken into account. Several chapters in this volume [61–64] elaborate on these aspects.

3 Methodological Challenges

3.1 Defining ICT

ICT is the result of a convergence of three lines of technological development. First, technologies bridging *space*, i.e., extending the spatial range of communication, from flags and fires used for transmitting messages over some distance to the wires and electromagnetic waves we use today. The second one is the development of technologies for bridging *time*, i.e., extending the temporal range of communication, from carving messages to future generations into stone, writing and printing on paper to today's digital electronic storage. The third line, finally, runs from using the abacus and mechanical calculators to the digital computer.

During this convergence, which is still ongoing, many types of devices and infrastructures emerge and vanish again from the markets. It is therefore easier to enumerate specific types of devices, such as laptop computers, smartphones, IP routers or web servers, than to give a comprehensive and precise definition of ICT. Conceptual boundaries are, however, crucial because they imply the system boundaries explicitly or implicitly used in studies on energy consumption, which are then non-comparable.

In our tour through the history of ICT energy consumption, we encountered studies in which residential ICT was restricted to computers and their peripherals; other studies include "entertainment" devices such as TV sets. Today, the boundaries between computers and TV devices are blurring. Commercial ICT may or may not cover ICT infrastructure (data centers and networks). Data centers' energy use may comprise the infrastructure (cooling, uninterruptible power supply) needed to run the servers; in some studies these 50 % of energy used by the infrastructure are not considered.

Estimates of the energy intensity of the Internet diverge by a factor of 20,000, a part of which can be explained by different definitions of "the Internet" (for details see the two chapters on Internet energy intensity [63, 64] in this volume). By means of an explicit definition of the system boundary of each study in this field, unnecessary confusion can be avoided.

However, two ongoing developments will always make it challenging to draw clear conceptual boundaries around ICT:

- An increasing number of microprocessors (95 % according to Rejeski [115] or even 98 % according to Broy and Pree [116]) are not used in dedicated ICT devices but are embedded in other objects, such as cars, household appliances, buildings, or industrial processes [117]. A compilation of the world's technological installed capacity to compute information by Hilbert and Lopez in 2011 [118] showed that the computing capacity of digital signal processors (DSP) and microcontroller units (MCU), which are mainly not used in dedicated devices, is of the same order of magnitude as the computing capacity of personal computers and one or two orders of magnitude higher than that in servers, mainframes and supercomputers [119, Table S A-3, p. 8]. The amount of energy used by this embedded ICT is unknown, and estimates are difficult. In official energy statistics, their consumption is usually included in that of the "host" object, e.g. the fuel consumption of a car. This can create inconsistencies in statistical analyses. Very often, the monetary value of ICT sales is taken as a basis for estimating the installed capacities. While production figures of the manufacturing ICT industry include the embedded electronics, sales of ICT and investments in ICT cover mainly the "electronic devices" but not the "embedded electronics." Macroeconomic studies relying on ICT investment data may therefore be flawed.
- ICT products are changing their nature from owned goods to services; cloud computing is only one of the trends that opens the door to a world of complete service-orientation. This is not surprising, because it is in the end always a service (and not a device or infrastructure) the user is seeking and paying for. From a life cycle perspective, it has always been challenging to define a functional unit that truly reflects what the user wants to get from an ICT device or infrastructure. Given the inherent multi-functionality of ICT, the related problem of allocating impacts (such as energy consumption) to functional units has been known for a long time. This methodological challenge will increase with the cloud computing paradigm. It will be easier to define the immaterial ICT service that is provided to the user, but more difficult to define the material infrastructure producing it.

3.2 Data Collection and Modelling Methodology

Estimating the electricity demand of a set of devices does not need a complex model but requires much input data, not all of which are available or statistically significant. Electricity consumption in the use phase is usually evaluated with a bottom-up approach:

$$\mathrm{Energy}(\mathrm{t}) = \Sigma_{\mathrm{ijk}} \mathrm{n_i}(\mathrm{t}) \times \mathrm{e_{ij}}(\mathrm{t}) \times \mathrm{u_{ijk}}(\mathrm{t})$$

with n: number of devices of type i
e: electric power load in functional state j
u: intensity of use by user k

For some types of equipment, the number of equipment can be deduced from statistics based on surveys (such as the "Information Society" indicators for Switzerland, [120]). But these data are usually not adequately detailed and must be complemented by sales statistics. With assumptions about the lifetime of the equipment, it is possible to deduce the number of equipment in use. Assumptions about "lifetime" are highly uncertain even when combined with data from electronic waste collection because devices can be stored in homes for years or have a "second life" before they enter the waste stream.

Furthermore, sales statistics do not tell us where the equipment is used, whether in an office or at home. And they do not cover all distribution channels. One example is discussed by Koomey [3, footnote 1 to Table 4, p. 23]: "Because Google creates its own custom servers, the company is treated as a server 'self-assembler' so its servers are not included in the IDC world totals." Koomey estimates the electricity consumption of Google's data centers to be on the order of 1 % of all data centers worldwide. Whether all supercomputers and mainframes are covered by the sales statistics has not yet been investigated.

The power in the different functional states is nowadays declared for standard models, but not for more specific configurations.

By far the largest uncertainty affects the intensity of use of the device. This begins with the question of whether the user has changed the settings of the automatic power management and ends with the uncertainty of switching off the devices when not used. What about the second or third computer at home: Is it used at all? Is it used for watching TV? Even extensive surveys and metering campaigns (some of which have been conducted) are outdated quickly because of the fast innovation cycles in ICT.

The resulting estimation of the electricity demand of ICT is highly uncertain. The fact that most of the studies show rather compatible results—the rare outliers, e.g. the papers by Mills [121, 122], are mostly implausible—may be less a sign of accuracy than the consequence of using the same or similar data and making similar assumptions. The uncertainty is highest for the *absolute* levels of electricity consumption. The calculated *trends* (temporal development) are more reliable, because the variation of the number of devices is quite well known and changes in the electric power load due to different functional states and changing intensity of use are rather slow.

If we extend the system boundary from the use phase to the entire life cycle of ICT hardware (as described above in Sect. 2.5), there are even more challenges in collecting the inventory data [123] and modelling the production and end-of-life stages of the life cycle as well.

3.3 *Quantifying the Effect of Software on ICT Energy Demand*

Although software products are immaterial goods, their use can induce significant material and energy flows. Software characteristics determine which hardware capacities are made available and how much electric energy is used by end-user devices, networks and data centers. The connection between software characteristics and the demand for natural resources caused by the manufacture and use of ICT systems has not been the object of much scientific study to date (see the chapter by Naumann et al. [124] in this volume for a current overview).

Quantifying the effect of a software product on energy demand and defining criteria for "green" software has proven to be methodologically challenging because each software product considered in isolation fulfills its function only as part of a complex ICT system, and therefore only in interaction with other software and hardware components (as well as the user). But it is the total required hardware capacity that determines the demand for natural resources in the form of electricity consumption and the hardware life cycle. In addition, the innovation cycles in the realm of ICT are so short that results based on snapshots in time quickly become outdated. Therefore, the focus of the analysis has to be on qualitative causal relationships and the dynamics of developments in the field. The following discussion is based on [114].

Figure 9 shows the ICT product system, which includes the life cycles of application software, system software, and hardware. In the use phase these three product types combine in an ICT system, which provides the desired performance. This depiction is highly simplified, since these days ICT systems are normally a distributed system in which a number of connected hardware and software components interact over a network.

Conducting an LCA of a software product, even if the scope of the study were restricted to the use phase of the software, would have to quantify the following causal relationships between software and hardware:

1. Power consumption: How much power consumption by the hardware does the software cause during its execution—not only in local end-user devices but also in network components, servers, and other devices involved in the process?
2. Hardware load: How much of the available hardware capacity is used by the software product during its execution? Since during this time this capacity cannot be used for other purposes, a corresponding portion of the overall life cycle of the hardware is attributable to the software. From an economic perspective, these are opportunity costs which are independent of power consumption attributable to use.

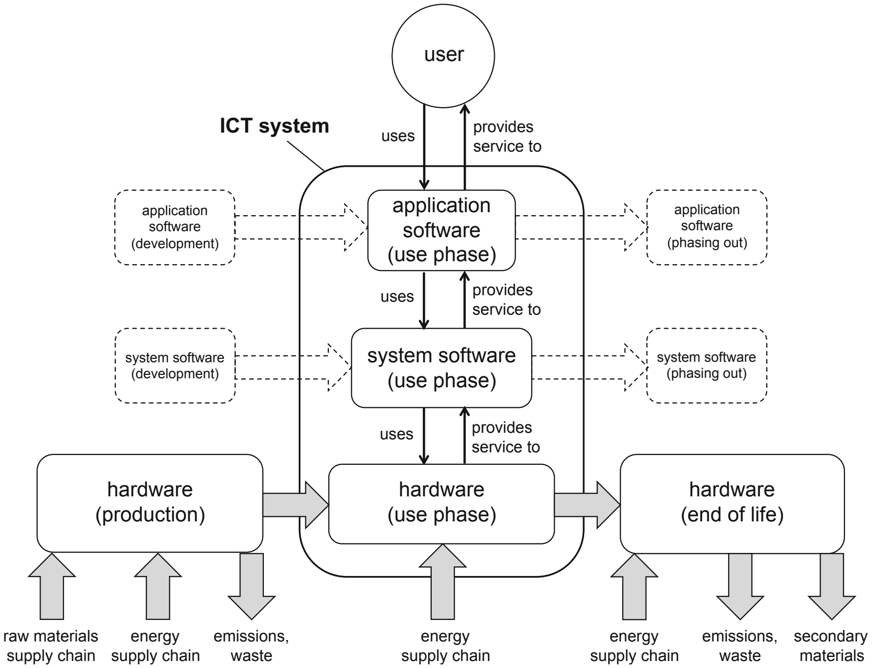

Fig. 9 Simplified representation of the IKT product system. *Grey block arrows* stand for the most important material and energy flows. (*Source* Translated from [114])

3. Hardware Management: Software can influence the operating states of the hardware, especially by using or preventing power-saving modes. In addition, it can distribute the computing or memory load in networks. In this way, a software product may influence the extent and the timing of power consumption by the hardware as well as the efficiency of hardware usage. How can this kind of influence be quantified?
4. Useful life of hardware: Software products can influence the timing of the decommisioning (obsolescence) of hardware products. For example, new versions of software products may require replacing functioning hardware sooner with more powerful hardware; or the reverse may take place through the installation of smaller or more efficient software versions, enabling the continued use of older hardware. How can such properties of software products be quantified? (See also the chapter by Remy and Huang [125] in this volume.)

ICT's future energy demand will also depend on how successfully solutions to these methodological problems can be found, as well as on the extent to which awareness can be raised of the considerable influence software properties can have on the energy flows triggered by the software.

4 Conclusions

The history of ICT energy demand shows a dynamic balance between two amazingly rapid developments:

- Increasing demand for ICT services, including the performance per device as well as the number of devices in use and of components embedded in other objects.
- Increasing energy efficiency of ICT, including progress in semiconductor technology as well as policies stimulating the use of efficient technologies, as the history of the reduction of standby losses and inefficient power conversion clearly shows.

This dynamic balance should not be taken for granted. The total amount of energy that society devotes to ICT could grow much faster than today if progress in efficiency slows down or comes to an end for some technological or political reason.

Research into the socio-technical system of ICT and its energy consumption currently faces several methodological challenges:

- The distributed nature of the ICT systems providing the final service to the user and the increasing share of embedded ICT make the definition of the system boundary of a study a non-trivial task with decisive consequences for the results.
- There is an increasing need to consider the life cycles of end-user devices, network components, servers and supporting infrastructures, spanning the extraction of raw materials to end-of-life treatment of obsolete hardware. The collection of data on the life cycle of each component, the creation and validation of models for each phase of the life cycle (including user behavior in the use phase) are issues calling for interdisciplinary efforts.
- Understanding ICT energy demand also requires a better understanding of the influence of software products on the demand for hardware capacity, on use-phase energy consumption and on the obsolescence of ICT components.

We hope that the research described in the present book helps overcome these challenges and will stimulate future research.

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Semiconductor Technology and the Energy Efficiency of ICT

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Abstract CMOS circuits have been the workhorse of ICT for 40 years. Due to the unique scaling property of this technology, energy efficiency has enormously improved during that time, notably by lowering the supply voltage from the long-time standard of 5 to 1 V and less. As the era of "happy scaling" has come to an end, progress becomes increasingly difficult and techniques beyond 2D size reductions have come into play. A superior and viable alternative to CMOS has yet to be found.

1 Why Has CMOS Become the Sole Technology for Information Processing?

CMOS (complementary metal oxide semiconductor) circuits totally dominate information processing and memory devices (RAM) today, both for professional ICT and consumer products. Also, solid-state disks assembled from flash-type memory chips are currently making ever deeper inroads into permanent mass storage, the traditional realm of magnetic disks. To fully understand that situation, we begin this review with a brief account of why CMOS technology displaced all contenders.

Initially a slow alternative to TTL, ECL, GaAs and other circuit technologies, CMOS had two unique and highly valuable traits:

1. n- and p-channel MOSFETs (metal oxide semiconductor field effect transistors) are manufactured side-by-side on the same silicon chip and work together as pairs in each logic gate. As these complementary switches turn "on" and "off" in an alternating fashion, supply current dropped to zero once a circuit had settled to a steady state. As a consequence, power dissipation was directly

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proportional to the switching activities in a circuit or, in other words, to the overall computational burden. This was in stark contrast to competing circuit technologies that draw significant amounts of DC current even when idle.

2. Almost all figures of merit of a circuit benefited from smaller layout geometries. Over the past 40 years, transistors, interconnect lines, and the separations between them have been downsized by a factor of approximately 1.4 with each new process generation. Each such shrink improved

    - the number of transistors per area,
    - the switching speed and, hence, the attainable clock frequency,
    - the computational performance and the storage capacity,
    - the energy dissipated per switching event, and
    - the unit costs per function (transistor, logic gate, computing operation, memory bit, etc.).

The first person to recognize the tremendous potential of CMOS scaling was Robert Dennard, who in 1974 formulated a set of rules that involved both geometrical and electrical quantities. Scaling is what has made it possible to serve ever higher computational and storage needs over several decades. Dennard scaling can indeed be understood as the explanation behind Moore's law. To this day, the ability to offer better performance at lower unit costs constitutes the competitive advantage that drives the semiconductor industry and that justifies ever larger investments. Established companies and start-ups eagerly picked up on the new possibilities, offering ever more sophisticated products, software applications, and services to the public.

Watch circuits, in which speed is immaterial and zero standby power crucial, were in fact among the earliest CMOS applications before the technology entered embedded computing in the form of microprocessors for its robustness, low power, and—at the time—relative simplicity. Affordable CMOS microprocessors later helped create the home computer, a product and a market that had not existed before and that paved the way to personal computing. Gaining in density and performance with each new process generation, CMOS Very Large Scale Integration (VLSI) circuits gradually moved up the ladder and eventually made their way into supercomputers. Integrating many millions of logic gates on a single silicon microchip ultimately proved more useful than squeezing the maximum operating frequency out of a handful of gates manufactured using a fancy technology.

Over the same time frame, VLSI chips also enabled mobile computing, broadband and digital wireless telecommunication, handheld music players and GPS devices, smartphones, download services, video streaming, Internet shopping, social networks, and all those applications that we see today.

As long as a typical processor dissipated only a few watts due to its relatively modest transistor count and operating frequency, VLSI designers had no reason to pay much attention to energy efficiency. Cost and performance invariably came first, and much the same applied to memory chips. This attitude radically changed in the 1990s with the advent of mobile computing which turned battery run time

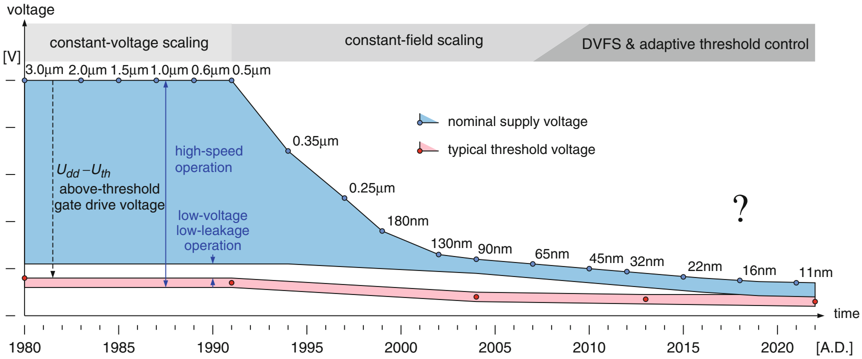

Fig. 1 Evolution of CMOS supply and threshold voltages. Source [1]

into a key issue. Mains-operated computers also ran into power limitations due to the problems associated with carrying away the heat produced by high-performance CPUs and graphic processors. This is because thermal flows in excess of 100–120 W drive up the costs for heat sinks, cooling fans, heat pipes, and related equipment to uneconomical heights. As the energy dissipated by a CMOS circuit for a given computation grows with the supply voltage squared, devising circuits and architectures that could provide the same level of performance from a lower voltage was a natural choice; see Fig. 1. Suspending the clock to inactive circuit blocks, known as clock gating, was an important innovation, but there were many others such as input silencing, delay balancing, and dynamic back biasing.

Over many product generations, the combined efforts of scaling and improved engineering led to a reduction in the amount of energy spent on a given computing or storage operation by several orders of magnitude. Yet, the explosion of new ICT products and services and their general adoption simply outpaced those efficiency gains. Today, the primary goal of VLSI design is to provide more computing performance and more storage capacity within the current power and energy budgets.

2 Where Does CMOS Technology Stand Today?

Dennard scaling, where geometric shrinking is accompanied by a proportional reduction of the supply voltage to maintain a constant electric field, came to an end around 2004, at the same time as the Gigahertz race; see Figs. 1 and 2. This is because to maintain the operating speed, MOSFET threshold voltages must be scaled down along with the supply voltage. Unfortunately, the lower its threshold voltage, the more a MOSFET tends to leak when turned off. To make things worse, the dependency is inherently exponential as any further reduction of a mere 70–100 mV inflates the sub-threshold current by a factor of 10. And to complicate

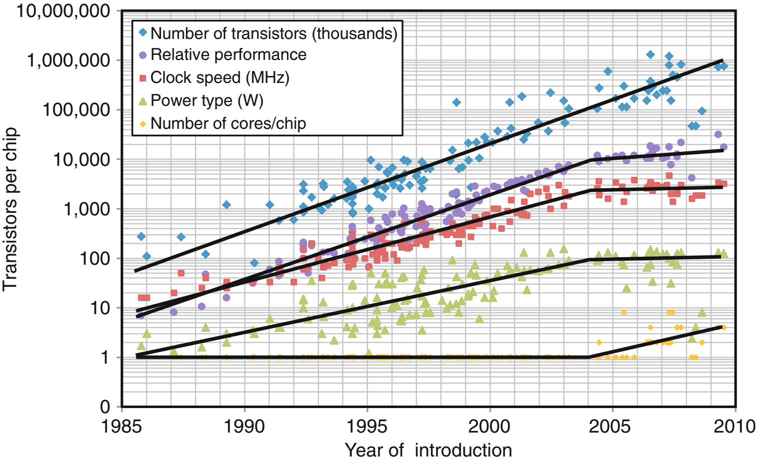

Fig. 2 Transistors, frequency, power, performance, and processor cores over time. The original Moore's law projection of increasing transistors per chip remains unabated even as performance has stalled. Source [2]

matters further, leakage is highly dependent on temperature and subject to important variations from the fabrication process. All this, in conjunction with the billions of potential leakage paths present in any complex VLSI chip, currently prevents industry from generally adopting core supply voltages much below 0.8 V. Instead, supply and threshold voltages are chosen so as to balance dynamic and static power in search of the maximum overall energy efficiency.

As a collateral damage, advanced high-performance VLSI technologies have lost the original CMOS virtue of zero or close-to-zero quiescent current. A circuit technique known as power gating had to be introduced to electrically disconnect temporarily inactive circuit blocks from the supply voltage. "Dark silicon" is a buzzword coined to describe the growing gap between the number of logic gates that can be manufactured on a chip with each process generation and the number one can actually afford to operate simultaneously without exceeding the thermal envelope.

As Dennard scaling ran out of steam, semiconductor technologists began to resort to low-ϵ_r inter-level dielectrics, copper interconnect (instead of aluminum), crystal straining, high-ϵ_r metal gate (HKMG) stacks, silicon on insulator (SOI) fabrication, and other alternative approaches. The finFET—announced in 2011 and referred to as "tri-gate transistor" by Intel—significantly improved current control by allowing the gate field to impinge on the conducting channel from two or even three sides (instead of just one as in planar devices; compare Fig. 3a, c). This has made it possible to reduce voltage levels from 1.0 to 0.8 V, but necessitated a total redesign of the MOSFET's spatial arrangement and manufacturing steps [3]. The ultimate stage of development in this direction would be the "gate-all-around FET" where an annular gate completely surrounds a silicon nanowire; see Fig. 3d.

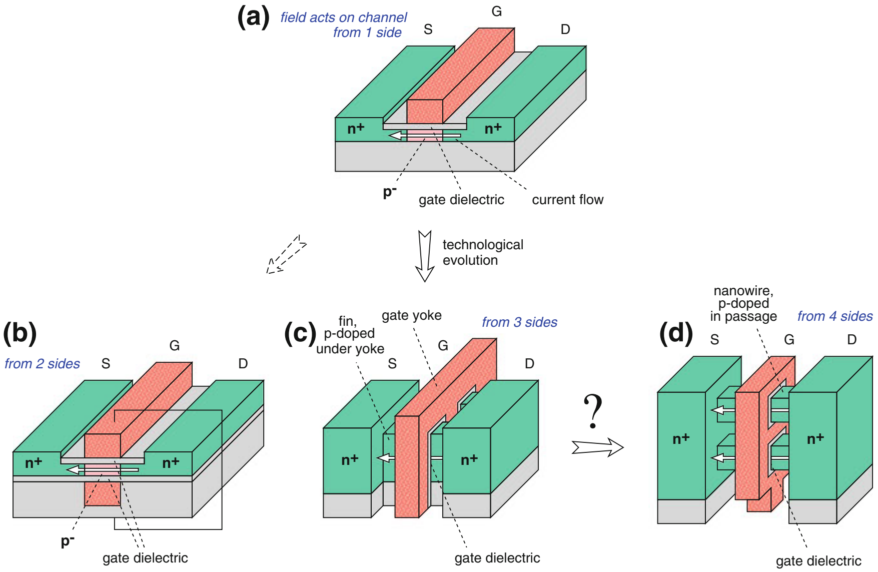

Fig. 3 Topological options for field-effect devices. Fully depleted n-channel MOSFET (**a**), planar double-gate MOSFET (**b**), fin-FET (**c**), and nanowire gate-all-around transistor (**d**) (simplified). Source [1]

Samples have been demonstrated in the laboratory, but the industrial viability is yet to be proven.

Circuit and architecture designers also continue to develop innovative ideas including multiple sleep and power saving modes, dynamic voltage and frequency scaling (DVFS), heterogeneous multicore architectures, and approximate/inexact/probabilistic computing. However, as the low hanging fruits have been harvested, alternative techniques tend to suffer from diminishing returns.

3 What Are the Perspectives?

Now at the 22 nm generation, CMOS technology is approaching atomistic dimensions. As size reductions cannot go on indefinitely,[1] important decisions lie ahead after 40 extremely successful years of geometric scaling. Compared to the tried and tested MOSFET, a superior switching device ought to

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[1] Current expectations are that MOSFETs should continue to behave as such down to a channel length in the order of 7 nm before source-to-drain tunneling will likely render further shrinks pointless. Whether the electrical properties and unit costs of such devices will justify the tremendous capital expenditures required to develop and produce them remains an open question, though.

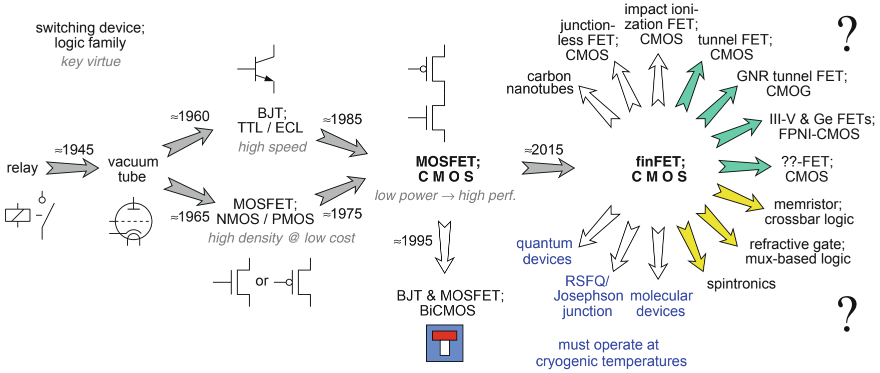

Fig. 4 Predominant computing technology, past, present, and future (note: years indicate massive shifts, not date of announcement). Source [1]

- operate with a lower voltage swing,
- exhibit a more abrupt “on”-“off” transition,
- manage with smaller electrical charges, and
- be insensitive to or take advantage of atomistic effects.

Fabricating isolated devices does not suffice to supersede CMOS, however. Any realistic alternative must

- combine billions of switches in a tiny volume,
- offer comparable levels of performance,
- be produceable in large quantities at comparable cost, and
- operate at room temperatures.

Research into a “new switch” has been underway for quite some time. Many ideas have been published, many prospective devices have been studied and simulated, some have even been manufactured in the lab. However, no truly superior and industrially viable replacement for the MOSFET has been demonstrated yet, and research continues in multiple directions as summarized in Fig. 4. In a joint effort by industry and academia, the semiconductor community regularly publishes their assessments in the “International Technology Roadmap for Semiconductors” [4].

In the meantime, industry is experimenting with ultra compact 3D assemblies of processor and memory chips that reduce parasitic capacitances and so afford further energy efficiency gains. This requires vertical interconnects between stacked semiconductor chips, called through-silicon vias, and poses heat evacuation problems. Another active research avenue aims at locally replacing the silicon in the transistors by high mobility semiconductors such as indium gallium arsenide (for the n-channel MOSFETs) and germanium (for the p-channel devices). Current plans are to deposit thin films of those materials on silicon wafers to avoid the costs of exotic substrates. What justifies the extra process complexity is the promise of energy efficiency gains on the order of 60 % that should result from bringing the supply voltage down to a mere 0.5 V with no loss in performance [5].

A major challenge on the architecture side is to reconcile flexibility and a simple programming model with energy efficiency. Agreeing on stable standards for all those data and signal processing algorithms that involve frequent and stereotypical calculations would allow the ICT industry to develop fixed function blocks for them and to incorporate those into future processors as a kind of "hardware subroutines". This would help because instruction set architectures waste orders of magnitude more energy for certain highly repetitive calculations than hardwired logic does.

4 Conclusions

While it is utterly clear that there can be no further progress without corresponding improvements in energy efficiency, the thirst for ever higher data bandwidths, the quest for better video resolutions, the current move towards storing everything in the cloud rather than locally,[2] the desire to communicate even with humble objects over the Internet, and similar trends will in all likelihood continue to drive up the energy demand of ICT as a whole. Unfortunately, CMOS scaling alone can no longer be counted upon to yield the same gains in terms of performance, efficiency, and cost reduction as in the past. And unless a radical breakthrough occurs, growing capital needs will further restrict the number of manufacturers in the semiconductor industry.

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[2] See [6] for a study on the impact of cloud computing on ICT energy consumption.

The Energy Demand of Data Centers

Gunnar Schomaker, Stefan Janacek and Daniel Schlitt

Abstract Data centers are the backbone of today's information technologies. With increasing usage of cloud services and web applications, the need for remote computing and storage will only grow. However, one has to consider that increasing numbers of server and storage systems also mean increases in energy consumption. The power demand is caused not only by the IT hardware, but is also due to the required infrastructure such as power supply and climatization. Therefore, choosing the most appropriate components as well as architectural designs and configurations regarding energy demand, availability, and performance is important. This chapter depicts influencing factors and current trends for these design choices and provides examples.

Keywords Data center · Energy demand · Metrics · Renewable energy · Virtualization · Cooling concepts · Power supply

1 A Short Introduction to Data Centers

In our daily lives, we increasingly access data located "somewhere else," at a place most of us do not have to care about. Usually, this place is a data center, closer or farther from the end user, completely opaque with its high intrinsic technical complexity and specific requirements. This chapter offers a basic explanation of data centers and especially how their power consumption is pieced together, why they need to consume a significant amount of energy and how that turns information processing into a cost-intensive task.

Most basically, a data center is a dedicated building or at least a dedicated, separated room, exclusively held available for the placement of IT hardware. This definition deliberately excludes small storage rooms that many (smaller)

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companies use to hold a rack containing some servers. While some define data centers to include the IT hardware, others do not. This is due to the fact that data centers can be run with different business models and operating strategies. A company might build a data center but not place a single server they own in it. Instead, third parties may buy their own servers and send them to the data center for it to manage their hardware. The data center's operating company only rents the "building" including all infrastructure needed to operate the servers, but not the servers themselves. This business model is called a co-location data center. Other data center operators construct and run the data center completely, including all hardware and software, selling only their services to their customers. A popular business model that uses exactly this scheme is very well known and roughly summarized by the term "cloud." This makes use of the possibilities gained by the technology of virtualization, which is explained later in this chapter. Here we assume that a data center contains the building, the IT hardware, and all infrastructure needed to successfully and safely operate it.

One of the main reasons why data centers have become complex and cost-intensive structures is reliability. This entails two areas: security and availability. It is fairly easy to explain why everyone using remote services or accessing data should care about security: to prevent others from spying on their personal or business files. For a data center, this not only means securing its digital entrances through firewalls and intrusion detection systems, but also reducing to the greatest possible extent the possibility of a break-in, the impact of natural disasters or misuse of any hardware by unqualified personnel. To prevent these incidents, data center buildings often resemble high security zones protected by video surveillance, road barriers, alarm systems, isolating devices, and fire protection systems. The building grounds of a data center should be above the levels of near water sources and be save from flooding.

Availability means the minimization of blackouts and deficiencies of the services. These may be a result of fluctuations in the power system or even entire power blackouts, but also of hardware failures or similar faults that may occur anytime during operation. To prevent service downtime or hardware damage, data centers use an elaborate combination of redundant systems for almost all technological layers. Starting with the power supply, a data center may use external emergency power supplies fueled by diesel and pre-heated to ensure the immediate operation until the outage can be resolved. There are also internal uninterrupted power supplies (UPS) with extensive battery packs that are able to power the data center for at least several minutes to bridge the time until the emergency power supply is activated or to filter a deterioration of quality caused by the energy supplier. In the worst case, at least the provided time frame allows the controlled shut-down of hardware to avoid damage or data loss.

The level of safety and redundancy is described by the tier level of a data center and finally results in reducing annual failing hours. The higher this level, the more redundancy the data center uses and the better it can guarantee a significantly higher availability [1]. However, all these security devices and redundant components come at a price: besides the acquisition costs of additional devices, the operational costs further increase due to more devices being run in parallel with reduced operational efficiency or at least in standby, waiting to take over in a predefined emergency case.

Data centers can be classified as follows:

- **Small data centers** contain 100–500 servers and have power inputs of about 50 kW.
- **Medium sized data centers** may host 500–5,000 servers with a power input of 240 kW.
- **Big data centers** host more than 5,000 servers, reaching a power input of about 2.5 MW, or even higher.

In Germany, for example, there are only about 50 big data centers, whereas there are about 370 medium sized data centers and 1,750 small ones [2].

2 Energy in the Data Center

A data center consists of several classes of devices, which all need a certain amount of power. Mainly these are the servers, the air conditioning, emergency power supplies and UPS, storage devices, network devices such as switches and routers, power distribution and other infrastructural devices, i.e. lighting, alarm or monitoring systems. Figure 1 shows a power consumption breakdown of these device classes. In efficient data centers, most of the power should be consumed by servers and other IT hardware whereas the air conditioning should consume less power; nevertheless, this is one of the main areas besides the servers that needs a significant amount of energy.

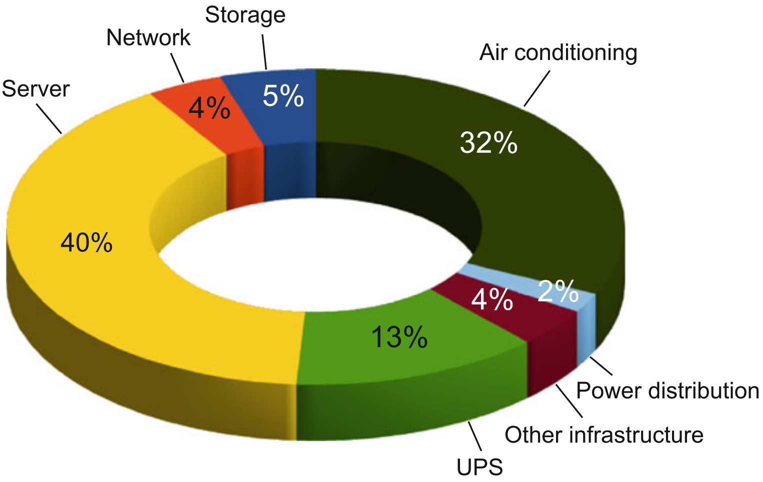

Fig. 1 Power breakdown of a typical data center; data from [3]

The air conditioning includes all components used to create cool air, distribute it and extract the hot air from the servers and devices. A common misconception is that only the servers generate waste heat and need to be cooled. It is true that the servers are the major heat producers, but each other device that consumes electric energy dispenses warm air, heating up the surrounding air and thus the entire room. If the electric components cannot be provided with enough cool air, serious hardware damage may result. Besides the servers, the UPS devices generate a significant amount of heat that needs to be transported out of the data center's room. Basically, according to the physical law of conservation of energy, the energy going into a system is equal to the energy coming out of the system. For a data center this means the energy in the form of power consumed must exit the data center, normally in the form of heat transported by hot air or water.

2.1 Dynamic Power Consumption and Efficiency Factors

When a new data center is designed and constructed or when old hardware gets replaced, the maximum power consumption of components is considered and all components are chosen wisely in order to keep within the maximum possible power a UPS might provide, for example. The relevant value for this process is mostly each component's plate power, thus the power printed on the back of each device, depicting its maximum theoretical consumption value. However, this value is seldom reached. First, the hardware manufacturers need to guarantee that their device will not extend its plate power, and as a result, the value is maximized. Second, modern power scaling technologies enable many devices to save power in times of low load, resulting in consumption values far below their plate power.

For servers, research has shown that a server's power consumption is significantly influenced by its current application load, mainly its processor's load [4]. Hence, if a server has less work to do, it will consume less power. Processor technologies such as clock/power gating or dynamic voltage and frequency scaling (DVFS), which changes the processor's voltage and frequency according to the current system load, have found widespread acceptance and lead to an even further improved dynamic power behavior of servers. This is also true of modern UPS and cooling devices, enabling the entire data center to adapt its power consumption to the current needs.

However, a fact that is often neglected is the efficiency factor of each device. The efficiency factor means that each device has a specific load range at which it shows the best relation of performance and consumed power. Operating a device out of this range results in a suboptimal efficiency, mostly implying a higher power consumption than it could have. The combination of several components in a complete system environment (e.g. a complete cooling chain) worsens this problem, as not every component can be operated at its optimal operation point. In this case, the best operation point holistically for all affected components should be found and used.

Considering these technologies and observations, the power consumption profile of a data center is mainly influenced by its application load profiles. If, for example, most of a data center's servers are used by employees of an office, and they follow regular working schedules, the power consumption profile of these servers may clearly show load peaks in the morning and afternoon, while being almost completely idle at nighttime.

One of the challenges of data center operators is to enable maximum performance operation during these peak hours while reducing the power consumption during low load times. Peak hours or low load, the accurate operation of all services must always be guaranteed. Later sections in this chapter show how this effort may be achieved by using technologies such as virtualization.

2.2 (Emergency) Power Supply

As stated above, the availability of the data center is a serious concern. Several redundant systems are thus used. The power supply system is often heavily redundant. To circumvent total power blackouts, on-site emergency power generators are used for a mid-term power supply. These are normally diesel-fueled generators standing near the data center's main facility. Even if the grid is stable and no power blackouts occur, these generators must be tested and refueled on a regular basis to prevent quality issues with older fuel.

The power path of a typical data center is shown in Fig. 2. Inside the data center, UPS systems are used to secure the power supply of the most important IT devices. These are the devices shown in the grey rectangle in the figure. Modern UPS systems are able to power these devices in case of power shortages for a few minutes. For this, they can fall back on a grid of battery packs. Similar to diesel generators, these need regular testing and maintaining. However, merely supplying power is not the only task for UPS systems in data centers. As many of the server and network devices are very sensitive to power or frequency fluctuations, the UPS also provides a netfilter functionality, dampening those effects and also preventing electrical surges.

Behind the UPS systems follows a wisely implemented power distribution system, consisting of modern power distribution units (PDU) that resemble normal multi-plugs, only with much more functionality. These units are able to measure and monitor the current power consumption of one rack or a single server; measured values are transmitted over ethernet connections to logging servers, managing this big data. Even remote shutdowns and switch-ons of single power ports are possible. These new possibilities enable the detailed energy logging of data center IT hardware and future automated power management of components lacking their own power saving functions. Of course, these intelligent, computerized PDUs also need power for themselves.

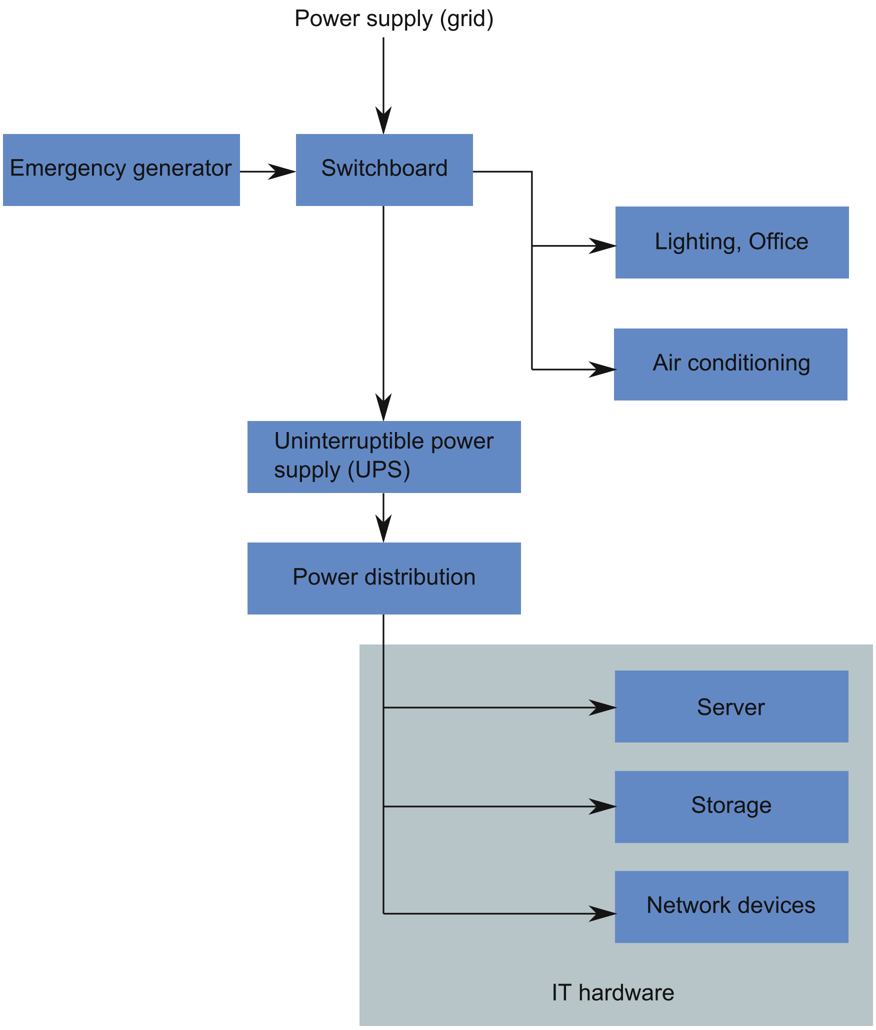

Fig. 2 Power path of internal data center components; IT hardware is highlighted in the *grey rectangle*

2.3 Hardware: Saving Potentials and Recent Developments

Over the last few years, the efficiency of data center hardware has changed considerably. A major trend has been to build faster and more compact servers, increasing their performance but also their energy density. This has lead to higher energy densities in racks, assuming that racks are not left half empty. Theoretically, a few of these modern servers are able to handle the work of many older ones, but because of rising workloads and requirements, the total number of servers has not decreased but rather often increased. As a result, new ways to handle this greater energy demand had to be found, specifically for both energy forms: incoming power and outgoing heat. Building thicker power tracks and higher dimensioned switchboards is relatively easy compared to the challenge of removing the heat from such a densely equipped rack in an efficient way. One possible solution is using cold aisle containments in combination with raised floor cooling. For a cold aisle containment, an encasement is built around two neighboring rack rows. Cold air is blown through the raised floor into this containment, and the servers in both racks may now take in this air through their fans. On the back of each rack, the heat leaving the servers is dispensed into the air, and a computer room air handler (CRAH) extracts it. The CRAH then cools the air with chilled water from a second cooling circuit. This technology leads to increased air conditioning efficiency.

An alternative method for heat removal in the highest energy density racks is to bring the chilled water not only to a CRAH but directly to the racks. From there the fully enclosed racks can be cooled by using in-row cooling devices, with air cooling devices in the raised floor, or by backdoor cooling. The purpose of in-row cooling and raised floor cooling devices is to minimize the distance the chilled air has to cover. Thus, the air loses less "cooling energy." Backdoor cooling devices aim to eliminate heat directly at the server outputs in order to maintain a homogeneous room air temperature. These techniques are more complex to build as the chilled water circuit has to reach every rack. However, the higher cooling efficiency and thus the ability to increase the IT packing density are key reasons they will continue to be used.

The type of cooling technology and the desired cool air temperature both affect energy costs. The lower the desired temperature, the more energy will be spent to cool the air down to this temperature. In order to save energy for air conditioning, a possibility is to slowly increase the cool air temperature by a few degrees. The ASHRAE (formerly: American Society of Heating, Refrigerating and Air Conditioning Engineers) [5] offers standards and recommendations for data centers regarding this temperature value. However, the precise temperature depends on the used hardware, infrastructure and architectural design of the data center and of all components used. There are data centers that operate with a temperature in a range of 20–27 °C while others operate at up to 40 °C.

Besides these data center internal cooling technology trends, another question is how to efficiently cool down the heated water coming from the CRAH or the rack-based cooling devices. Conservative solutions use traditional refrigeration; however, this may be soon the most energy-inefficient way of cooling down the water. Instead, new solutions take advantage of natural conditions prevailing at the data center's location. The simplest example of such a condition is a particularly low ambient temperature, enabling the data center's cooling to apply free air cooling. Also, cold water reservoirs may be used.

2.4 Software: Saving Potentials and Recent Developments

Although the data center is mainly defined by hardware devices, some software trends have still had a major influence on the data center industry. One of them is the concept of virtualization. It allows the separation of physical servers and virtual machines that run the software provided to the users or customers. One physical server may execute several different virtual machines at the same time these share the physical machine's resources. This technology was originally introduced to improve the maintainability and flexibility of servers in a data center. Here, virtualization allows one to migrate virtual machines to a different server without stopping its running services. Old or faulty servers may be emptied in this way and then get substituted by new ones. However, this technology had much more potential than originally thought. The technology of live migration allows the migration of virtual machines between servers with practically no service downtime (in millisecond range) and within small time ranges of a few seconds. A recent trend is to use this concept to move as many virtual machines as possible to a single server and switch off currently not needed, "empty" servers [6, 7]. This allows significant energy savings, but also bears dangers. The data center's operator must guarantee to a certain extent that the execution of its services will proceed without problems. High variations in application load profiles may however lead to resource shortness on a physical machine when there are too many demanding applications. In this case, an early switch-on of more servers is needed to migrate some virtual machines to them, just enough to allow the accurate operation of all applications. This concept is known as load management and is currently the subject of heavy research and development, with some solutions already on the market [8].

2.5 Hardware Life-Cycle

Regarding the aspect of sustainability, life-cycles of data center hardware, especially servers, may become a concern. Normally, server hardware gets exchanged every few years, because faster and more energy-efficient hardware becomes available. Some of the discharged hardware may still be used for less important services, but at some point, this hardware will be disposed of. Hard disks will never be reused, since no company can take the risk of spreading stored data; as a result, these will be destroyed. Many companies exist that are dedicated to IT hardware recycling; however, the number of these devices that actually get recycled is hard to determine and reliable numbers are hard to find. Since UPS systems need regular tests and the life of batteries is limited, a similar problem arises with these. At least, many UPS distributors companies offer take-back of the batteries.

2.6 Energy Efficiency Rating

Most well-known energy efficiency metrics for data centers are based on the electrical energy as the sole analyzed energy form. The main differences between the metrics are the coverage of observed influencing parameters and thus their suitability for drawing certain conclusions. Some metrics only consider the actual used energy in a data center and lack the possibility to compare results between two data centers or within the same data center with different configurations. Other metrics try to relate the useful work to used energy, but fail to define a general concept for evaluating useful work.

The prevailing energy efficiency metric for data centers is the Power Usage Effectiveness (PUE) and its reciprocal Data Center Infrastructure Efficiency (DCiE). Both metrics were developed by The Green Grid [9]. The PUE is defined by total facility energy demand divided by IT energy demand with measurements over a whole year. However, its common application as a general energy efficiency metric for data centers is not quite correct. By definition PUE represents the additional energetical overhead of infrastructure components to run the IT systems. It is a good measure for evaluating optimizations on the infrastructure side, but once IT systems have been changed, the comparability is lost. As PUE is defined for a whole data center facility only, the partial PUE (pPUE) [10] has been derived from it to assess data center subareas.

A shortcoming of PUE is its inability to represent power dynamics in a data center. Thus, additional metrics have been proposed that focus on the dynamic power behavior of IT and infrastructure. PUE Scalability [10] by The Green Grid and Infrastructure Power Adaptability by Schlitt et al. [11] indicate the IT and facility/infrastructure power relation to rate the adaptability of infrastructure power in addition to the absolute overhead given by PUE.

In addition to PUE, there are several energy efficiency metrics with a focus on computing that can rather be applies as a general metric. These metrics assess power/energy demands in relation to the useful work done. As a whole, they only differ in their approach to how to assess useful work. However, all of them possess a subjective component, as the productive outcome (e.g. processed orders per time) of data center applications must be defined by humans. Thus, an application of such a metric is complex and unique for each data center. This effectively precludes a fair comparison between different data centers. Illustrative metrics are data center performance per watt (DCPpW) [12] by Dell and data center energy productivity (DCeP) [13] by The Green Grid. Because of the mentioned definitional problems, there are also eight proxy measures, which can be used instead of useful work. These proxies reduce the useful work essentially to performance or utilization.

For a more detailed insight into the energy efficiency of single IT hardware components, there are several kinds of energy benchmarks. Three well-known examples have been specified. (1) SPECpower_ssj2008 [14] by the Standard Performance Evaluation Corporation (SPEC) runs a server-side java application and measures the power demand of servers at 11 throughput levels. The benchmark delivers a performance/power value for each load level as well as an average value. (2) The TPC-Energy [15] benchmark by the Transaction Processing Performance Council (TPC) rates the energy efficiency of a full system under test conditions consisting of several server and storage systems with an interconnecting network. It runs an online transaction processing workload and measures throughput and power at full load as well as in idle. (3) SPC-1/E [15] by the Storage Performance Council (SPC) stresses storage (sub)systems with typical functions of business-critical applications and measures maximal throughput as well as the power demand at up to five load levels. Although these energy benchmarks describe the energy efficiency of IT components reliably, a high-level view of the facility is missing. However, in future energy efficiency metrics, system-level energy benchmarks will play a key role. An example of such a metric is the load-dependent energy efficiency (LDEE) [16], which is currently in development.

If the focus of data center assessment evolves from energy to resource efficiency, there are some other known metrics. The Energy Re-Use Efficiency (ERE) [17] modifies the PUE regarding the reuse of waste energy. If for example the data center's waste heat is used to heat nearby offices, that fraction of energy may be subtracted from the facility consumption in the PUE equation. Thus, ERE demonstrates the commitment to sustainability. The Carbon Usage Effectiveness (CUE) [18] represents the sustainability of data centers by relating the PUE with the carbon emissions produced. High carbon emissions per kWh result in a worse efficiency whereas low carbon emissions, for example by using renewable energy, may compensate for bad PUE ratings. The Water Usage Effectiveness (WUE) [19] takes the same line except it focuses on water usage instead of carbon emissions.

3 Renewable Energy and Energy Reuse

One of the most recent trends regarding sustainability and green data center operation is the emergence of the usage of renewable energy for data centers [20–23]. At first glance, this idea seems to contradict all the requirements of a data center: reliability and availability of services under almost all circumstances. Most of the currently available renewable energy sources are heavily intermittent; for example, wind generators and photovoltaics depend on the current weather situation, with the latter clearly seasoning power generation at nighttime. And power storage opportunities are still far behind the current needs. Despite all these obstacles, some companies have already started building "green" data centers. Most of them use a combination of different technologies and strategies to ensure their reliable operation. The first step is to construct on-site renewable energy generators such as wind generators, photovoltaic or biogas. These should be connected to the public grid to enable the usage of excess power by nearby consumers such as other industrial facilities or private households. Since at some time grid power will need to be purchased, CO_2 neutrality can be achieved by buying certificates or power from remote renewable energy generator parks. An example of a company with a green data center is Apple with its data center in Maiden, North Carolina, USA [24].

According to the physical law of conservation of energy, all energy going into a data center must leave it in some form. From a physical point of view, a data center may be seen as an energy converter, consuming electric power and generating heat. To render today's data centers more sustainable, the usage of this waste heat is an increasing challenge [25] and not always easy to achieve. One of the major aspects of waste heat usage is the temperature potential that needs to be reached in order to make waste heat usage beneficial. As an example, one Swiss data center heats a swimming pool with its generated waste heat [26].

4 Conclusion

Although the data center industry is a market of hard requirements, it still looked out for new energy-efficient and sustainable technologies. Besides the efforts data center operators and hardware distributors have made in this area, scientific research and development is ongoing, creating new and interesting ideas and products for future data center designs, architectures and more efficient components. One example of a relatively new architecture innovation is the switch towards a direct current (DC) power distribution in data centers, simplifying the power supply of servers and other devices. However, it is important to note that not all research efforts will lead to successful improvements and not every new trend will be adopted by the data center industry.

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Consolidation, Colocation, Virtualization, and Cloud Computing: The Impact of the Changing Structure of Data Centers on Total Electricity Demand

Ralph Hintemann

Abstract The IT industry in general and data centers in particular are subject to a very dynamic development. Within a few years, the structure and components of data centers can change completely. This applies not only to individual data centers (see [27], in this volume), but also to the structure of the data center market at the national or international level. The sizes, types, and locations of data centers are changing significantly because of trends such as the consolidation of data centers, the increasing use of colocation data centers, virtualization, and cloud computing. The construction of large cloud data centers, for example Google in Finland, Facebook in Sweden, or Microsoft in Ireland, is an example of these developments. In consequence, there is an impact on the overall energy demand of data centers. This chapter discusses these developments and the impact on the overall energy consumption of data centers using the example of Germany.

Keywords Data center · Energy consumption · Consolidation · Colocation · Hosting · Cloud computing · Virtualization · Typology

1 Introduction

Data centers account for a considerable share of electricity consumption. Koomey assumes that they consumed 1.1–1.5 % of global electricity in 2010 and estimates that the figure for the US is between 1.7 and 2.2 %. What is more, global electricity consumption increased by 56 % from 2005 to 2010 [1]. The Borderstep Institute calculated that data centers are responsible for 1.8 % of total electricity consumption in Germany [2]. In places with a very high density of data centers, such as the Frankfurt area, their share of power consumption is even on the order

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of 20 % [3]. The power consumption of major data centers, such as Facebook's in Finland or Microsoft's in Chicago, is more than 50 MW [4, 5]. These figures and examples reveal two things:

- Data centers are of high significance with regard to total electricity consumption;
- Besides total power consumption, the development of the structure of data centers is important, e.g. are more large or small data centers added, what is the purpose of the data centers, and where are they located geographically?

IT trends such as data center consolidation, virtualization, and cloud computing, as well as increasing use of colocation opportunities are giving rise to changes in the structure of data centers. This chapter deals with the impacts of these structural changes on the energy consumption of data centers overall.

Such an analysis must first confront three major challenges. Firstly, in some cases it is not quite clear how the term "data center" is defined. To date, there is no uniform definition accepted by scholars and practitioners alike [6]. Various definitions exist, depending on how data centers are used [7, pp. 5–6]. An important reason for this is that the sizes and purposes of data centers vary considerably. At one end of the scale, there are small entities with a few elements, e.g. the server room in a medium-sized engineering company with, say, twenty servers. At the other, we find factory buildings the size of a soccer field housing tens of thousands of servers, storage systems, and network devices and involving comprehensive infrastructure such as equipment for cooling and climate control, power distribution, uninterruptible power supply, emergency generators, fire safety, access control, etc.

The second challenge is the high speed of investment in ICT in general and in data centers in particular. The structure of data centers is changing very rapidly because of new hardware and software technologies, new IT concepts such as cloud computing, and new approaches with regard to infrastructure, such as direct free cooling. Studies and publications on data centers prepared 4–5 years ago [8–12] no longer reflect current reality adequately.

The third challenge when analyzing the structure of data centers is obtaining up-to-date information about them. There are no official statistics concerning data centers. The opportunities to obtain information by means of surveys are also limited because data center operators consider them to be "critical infrastructure." Failures or malfunctions would have strong economic impacts on the company which could even threaten its existence. From the perspective of data center operators, it is therefore rational to provide as little information as possible about the location, components, and structures of their data centers. A further methodological problem is the fact that data centers are not economic entities of their own. In many cases, they merely have a supporting function, for example within companies of a particular sector (engineering, finance, chemistry, etc.). What is more, the quality of the relatively small amount of information available about data centers is difficult to assess. The results of analyses are often contradictory. One reason for this is surely that there are different definitions of what constitutes a data center.

It can be said that hardly any robust data and statistics on the structure of data centers are available. Therefore, studies to date on the energy use of data centers usually focus on analyzing individual data centers (e.g. [13–16]) or determining the total electricity consumption of a country or region [1, 2, 8–10, 12, 17, 18].

Despite these challenges, I attempt to analyze and evaluate the relevance of the structure of data centers for total energy use in this chapter, using the following approach. First, the methodology will be described, followed by an introduction of a typology of data centers. This typology permits more detailed analysis of the structure of data centers as well as the determination of implications of structural changes on energy consumption. Finally, some structural changes will be presented, using the development from 2008 to 2013 as an example, and impacts on data centers' energy consumption will be discussed. In order to illustrate the data, which are valid overall, with empirical data, and to provide a foundation for the results, I have selected Germany as an example, as comprehensive data are available at the Borderstep Institute.

2 Methodology

For this chapter, a data center is defined as follows [12, pp. 13]:

> A data center is a building or space which houses the central data processing technology of one or more organizations. It must consist at least of a room of its own with a secure electricity supply as well as climate control.

Various information sources were used to obtain valid information about the current structures and components of data centers and their changes:

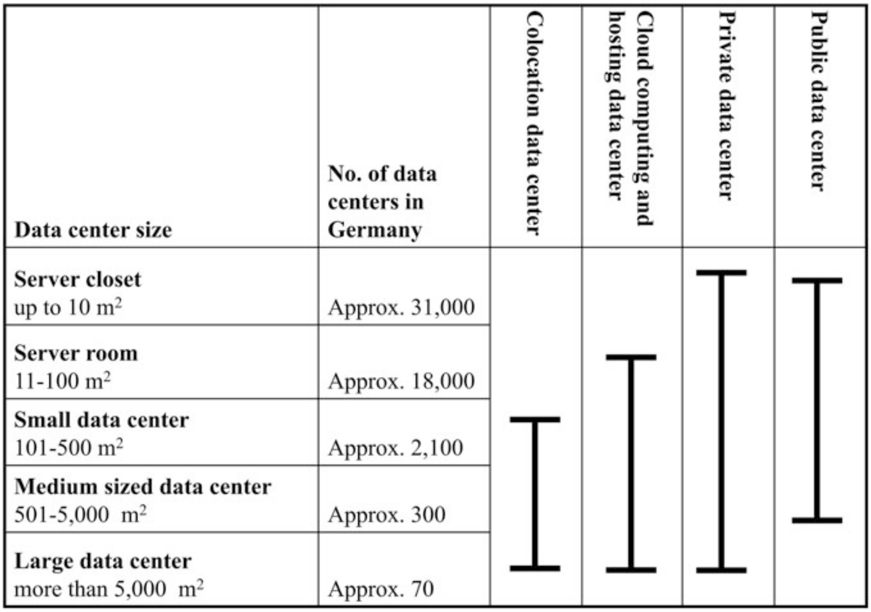
- A model of the structure of data centers in Germany is available at the Borderstep Institute. The model forms groups of data centers according to size and describes the average IT hardware equipment for each group as well as infrastructure elements such as climate control solutions, uninterruptible power supply, etc. The model was elaborated for the base year 2008 in a study commissioned by the German Federal Environment Agency [12] and has been developed further and updated annually in the context of the project Adaptive Computing for Green Data Centers (AC4DC, www.ac4dc.com). Above all, the model uses current sales figures for servers as well as storage and network components compiled by the market analysis firm Techconsult [19] and other available data from market studies (e.g. [20–23]). In addition, interviews with experts in the field have been conducted several times a year as well as annual surveys of data center equipment suppliers and data center operators.
- A database of the major data centers in Germany was established at the Borderstep Institute in order to test the model and develop it further. Using the model, the number of data centers with more than 500 m^2 of IT floor space was estimated at approximately 300. Internet and literature searches and especially

confidential information obtained directly from operators, planners, and equipment suppliers of data centers have made it possible to identify and describe two-thirds of them with regard to their location, operator, and purpose.

The following deliberations are based on the results of the data center model as well as the existing database on data centers.

3 Typologies of Data Centers

Before analyzing the structure of data centers, we must first clarify which types of data centers are to be differentiated. In the project AC4DC, a typology of data centers was developed which was used for this chapter as well. The typology (see Fig. 1) is oriented toward the type of IT use and includes two dimensions: the data centers' size and their purpose. The purposes of data centers include colocation data centers, cloud and hosting data centers, private data centers, and public data centers. As data centers may serve several of these purposes, they are allocated according to their main purpose. The gray areas show which sizes are typical of the various data center purposes. Data center size is differentiated between the categories "server closet," "server room," "small data center," "medium data center," and "large data center."



Data center size	No. of data centers in Germany	Colocation data center	Cloud computing and hosting data center	Private data center	Public data center
Server closet up to 10 m²	Approx. 31,000			│	│
Server room 11-100 m²	Approx. 18,000		│	│	│
Small data center 101-500 m²	Approx. 2,100	│	│	│	│
Medium sized data center 501-5,000 m²	Approx. 300	│	│	│	│
Large data center more than 5,000 m²	Approx. 70	│	│	│	

Fig. 1 Typology of data centers (overview) (*Source* Borderstep)

Commercial providers rent out infrastructure capacity for outsourcing or situating servers in colocation data centers. The spectrum of services offered there includes providing floor space or rack space for IT hardware, electricity supply, cooling, access control, fire protection, etc. as well as connections to existing telecommunications networks. Colocation data centers' customers are companies and institutions that, for various reasons, cannot or prefer not to operate their own infrastructure.

Cloud computing and hosting data centers offer their customers services via the Internet, e.g. providing IT infrastructure (e.g. virtual or dedicated servers, storage space on the Internet), platform services, or software as a service. Many experts see a difference between cloud computing and hosting with regard to the type of customer relationship. As a rule, hosting companies have one-on-one relationships and longer-term contracts with their customers, whereas typical cloud services are offered to large numbers of customers simultaneously as standard products. Usage of cloud services can vary greatly, both in terms of time and amount [20]. There are no clear boundaries between cloud computing and hosting, and in practice, the two types of data centers are very similar. For this reason, they are considered as a single category in this chapter.

Private data centers are data centers used by companies for their own purposes. These data centers run services such as e-mail, database systems, Internet platforms, software to support business processes, e.g. bookkeeping, controlling, distribution, procurement, production, warehousing, and human resources, or software employed for research and development. The components and structures of the data centers and the types of services differ widely, depending on the company's activities. This category also includes data centers whose operators offer their customers complex services on the basis of their (the data centers') IT infrastructure.

Public data centers are data centers run by public institutions or state-owned companies. They often run services similar to those in private data centers. The public data centers also include data centers at universities and municipal or regional data centers offering services for public-sector customers. These services range from colocation to cloud and hosting to taking on entire business processes.

4 Implications of Various Types of Data Center on Electricity Demand

4.1 Colocation Providers' Data Centers

There are more than 200 providers of colocation facilities in Germany, and they are often very large—roughly 45 % of the data centers in the category "large data centers" are colocation data centers. The biggest colocation data centers in Germany have more than 50,000 m^2 of IT floor space and power consumption on the order of 50 MW. Large colocation space providers generally operate internationally and offer sizable data center capacities in practically all major German cities.

According to Borderstep Institute surveys, IT floor space in colocation data centers in Germany increased by 25 % between 2008 and 2013 and now accounts for approx. 18 %, or about 320,000 m^2, of total data center space in Germany. In the future, the space provided by colocation data centers is expected to increase significantly. The Broadgroup assumes that gross data center floor space offered by third-party data center providers will grow by 33 % between 2012 and 2016 [21].

With regard to the implications of colocation data centers as a type of data center on energy consumption, three important factors must be mentioned. First, electricity costs are a very significant factor for colocation data center providers, and for some colocation providers, they account for approx. one-third of total costs. As a result, operators of colocation data centers are highly interested in improving energy efficiency. Therefore, newly built colocation data centers are planned for high efficiency. Second, colocation providers' strong interest in energy efficiency is countered by the fact that they have no direct influence on their customers' IT usage. This largely rules out comprehensive optimization of IT hardware and data center infrastructure, for example. Third, colocation providers are not entirely free to act when implementing modernization measures for improving efficiency, since they serve several customers in a single data center and must generally guarantee continuous operation. While data centers with just a single IT user can modernize their infrastructure relatively well when replacing IT components, this is practically impossible if many customers are involved, as they will replace their IT hardware at various different times.

4.2 Data Centers Operated by Cloud Computing and Hosting Providers

There are more than 2,000 hosting providers in Germany. With few exceptions (1und1, Strato, and Hetzner), the providers whose only service is hosting are small or medium-sized companies. In addition, there are also a number of large and internationally operating providers such as IT manufacturers (HP, IBM, Fujitsu, etc.), service providers (T-Systems, Atos, Unisys, Capgenimi, etc.), and cloud providers established specifically to provide these services (Amazon, Google, Salesforce, etc.) [20]. Some cloud and hosting data centers are very large. More and more mega-data centers with tens of thousands of servers are being established around the globe, e.g. by Google, Facebook, or Microsoft. According to Borderstep surveys, roughly one-quarter of the large data centers in Germany are cloud and hosting data centers. Their IT floor space is constantly increasing. For example, Deutsche Telekom built a cloud data center in Magdeburg measuring 24,000 m^2 [24]. Overall, high growth is forecast for the market in cloud services. The Experton Group expects annual growth of 40 % from 2011 to 2015 [20].

Borderstep Institute surveys show that the IT floor space of cloud and hosting data centers in Germany increased by approx. 25 % from 2008 to 2013, and that these 250,000 m^2 account for approx. 14 % of all IT floor space in Germany. It is safe to assume that this market will continue to develop dynamically in the future, especially because of the strong growth in cloud computing.

The most important implications of this type of data center on the development of energy efficiency can be summarized as follows. Energy costs account for a high proportion of the total costs of cloud and hosting data centers, usually between 10 and 20 %. Therefore, there is a relatively strong incentive to implement energy-efficiency measures. Hosting and cloud data centers often have a relatively homogeneous IT structure. This makes more extensive efficiency measures possible, ranging from efficient cooling technologies such as direct free cooling to sourcing hardware constructed specifically for this purpose, as in the case of Google, for example [11, pp. 6]. Thus, modern cloud data centers attain power usage effectiveness (PUE) figures on the order of 1.1–1.2 [4, 25]. PUE is a measure of the efficiency of data center infrastructure, indicating the ratio between energy use of the entire data center per year and the IT hardware's energy use. The closer the PUE value is to 1, the more efficient the data center's infrastructure.

4.3 Data Centers Used by Companies Themselves ("Private Data Centers")

The category with the largest number of data centers comprises data centers used by companies for their own purposes. Almost 90 % of data centers in the categories server closet and server room fall into this category. Private data centers account for just under 60 % of total data center space in Germany. The components and structures of the data centers and the types of services provided vary greatly, depending on the company's activities.

In Germany, large data centers with power consumption in the megawatt range are operated by companies in the financial, telecommunications, or automobile sectors, for example. Approx. 20 % of the large data centers fall into this category.

When considering implications of data center type on the development of energy efficiency, it is important to note that smaller data centers often have only minor incentives to increase energy efficiency. Especially because of the higher proportion of management costs in smaller data centers, the fraction accounted for by electricity is relatively low, often on the order of 5 % or less. In relation to the total costs of a company in which operating the data center accounts for just a small share of the company's activities, the energy costs for running the data center are generally very low. In addition, the expertise and resources for introducing energy efficiency measures in a data center are often not available in the case of small locations.

4.4 Data Centers in Public Agencies and Other Public Institutions ("Public Data Centers")

The category of public data centers also includes a large number of locations that tend to be smaller. It is reasonable to assume approx. 5,000 public data centers in Germany in 2013. They account for approx. 10 % of the total space of all data centers. The majority of public data centers is operated by municipalities. At the federal level, there are approx. 1,000 data centers.

In recent years, public data centers have seen a trend toward concentration. Public-sector service providers are now operating larger data centers in which the tasks of the various municipal and regional authorities are concentrated. They provide comprehensive IT services, but also hosting and colocation services. Universities and research institutions usually also have a high demand for computing capacity, both for research in the natural sciences and engineering and for operating their own websites as well as communication and online learning platforms. This capacity can be provided by means of high-performance computers and computer clusters in data centers.

Concerning the implications of this type of data center on energy efficiency, it can be stated that the operations of public data centers are often influenced by goals that are not purely economic in nature, for example, the requirement to store data within Germany. As increasing energy efficiency is a politically endorsed goal, politics may also directly impact data center operations. For example, public calls for tender often accord high importance to the issue of energy efficiency in the procurement of new goods. Another example of direct political influence is the goal adopted by the federal government to reduce the absolute amount of energy it uses for IT by 40 % between 2008 and 2013 [10].

5 Development of Data Center Structure and Energy Demand: The Example of Germany

What are the impacts of the structure of data centers on their energy consumption? Answering this question involves considering how the distribution of data centers by size has developed, using the example of Germany. Figure 2 shows the development of IT floor space in the various categories of data centers. Growth of data center space was relatively low through 2010, especially because of the economic crisis, and has shown significant growth only since then. The growth from 1.54 million m^2 in 2008 to 1.76 million m^2 in 2013 (annual average: approx. 2.7 %) is due almost exclusively to the increasing space provided in larger data centers. The space in small locations such as server closets and server rooms has even decreased. As mentioned above, a major part (approx. 51 %) of growth was in colocation data centers and in cloud and hosting data centers.

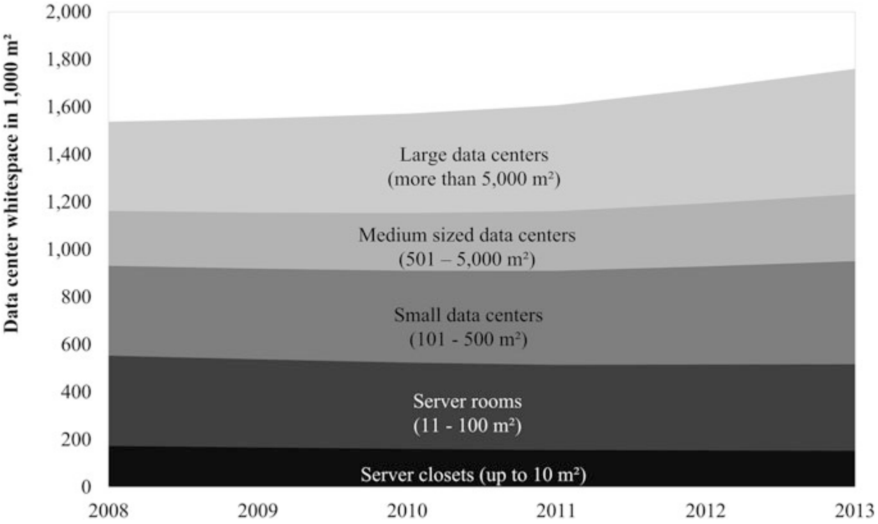


Fig. 2 Development of IT floor space in German data centers by group according to size (*Source* Borderstep)

The development of energy consumption by servers and data centers in Germany changed distinctly in 2008 (see Fig. 3). Total energy consumption declined slightly from 10.1 TWh (terawatt hours) in 2008 to approx. 9.7 TWh in 2013. There are two main reasons for this: First, the growth in data centers' energy use was slower because of the economic crisis, similar to the development in other fields of economic activity. Second, initial successes in energy efficiency have been achieved—especially as a result of the increasing discussions about data centers' energy needs [1]. In particular the newly built large data centers are distinctly more efficient than legacy data centers. According to a Borderstep survey conducted in February 2014, the PUE of good, new data centers in Germany is currently between 1.2 and 1.5. Thus, they require over 25 % less energy than a comparable legacy data center with a PUE of approx. 2, simply because of increases in infrastructure energy efficiency.

Unfortunately, the available data does not yet permit detailed analysis of the development of electricity consumption in the individual data center types broken down by size and purpose of the data center. Further research is required here. Yet there are many indications that a significant part of the efficiency gains were attained by building new, large data centers—especially in the fields of colocation as well as cloud and hosting. The federal government's Green IT Initiative is also responsible for a part of the reduction in data centers' energy use. It can be estimated on the basis of available data [26] that 25 % of the calculated absolute decline in data centers' energy use is due to the federal government's data centers alone.

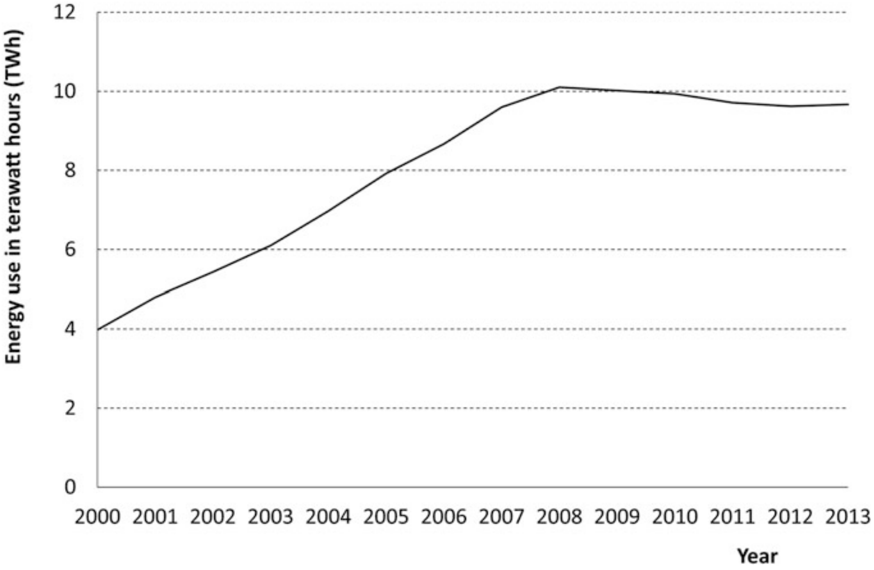


Fig. 3 Development of energy consumption by servers and data centers (*Source* based on [12], updated)

6 Summary, Discussion, and Outlook

The structure of data centers in Germany is changing, and this chapter has shown the extent of this shift. The number of small locations has clearly decreased since 2008, while the number of larger data centers is increasing. The segment of data centers with more than 5,000 m^2 IT of floor space is growing particularly rapidly. This growth is due especially to the increase in colocation as well as cloud and hosting data centers. Since the proportion of electricity costs in relation to total costs is relatively high for these two types of data centers, they have a major incentive to use efficient technologies. It can be assumed that the colocation as well as cloud and hosting market segments will continue to grow in the future. Yet is is questionable whether this will result in a decrease in data centers' total energy use. First, there are certain limits to a further increase in energy efficiency in colocation data centers, as discussed. Second, one must assume that cloud data centers in particular will grow so much that their energy use will increase overall in spite of improved efficiency. In light of the development to date, one must doubt that the computing capacity in private data centers will be reduced to the same extent as it is expanded in cloud data centers. Therefore, a significant rebound effect in cloud computing is to be expected.

The deliberations in this chapter have clearly shown that there is a substantial relationship between the structure of data centers and their energy consumption. Research in this field is still in its infancy. Above all, it is necessary to continue improving the availability and quality of data on the components and structure of data centers. Studies similar to this one for Germany must be conducted for other countries and regions as well. The international distribution of data centers in different locations is expected to be of major importance, not least because of the different climatic conditions.

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The Energy Intensity of the Internet: Home and Access Networks

Vlad C. Coroama, Daniel Schien, Chris Preist and Lorenz M. Hilty

Abstract Estimates of the energy intensity of the Internet diverge by several orders of magnitude. We present existing assessments and identify diverging definitions of the system boundary as the main reason for this large spread. The decision of whether or not to include end devices influences the result by 1–2 orders of magnitude. If end devices are excluded, customer premises equipment (CPE) and access networks have a dominant influence. Of less influence is the consideration of cooling equipment and other overhead, redundancy equipment, and the amplifiers in the optical fibers. We argue against the inclusion of end devices when assessing the energy intensity of the Internet, but in favor of including CPE, access networks, redundancy equipment, cooling and other overhead as well as optical fibers. We further show that the intensities of the metro and core network are best modeled as energy per data, while the intensity of CPE and access networks are best modeled as energy per time (i.e., power), making overall assessments challenging. The chapter concludes with a formula for the energy intensity of CPE and access networks. The formula is presented both in generic form as well as with concrete estimates of the average case to be used in quick assessments by practitioners. The next chapter develops a similar formula for the

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core and edge networks. Taken together, the two chapters provide an assessment method of the Internet's energy intensity that takes into account different modeling paradigms for different parts of the network.

Keywords Internet · Energy intensity · Energy efficiency · Customer premises equipment · Access network

1 Introduction

Information and Communication Technologies (ICT) are increasingly perceived as enablers of a reduction of anthropogenic greenhouse gas (GHG) emissions. Studies providing evidence for this enabling effect come not only from academia [1–3], but also from organizations as diverse as ICT industry associations [4], the European Commission [5], and the World Wildlife Fund [6]. Reductions are usually estimated based on quantitative scenarios [7], yielding an abatement potential which has to be adjusted downwards by an estimate of the ICT applications own footprint to calculate the net effect.

ICT can reduce energy consumption and related GHG emissions through three mechanisms: (i) from optimization effects in domains such as smart engines, buildings, or logistics, (ii) due to ICT-supported novel paradigms for the generation and distribution of electricity (i.e., smart grids), and (iii) due to substitution effects in which information and communication services partly replace other more energy-intensive activities [4, 8].

Two problems must be solved to quantify the net effect of ICT applications in these cases: First, the energy savings induced by ICT must be assessed. As we argue in [9] and [10], this is methodologically challenging: The baseline scenario, among other factors, as it expands into the future, is inherently speculative. Moreover, allocation issues are raised by the fact that ICT typically does not induce efficiency on its own, but only in a suitable technological, political, or organizational context. Secondly, the energy consumption of the ICT solution involved must be determined. This is also technically challenging, and existing literature reports diverse results. The current and the subsequent chapter explore this issue, with a particular focus on Internet services.

The *energy intensity* of the Internet, expressed as energy consumed to transmit a given volume of data, is one of the most controversial issues. Existing studies of the Internet energy intensity give results ranging from 136 kWh/GB [11] down to 0.0064 kWh/GB [12], a factor of more than 20,000. Whether and to what extent it is more energy efficient to download a movie rather than buying the DVD, for example, or more sustainable to meet via videoconference instead of travelling to a face-to-face meeting are questions that cannot be satisfyingly answered with such diverging estimates of the substitute's impact.

The Internet's energy consumption, and the energy intensity of the Internet as a suitable metric, are the topics of both the current chapter and the next one. The current chapter presents a review of existing studies and provides explanations for the large spread in their results. The chapter then recommends a definition of the system boundary that is most useful for decision-making and concludes by zooming in on the peripheral parts of the network and assessing their contribution to the energy intensity of the Internet. Chapter 9 [13] will focus on the remaining components, i.e., the core of the Internet.

2 Definitions and System Boundaries

In the late 1960s and early 1970s, the term *Internet* literally indicated the interconnection of a small number of local area networks on university campuses; back then, "the Internet" comprised a few routers and cables. Today, the Internet is the vast and heterogeneous infrastructure connecting billions of computers worldwide using the TCP/IP family of communication protocols. The majority of these computers belong to private users who connect to the Internet through their *Internet service provider* (ISP).

Figure 1 presents a high-level structure of the Internet. We comment only briefly on this structure here; more detailed discussions can be found in the following chapter in Sect. 2.1, and in the network models presented by Baliga et al. and Hinton et al. [14, 15]. Users' devices (such as desktop, laptop or tablet PCs and smartphones) connect through what is referred to as *customer premises equipment* (CPE), which are mainly WiFi routers and modems, to their ISP. The ISP bundles the data from several users in multiplexers. These vary depending on the subscription technology; for the widely used DSL connectivity they are *digital subscriber line access multiplexers* (DSLAM). Together with the cables connecting them to the CPE, these multiplexers constitute what is called the *access network*. After passing through an edge router, the traffic enters the metro and core parts of the Internet where routers with increasing capacities bundle the traffic. On the other side, the traffic is decomposed according to its destination; a large part is directed to data centers, while a smaller part is directed to other users (not represented in Fig. 1).

First attempts to understand the energy consumption of this distributed and heterogeneous power-consumption system were undertaken a decade ago, in 2003–2004. Starting from statistical data and studies on the ICT equipment in use, both [16] and [11] estimated the yearly power consumption of the Internet in the US. Dividing this value by an estimate of the US Internet traffic for that year resulted in estimates of the energy intensity of the Internet, i.e., the energy consumed throughout the Internet per amount of data transferred.

The two studies differed in their definition of what constitutes the Internet. While [16] considered only networking equipment (i.e., Ethernet hubs, LAN and WAN switches in offices and buildings, together with the routers of the Internet), [11] also took into account devices in data centers such as servers or data storage (see Fig. 1). As we discuss in more detail later, this definitional discrepancy across

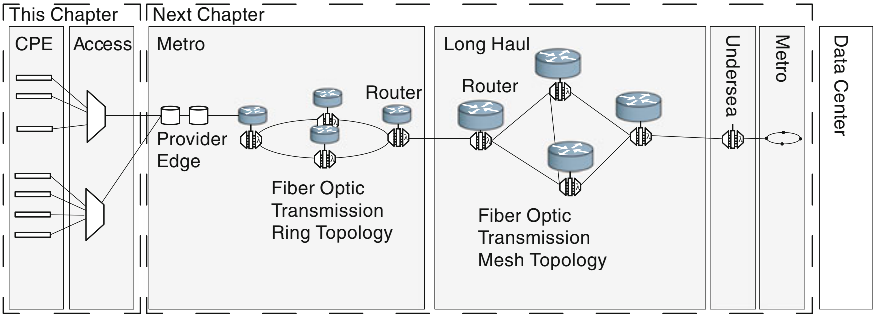

Fig. 1 Model of the Internet structure

studies persists until today, and is one of the main causes for the large spread of the published results.

Before going into detail, we note that we discuss estimates for direct energy consumption in the form of electricity only. The energy supply chain (containing the supply of primary energy, power plants transforming primary energy sources to electricity, and grids bringing them to the consuming devices) is excluded from the system under study. We also exclude the "grey" energy embedded in ICT hardware, although the material flows caused by producing and disposing of hardware are significant (see [17] and the chapter by Hischier et al. [18] later in this volume).

All studies that will be discussed apply an average allocation rule, distributing the equipment energy consumption evenly among the total traffic volume over a certain period of time. We found no study focusing on marginal instead of average effects.

3 Existing Assessments and Methods Used

The two assessments mentioned above, [11] and [16], both used the same methodology: dividing an estimate of the overall US Internet energy consumption by the estimated total Internet traffic in the US. Since then, several more studies used the same approach, while other studies deployed different methodologies. According to the basic methodological approach they use, existing studies can be classified in two classes:

Top-down. According to [19], *top-down* analyses are based on two estimates: (1) the overall energy demand of either the entire Internet or a part of it (e.g., a country or a continent), and (2) the total Internet traffic of that region.

Bottom-up. By contrast, *bottom-up* approaches model parts of the Internet (i.e., deployed number of devices of each type) based on network design principles. Such a model combined with manufacturers' consumption data on typical network equipment leads to an estimate of the overall energy consumption [15], which is then related to an estimate of the corresponding data traffic. Bottom-up studies can also use direct observations made in one or more case studies. These provide primary data on one or more of the following: deployed equipment, network topology and routing, power consumption of specific devices, and data volume passing through specific devices. Case studies present energy intensity values for specific cases, typically followed by a discussion of how the results can be generalized.

3.1 Top-Down Assessments

The earliest top-down assessments were introduced above: Gupta et al. published their results in 2003 [16], and Koomey et al. in 2004 [11]. The two studies used the same statistical inventory data on ICT equipment in commercial buildings in the US for the year 2000 [20]. Despite building on the same inventory, they make different assumptions as to which devices belong to the Internet and thus yield distinct consumption results.

The assessment by Gupta et al. [16], taking into account Internet routers, WAN and LAN switches as well as Ethernet hubs, yields a yearly energy consumption of 6.05 terawatt-hours per year (TWh/a) for all networking devices in the US. In assessing the energy intensity of “the Internet” in the US, the study narrows the focus even more. It leaves campus devices (i.e., LAN switches and hubs) outside the calculation, and considers only the consumption of WAN switches and Internet routers, estimated at just 1.25 TWh/a in 2000.

Koomey et al. [11], on the other hand, consider not only the campus networking devices, but also data center devices—servers (10.2 TWh/a) and data storage (1.5 TWh/a)—as well as uninterruptible power supplies (5.8 TWh/a), leading to a total of 23.65 TWh/a. Furthermore, they multiply this result by 2 to account for overhead such as cooling and ventilation, leading to a total of 47 TWh/a, 37 times higher than the value in [16].

The two studies also use an identical source to estimate the US Internet traffic: data from the Minnesota Internet Traffic Studies (MINTS) by Andrew Odlyzko and colleagues. These data, published e.g. in [21], estimate a US Internet traffic in 2000 of 20,000–35,000 TB/month. Using the same traffic data, and consumption data different by a factor of 37, one could expect from the two studies energy intensity results differing by the same factor 37. This, however, is not the case. Koomey et al. [11] use the lower end of the Internet traffic data from [21] but complement it with traffic on other public data networks and private lines, leading to a total traffic of 348,000 terabyte per year (TB/a). The study thus yields an energy intensity of 136 kWh/GB (kilowatt-hours per Gigabyte) [11]. As for the other study, we can only speculate that Gupta et al. [16] misinterpreted the data in [21] as yearly instead of monthly traffic values. The study thus calculates with the range of 20,000–35,000 TB/a, which leads to an energy intensity of 0.128–0.225 Joule/Byte, or 38–67 kWh/GB. The correct energy intensity for the system boundaries used by [16], however, should have been twelve times lower because the yearly traffic estimate was actually twelve times higher. The corrected values for [16] are 3.2–5.6 kWh/GB (see Table 1).

An update for Koomey et al. [11] was published a few years later. The new assessment by Taylor and Koomey [22] referred to the year 2006. Estimating again the US Internet energy consumption and using three existing estimates of the US Internet traffic per year, the new study yielded as result the range 8.8–24.3 kWh/GB [22]. This 2006 estimate was yet again updated for the year 2008 in an article by Weber et al. [23]. For this period, the authors assumed that total Internet traffic increased by 50 % per year, and that total Internet electricity use grew at a yearly rate of 14 %, which had been the average global growth rate of data center electricity use between 2000 and 2005. These assumptions resulted in an average Internet electricity intensity of about 7 kWh/GB for 2008 [23].

The study by Lanzisera et al. [24] is another well-known top-down estimate. The analysis only includes networking equipment, excluding not only end devices but also the transmission lines. Estimating the total of both the US and the world networking equipment stock for 2008, the power of each device and their individual usage patterns, the article computed an annual electricity consumption of 18 TWh for all networking equipment in the US and of 50.8 TWh for the world. The study did not relate this consumption to traffic values to compute the Internet energy intensity. To make the result comparable with other studies, we divide it by an estimate for Internet data traffic for 2008 in order to calculate the energy intensity. According to Cisco's "Visual Networking Index", "global IP traffic grew 45 % during 2009 to reach an annual run rate of 176 exabytes per year" [25]. We therefore assume a traffic volume of 121 exabytes (EB) for 2008. Using this value as a worldwide traffic estimate for 2008 yields an energy intensity of 0.39 kWh/GB for the world average.

3.2 Bottom-Up Assessments

The model-based approach has been used by Kerry Hinton's research group at the University of Melbourne [12, 14, 15, 26, 27], as well as in [28] and [29]. Some of these studies are not directly comparable to the results of top-down assessments because they have different focuses such as analyzing only a part of the Internet transmission (e.g., [27]) or analyzing the Internet power consumption per subscriber and not per amount of data [26]. A few of these results may, nevertheless, be adapted to be made compatible with studies on Internet energy intensity. As we present in detail in [30], the very first assessment from the Melbourne group [26] yields an Internet energy intensity of 0.91−2.52 kWh/GB, depending on the estimate of worldwide Internet traffic used.

Baliga et al. [14] provides a direct estimate of the energy intensity of Internet data transmission: 75 μJ/bit (micro-Joule per bit), equal to 0.179 kWh/GB, at the access rates typical of 2008. As the authors point out, their result represents a lower bound or optimistic estimate in terms of energy consumption, because the model assumes only state-of-the-art equipment and ignores the fact that less energy-efficient legacy network equipment is still in use. They further state that they expect this energy intensity to drop in the near future to 2–4 μJ/bit with increasing access rates.

Baliga et al. [12] puts forward a value of 2.7 μJ/bit. This value corresponds to 0.0064 kWh/GB and represents the lowest value published thus far. This study, however, aimed to compare the energy demand of traditional computing with that of cloud computing. As the energy consumption of the access network is largely independent of the traffic and would leave the result untouched, the authors legitimately ignored it: "The access network does not influence the comparison between conventional computing and cloud computing. Therefore, it is omitted from consideration and is not included in our calculations of energy consumption" [12]. While this assumption stands to reason within the scope of the study, it can lead to misinterpretation if taken out of context, as we will discuss in the next section.

Finally, Schien et al. [29] used a network model to analyze the download of the UK newspaper "The Guardian," as well as the download of a 640 s video from the Guardian's video section. The newspaper's html homepage was located on a server within the UK, while video and images were outsourced to a Content Distribution Network (CDN) and mirrored on several continents within the CDN's network. Downloads from clients in Oceania, North America, and Europe were studied. Results showed that because of the CDN architecture, geographical distance played only a minor role; the energy intensities of the downloads from different continents were similar. For both the homepage and the video, the intensity was 8–9J/mbit (Joules per megabit), which corresponds to approximately 0.02 kWh/GB. The study, while considering access, metro, and core parts of the Internet, did not account for the CPE.

In [31], this work was extended to include CPE and end devices, and to explore uncertainty and variability in assessments of digital services. In contrast to this chapter and to [30], which try to represent the existing variability in previous assessments, [31] estimates how uncertainty in energy intensity affects the overall result. Combining earlier results in a triangular distribution, the study arrived at a mean energy intensity for metro and core networks of 0.038 kWh/GB. For access network and CPE together, and excluding end devices, it provided a mean energy estimate of 0.019 kWh/GB.

In [32], Coroamă and Hilty present an assessment of a 40 Mbps (megabit per second) videoconferencing transmission of the case study introduced in [33]. For a system boundary that included network devices and optical fibers but no end devices, and making pessimistic assumptions in terms of energy consumption where specific data were not available, the study yielded an energy intensity of

Table 1 Estimates of the energy demand of Internet transmissions

Study	Method	System boundary					Data on [year]	Energy intensity [kWh/GB]
		CPE	Access	Core	Links	DCs		
[16]	Top-down	–	–	X	–	–	2000	38–67
[16], corrected	Top-down	–	–	X	–	–	2000	3.2–5.6
[11]	Top-down	–	–	X	X	X	2000	136
[22]	Top-down	–	X	X	X	X	2006	8.8–24.3
[23]	Top-down	–	X	X	X	X	2008	7
[24]	Top-down	X	X	X	–	–	2008	0.39
[26]	Model	–	X	X	X	–	2007	0.7–2.1
[14]	Model	X	X	X	X	–	2008	>0.179
[12]	Model	X	–	X	X	–	2011	0.006
[29]	Model	–	X	X	X	–	2009	0.02
[31]	Meta-analysis	X	X	X	X	–	2009	0.057
[32]	Case study	X	X	X	X	–	2009	<0.2

The columns below “system boundary” show which parts of the Internet and of the end devices (as introduced in Fig. 1) were accounted for by the individual studies. *CPE* is the customer premises equipment. *Core* stands for the metro and long haul Internet together—all studies consider both of them. *Links* are the optical transmission lines, and *DCs* stands for the equipment in data centers

0.2 kWh/GB for 2009. As we argued in [32], many characteristics of the study (such as an above-average number of hops) justify considering its result above-average in terms of energy intensity. This implies that the case-study result, when generalized, should be considered an upper bound for the average energy intensity.

The setting of this case study was such that no CPE or access network was distinguishable. The conference was held between a large conference center in Switzerland and a university campus in Japan. Both sites were directly connected to the metro network in the same way that Fig. 1 depicts data centers. Yet, the edge routers on each side of the connection behaved similarly as CPE and the access network behave in the typical setting: they had a low load far from their capacity, and with an energy consumption that had to be allocated entirely or to a large extent to the case study.

4 Factors Influencing the Results

Results of the surveyed studies span a very wide range: from the 136 kWh/GB of [11] down to the 0.006 kWh/GB from [12], there is a spread of four orders of magnitude. In this section, we show how the distinct assumptions about the system boundary and further factors affected the results of the individual studies.

Table 1 summarizes the characteristics and the results of the studies presented. Special emphasis is given to their system boundaries. Our analysis revealed the following factors to be the most important influences on the result:

- The reference year of the study,
- the inclusion of data center devices within the system boundary,
- the inclusion of customer premises equipment and access network, and
- the inclusion of overheads such as cooling and redundancy equipment.

Each influencing factor is discussed in the following subsections.

Reference Year. An important part of the large differences can be explained by the year of reference of the individual studies, ranging from 2000 [11, 16] to 2011 [12]. The ICT sector is characterized by fast innovation cycles, and the equipment is becoming ever more energy efficient, needing less energy per amount of data being processed or transmitted. Taking [22]‘s estimate that the energy intensity of the Internet decreases by 30 % each year, this technological progress alone leads to a reduction by a factor of 50 over the period of 11 years covered by the studies.

System Boundary: Data Centers. The most important determining factor is the system boundary, in particular, whether or not data center devices (i.e., data storage and server-type devices running in server rooms or data centers) are viewed as part of the Internet. This decision has a large impact on the result: As shown in Table 1, for 2008, which is referred to by several studies, the two studies not including data centers result in energy intensities of 0.39 [24] and 0.179 kWh/GB [14]—factors of 18 and 39 below the 7 kWh/GB of the study that includes data centers [23], respectively.

The original statistical data from [20] (used by both [11] and [16]) supports this observation. While the consumption of core Internet devices was estimated at just 1.25 TWh/a, the consumption of storage devices and servers together was estimated at 11.7 TWh/a.

System Boundary: CPE and Access Networks. From the equipment inventories in [16] and [11] (presented in Table 1 of each paper), it is clear they do not consider customer premises equipment or access networks. This stands to reason: both rely on 2000 inventory data for ICT in US *offices*, not in homes. And the Internet had not yet exploded, reaching every home as it does today. In 2000, ISPs, access networks, and customers' modems and routers were not nearly as prevalent or important as they later quickly became. Taylor and Koomey [22] and Weber et al. [23], on the other hand, explicitly include access networks and exclude CPE. Most of the other

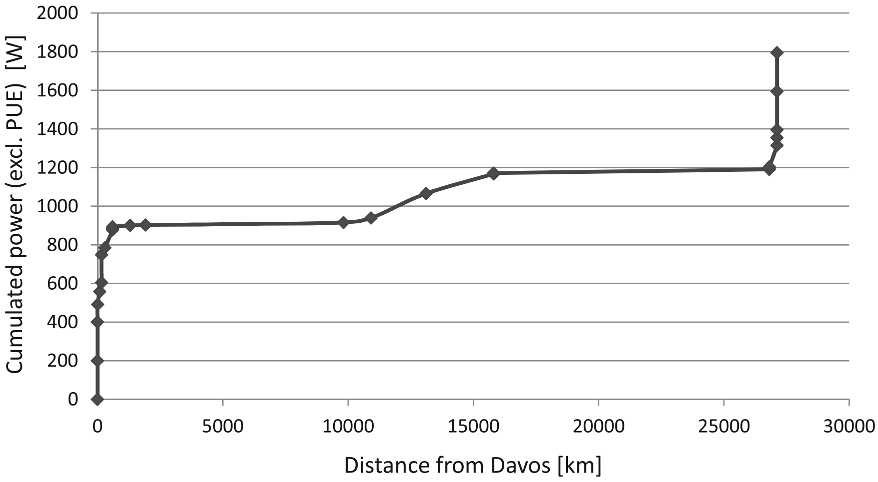

Fig. 2 Cumulated power demand for the videoconference case study [33] along a distance of 27,000 km. The power demand of local network components, albeit relatively small, is allocated to a relevant extent to the case study's traffic due to the low average load of the local components. These local components therefore clearly dominate the overall power consumption of the transmission. The large core Internet nodes and the transoceanic "data highways," while utilizing a relatively large amount of power, typically have a switching/transporting capacity on the order of hundreds of GB/s, or even TB/s. Their contribution to the overall demand amounts to less than 1 Watt/Mbps in the case study. By contrast, the power demand of transcontinental links does contribute significantly to the overall consumption, due to their relatively low bandwidths

studies account for both, except [27] and [29] which do not include CPE in their assessment and [12] which does not consider the access network.

Not considering CPE or access networks, however, has a great impact on the result. When the otherwise dominating data centers are excluded from the calculation, numerous studies point out that CPE and access networks dominate the energy intensity of the Internet over core and metro networks. Figure 2, for example, shows the cumulated power consumption of the case study presented in [32]. The peripheral parts of the network clearly dominate the overall power consumption.

Both [14] and [15] also point out that for the peak access rates typical of 2008 and 2010, respectively, access networks dominate the power consumption of the Internet. Core and metro networks would become the dominating part only if access rates were to grow extensively and reach peak access rates in excess of 100 Mbps (for the energy efficiency of 2010 networking technology). For networking technology that becomes more efficient along the foreseeable trends, typical peak access rates would have to be over 1 Gbps for the core and metro networks to surpass the power consumption of the access networks. For the moment, as typical access rates are much lower, access networks use more energy than the core of the Internet and their exclusion profoundly changes the result.

The consumption of customer premises equipment is within the same order of magnitude as the access network but, as a general tendency, is slightly higher:

according to [14], the access network needs 2.8 W of power, while the CPE needs between 4–10 W, depending on the technology used. Schien et al. [31] calculate with 2 W per subscriber for the DSLAM of the access network and with 10 W for the CPE (5 W for the modem and another 5 W for the WiFi router). As with the access network, the decision of whether or not to include the CPE decisively influences the result.

Overheads: Cooling and Redundancy Equipment. The facilities (rooms, buildings) hosting ICT networking equipment and datacenters induce a power overhead due to non ICT-related consumption such as cooling or lighting. The measure widely used to account for this consumption is the *Power Usage Effectiveness* (PUE). The PUE is computed as a facility's total power divided by the power needed to run the ICT equipment only [34]. As the former includes the latter, the PUE is larger than, or equal to, 1. The closer the PUE is to 1, the less power is "wasted" for activities other than information processing. The average PUE for datacenters nowadays is slightly lower than 2 [35] with a decreasing tendency; for Internet routers it was around 1.7 in 2009 [36]. Most studies do consider a PUE between 1.78 [29] and 2 [12, 14, 26, 32] in their calculations. Notable exceptions are [16] and [24] that do not account for the PUE, i.e., they present results one would obtain for a PUE = 1.

Another overhead is induced by redundancy devices. Referring to routers, [31] notes that "devices are operated with at least dual redundancy in order to cope with failure". Baliga et al. [14], too, notes that a minimum of two uplinks are used for redundancy in metro and core networks. Several of the bottom-up studies (both model-based and case studies) account for the redundancy equipment via a redundancy factor of 2 [12, 14, 29, 31, 32].

5 Discussion

As the system boundary plays such a decisive influence on the end result, this section discusses possible best practices in defining the system boundary of the Internet for energy-related studies. It then shows how the access network and CPE differ from the more central parts of the network, and concludes with an assessment of the energy intensity of the former.

5.1 System Boundary

End Devices. Coroama and Hilty [30] argue extensively against the inclusion of end devices (both user end devices such as personal or laptop computers, as well as servers and storage in data centers) within the system boundary for the energy intensity of the Internet. As we have shown above for data centers, including such devices can dramatically change the results. This, however, is inadequate not only as a matter of semantics; The concept of the Internet by definition does not include end devices but only the infrastructure connecting them. There are also practical arguments against including end devices, since that would yield results ill-suited and potentially misleading on most questions:

- The consumption in access, metro and core networks is largely independent of both the end devices and the application generating the traffic. Meaningful averages can thus be defined and estimated. By contrast, end devices such as desktop computers, smartphones or web servers have very different power demands. Different applications imply different sets of end devices: web browsing a server at a data center and a desktop, laptop or tablet computer; peer-to-peer file exchange two computers; and high-end videoconferencing two large LCD screens in combination with codec devices.
- Moreover, even for identical devices at both ends, distinct applications can induce very different consumption levels per amount of transferred data. While a peer-to-peer file exchange, for example, can use a bandwidth of several Mbps, a Skype voice call gets by with a bandwidth of only 60 kbps. Assuming exclusive usage of the two client devices, the low-bandwidth case induces a much higher energy consumption *per bit* at the terminal nodes due to the low utilization. This could lead to the seriously misleading conclusion that “the Internet” uses more energy per amount of data for applications with lower bandwidth demand, in this case for a Skype voice call, than for a highly demanding file exchange.

Under these circumstances, with different devices and different applications inducing varying consumption in the end devices, it is unclear how these consumption levels could be aggregated into meaningful averages. It seems more meaningful always to assess network energy and the energy of end devices separately, and to add them up when needed—for example, for the assessment of the energy needs of a specific service [32].

CPE and Access Networks. The consumption of customer premises equipment and access networks, on the other hand, should always be considered. Unlike end devices, these devices have no stand-alone meaning. They only exist to connect end devices and thus semantically belong to the Internet.

Moreover, as shown in several studies [14, 15, 32], CPE and access network dominate the energy consumption of the Internet over metro and core network. Although this might not be true for services with a very high bandwidth usage (see next chapter [13]) and might permanently change in the future with increasing access rates [15], it is certainly the rule for the moment. It is advisable always to include these factors, even if they make an equal contribution in the cases under scrutiny. Although dropping such factors may simplify comparisons such as in [12], it will also change the absolute values which, if taken out of context, may lead to misunderstandings.

Overhead: PUE and Redundancy. The cooling and other types of overheads included in the PUE, as well as the redundancy equipment, provide support or safety functions in the Internet. Hence, their consumption should be accounted for.

As one of their few advantages over bottom-up assessments, top-down studies inherently include the redundancy equipment, as this is included in the stock inventories these are based on. Bottom-up analyses must account for them explicitly—as mentioned above, a factor of 2 for redundancy and a factor of 1.7–2 for the PUE are the values most studies use.

It must be noted, however, that both PUE and redundancy only apply to access, edge, metro and core equipment. CPE have no redundancy nor are they cooled. Whether redundancy and overheads are considered thus has a relatively low influence on end results that include CPE, and there is a risk of overestimation if one includes redundancy and PUE for the CPE as well (as we did in [32]).

Fibers. Whether the power of the amplifiers along the fiber cables is considered (as it is in most studies) or not (as in [16, 24]), also has only a marginal impact on the result. The relatively high power of dozens of kilowatts of transoceanic fibers gets divided by such a large amount of traffic that the contribution per amount of data becomes negligible [32]. The consumption along fibers only becomes relevant for fibers with a low load such as the US transcontinental links in [32]. Such a case leads to a considerable allocation to relatively low amounts of traffic. Often, however, this is not the case. [14] argues that "the core optical transport (wavelength division multiplexed links) accounts for only a small fraction of the total energy consumed by the Internet". But even when relevant, the consumption along the fibers was still smaller than the consumption of the access network [32].

5.2 *The Challenge of Defining the Energy Intensity of the Internet*

A basic methodological problem with the energy intensity of the Internet is that for some devices the energy consumption scales with the traffic volume and for other devices it scales along different dimensions, especially time of usage [30, 31]. The former is true of most networking devices in the metro and core network [31], while the energy consumption of devices in the access network and CPE (as well as end devices, which have been excluded from the analysis) usually scales with the time of usage and is largely traffic-independent [27].

To account for these differences, [31] recommends allocating the energy consumption of a device based on an approach that takes into account the limiting factor of the device—i.e., the factor that, if increased, would first limit the quality of service. If the limiting factor is in practice very hard to reach, the approach allocates energy according to the dimension that, if changed, results in the most significant change in energy consumption [31]. For the overall network energy intensity, [30] thus suggests using a combined approach that encompasses intensities defined as both energy per data and energy per time (i.e., power) where appropriate. We will elaborate on this approach in Sect. 5.3.

Existing studies, however, do not differentiate between categories of devices when defining a metric for the energy intensity. Instead, each study defines the energy intensity for all devices along the same dimension: Most studies define the network energy intensity as energy per amount of data [11, 16, 22, 23, 29, 32]. With a partial focus on CPE and access networks, [31] defines the energy intensity for those devices as energy per time. Some studies with a focus on access networks, noting that access networks' devices are always on and their consumption is thus both traffic- and time-independent, define the energy intensity as energy per subscriber [26, 27]. Finally, top-down studies can avoid the problem altogether by computing only the overall energy of the Internet and not relating it to any other dimension for a measurement of energy intensity (e.g., [24]).

We conclude this chapter by putting forward a formula for the computation of the energy intensity of the access network and customer premises equipment. The next chapter in this volume [13] addresses the metro and core networks, and proposes a formula for the energy intensity of those parts of the Internet. That energy intensity is defined as energy per data. Summing these two leads to the first formula for the energy intensity of the Internet that combines an energy per time component with an energy per data component and thus models reality more closely than previous work.

5.3 The Energy Intensity of CPE and Access Networks

In this subsection, we develop the formula for the energy intensity of CPE and access networks. We build on the analysis of [31], which analyzes the energy consumption of online multimedia services. For the consumption in access networks and CPE, that article puts forward the following formula (formula 9 in the article):

$$E_{AN} = t_s \left(\frac{P_{CPE}}{N_{CPE}} + \frac{P_{TU}}{N_{TU}} PUE_{Net} \right) \qquad (1)$$

where

- E_{AN} is the energy consumption in the access network (including CPE in that article's terminology) for the consumption of a given service,
- t_S the time of service consumption,
- P_{CPE} and N_{CPE} the power of all CPE taken together and the number of users connected to them, respectively,
- P_{TU} and N_{TU} the power of the access network devices and the number of users connected to them, respectively, and
- PUE_{Net} the PUE of the DSLAM, which typically requires cooling.

We start from this formula to define the energy intensity per unit time (i.e., power) of customer premises equipment and access networks. For more clarity, we consider access network and CPE separately and add them back together in the end. As we are interested in the energy intensity and not the total amount of energy, the time factor t_s disappears. Additionally, the energy intensity of the Internet is the average value for one Internet communication and thus always includes exactly one set of typical customer premises equipment ($N_{CPE} = 1$)—what “typical” means in this context will be addressed shortly.

With these observations, and renaming P_{TU}, N_{TU}, and PUE_{Net} to P_{AN}, N_{AN}, and pue_{AN} for more consistency, the intensities of the access network and the CPE, i_{AN} and i_{CPE}, are:

$$i_{AN} = \frac{P_{AN}}{N_{AN}} pue_{AN} \tag{2}$$

$$i_{CPE} = P_{CPE} \tag{3}$$

The trivial formula 3, however, ignores one important aspect that was not considered in [31] either: the energy used by CPE while idle, i.e., while not providing any service. This energy has to be somehow distributed among the services provided during a certain period [37]. We choose to distribute the idle energy consumption among the services provided over a given period of time proportionally to the time those services are active.

For the entire cycle over which meaningful averages can be built (i.e., a day, a week, a year), we define

- t_{On} the total time in which the equipment is on,
- t_{Use} the total time in which the CPE is in use, i.e., in which it is used for data transmission, and
- t_{Idle} the total idle time, when the CPE is on but not used $(t_{Idle} = t_{On} - t_{Use})$.

The CPE consumes power for the time t_{On} but only provides services during t_{Use}. Distributing the entire power on the services provided during t_{Use} needs the factor t_{On}/t_{Use} for extrapolation. With this, formula 3 becomes

$$i_{CPE} = \frac{t_{On}}{t_{Use}} P_{CPE}, \tag{4}$$

which, because $t_{On} = t_{Use} + t_{Idle}$, can also be written as

$$i_{CPE} = \left(1 + \frac{t_{Idle}}{t_{Use}}\right) P_{CPE} \tag{5}$$

The energy intensity of the access network and CPE taken together is

$$i_{CPE\&AN} = \left(1 + \frac{t_{Idle}}{t_{Use}}\right) P_{CPE} + \frac{P_{AN}}{N_{AN}} pue_{AN} = \frac{t_{On}}{t_{Use}} P_{CPE} + \frac{P_{AN}}{N_{AN}} pue_{AN} \tag{6}$$

While such a generic formula is interesting from a theoretical point of view, for added practical relevance, the formula should ideally be parameterized with meaningful average values. These values should be based on the equipment and usage patterns considered typical and will change over time.

For the access network, the fraction P_{AN}/N_{AN} represents the energy intensity per subscriber. For ADSL2+, this was assessed as 3.4 W by [14] and 2 W by [31]. As [31] is the more recent analysis, we use its value. We further assume a PUE of 2, following the majority of studies.

For the power of the customer premises equipment (P_{CPE}), a few older studies consider only modems [14], while the more recent studies consider both modems and WiFi routers [24, 31, 37]. We follow [24] who assumes that only a few users use a modem without a WiFi router and that their number is comparable to those with multiple WiFi routers or WiFi repeaters. This is equivalent to assuming that 100 % of users use both a modem and a WiFi router, either as two separate devices or integrated into an *Integrated Access Device* (IAD). Taking into account the US distribution of IADs versus modems with WiFi routers, [24] puts forward 7.1 W as average CPE consumption for DSL and 9.5 W for cable. The November 2013 Energy Star requirements for small network equipment [38] call for a base power of at most 5.5 W for ADSL and 6.1 W for cable IADs, respectively, allowing another 0.8 W for fast Ethernet and WiFi, and 0.5 W for the telephony functionality of DSL modems. Considering these numbers as well, both ADSL and cable IADs are required to be just below 7 W. Allowing for the slightly higher consumption of two separate devices as well as for legacy equipment, we use $P_{CPE} = 8\ W$.

Finding data for the idle and usage times of modems is far more challenging and is by far the greatest source of uncertainty. A 2011 BBC study [39] found that set-top boxes (the modems which deliver both cable TV and Internet connectivity) are on for 15.57 h/day, but it did not address their usage time. A 2007 study found that in Europe, DSL modems are idle for 20 h/day and in use for the remaining 4 h/day [40]. Although this study is older, we use its assumptions. The study distinguishes between the on and idle state of modems, and we feel that the on-time of 24 h/day from [40] better reflects reality than the 15.57 h/day from the 2011 study [39]. With these assumptions, $t_{On}/t_{Use} = 6$.

With all these specific values, formula 6 leads to a "currently typical" value for the energy intensity (per time) of the access network and CPE of

$$i_{CPE\&AN} = 6 * 8W + 2W * 2 = 52W \tag{7}$$

The average value from formula 7 already includes the PUE of the access network and the idle consumption of the CPE, and can thus be used for quick assessments of energy consumptions in access networks and by consumer premises equipment. As mentioned above, however, the formula has a relatively large degree of uncertainty, especially due to the uncertainty of the idle time of the CPE.

6 Conclusion

We have shown that the energy intensity of customer premises equipment and access networks has to be assessed differently from the intensity of metro and core networks. We proposed a formula for the intensity of the former, both generically and parameterized with typical data for 2014. The next chapter [13] complements this work with a formula for metro and core networks. Taken together, the two chapters provide an assessment method for the Internet energy intensity that appropriately uses different allocation approaches for different parts of the network. Parameterized with typical values for 2014, this method can be used by practitioners for quick assessments of various Internet-based services.

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The Energy Intensity of the Internet: Edge and Core Networks

Daniel Schien, Vlad C. Coroama, Lorenz M. Hilty and Chris Preist

Abstract Environmental assessments of digital services seeking to take into account the Internet's energy footprint typically require models of the energy intensity of the Internet. Existing models have arrived at conflicting results. This has lead to increased uncertainty and reduced comparability of assessment results. We present a bottom-up model for the energy intensity of the Internet that draws from the current state of knowledge in the field and is specifically directed towards assessments of digital services. We present the numeric results and explain the application of the model in practice. Complementing the previous chapter that presented a generic approach and results for access networks and customer premise equipment, we present a model to assess the energy intensity of the core networks, yielding the result of 0.052 kWh/GB.

Keywords Internet · Energy efficiency · Energy intensity · Video streaming · Online news

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1 Introduction

Assessments of individual digital services such as video, web browsing or file downloads delivered over the Internet need to factor in a share of the energy consumption by the network—called an energy footprint—as the use-phase part of the environmental impact from the service life cycle. Most commonly, such a footprint is derived from multiplying an estimate of average network energy intensity per bit with the data volume transferred by the digital service. The energy intensity for an individual network device such as a router is the ratio of its power consumption (measured in watts) and its throughput capacity (measured in bits per second). The energy intensity of the network is the sum of the energy intensity of all devices along a route through the network between two endpoints, usually a client and a server.

Past studies, such as [1–4], have applied differing models and assumptions [5]. This has lead to increased uncertainty and reduced transferability of assessment results. Meanwhile, existing standards for environmental assessment of IT services [6, 7] do not recommend concrete models and parameterization. Thus, those wanting to perform environmental assessments of digital services are left without a guideline on how to assess network energy consumption.

In this text, we present a bottom-up model for the energy intensity of the Internet that draws from the academic state of the art and is specifically directed towards assessments of digital services. We present the numeric results and explain the application of the model in practice.

We begin with a description of the structure of the Internet in the next section. Based on that we present the models and their parameterization in Sect. 3. Subsequently, in Sect. 4 we present the numerical results and finish with a discussion of their practical application.

2 Background

2.1 The Structure of the Internet

Development of the Internet data network began as a service delivered on top of the telephone network and gradually separated from the latter as generations of network technology replaced one another. Our description is focused on the current state of the art in Internet Service Provider (ISP) networks. As a result, some legacy technology that might still be in operation is not presented here and may contribute to the uncertainty of the models. Interested readers are referred to [8–10] for more detail.

One frequently applied decomposition of the network, and the one adopted here, distinguishes the four layers of access, edge, metro and long haul networks as displayed in Fig. 1. Metro and long haul networks are frequently referred to as network core. As data travels from access to core, each layer handles increasing

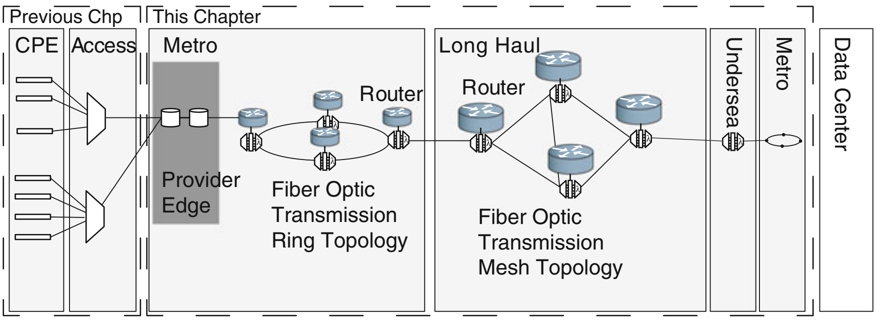

Fig. 1 Structure of the Internet for residential customers. Customer Premise Equipment (CPE) in the home, such as a DSL or cable modem, connects to the access network terminals that aggregate data traffic in a neighborhood and connects to provider edge switches. In the metro network traffic from several edge network devices is aggregated and passed to the long haul network for long-distance transmission to the metro network connecting to the data center where the service provider operates servers

volumes of traffic and provides aggregation of traffic from multiple links in previous layers. These networks are frequently operated by separate organizations, which are contract with one another and transport data traffic on one another's behalf.

Consumers operate customer premise equipment (CPE) such as modems and routers to connect to their broadband service provider network through a feeder network, also often referred to as the last mile or local loop, such as the copper lines of the telephone service that provide DSL connectivity, coaxial cable for cable connection or fiber optic cables. In the case of DSL and cable, signals from the customer modem are disaggregated into a data and a voice/video stream in a multiplexing node such as a DSLAM or a CMTS, which is connected to a metro network. The specific types of devices operated in the access network depend on the technology that is required to be supported in the access network.

Traffic by multiple access network multiplexers is typically aggregated by Ethernet switches before being passed on to the next higher network hierarchy. These switches provide subscriber traffic management to the broadband service provider. The specific type of device varies depending on the access network technology. In the case of DSL the DSLAMs connect via switches to broadband remote access servers (B-RAS). In the case of cable, the CMTS provides the subscriber management and modem function in one device.

Traffic then passes an Internet service provider (ISP) edge (PE) router and at this point enters the metro network. This part of the metro network is sometimes referred to as "edge network." The ISP is frequently a separate organization from the broadband service provider. The majority of ISP networks apply multiprotocol label switching (MPLS) for their greater traffic management capabilities over earlier systems and these provider edge routers are the ingress and egress nodes to the MPLS network. At the PE router the decision is made which part of the traffic to route outside of the metro network towards the long haul network, depending on the location of the data packet. The destination might be a server in a data center or another customer computer in the case of P2P traffic. Campus networks and data centers can connect directly to provider edge routers that manage their services.

While the routing (i.e., finding paths between networks) in metro and long haul networks is performed on the IP/MPLS layer, the physical connection between routers is established by fiber optic cables using either time division or wavelength division multiplexing (TDM or WDM). In the optic core, transport is realized by dense wavelength division multiplexing (DWDM) networks. As [10] note, use of DWDM in the metro networks is less frequent, and TDM links are used instead. Commonly, a wrapper for TDM channels called optical transport network (OTN) is used to simplify the existing infrastructure and provide TDM transport in metro networks. The conversion of IP packets to the containers that these various protocols use is implemented in IP router line cards.

Metro as well as long haul routers are composed of a chassis that provides slots for line cards, which are also called interface modules or port cards. The line card then hosts slot cards. Routers perform routing, in electronic circuitry, and via the OTN line cards connect to fiber optic cables for transport. The fiber cables then connect to WDM terminal systems.

Figure 2 is an illustration of the technology stack. At the top, a router determines the destination for a (labeled) packet, then sends it out via an OTN interface module to the WDM system where the light wavelength containing the data is added to a channel. At the next WDM terminal, the wavelength is either passed on to the next DWDM node or dropped from the wavelength and send to the router. The link between two terminals is called a hop. The number of routers in a route of n hops is thus $n + 1$.[1] If the distance exceeds 80–100 km, then amplifiers are placed on the fiber cable.

Intercontinental traffic usually traverses undersea cables that are terminated on either side with a particular type of WDM terminal and amplified.

The majority of end user traffic is directed to servers in data centers. These are directly connected to metro networks by edge routers.

A model of the energy footprint takes into account the energy consumption by all these device types. The majority of web traffic traverses the network between a single source and destination, also called “unicast”.[2] The number of devices in each layer is then equivalent to the diameter of the network segment. The particular segments that are being traversed may differ depending on the particular service. For example, a significant portion of traffic to a national news website might be intra-continental and thus not traverse an undersea cable. Instead, such traffic only traverses the customer-facing access network, the metro network in the customer region, the long haul network, the metro network in the data center region and an edge router in the service provider data center.

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[1] In our model, we neglect this additional network link in order to simplify the model structure.

[2] As opposed to multicast or broadcast where data from one source node is directed to multiple destination nodes.

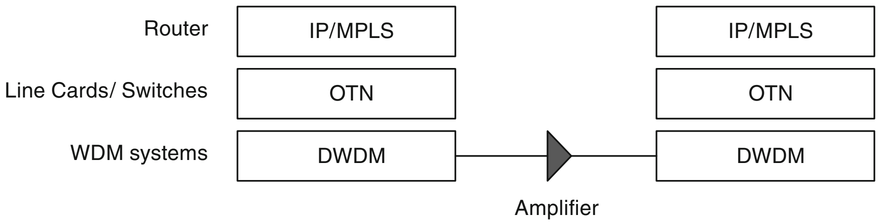

Fig. 2 Illustration of the device stack in core networks. IP/MPLS (Internet Protocol, Multi Protocol Layer Switches) routers perform routing functions (i.e., establish a route between source and destination across networks) and DWDM (Dense Wavelength Division Multiplexed) systems add or remove wavelengths to fiber cable links. The IP/MPLS devices connect to the DWDM systems over OTN fiber connections. Depending on the distance between network nodes, the signals traveling along links are amplified

3 Methodology

3.1 Bottom-Up Model

The energy footprint of an individual service (as opposed to the total energy consumption of the entire network) is a share of the energy consumption of the network devices that carry data between end points. For any given connection between a user and a server, not all devices in the network will carry the connection data. This will be done only by devices in the specific route, which for illustration can be thought of as the shortest connection through the network between the end points which does not contain circles. The energy intensity is a metric in which the per-device energy intensity over all devices in the typical route between end points is summed up. The energy intensity of a device is the ratio between its energy consumption (including overheads for cooling and power transformation) and its actual data throughput. Actual data throughput differs from nominal data capacity as it takes actual utilization or unused capacity into account.

The model distinguishes between metro and backhaul networks and separately undersea connections. The structure of the model is similar between metro and long haul networks. The full model including implementation details for computational simulation is available at [11].

We exclude the access network (see previous chapter and the inter-data center networks). For the metro segment, the energy intensity is estimated per router and then summed up over all routers involved. Optical transport networks are also included. They too are modeled by the energy intensity per individual device, which is then summed up over all transport devices. The structure for the long haul network is assumed to be identical to the metro network, while the energy intensity per router is lower but the number of optic transport devices is higher. The device energy intensity is multiplied by a PUE value, and overheads for utilization and redundancy are applied. For illustration, the energy intensity of the metro transmission network is estimated as:

$$I_{M_{TM}} = R \cdot n_{M_R}(c_{ON} \cdot I_{ON} + n_{M_{OA}} I_{OA})$$

where R is redundancy, n_{M_R} the number of metro routers, c_{ON} the ratio of WDM systems relative to routers, I_{ON} energy intensity per WDM system, I_{OA} the energy intensity per optical amplifier and $n_{M_{OA}}$ the number of metro network optical amplifiers per hop.

3.2 Parameterization

Accuracy of model-based assessments depends on the amount of uncertainty contained in the model assumptions. A structured approach to identifying such sources of uncertainty distinguishes between aleatory and epistemic uncertainty. Aleatory uncertainty refers to non-reducible statistical variance in the processes modeled, which is typically described with random variables that in turn can optionally be represented by average values. While such uncertainty prevents precise prediction, it does not affect the accuracy of model results inside the combined bounds of the underlying uncertainty variables.

An example of aleatory uncertainty is deciding on capacity for servers in response to anticipated demand, which depends on the time users access the service: For some services, such as reading news on a tablet, it might not be possible to predict when a particular customer will access the service. Nonetheless, the service provider can collect time series data on the basis of which he can make a statistical inference the accuracy of which only depends on the accuracy of the underlying random variable. Although the service provider might not be able to predict a visit by a specific user, his model might be accurate enough to predict demand most of the time.

If the model fails to predict occasional spikes of demand, for example as a response to political events, this would be a form of epistemic uncertainty, as knowledge about the system was inaccurate. Models for which the predictions can be tested against some empirically measured data become corroborated, and confidence in their accuracy increases. In the example above, corroboration occurs when actual demand is within the predicted bounds.

If empirical data to corroborate models is lacking, then epistemic uncertainty can result in significant discrepancies between predicted and actual system performance.

Therefore, it is necessary to improve understanding of the system by including expert opinion and corroboration of model parts where possible. These efforts can be directed by performing sensitivity analyses: identifying those model parts that contribute most strongly to the model result and are thus most relevant. Computation models can evaluate the overall variance through Monte Carlo-style sampling simulations. It is however important to note that sensitivity analysis does not express epistemic uncertainty—it makes no statements about how closely a model parameter is to the actual system property but only how strongly certain assumptions affect the prediction result.

Once a sensitivity analysis has identified the most relevant variables, experts can be consulted for the calibration of the model. For example, ISPs could report the model and configuration of all network equipment to a central database where each model was listed with energy consumption on which to base calculations. Similarly, the capacity and utilization of devices could be learned.

In the model presented here, the parameters are selected from recent peer-reviewed academic works as well as manufacturer specification, notably [12–15].

Edge Switch Energy Intensity. Devices in the edge network include switches that connect devices but also routers that provide services to the access network and are more energy intensive. For the switch we assume an energy intensity of 8 Joule per Gigabit (J/Gb) and for the router we apply a triangular distribution with a min of 16 J/Gb, mode of 40 J/Gb and max of 137 J/Gb, resulting in an average of 64 J/Gb.

Router Energy Intensity. The mean energy intensity of the entire population of metro routers in our model is 39 J/Gb. OTN router interface modules are accounted for as part of the router energy efficiency such that when added together they result in an intensity of 16.1 J/Gb for metro routers. For long haul routers the average value energy intensity is assumed to be between 17.2 J/Gb and 50 J/Gb for the most and least efficient configurations with either all or only one line card slot filled, with an average intensity of 26.7 J/Gb. Given the relatively close range of the sample points with only two outliers, we parameterize our model by resampling from a Gaussian kernel density estimated distribution over all values for both long haul and metro routers.

Route Length and Router Count. For the average route length representing connections from both residential setups as well as campus networks, we assume that the value of 6 routers plus aggregation switch on the edge to the access network is representative. In our simulation we evaluate the sensitivity of the energy intensity by applying a triangular distribution with a min value of 3, a mode of 6 and a maximum of 8 routers. *Long haul Networks.* For connection within the same continent or country, a value of 4 is likely to be representative. For transcontinental connections, the count of long haul routers is likely to be higher. In our model we apply a triangular distribution with a minimum of 4, mode value of 6 and maximum of 8 routers with a mean of 6.

WDM Terminals and Amplifiers in Edge and Core. We assume all interoffice transmission is via WDM systems. We assume a cumulative, nominal energy intensity of the optical transmission system to vary between 230, 147 and 316 J/Gb (average, 25th, 75th percentile) for metro and 1593, 893 and 2292 J/Gb (average, 25th, 75th percentile) for core networks, respectively. On top of this nominal energy intensity, overcapacity will be allocated for as described below.

Network Utilization. Results from the bottom-up model are strongly influenced by assumptions of the network utilization or overcapacity. This refers to the difference between maximum capacity, which serves as the basis for the calculation of the devices' energy intensity, and the actual use of capacity. We assume that long haul networks are utilized to around 33 % on average (utilization factor of 3). We assume the same value for fiber optic links. For the sensitivity analysis we apply a triangular distribution with a min of 2 (50 %), mode of 3 (33 %) and max of 5 (20 %), which results in a mean of 3.33 (30 %).

For the metro networks, we assume that utilization values are lower and use a triangular distribution with a min of 4 (25 %), mode of 6 (16.67 %) and max of 10 (10 %), resulting in an average value of 6.67 (15 %).

PUE and Redundancy. We follow the existing studies that all assume a PUE of 2.0. We further assume that commercial ISPs operate redundant nodes and apply a factor of 2.0.

Undersea Traffic. We model undersea traffic by intensity per distance and vary the intensity parameter uniformly between 0.026 J/Gb*km and 0.123 J/Gb*km with an average of 0.0745 J/Gb*km. We vary the distance uniformly between 6,000 and 12,000 km. The portion of traffic that crosses an undersea cable varies depending on the location of the user. For users from the US, on average fewer content and services will be delivered via undersea cable than for users in other parts of the world. In order to evaluate the influence of this value, we vary it over a uniform distribution with min of 10 %, a maximum 50 % and a resulting average of 30 %.

4 Results

4.1 Absolute Results

Given the above variable values and model structure, the average energy intensity of data traffic through edge, metro and long haul networks including an undersea cable link, but excluding access networks, evaluated to Kilowatt-hours per Gigabyte (kWh/GB) 0.052 kWh/GB. The contributions by the route segments in edge, metro and long haul network are 0.0043 kWh/GB, 0.02 kWh/GB and 0.028 kWh/GB, respectively.

Figure 3 shows a whisker plot of the distribution of network energy intensity as result of the Monte Carlo simulation. The first and third quartiles are positioned at 0.039 kWh/GB and 0.064 kWh/GB, respectively.

4.2 Sensitivity Analysis

In order to understand how strongly the uncertainty of each parameter affected the overall result, a sensitivity analysis based on Monte Carlo style resampling was applied. Based on the resulting distribution, Spearman ranks for the model parameters were calculated. These rank values are correlation scores that represent the direction in which the total result changes with a change of a model variable on an interval between -1 and 1. A score of 0 means that there is no correlation at all, 1 means perfect correlation and -1 means perfect anti-correlation.

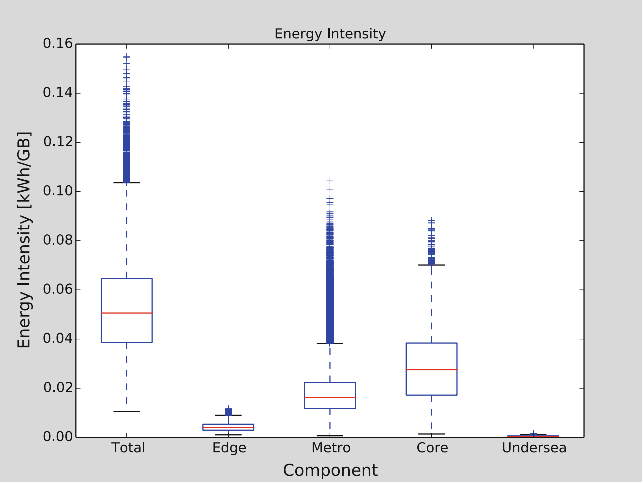

Fig. 3 Whisker plot of the distribution of total energy intensity and its components from the Monte Carlo simulation of the results. The *red* line represents the median values. The *top* and *bottom* borders of the boxes represent the first and third quartiles, respectively. Outliers are those points that are more than 1.5 standard deviations from average and are marked with *crosses*

Table 1 shows the Spearman ranks of the most relevant model variables (rho greater than 0.1). The table contains subcomponents (italics) as well as subcomponent variables.

According to this, long haul networks are more significant than metro networks. For both long haul and metro networks, the optic transmission layer (transmission system and fiber terminals) is more energy intensive than the routing layer.

Figure 4 shows the model results in comparison with the three models that are the most relevant sources for parameters and model structure. In order to make these studies comparable, we set the system boundaries to include a path that each study covers: only one leg of the edge, metro and long haul networks. In this way, we can calculate network paths. Depending on the number of segments included, the model will be more or less representative for regional specificities.

The results of the current model are displayed in column 2. The study [12] finds that long haul transmission networks are far more relevant to the overall energy intensity than long haul routers. The studies by [13, 14] on the other hand reach the opposite conclusion. The parameterization of the current model is a combination of both perspectives. The disagreement indicates the need for more investigation.

5 Discussion

An energy footprint of a digital service is a share of the energy consumption of the network. The energy intensity provides a metric that yields this share when multiplied by the data volume per service. The energy intensity metric presented

Table 1 Spearman ranks of model components with a rank greater than 0.1. Italic titles denote entire network layers. Normal font denotes variables representing device characteristics

Component	Spearman rank
Long haul	*0.77*
Long haul optic component	*0.73*
Long haul transmission	*0.67*
Metro	*0.54*
Metro IP component	*0.50*
Metro router energy intensity	0.44
Long haul IP component	0.27
Long haul overcapacity	0.26
Metro optic component	0.22
Long haul router efficiency	0.21
Metro overcapacity	0.18
Metro transmission	0.16
Number metro routers	0.11

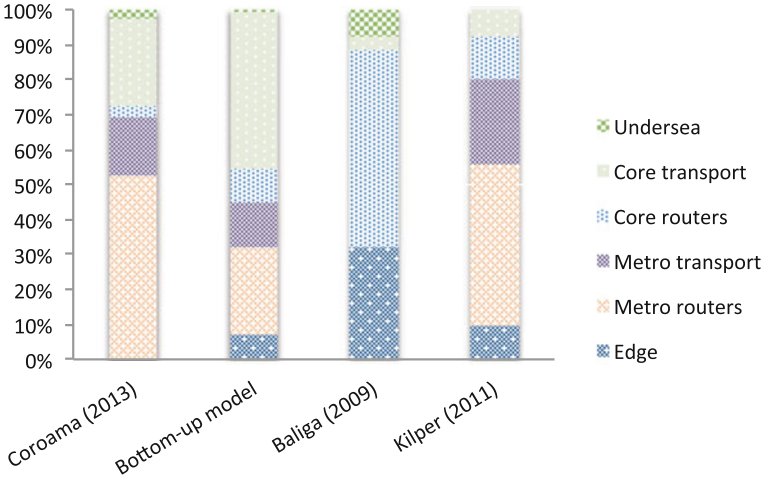

Fig. 4 Relative composition of energy intensity of Internet data traffic in this model (*2nd column*) and relevant previous studies

here can be used to calculate a balanced account of energy consumption: if the assumed values for the energy intensity are correct, then the sum of the energy footprints of all services equals the total network energy consumption if no double counting of data volumes occurs.

The energy intensity depends on the network layers taken into account. For the majority of cases this will include all layers presented in Sect. 2: the metro network twice, the long haul network and optionally a leg of undersea transport. The undersea transport might be excluded for a share of traffic that is known to be intra-continental.

A necessary step in the calculation of the footprint is thus the collection of all data traffic that is part of a service in an inventory. Separate inventories of data volumes might be appropriate for traffic in separate network segmentations. Care must be taken that all data sources are accounted for. Specifically, many online services draw data not just from the servers of the service provider but also include data from third parties.

The energy footprint is then calculated from the product of energy intensity and the data volume. For a full assessment, the energy intensity of access networks (see previous chapter), campus network and in-data center network devices (including firewalls and load balancers) must be added to this.

In our model we estimate the total energy intensity of the typical route through the Internet between two endpoints, typically user and server, mainly based on the energy intensity per router and optical terminal, by dividing their power consumption by the average data throughput of the device. This step is a form of allocation that is supposed to provide an apportioning of a flow **with a significant environmental impact** (here energy consumption) between multiple outputs (here all Internet connections world-wide) when necessary. Because energy consumption in network devices is highly inelastic [16, 17], the energy intensity should not be used for change-oriented assessments of energy footprints.

For the estimation of carbon footprints from energy footprints, we suggest using per-continent average carbon intensity values for electricity because of the high uncertainty around the location of core network devices.

The update of these results is strongly encouraged. If new expert knowledge becomes available, for example for a specific region, the parameter values should be adjusted. The modular structure of the model should accommodate this. For example, the submarine cable component is completely additive and can be excluded if it is known that a service reaches an intra-continental audience exclusively.

6 Example Footprint Calculation

As an illustration of the use of the energy intensity metrics described in this and the previous chapter, we compare the network energy consumption from watching 1 h of video stream in HD quality from the BBC iplayer service to browsing an online news service such as The Guardian website for 1 h and reading articles. We assume that the user is based in the UK and that content is consumed with an iPad connected via WiFi to a DSL Modem with integrated WiFi router, which is in turn connected to a DSLAM and then the rest of the Internet. In our example, we exclude the energy consumption of the server.

Given the model of the access network presented in the previous chapter [18] and this one, we estimate the energy consumption by time for the access

Table 2 Input data and results for video and web browsing scenarios

Input data	Video	Text	Unit
Time per page	–	60	s
Pages	–	60	–
Page size	–	2	MB
Bit rate	278	–	KB/s
Data volume	1	0.12	GB
Time	3,600	3,600	s
Energy intensity	0.052	0.052	kWh/GB
Power DSLAM	2	2	W
PUE	2	2	–
Power CPE	8	8	W
Idle overhead	6	6	–
Power iPad	2.4	2.4	W
Energy consumption			
Internet	0.052	0.00624	kWh
DSLAM	0.004	0.004	kWh
CPE	0.048	0.048	kWh
iPad	0.0024	0.0024	kWh
Total	0.1064	0.06064	kWh

Time is given in seconds s, page size in megabyte MB, data volume in gigabyte GB, video bit rate in kilobyte per second KB/s, internet energy intensity in Kilowatt-hours per gigabyte kWh/GB. Power consumption values are stated in Watt W. Energy consumption in Joule J and kilowatt-hour kWh

network and by data volume for the metro and long haul networks. Given the parameters provided for customer premise network equipment and the DSL access multiplexer, and allowing for overheads for idle standby of customer equipment, we estimate that the effective power consumption per subscriber household is about 52 W. Thus, the total energy consumption of a service can be described as:

$$\mathrm{E(S)} = \mathrm{t(S)} * 52\,\mathrm{W} + \mathrm{GB(S)} * 0.052\,\mathrm{kWh/GB}$$

where t(S) is the time of the service, 52 W the estimate for the average consumption of access networks and CPE, GB(S) the amount of data sent and received by the service (measured in GB), and 0.052 kWh/GB the estimate for the average energy intensity of long haul and metro networks.

In order to emphasize the varying intensity of the network parts, we assume that the duration of both activities is identical. During that 1 h, the user is assumed to continuously visit different articles at an average rate of one article per minute or continuously receive the video stream. The news web pages are assumed to have an average size of about 2 MB per page. Table 2 contains the input data for our calculation. We assume the video stream results in a total data volume of 1 GB

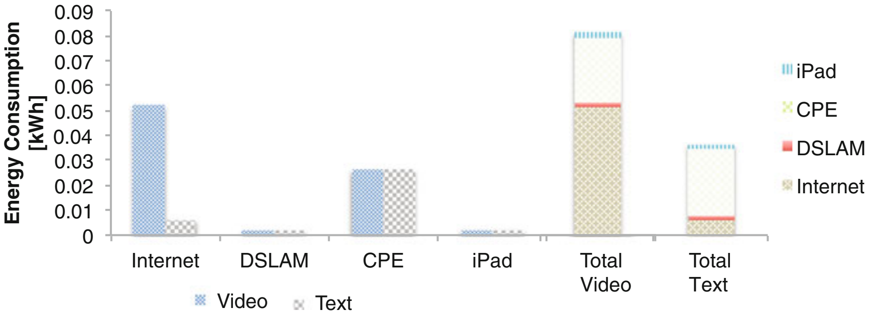

Fig. 5 Comparison of total energy consumption and system components when streaming 1 h of HD video or browsing a news website for 1 h

being downloaded during the 1 h duration. We further assume that the iPad consumes 2.4 W while showing video and browsing the web.

We assume the power consumption is constant during that time and estimate that the total energy consumption is 0.11 kWh for 1 h of video watching and 0.06 kWh for 1 h of browsing news.

Figure 5 illustrates the results. While the energy consumption by the access network equipment and the user device does not vary, as these are independent of the data volume transferred, the estimated energy consumption by the network varies substantially. For relatively low data volumes, most energy is consumed by the customer premises equipment. As the data volume transferred by the service grows, the long haul and metro routers become the dominating factors.

7 Conclusion

In order to estimate use-phase energy footprints and carbon footprints of digital services, estimates of energy intensity of the Internet can be of use. In this text we have combined the current empirical evidence and insight into the structure of the Internet to estimate the energy intensity of the Internet for environmental assessments of digital services. The energy intensity metric we propose is based on a model segmented into metro, long haul and undersea traffic and, combined with digital service data volume, yields estimates of a service energy footprint.

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Grey Energy and Environmental Impacts of ICT Hardware

Roland Hischier, Vlad C. Coroama, Daniel Schien and Mohammad Ahmadi Achachlouei

Abstract Direct energy consumption of ICT hardware is only "half the story." In order to get the "whole story," energy consumption during the entire life cycle has to be taken into account. This chapter is a first step toward a more comprehensive picture, showing the "grey energy" (i.e., the overall energy requirements) as well as the releases (into air, water, and soil) during the entire life cycle of exemplary ICT hardware devices by applying the life cycle assessment method. The examples calculated show that a focus on direct energy consumption alone fails to take account of relevant parts of the total energy consumption of ICT hardware as well as the relevance of the production phase. As a general tendency, the production phase is more and more important the smaller (and the more energy-efficient) the devices are. When in use, a tablet computer is much more energy-efficient than a desktop computer system with its various components, so its production phase has a much greater relative importance. Accordingly, the impacts due to data transfer when using Internet services are also increasingly relevant the smaller the end-user device is, reaching up to more than 90 % of the overall impact when using a tablet computer.

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1 Introduction

Direct energy consumption of ICT [1], data centers [2], and the Internet [3, 4] are described in detail in other chapters in this volume—however, this direct energy consumption (also called "end energy" in energy statistics) is only "half the story." Extraction of the various metals required to produce the different electronic components necessary in the various devices, e.g., in order to transport an e-mail from the sender to the addressee, consumes energy as well. The same is true of the actual production of the various components, for the final assembly of each of the involved devices, etc. Hence, in order to get the "whole story," energy consumption during the entire life cycle of such devices and services has to be taken into account. Such a life-cycle view of (indirect) energy consumption emerged in the late 1970s [5] and can be assessed today via "cumulative energy demand" (CED) [6], or "grey energy" [7]. The term "grey energy" was coined at the end of the last century in a study conducted by the Swiss Federal Office for the Environment, describing a method using cumulative energy demand for ecological assessment [7]. According to the recent standard 2,032 of the Swiss Association of Engineers and Architects (sia) [8], "grey energy" is calculated as the sum of non-renewable energy consumption during the life cycle—i.e., equal to the non-renewable part of "cumulative energy demand" as defined in standard 4,600 of the Association of the German Engineers (VDI) [6].

However, in order to get a comprehensive picture in terms of the environmental consequences, i.e., of the sustainability of a product or a service, not only total energy consumption is relevant, but consumption of (further) material resources as well as all the releases into the environment (i.e., waste streams, emissions into air and water) along the entire life cycle also need to be taken into account. This chapter is a first step toward such a more comprehensive picture. In addition to the "grey energy" along the entire life cycle (i.e., the overall energy requirements), it also covers the releases (into air, water, and soil) along the entire life cycle. The topic of (non-energetic) material resources along the life cycle will not be covered here, but in the chapter by Wäger et al. [9]. The present chapter is structured as follows: in a first section, various methods and tools for "grey energy" or a more complete sustainability assessment (in order to take into account releases along the life cycle) are critically discussed and compared. The most appropriate of these methods/tools are applied to various examples of ICT hardware components in view of their "grey energy," and their releases along the entire life cycle are assessed in the second part of this chapter.

2 Methods

Since the publication of the Brundtland report [10], which defined the issue of "sustainability," the scientific community has developed a whole set of different methods to measure sustainability—i.e., to measure the overall environmental, social, and economic impacts related to a process and/or service. In 2007, Ness et al. published their effort to categorize various sustainability assessment methods [11]. They realized that neither can any of these methods be used in all situations, nor do these methods take into account the various aspects of sustainability to the same degree. Their investigation put the focus on three key aspects of such methods—(i) the temporal aspect (i.e., is the method used to assess existing products or services, or can the method also be used to look into the future), (ii) coverage (i.e., is the method suitable for products), and (iii) the degree of integration of the three dimensions of sustainability—i.e., ecological, economic, and social aspects. Ness et al. allocated these methods to the following umbrellas: "indicators/indices," "product-related assessment," and "integrated assessment." Among these three umbrellas, "product-related assessment" covers methods focusing on the material and/or energy flows of a product or a service from a life cycle perspective [11]; i.e., the type of method required to measure the overall energy consumption of a laptop computer. Methods belonging under this umbrella include life cycle assessment (LCA), life cycle costing (LCC), substance flow analysis (SFA), process energy analysis, and exergy analysis.

Among them, LCA is considered by Ness et al. as the most established and well-developed method in this category [11]. LCA is a method to assess the potential environmental impacts and resource consumption throughout a product's life cycle, i.e., from raw material extraction to waste management, including the production and use phases [12]. According to Ayres, LCA has its seeds in the 1970s, when for the first time, a study was conducted in the United States that looked not only at energy, but also at waste emissions along the various life stages [13]. Roughly in the same period, initial activities began in Europe as well—motivated by efforts in the area of pollution prevention [14]. During the second part of the 1990s and the beginning of this century, the method was then standardized by ISO (International Standardization Organization) as the ISO 14 040 series [12, 15]. The ISO standard distinguishes four main steps within an LCA study—i.e., goal and scope definition, inventory modeling, impact assessment, and the final interpretation phase [12]. In the first step, the boundaries of the study are defined—as a study is always established relative to the objectives that are to be achieved (for a more detailed description see, e.g., [14]). The second phase is often the most time-consuming part, as the input and output values of each process within the boundaries have to be collected here—before the totality of all these material and energy flows is assessed in the third step, based mainly on ecological criteria. For this assessment, a whole host of different life cycle impact assessment (LCIA) methods has been developed and is applied nowadays (an overview can be found, e.g., in [16]). Among the most recent developments is the method ReCiPe [17], actually an update and advancement of two older, often-used methods—the CML method [18] and the Eco-Indicator'99 [19]. Applying this method is a very convenient way of presenting the results on a midpoint[1] and an endpoint[2] level at the same time. The large choice of midpoint indicators included in ReCiPe allows fulfillment of the requirements of the ISO standards [12, 15]—which prescribe a "selection of impact categories that reflects a comprehensive set of environmental issues related to the product system being studied, taking into account goal and scope."

As mentioned above, measuring (indirect) energy consumption emerged at the end of the 1970s as "cumulative energy requirements analysis (CERA)" [5]. From the beginning, this measure of "cumulative energy demand (CED)" has actually been considered the "most important aggregated result of the inventory used for comparisons of product-related systems," as stipulated by Klöpffer in an editorial in the International Journal of Life Cycle Assessment [20]. According to the research by Huijbregts et al. "fossil CED correlates well with most impact categories, such as global warming, resource depletion, acidification [...]"; but its use as a stand-alone indicator for the environmental impact of a product is nevertheless limited due to "the large uncertainty in the product-specific fossil CED-based impact scores" resulting from releases and land use due to non-fossil energy consumption [21]. In this study, the non-renewable part of the CED was calculated as described in [22] in order to obtain a value for the "grey energy" of the examined ICT devices. And in order to get "the whole story," a group of mid- and endpoint indicators of the ReCiPe method are shown as well that assess the ecological sustainability of these various ICT devices/services examined here.

3 LCA and ICT: A Short Historical Overview

More than 20 years ago, in a paper entitled "Applications of Life Cycle Assessment in the Electronics Industry for Product Design and Marketing Claims," Rhodes wrote that LCA "offers the electronics and power products industry an opportunity" [23]. He concluded that LCA can help this industry sector to identify the areas for improvement and at the same time determine their potential.

In these more than 20 years, a broad variety of LCA studies dealing with different ICT devices have been published. In a recent publication comparing different modeling strategies for modern ICT devices, the author presented an overview of LCA/LCI studies in the area of modern ICT media devices [24]. Another recent overview is the study by Arushanyan et al. reviewing LCA studies not only of ICT products, but also of ICT services [25]. Both overviews show that

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[1] The midpoint level is defined in [17] as being "at the place where mechanisms common to a variety of substances come into play".

[2] The endpoint level is defined in [17] as corresponding "to areas of protection that form the basis of decisions in policy and sustainable development".

popular ICT devices like television devices or desktop computers are covered by several studies, while other devices such as smartphones, game consoles, or network components are hardly covered by such studies so far. An important point raised in both of these review studies is the rapid technological development of the ICT sector—leading to high variability of the results. In their 2010 study, Andrae and Andersen compared results from various LCA studies of consumer electronics devices (desktop and laptop computers, mobile phones, and television devices) in terms of their consistency [26], focusing on global warming potential results and primary energy usage. Andrae and Andersen conclude that "published LCAs for mobile phone and television sets are consistent, whereas for laptop and desktop computers, the studies occasionally give conflicting messages" [26]. However, when digging more deeply into these "conflicting messages," it could be observed that one of the main points highlighted by the authors is the high release of NF_3 in the LCD production step, as modeled in ecoinvent [27]—an erroneous value that was corrected by the ecoinvent team in version v2.2 [28], reducing this release by a factor of almost 1,000 [29] and having a major influence on the laptop computer as well as all desktop computer systems using LCD screens.

Publications expanding the scope beyond a simple view of end-user technologies (e.g., laptop computers) toward an assessment of the services provided by such devices, e.g. the use of the Internet (reported, e.g., in [30–33]) have emerged recently, showing the relevance of end-user devices in comparison to the entire infrastructure required in order to access Internet data. In a recent conference contribution dealing with changes of the environmental impacts from ICT over time, Lunden and Malmodin conclude that although the "impacts per connected device and data volume are lower than in the past," further decreases can be achieved only by reducing energy consumption at core sites, data centers, and in the end user devices [34].

Today, various LCA databases contain more or less detailed background data for a variety of different ICT hardware components. Here, the database ecoinvent—in its version v3.01 [35], allocation-based system model—is used, as ecoinvent is the only transparent and easily accessible public LCI database currently available.[3]

4 LCA of ICT Hardware

The origin of today's desktop computer has to be seen in the IBM personal computer (PC) model 5,150, commercialized in 1981 [36]—which was for the first time a system combining a screen, a computer device, and a keyboard in three different casings. Sales numbers of such systems grew until the mid-2000s, when laptop computers started to take over more and more market share from desktop

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[3] Two other LCI databases containing extensive information on electronics products are GaBi and EIME—but due to the high price of access to these data, they are not considered public databases in this article.

computers [37]. And since the presentation of the first generation of Apple's iPad, another class of devices has been taking over ever greater parts of the market in mobile computer devices: tablet computers [37].

In this section, the first subsection describes an example of each of the three types of end-user devices mentioned above (i.e., a desktop, a laptop, and a tablet computer), followed by a subsection dealing with some of the most relevant ICT components required for the use of today's Internet services. The third subsection shows a comparison and combination of all the data presented in the two preceding subsections. Active use of all shown devices in Germany is assumed for the calculations.

4.1 End-User Devices

Desktop Computer System. Here, a typical desktop computer system as sold in the mid-2000s is modeled—assuming that such a system is composed of the actual computer device, a keyboard, an optical mouse, as well as a 17-inch LCD flat screen monitor. The inventory data for the computer device, the keyboard, and the mouse are taken directly from the database ecoinvent [28], while the data for the LCD monitor were established in the framework of a study for the Swiss visual communications industry [38], actually representing a 17-inch screen sold around 2010. The resulting inventory data of this entire system are summarized in Table 1. The environmental impacts due to the production of the devices, as well as for the whole life cycle—based on an assumed lifespan of 6 years (for all four components) and 2 h of daily use of such a system, assuming an average European electricity mix—are summarized in Fig. 1.

Table 1 Life cycle inventory data for a desktop computer system

Component	Weight (kg)	Modeled as …
Chassis	0.395	100 % Aluminum profiles
Housing	8.120	7 % Plastics (ABS), 7 % aluminum, 86 % steel
Power supply	1.470	Power supply unit
Display	4.010	LCD Module of a 17-inch LCD Screen
HDD and CD-ROM	1.510	1 HDD and 1 CD-ROM
Circuit boards	0.718	Printed wiring board, desktop motherboard
	0.493	Printed wiring board, unspecified
Keyboard, mouse	1.370	27 % steel, 3 % Cu, 6 % circuit boards, 64 % plastics (ABS)
Cable	0.321	45 % Cu, 55 % plastics (HDPE, ABS)

Data represent a standard desktop computer with a keyboard and a mouse (all data taken from [27]), and a 17-inch LCD flat screen (data calculated for [38]—based on a survey of available screens)

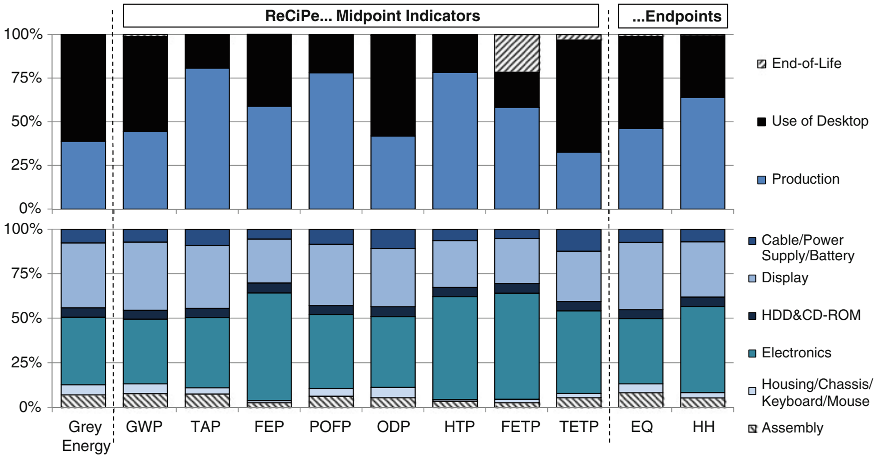

Fig. 1 *Upper part* Environmental impact of a desktop computer, used for 6 years (2 h/d). *Lower part* Environmental impact of its production only. The following indicators are shown: "grey energy" in form of non-renewable cumulative energy demand (CED), the ReCiPe midpoint indicators global warming potential (GWP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), photochemical oxidant formation potential (POFP), ozone depletion potential (ODP), human toxicity potential (HTP), freshwater ecotoxicity potential (FETP), terrestrial ecotoxicity potential (TETP), and the ReCiPe endpoint indicators damage to ecosystem quality (EQ) and damage to human health (HH)

A comparison with published values for desktop computers can be made for the first two impact categories shown in Fig. 1—"grey energy" and GWP, as these are the only factors that have been systematically reported in the studies published to date. Teehan and Kandlikar compared these two impact categories in their recent article, dealing with exactly this topic [39]. One of the models taken into account is the desktop computer reported in the ecoinvent database [27]; i.e., the model used here. The authors conclude in their study that "the weight of evidence strongly suggests that (…) the use phase is the dominant life cycle phase"—however, they take only the bare desktop computer device into account, but no screen. This makes a direct comparison of the results from [39] with the results here impossible. In the study by Andrae and Andersen [26], entire desktop systems from various data sources are compared; among them again the system reported in ecoinvent (however, as stipulated above, based on the erroneous version v2.1 of the LCD screen). From [26] it became evident that apart from the ecoinvent dataset, only one further data source reports a system using an LCD flat screen, the preparatory study for the eco-design requirements of the European Commission [40]. A comparison of the results from these two studies revealed rather large differences, especially concerning the production and the EoL phases. In these two life stages, the (absolute) values from the modeling here (and thus from the model within the database ecoinvent) are about 3 times higher ("grey energy" and GWP); while the value for the use phase show a similar result. This result for the production phase is even more astonishing, as the composition of the two desktop

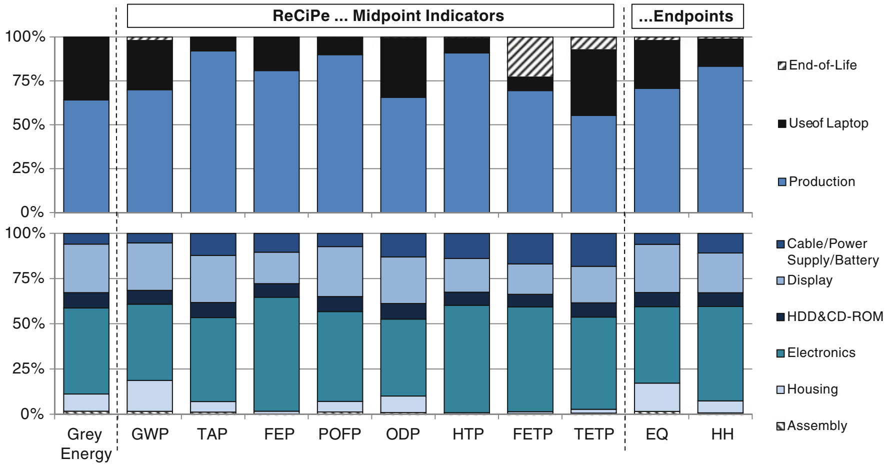

Fig. 2 *Upper part* Environmental impact of a laptop computer, used for 4 years (2 h/d). *Lower part* Environmental impact of production only. The same factors as in Fig. 1 are shown

computers is rather similar (as shown in Fig. 2 of [39]). From this it could be concluded that the dataset here—based on the ecoinvent database—represents a more comprehensive and thus more appropriate picture of this type of device.

Laptop Computer. Developments in recent years at both the economic and the technological levels in the area of portable computer systems have been enormous; resulting in a strong propagation of this kind of device, including in private acquisitions since the mid-2000s.

The basis for this publication is a typical 14/15-inch laptop computer, as sold in the years 2008–2011, modeled in the framework of a study for the Swiss visual communications industry [38]. The efforts for the final assembly of this laptop are extrapolated from the reported efforts for the (older) laptop model in ecoinvent [27]. The inventory data of the modeled laptop computer are summarized in Table 2; the resulting environmental impacts (the impacts due to the production of the device, as well as for the whole life cycle—in this case based on an assumed lifespan of 4 years, and again on 2 h daily use) are shown in Fig. 2.

Again, the study by Andrae and Andersen [26] is used as a starting point in order to compare the results from the current study with other studies of laptop computers. In this study, apart from the original ecoinvent dataset, GWP results for four further datasets of laptop computers (taken from [40, 43–45]) are reported and compared to each other. A comparison of these values reported in [26] with the results of the present study is shown in Fig. 3 (top, left, line “original”) over the entire life cycle of such a device. Actually, the main information in this figure is a comparison of these studies, based on corrected values, assuming a similar use phase for all studies. With such corrected values, two of the studies show quite similar results to the dataset above. As can be seen from the data for the production and end-of-life phases (i.e., the two graphs on the right side of Fig. 3), the values

Table 2 Life cycle inventory data for a typical 14/15-inch laptop computer

Component	Weight (kg)	Modeled as …
Heat sinks	0.026	Aluminum profiles
Housing, bottom	0.361	Equally split between aluminum, ABS/PC, and magnesium alloy
Housing, top	0.247	Equally split between aluminum, ABS/PC, and magnesium alloy
Glass	0.044	Coated flat glass
Display	0.561	LCD module
HDD and CD-ROM	0.267	1 HDD and 1 CD-ROM
Circuit boards	0.206	Printed wiring board, laptop motherboard
Battery	0.363	Li-Ion battery
External power supply	0.531	Power adapter
Keyboard, track pad	0.144	100 % as ABS (proxy)
Remaining parts	0.305	Assumed as 30 % Cu, 30 % steel, 40 % plastics (ABS)

Data represent an unweighted average of three laptop computers, reported in [41] and in [42]

reported in the various studies do not vary much. In every case, the study showing the biggest deviation is the one by PE International; a study for which this adaptation of the use phase has not been possible due to the qualitative description of the modeled use phase in [43]. Therefore, as a proxy we assume that for the original data the models from [40] for office and home use (with $^2/_3$ office, $^1/_3$ home) were used. For the data from Lu et al. no adaptation was possible due to the high degree of aggregation of the results in the original presentation.

All in all, based on the comparison in Fig. 3, the model of a laptop computer presented here is a reasonable compromise between all the currently existing models.

Tablet Computer. Another type of end-user device that emerged very rapidly in the 2000s is the tablet computer—situated between a traditional laptop computer and a cellular phone [37]. One of the most popular such tablet computers—Apple’s iPad2 model—has been modeled in various studies (see, e.g., [38, 46]). A recent comparison of various approaches for modeling this device has shown that the production phase has a distinctly higher impact in the case of a lab-based approach [24]. The main reason is the higher density (per m^2 of printed wiring board) of integrated circuits (ICs) in comparison to, e.g., the laptop computer used in other studies as the basis for the tablet model. The lab-based approach using inventory data on the level of individual components (i.e., on the level of ICs, resistors, etc.) results in a more complete, and thus more appropriate model for the whole device. The inventory data of this lab-based model are summarized in Table 3. The corresponding environmental impacts (again for the production of the device, as well as per hour of active use—assuming for this device a lifespan of 2 years, and again with 2 h of daily use) of such a tablet are then shown in Fig. 4.

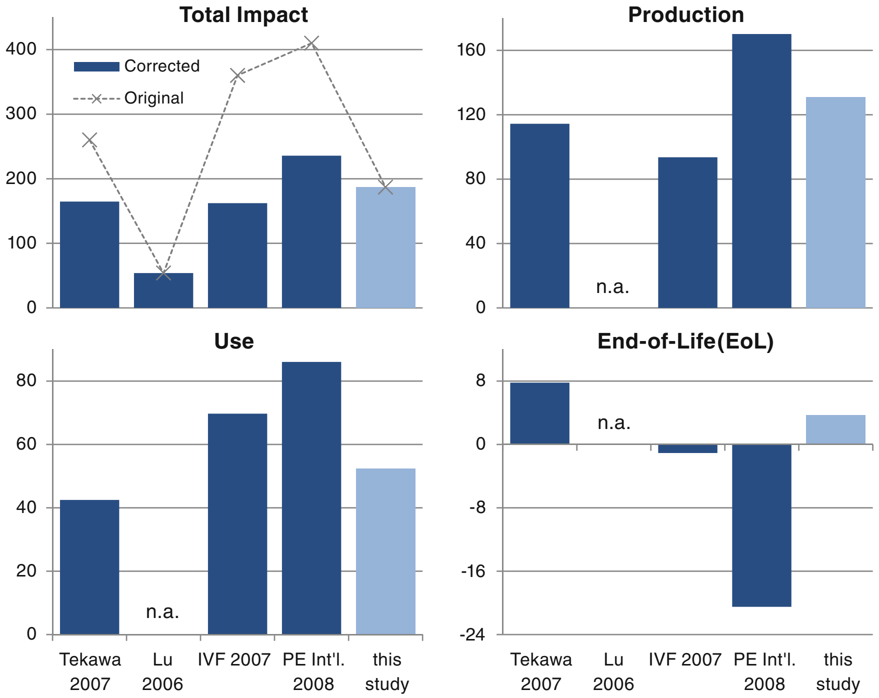

Fig. 3 Global warming potential (in kg CO_2-Eq) for the life cycle of a laptop computer. The figures show the total value (*top left*) as well as the contribution to the individual life stages production, use and end-of-life. For the use phase (*bottom left*) the use profile of all studies was aligned to the use profile of this study (2 h daily for 4 years)

Table 3 Life cycle inventory data for a tablet computer

Component	Weight (kg)	Modeled as …
Housing, back panel	0.140	Aluminum sheets
Housing, plastics	0.018	Equally split between ABS and rigid PUR
Battery	0.135	Li-Ion battery
Circuit boards	0.039	Modeled at the component level, as described in detail in [46]
Display	0.145	LCD module
Glass	0.109	Coated flat glass
Other materials	0.026	Assumed are 50 % copper, 50 % steel (unalloyed)

The data represent an Apple iPad2, as reported in [24] (the result of the lab-based approach in [46]) connected with ecoinvent data

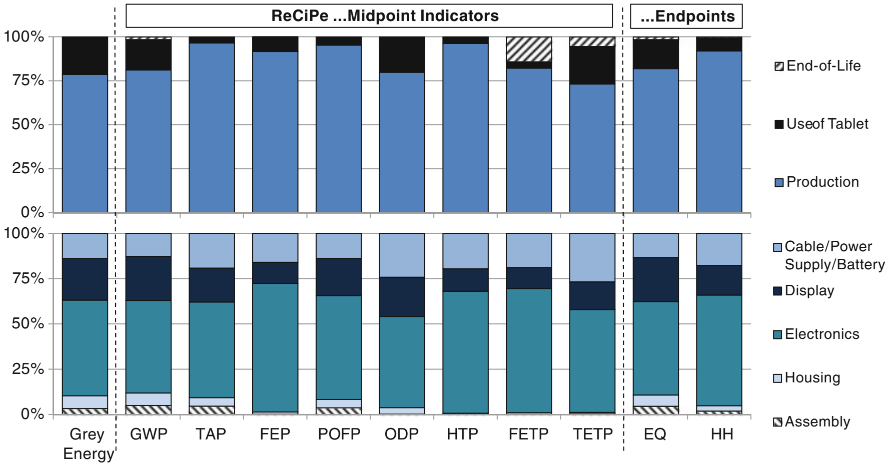

Fig. 4 *Upper part* Environmental impact of a tablet computer, used for 2 years (2 h/d). *Lower part* Environmental impact of production only. The same factors as in Fig. 1 are shown

4.2 Internet (Services) and Data Centers

According to Coroama et al. [3], in addition to the end-user device (e.g., a tablet), Internet services require four types of devices: (i) the customer premises equipment, CPE (= equipment used by the user for accessing the Internet, e.g., the ADSL modem and/or WiFi routers), (ii) the access network (i.e., the connection between CPE and the actual data network, including cables and multiplexing nodes such as DSLAMs), (iii) the edge and core network with the edge switches and the large (metro and core) routers for transferring all the data between the various users and data providers, and lastly (iv) the actual data centers. Table 4 summarizes exemplary components for each of type by showing key technical information (weight and energy consumption) and the data sources used for the modeling of these components in the LCA calculation.

Information about the core components (including their energy consumption and their weight) is only one element necessary in order to calculate the grey energy and all further environmental impacts due to Internet use. The other necessary element is information about the number of these components in use, their lifetimes, as well as the actual data capacity per time unit of these devices, finally allowing an allocation of the impacts per MB of downloaded data. Table 5 summarizes this additional information for the exemplary components taken into account here.

Estimating the number of Internet servers installed worldwide is challenging, and different sources report divergent numbers. DCD Intelligence, the research division of a provider of B2B services for the data center industry, estimates the power consumption of all data centers in the world at 40 GW in 2013 [52].

Table 4 Key data for modeling various infrastructure components used to access/use Internet services

Component (Energy consumption)	Weight (kg)	Data sources/Modeled as …
1 *Customer premises equipment (CPE)*		Source(s): [3, 47, 48]—market dataset "Internet access equipment" from [35] is used as a proxy; adjusted according to weight
Modem + WiFi router (8 W)	0.486	
2 *Access network*		Source(s): [3, 48]—market dataset "Internet access equipment" from [35] is used as a proxy; adjusted according to weight
DSLAM (4 W)	15	
3 *Edge and core network**		Source(s): [4, 49]—market dataset "Router, Internet" from [35] is used as a proxy in all three cases; adjusted each time according to weight
Edge ethernet switch (6.25 J/Gb)	13	
Network, metro router (39 J/Gb)	133	
Network, core router (26.7 J/Gb)	503	
3 *Data center*		Source(s): [50, 51]—market dataset "Computer, desktop, without screen" from [35] is used as a proxy in all three cases; adjusted each time according to weight
Volume server (222 W)	21	
Mid-range server (607 W)	55	
High-end server (8,106 W)	1,318	

Data represent exemplary devices. The energy consumption of the CPE and the access network takes power usage effectiveness (PUE) into account (as reported in [3])

*In case of the edge and core network, reported energy consumption is multiplied with a factor of 26 in order to take into account overcapacity and redundancy of these devices, as well as the electricity consumption of the optical transport along this network

Assuming a power consumption of 222 W per volume server and doubling this number for cooling and other overhead implies around 90 million servers in use worldwide. We follow Malmodin et al. [53] in assuming that half of these servers communicate over the Internet, while the other half are used by organizations and enterprises in closed "intranet" environments. This estimate leads to 45 million Internet servers. A different approach to estimate the number of Internet servers is to start from sales numbers. IDC, a market research firm specialized in the IT market, reports around 8 million servers sold worldwide in 2012 [54]. Assuming a lifespan of 3–5 years, and considering that some of these servers are not being used, yields a figure of around 30 million servers in use worldwide. The same assumption as above then leads to a number of 15 million Internet servers in use. We use this smaller estimate, because it compares better to a third figure, the number of worldwide Internet servers reported by the 24 largest companies owning such devices (based on information reported in [55–57]).[4]

For all components it is assumed that they are active 24 h a day during the whole year; even the ADSL modem. This latter is based on the split of 4 h active

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[4] 4.5 million. It seems more plausible that the likes of Google, Amazon and Facebook together own roughly 1/3 (and not only 1/10) of the Internet servers.

Table 5 Key data for modeling various infrastructure components

Component	No. of devices	Lifetime (years)	Data capacity	Data sources
1 *CPE*				[59] plus own assumptions
modem + WiFi-Router	1 + 1	6	7.2 Mb/s (average xDSL value for Europe)	
2 *Access network*			(similar to the ADSL-Modem)	own assumptions
DSLAM	1 port	6		
3 *Edge and core network*				[4, 49, 60]
Edge ethernet switch	1	6	32 Gb/s	
Network, metro router	6	6	47 Gb/s per router	
Network, core router	6	6	828 Gb/s per router	
4 *Data center*				[50, 55–57]; and [61]
Total no. of devices	15 million		1.1 ZB (annual global data center IP traffic 2010)	
Of this: volume servers	(96.6 %)	3		
Of this: mid-range servers	(3.0 %)	3		
Of this: high-end servers	(0.4 %)	3		

The second column shows the allocated number of devices for using Internet services for the components (i) to (iii), and an estimate for all servers in data centers worldwide for component (iv). All these are allocated to corresponding data in column 4 (data capacity as traffic flows per second in the first three cases, as total annual Internet traffic in the world for the last case), thus leading to compatible/comparable allocation results

and 20 h idle (i.e., consuming energy, but without active data transfer) time, reported in a study published in the framework of the European Eco-Design Directive [58] and used in the chapter dealing with the energy consumption of the Internet as well [3].

Figure 5 summarizes the resulting impacts per MB of data downloaded, using these assumptions. When distinguishing merely between the different elements of the Internet (shown in the top part of Fig. 5), the picture of the environmental impacts shown here is rather similar, despite some slight variations, i.e., in almost all cases, about 50 % of the impact is due to the data center and another roughly 40 % to the edge and core network, while the access network together with the CPE contributes only about 10 % to the impact. The bottom part of Fig. 5 distinguishes between the infrastructure and the energy consumption within each of these three parts of the Internet. In most impact categories, energy consumption is responsible for a large majority of the respective environmental impact; only two of the toxicity categories (HTP and FETP), in which the server infrastructure causes around 15 % of the overall impact, are slightly different. But in general, the infrastructure shows a very low impact only with regard to the consumed electricity.

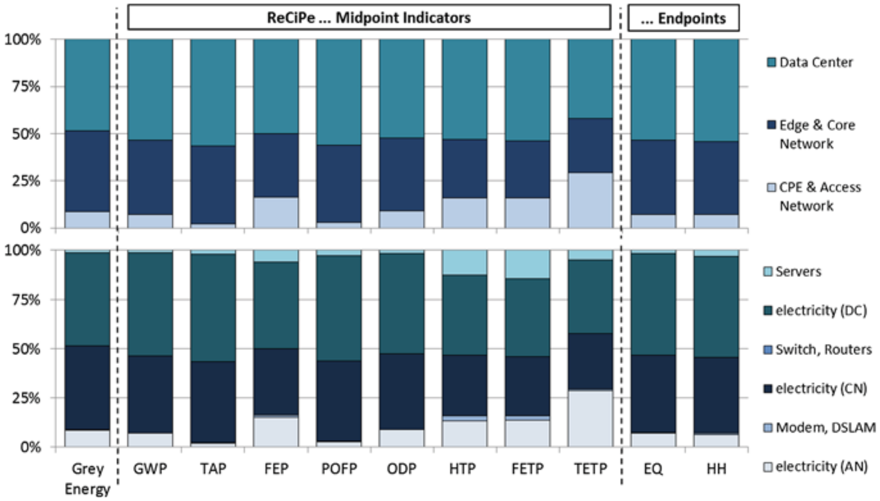

Fig. 5 Environmental impact per MB of data downloaded—broken down by the various parts (*top*) and further distinguishing between infrastructure and energy consumption within each part (*bottom*) of the Internet, as in Tables 4 and 5. The same factors as in Fig. 1 are shown (with AN = CPE and access network, CN = edge and core network, and DC = data center)

4.3 Comparison and Combination

In a first part of this third subsection, the impacts due to one hour of use of the end-user devices described above (i.e., desktop computer, laptop computer, and tablet) are compared to each other; again assuming that each of these devices is used for 2 h per day. Figure 6 shows the resulting impacts (per hour of use) for the three devices. As clearly shown in this figure, the picture for all examined impact assessment factors—including grey energy—is rather similar; i.e., the laptop computer results in an environmental load that is about 5 times lower than the desktop computer—and the impact of the tablet, in turn, is lower by a factor of 3 to 4 than that of a laptop computer.

Last but not least, the impact of these three end-user devices is combined with the data for Internet services, which were detailed in the preceding subsection. Figure 7 shows the results—this time not per hour of use, but per MB of downloaded data. While the bottom part of Fig. 7 is similar to Fig. 6—simply adding the impact for downloading 1 MB to the impacts for the life cycle of the three different end-user devices—the top part of Fig. 7 shows the relative relevance of this download process in comparison to the use of the end-user device (the latter one again over the complete life-cycle). And this latter part of the figure shows clearly that the more mobile (and small) the end-user device, the more relevant the impact from the download process—i.e., while in the case of a desktop computer, the download is responsible for about 60 % of the overall impact; this same download operation is responsible for more than 90 % of the overall impact in the case of a tablet.

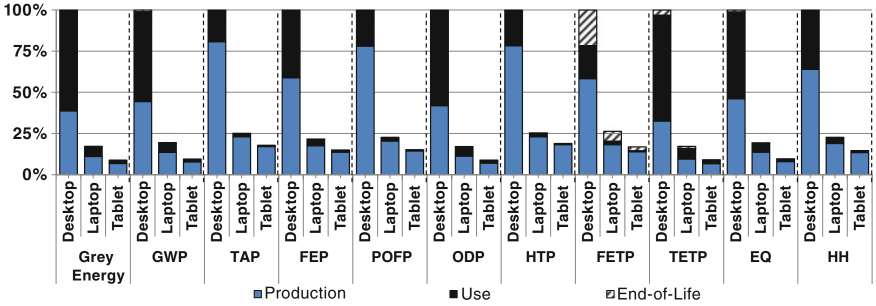

Fig. 6 Environmental impact for 1 h of use of desktop computer, laptop computer, and tablet, shown relative to the impact of the desktop computer for each impact category. The same impact categories are shown as in Fig. 1

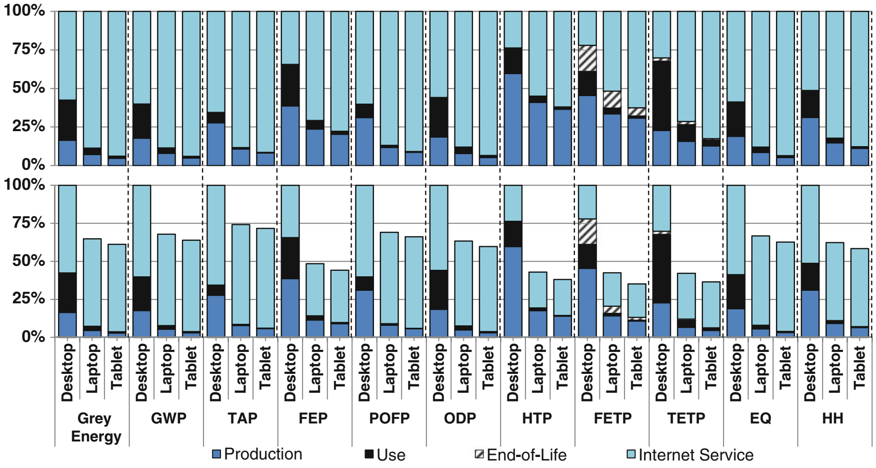

Fig. 7 Environmental impact of downloading 1 MB of data via desktop computer, laptop computer, and tablet (including end-user devices and Internet infrastructure, assuming a constant download rate of 7.2 Mbps), shown relative to the impact for the desktop computer for each impact category. The same impact categories are shown as in Fig. 1

5 Conclusion and Outlook

The various figures in Sect. 4 show clearly that a focus on direct energy consumption alone excludes relevant parts of the real (and total) energy consumption of ICT hardware—especially when taking into account the entire “data chain” (i.e., the Internet). Taking into account the entire life cycle of devices such as desktop computers shows the relevance of the production phase, which becomes more and more important the smaller (and the more energy-efficient) the devices are.

Correspondingly, when comparing the upper parts of Figs. 1, 2, and 4, it is evident that the relevance/importance of the use phase drops with the decreasing size of the device—due to the fact that a tablet computer is much more energy-efficient than a desktop computer system with its various components. On the other hand, the relevance of the impacts due to the data transfer in the use phase is more relevant, the smaller the end-user device. For a tablet computer, the upper part of Fig. 7 shows a contribution of 90 % and more by (the production and the energy consumption of) various components along the whole network, as well as the data centers.

These results demonstrate at the same time that the technological shift towards distributing computing with low-power user devices (e.g., tablet computers) connected to server systems as part of "the cloud" presents a form of burden-shifting away from the manufacturing and the use phase of the end-user device, and toward the Internet and data centers. The behavior related to the consumption of distributed services is becoming a major aspect with regard to environmental impact. Inducing consumer demand by increasing the efficiency of a production or a consumption process is also known as the rebound effect, an issue further elaborated in a later chapter [62].

Does the development of modern ICT hardware such as tablet computers and of novel paradigms such as cloud computing lead to more or less sustainability? In order to answer this question, a focus on individual devices—as done in this chapter—is not sufficient. Rather the general behavior of our society related to the consumption of distributed services is becoming a major aspect for the determination of the environmental impact. Hence, calculating absolute changes of the impacts due to such a technological shift depends in large parts on individuals' behavior and their use and handling of ICT hardware, another topic dealt with in a later chapter of this book [63].

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Sustainable Software Engineering: Process and Quality Models, Life Cycle, and Social Aspects

Stefan Naumann, Eva Kern, Markus Dick and Timo Johann

Abstract Sustainability intersects Information and Communication Technology in two domains: Green IT (how can we make ICT itself more sustainable?) and Green by IT (how can we achieve sustainability through ICT?). On a closer look, it is software that links these two fields: In "classic" Green IT, there are many ways to build and use hardware in a more energy-efficient way. On the software side, Green by IT has often been software-based until now, involving tools that help to optimize logistics and automate processes to save energy, for example. However, the debate over software-induced energy consumption is just beginning. To date, few studies have been conducted about the energy saving potential of software itself. Therefore, it is important to investigate the meaning of sustainable software and sustainable software engineering. This chapter provides definitions of these concepts. In addition, it presents a reference model of sustainable software as well as its engineering. However, it provides only a short introduction of the model itself. The sub-model "Sustainability Criteria for Software Products" and sustainable software process models are examined in greater detail.

Keywords Green software · Green IT · Sustainable software engineering · GREENSOFT model · Software process models

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1 Introduction and Motivation

Green IT and Green by IT are common terms in the debate over ICT and sustainability. *Green by IT* (also: Green through IT) covers the support of sustainable development by means of ICT. This includes for example software that reduces environmental problems through optimization. *Green IT* (also: Green in IT) denotes actions through which ICT itself could become more sustainable. This concerns hardware and software, where the hardware part is common knowledge. The software side, by contrast, is still the subject of current research projects. Here, two main questions are being investigated: What is sustainable software, and how can software be produced in a sustainable way? The first question deals with quality characteristics concerning the energy consumption of software, for example. Since software is a very complex product in its architecture, functionalities, and usage, this is not an easy task. The second question concerns the process of software engineering and how it can be improved in order to produce sustainable software in a sustainable way.

In this chapter, we present a model for sustainable software and its engineering, as well as an approach to defining sustainability characteristics for software products and a software life cycle.

2 What Is Sustainable Software Engineering?

In order to classify issues in sustainable software and its engineering, we provide some definitions.

First we define *Sustainable Software* as software whose development, deployment, and usage results in minimal direct and indirect negative impacts or even positive impacts on the economy, society, human beings, and the environment [1]. A prerequisite for sustainable software is a sustainable development process, which refers to the consideration of environmental and other impacts during the software life cycle and the pursuit of the goals of sustainable development.

Building on this we can define *Sustainable Software Engineering* as the art of developing sustainable software through a sustainable software engineering process. In this, software products must be defined and developed in such a way that the negative and positive impacts on sustainable development that result or are expected to result from the software product over its whole life cycle are continuously assessed, documented, and used for further optimization of the software product [1].

Both of these definitions are based on product life cycles in terms of Life Cycle Assessment (abbr. LCA) or a cradle-to-grave approach. Additionally, Lami et al. assert that a *(Green and) Sustainable Software Process* is a "software process that meets its (realistic) sustainability objectives, expressed in terms of direct and indirect impacts on economy, society, human beings, and environment that result from its definition and deployment" [2].

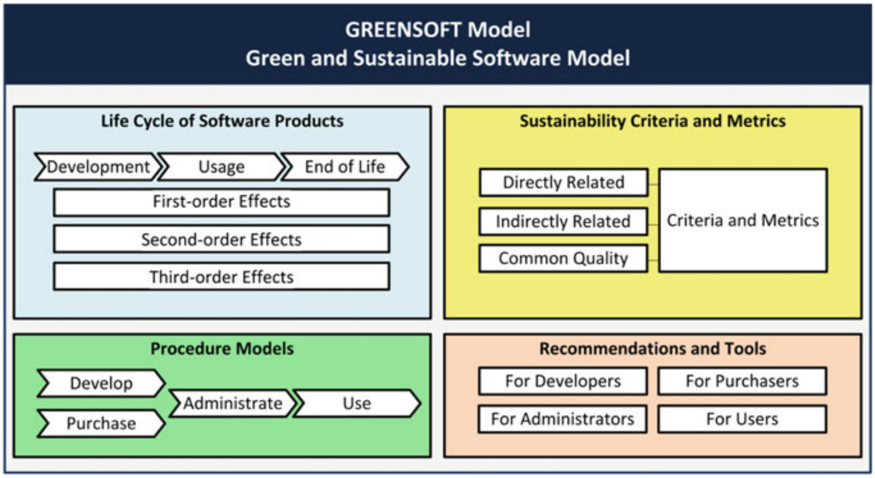

Fig. 1 The GREENSOFT reference model [3]

Summarizing these definitions, a sustainable software product ideally meets three conditions:

- The software is produced in a way that meets sustainability objectives.
- The software has minimal negative social and environmental impacts during its usage (first-order effects).
- The software functionality reinforces sustainable development or at least has no negative impacts on the society or environment (second-order and systemic effects).

The GREENSOFT Model (Fig. 1) classifies and sorts the described characteristics of sustainable software and its engineering [1]. This reference model contains four parts: the life cycle of software products; criteria and metrics that represent and measure sustainability aspects directly and indirectly related to the software product; procedure models for the different phases; and recommendations for action as well as tools. The model is described in detail in [1].

3 Related Work

Based on the definitions in Sect. 2 and the GREENSOFT Model, we summarize related work. A good overview of sustainable software engineering can be found in [4]: here, the author gathered 96 relevant publications on sustainable software engineering. They also discussed the question of what sustainability means in (and for) software engineering [5]. Amsel et al. [6] assert that sustainable software engineering should develop software that meets the needs of users while reducing environmental impacts.

A methodology to measure and incrementally improve the sustainability of software projects has been presented by Albertao et al. [7]. They advise implementing sustainable aspects continuously throughout the assessment phase, reflection phase, and goal improvement phase. In order to make the different sustainability issues manageable, they describe properties of a quality model, which they develop further in a later work that considers the overall software process [8]. Calero et al. [9] examine such software quality standards in greater detail, examining how they could reinforce sustainability.

Agarwal et al. [10] analyze and discuss the possibilities and benefits of green software. One of their findings is that more efficient algorithms will take less time to execute and thus support sustainability overall. In addition, they present methods to develop software in a sustainable way, compare them to conventional methods, and list some further environmentally friendly best practices for the development and implementation of software systems.

Based on the life cycle of software, Taina proposes metrics [11] and a method to calculate software's carbon footprint [12]. To do so, he analyzes the impacts of each software development phase for a generic project. The resulting carbon footprint is mainly influenced by the development phase, but also by the way it is delivered and how it will be used by the customers. Lami et al. [2] define software sustainability from a process-centric perspective. They define processes in a way that they can be measured in terms of process capability according to the ISO/IEC 15504 standard. They also distinguish between the sustainability factors power, paper, and fuel consumption. Dick et al. [13] discuss how particularly agile methods could improve sustainability in software engineering processes.

Another approach to Green Software Development is presented by Shenoy and Eeratta [14]. They also take the whole life cycle of software into account and offer suggestions for the typical development phases of software. Käfer [15] also presents conceptual and architectural issues concerning software energy consumption as well as ideas for incorporating energy efficiency issues into software projects. Mahaux [16], Penzenstadler [17] and Kocak [18] consider requirements for engineering, while Sahin [19] and Shojaee [20] look at the design of energy-efficient software.

4 A Quality Model for Sustainable Software

In order to decide whether or not software is sustainable, appropriate criteria are required. A first approach to developing these is offered by the Quality Model for Sustainable Software, presented in the following section. Overall, the different aspects can be grouped into common criteria, directly related criteria, and indirectly related criteria and metrics, as pictured in our Quality Model for Sustainable Software (Fig. 2).

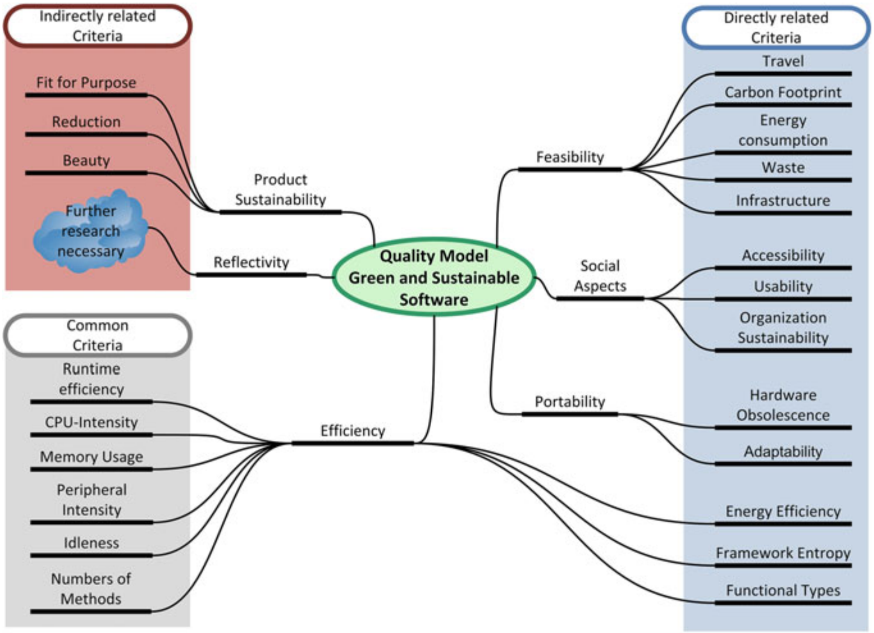

Fig. 2 Quality model for sustainable software [3]

Common Quality Criteria. The common criteria arise from the well known and standardized quality aspects for software, issued by the International Organization for Standardization [21]. The proposed quality model takes such aspects into account as *Efficiency*, *Reusability*, *Modifiability*, and *Usability*. These quality aspects extend to the field of sustainable development [8].

The quality aspects belonging to *Efficiency* are Runtime Efficiency, CPU-Intensity, Memory Usage, Peripheral Intensity, Idleness, and Number of Methods. *Runtime Efficiency* considers the time needed to finish executing depending on its implementation. In this context, Capra et al. [22] present the relation between faster application and higher energy consumption. The aspects *CPU-Intensity*, *Memory Usage* and *Peripheral Intensity* cover the resource utilization caused by software execution. In fact, the effects of the intensity of the resource consumption on the resulting energy consumption or even on system durability need to be analyzed. *Idleness* describes how often the system is idle. This aspect is relevant to certain types of software systems, such as virtual servers [11]. The total *Number of Methods* reflects the size of applications [22].

Directly Related Criteria. In contrast to common efficiency criteria, which can be considered as indicators of energy efficiency [23, 24], the energy efficiency of a system itself can be ranked in a reference system [25, 26]. This means its goal is to optimize the energy consumption in relation to delivered service items. Thus, the quality criterion *Energy Efficiency*, belonging to Efficiency in general, is assigned to the directly related criteria [1]. The *Framework Entropy* represents the grade of usage of external libraries and high level constructs. The different types of applications with their different levels of energy efficiency are indicated by the criterion *Functional Types* [22].

Hardware Obsolescence [1, 8, 27] considers the amount of hardware that needs to be replaced before the sustainably worthwhile lifetime is reached, due to software with higher system requirements. This criterion goes together with the quality aspect *Adaptability*. Both aspects belong to the criterion *Portability*. Here, Adaptability describes the possibilities to adapt the software to the specific consumer needs.

The quality criterion *Feasibility* evaluates the effects of the product development, or rather the software engineering process, on sustainable development. In this context, *Travel* includes business trips that belong to a software project and, where appropriate, the daily trips to work [8]. The resulting *Carbon Footprint* specifies the amount of CO_2 emissions caused by software development in the course of the software's life cycle [12]. The aspect *Energy Consumption* indicates the consumed energy caused by software development. *Waste* counts the resources consumed during software development for activities that do not have any additional value for customers or end users [11]. The aspect *Infrastructure* accounts for the conditions facilitating the usage of the software product.

From the perspective of the social aspects of sustainable development, there may be more qualities that require special measurements and assessment methods. As a first step, these aspects are called *Accessibility, Usability* and *Organization Sustainability*. Whereas Accessibility and Usability are well known aspects in software engineering, the sustainability of the organization is usually not considered in common software engineering processes and software's life cycle. *Accessibility* indicates whether the software product can be used by as many people as possible without any restrictions. *Usability* covers the understandability, learnability and operability of a software product, i.e. if the software usage is user-friendly and easily learned. The aspect *Organization Sustainability* covers the social situation in the software company, including working conditions, for example.

Indirectly Related Criteria. By using software, resources and energy can be reduced in other branches or application domains. Hence, criteria indirectly related to the software product itself also need to be considered.

Product Sustainability summarizes the effects of software on other products and services. It covers effects of usage, as well as systemic effects. The following aspects are presented by Taina [11]: *Fit for Purpose* takes the fitness of software for its specific operation purpose into account. The contribution of software within its application domain to reducing emissions, waste, and the like is indicated by the aspect *Reduction*. *Beauty* aims to value the software for its contribution to sustainable development [11]. Indeed, since a reference system is required to have a comparative figure, the exact quantification of these aspects may be difficult.

According to Taina [11], the quality *Reflectivity* refers to the quality aspect of efficiency. It specifies the manner in which the usage of software influences the resources that are indirectly needed by other persons or systems. Since the aspect *Reflectivity* does not belong to the first-order effects or the efficiency effects of ICT in the proper sense of the term but counts as an effect of use, it is indicated as a standalone quality of the indirectly related criteria. However, more research is required in this field in order to take into account user behavior and usage scenarios.

5 Process Models of Sustainable Software Engineering

According to our definitions, the precondition for creating software products that meet the presented sustainability criteria is a software engineering process that meets sustainability objectives. Hence, corresponding process models are needed. In the following, different approaches for such models will be presented and compared. First, we provide a description of the process-centric software sustainability according to Lami et al. [2], which defines a set of reference processes to be applied during sustainable software development life cycles. Then, we describe our process model for sustainable software development [13] and the green model for sustainable software engineering by Mahmoud and Ahmad [28]. These two models are checked for their compliance with the reference processes by Lami et al. [2], in order to determine which reference processes are covered by the models and which ones are missing.

5.1 Process-Centric Software Sustainability

Lami et al. [2] define a set of high-level reference processes which add sustainability concepts to the software reference processes defined in ISO/IEC 12207. The standard reference processes describe all activities directly and indirectly related to development, maintenance, and operation of software.

Lami et al. point out that processes regarding sustainability are missing in ISO/IEC 12207. Therefore, they define a set of three complementary sustainability processes: Sustainability Management Process, Sustainability Engineering Process and Sustainability Qualification Process.

These additional reference processes aim at continuously improving the sustainability of both software products and software processes. According to their definition of green and sustainable software processes, a process is sustainable if its impacts on sustainability are small (see definitions in Sect. 2).

Sustainability Management Process. The management process includes a preliminary phase, a planning phase, a monitoring phase, and a supplier sustainability control. In the preliminary phase, the principles and criteria for sustainability are established. In the planning phase, sustainability activities of the development process are indicated, and the corresponding requirements as well as necessary resources are planned. Afterwards, the sustainability of the deployed activities and their conformity with the requirements are monitored. The last part of the management process (supplier sustainability control) deals with sustainability policies and requirements for supplied products and services. Here, an agreement needs to be found and the supplier's sustainability needs to be monitored.

Sustainability Engineering Process. The engineering process is concerned with suitable tools and methods to enable and support a sustainable development process. In this context, sustainable issues and green principles for the development are defined, applied, and analyzed. The energy and resource consumption are factors that impact the sustainability and thus should be identified at the start of the engineering process. In the next step, the impacts of these effects should be analyzed in order to subsequently set sustainability objectives for the development process. In addition to the impacts of the process itself, the impacts of change requests on sustainability should be determined.

Sustainability Qualification Process. The qualification process applies to external resources such as engineering and management support tools. Aimed at sustainable products, these external resources need to be sustainable as well. In order to ensure their quality, a qualification strategy, an implementation plan for the strategy, documentation of the outcomes of the qualification, and a qualification report are required.

5.2 A Process Model for Agile and Sustainable Software Engineering

The Software Process Enhancement for Agile and Sustainable Software Engineering (GSSE) [13] was presented as an exemplary process that fits into the procedure model part of the GREENSOFT model (Fig. 1). It is not a complete software development process, but it claims to be adaptable to any process regardless of whether it works with iterations, phases or both. The only requirement is the possibility to inject its activities repetitively into the target process.

The enhancement is claimed to be lightweight. There are only two main activities that constitute the process: Process Assessment and Sustainability Reviews and Previews. The focus of Process Assessment is the sustainability of the software development process itself. The sustainability of the software product is addressed with Reviews and Previews. Both activities rely on a schematic life cycle model, inspired by life cycle assessment that denotes different impacts and effects of software on sustainable development that should be addressed.

The process distinguishes between three roles: the Customer Representative, the Development Team, and the Sustainability Executive. The Customer Representative represents the organization or the users who finance and use the software. The Development Team is responsible for developing the software as well as for improving the software with regard to sustainability-related non-functional requirements. The Sustainability Executive is responsible for continuous Process Assessment, organizing the Review and Preview meetings, and compiling a final report with the key figures and findings of Reviews, Previews and Process Assessment.

Process Assessment is a continuous activity alongside the software development process. It is meant to collect and edit data from the process that can be used for a carbon footprint calculation or even for life cycle assessment. The following data may be monitored and collected: Data regarding energy for running the developer's offices and IT infrastructure and for monitoring the means of travel for business trips and commuting, as well as the quantity of used stationery, e.g. paper for reports [29]. During the software development process, Process Assessment should briefly report to Reviews and Previews to keep the developers informed.

Sustainability Reviews and Previews focus on the software under development to optimize it in terms of its impacts and effects on sustainable development. During development, several Review and Preview meetings are conducted, e.g. after two-thirds of an iteration, which establishes a continuous improvement cycle. In reviews, the recent work is examined for any sustainability issues and solutions are then drawn up together with the expected rate of improvement, which is the preview part. In the subsequent Review and Preview session, these solutions are assessed to determine whether or not the issues have been addressed. Therefore, developers need methods and figures to explore these issues. In [13] a method to measure the energy efficiency of software is proposed that is based on unit testing. Other methods may be appropriate as well, because from a life cycle perspective, energy consumption is only one issue. Other aspects are resource and hardware requirements, accessibility, or even usage effects such as substitution, dematerialization, and rebound effects (cf. Fig. 2). Therefore, Reviews and Previews should already start in early process stages when the software product is defined [29]. The input from Process Assessment should be considered if there are issues that can be solved by the attendees themselves (e.g. chosen means of travel or local energy consumption).

At the end of the software development project, a report including the outcomes and key findings of Process Assessment (maybe a carbon footprint calculation) as well as Reviews and Previews should be handed over to the customer representatives. Additionally, outstanding results, lessons learned, and best practices should be preserved in a knowledge base to be available to other projects.

5.3 A Green Model for Sustainable Software Engineering

The Green Model for Sustainable Software Engineering (GSEP) [28] is inspired by the GREENSOFT Model. It is a two-level model that comes with a complete Green Software Engineering Process in the first level and a collection of exemplary software tools, promoting green computing in the second level. In the following, we provide a short overview of the engineering process. The process claims to combine the advantages of sequential, iterative, and agile software processes to produce a more sustainable one. The single phases of the process are either green processes or there are at least green guidelines.

The process consists of nine successive phases: Requirements, Design, Unit Testing, Implementation, System Testing, Green Analysis, Usage, Maintenance, and Disposal. As can be seen, the traditional phases of sequential software processes are extended with Green Analysis, Usage, and Disposal. An increment milestone can be set between Implementation and System Testing. The system release milestone occurs between Green Analysis and Usage. The process flow explicitly models possibilities to return to Requirements from Unit Testing, System Testing, Green Analysis, and Maintenance.

The Requirements phase is the most critical and important phase for the resulting greenness of a software product, because the requirements define the basic features and thus affect all the following phases. Hence, it is important that the requirements consider green issues and objectives. The requirements phase includes a risk assessment activity in terms of energy efficiency as well as a requirements test activity. If any issues are discovered during these activities, the Requirement phase may be started again.

The Design phase develops the system architecture based on the requirements. Three design decision guidelines are provided to support architects: (1) outline a compact design of data structures and efficient algorithms (however, a better performance does not necessarily result in a higher energy efficiency), (2) design smart and efficient functionality (results in an efficient algorithm and fewer lines of code during implementation), and (3) decide carefully which frameworks and external libraries are necessary (additional layers may cause additional processing time but may also simplify software engineers' work). Components should be reused if possible (requires less energy-consuming development efforts). If reused components do not meet the energy efficiency requirements, they should be reorganized to conform to these requirements. The Implementation phase is described together with the Design phase and does not come with any further process descriptions, since it depends on the Design phase.

Following Mahmoud et al., the Unit Testing phase comes before Implementation because if non-conformance with the requirements is encountered here, less energy is consumed if the process steps back to the Requirements phase than if Unit Testing comes after the Implementation. However, this does not mean that Unit Tests during the Implementation phase are not allowed. After Implementation and System Testing, the Green Analysis phase is performed. This phase determines the greenness of each increment by applying specific metrics to the developed code.

As an example of green performance indicators that characterize the greenness of each stage in the software engineering process, Mahmoud et al. suggest performance or CPU usage. The identified energy usages should be mapped to the source code to optimize the affected algorithms. Afterwards it is decided whether even (small) changes in requirements are necessary in order to optimize energy usage. In fact, this means that the process may step back to Requirements in order to add missing requirements, correct misunderstandings during the Requirement phase and in this way optimize the product. They argue that this step back is acceptable if it results in less severe mistakes. If only changes to the source code are necessary, these are directly implemented within this phase without stepping back.

Whereas Requirements, Design, Implementation, the Testing phases, and the Green Analysis phase come with some process and workflow descriptions, Usage, Maintenance, and Disposal come only with a set of general guidelines.

5.4 Comparison of the Process Models

In the following, we compare how Mahmoud and Ahmad's [28] Green Software Engineering Process (GSEP, see Sect. 5.3) and the process enhancement for agile and Sustainable Software Engineering (GSSE, see Sect. 5.2) by Dick et al. [13] implement the reference processes for green and sustainable software defined by Lami et al.

Both GSSE and GSEP processes implement only the Planning phase of the Sustainability Management Process. GSEP explicitly defines different sequential phases, including a specialized Green Analysis phase, as well as the possibility of having several iterations. It is necessary to plan the number of iterations and to schedule different activities connected to the Green Analysis phase. The same is true for GSSE, where the Reviews and Previews have to be scheduled after two-thirds of an iteration or phase. More specifically, the Sustainability Executive is responsible for organizing the sustainability-centric activities, which obviously include time planning as well as resource allocation. For the other phases of the reference process, the Preliminary phase, Monitoring phase, and Supplier Sustainability Control, no equivalents could be spotted in either GSEP or in GSSE.

The Sustainability Engineering Process is implemented by GSEP and GSSE and both processes supply the defined outcomes. GSEP identifies factors that affect sustainability explicitly within requirements engineering, whereas GSSE references a schematic Life Cycle model of software products that has the sole purpose of collating exemplary effects and impacts on sustainable development with life cycle phases known from Life Cycle Analysis (manufacturing, distribution, usage, end of life). Both processes perform sustainability analysis to determine the impact of the sustainability factors. GSEP has the Requirements and the Green Analysis phase and GSSE has the Reviews and Previews as well as Process Assessment. GSEP explicitly defines sustainability objectives in Requirements, whereas GSSE mentions sustainability objectives implicitly together with the role of the Development Team. The team is responsible for the non-functional requirements [13] and is therefore responsible to drive the Reviews and Previews. Exactly where the sustainability objectives as non-functional requirements are defined is left by GSSE to the specific implementation of the target process. GSEP and GSSE refer to principles and guidelines that are helpful to find adequate techniques and methods appropriate to accomplishing the sustainability objectives. Regarding the techniques and methods for sustainability, GSEP defines a large group of metrics and tools in its second level. GSSE mentions a carbon footprint calculation and especially methods and metrics to measure and assess the energy efficiency of software. The reference process requires an analysis of the sustainability of change requests, which is not specifically implemented by GSEP or GSSE. However, both processes claim to be agile and thus should welcome changes. GSEP may possibly analyze change requests in Requirements or the Green Analysis; GSSE may handle change requests in Reviews and Previews.

Both GSEP and GSSE focus on an implementation of the Sustainability Engineering Process. The Sustainability Qualification Process does not exist in either process model. As for the Sustainability Management Process, only the Planning phase can be seen to be rudimentarily implemented. Where GSSE was, according to the references, not designed with Lami et al. in mind, GSEP references Lami et al. and thus could have been designed to recognize more aspects of the reference processes. Both process descriptions should be extended to reflect more of the missing aspects. In particular, GSSE should describe how sustainability objectives are obtained or whose role it is to determine them. Taken as a whole, GSEP and GSSE cover most aspects of the Sustainability Engineering Process, while the aspects of the other processes are almost completely missing.

6 Conclusions and Outlook

In conclusion, we found that software plays an important role for ICT and sustainability. We looked especially at how software engineering can be made more sustainable. In our contribution, we presented a model for classifying sustainable software and it is engineering. If ICT and especially software are to make a contribution to sustainability, it is also necessary for software engineers to take the energy consumption into account. Our model especially showed quality aspects of software engineering. The main goal is to make the software itself as well as software's development process more sustainable.

Measured against the requirement to take all aspects of sustainability into account, one must concede that the social aspect has been neglected thus far [30]. Recent publications in the field of Sustainability Informatics mention social aspects only in passing. Therefore, one should also take a close look at the socialization of the software engineering process. The latest research shows the high likelihood of the inclusion of users and their communities in the engineering process of supporting and developing more sustainable systems [31].

Overall, Green IT, sustainable software or green software engineering and other concepts of ICT for Sustainability are not standalone problems. Moreover, every process of hardware and software development should involve aspects of Sustainable Development. In this context, we answered the questions "What is a green, or rather a sustainable software product?" "What are its criteria?" and "How can we develop metrics for sustainable software and its engineering?" To address these questions, it is necessary to provide additional tools and methods for software developers and for everyone else who has a stake in software development and usage. Aspects of sustainable development should be routinely addressed during the whole life cycle of software products. Ideally, even customers should understand Green IT as a "must-have" requirement. Hence, it is necessary to reach a degree of standardization in the field of energy-efficient software and its sustainable production.

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Part III
The Material Cost of Information Processing

The Material Basis of ICT

Patrick A. Wäger, Roland Hischier and Rolf Widmer

Abstract Technologies for storing, transmitting, and processing information have made astounding progress in dematerialization. The amount of physical mass needed to represent one bit of information has dramatically decreased in the last few years, and is still declining. However, information will always need a material basis. In this chapter, we address both the upstream (from mining to the product) and the downstream (from the product to final disposal) implications of the composition of an average Swiss end-of-life (EoL) consumer ICT device from a materials perspective. Regarding the upstream implications, we calculate the scores of the MIPS material rucksack indicator and the ReCiPe mineral resource depletion indicator for selected materials contained in ICT devices, namely polymers, the base metals Al, Cu, and Fe, and the geochemically scarce metals Ag, Au, and Pd. For primary production of one kg of raw material found in consumer ICT devices, the highest material rucksack and resource depletion scores are obtained for the three scarce metals Ag, Au, and Pd; almost the entire material rucksack for these metals is determined by the mining and refining processes. This picture changes when indicator scores are scaled to their relative mass per kg average Swiss EoL consumer ICT device: the base metals Fe and in particular Cu now score much higher than the scarce metals for both indicators. Regarding the downstream implications, we determine the effects of a substitution of primary raw materials in ICT devices with secondary raw materials recovered from EoL consumer ICT devices on both indicator scores. According to our results, such a substitution leads to benefits which are highest for the base metals, followed by scarce metals. The recovery of secondary raw materials from EoL consumer ICT

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devices can significantly reduce the need for primary raw materials and subsequently the material rucksacks and related impacts. However, increased recycling is not a panacea: the current rapid growth of the materials stock in the technosphere necessitates continuous natural resource depletion, and recycling itself is ultimately limited by thermodynamics.

Keywords ICT · Material rucksack · Mineral resource depletion · Scarce metals · Materials recovery

1 Introduction

Technologies for storing, transmitting, and processing information have a material basis. Modern ICT is based on a multitude of hardware devices with specific, complex materials compositions. The average materials composition of a consumer ICT device at the end of its useful life (reference year 2010) in Switzerland has the following characteristics: the majority of the mass of such a device consists of the base metals iron (Fe), aluminum (Al), and copper (Cu), polymers (mainly ABS, PC, PC/ABS, PE, PS, and SAN[1]) and glass [1–3] (see Fig. 1). Besides the three base metals, consumer ICT devices also contain a large number of scarce metals,[2] including, among others, gold (Au), indium (In), platinum group metals (PGM) such as palladium (Pd) and platinum (Pt), rare earth elements (REE) such as dysprosium and neodymium, silver (Ag), and tantalum (Ta) (see Fig. 1 for selected scarce metals occurring in consumer ICT devices). In the last few decades, an increasing number of elements represented in the periodic table has found its way into ICT [5], which requires devices for infrastructure (e.g., servers, routers, switches, base stations, and optical fiber cables) in addition to consumer devices (Fig. 2).

However, the material composition of ICT devices (see Fig. 1 for end-of-life consumer (EoL) ICT devices) tells only part of the story about the material basis of ICT. Both "upstream" processes (mining, refining, and production of the raw materials; production and assembly of the components; and the product itself) and "downstream" processes (product use, materials recovery, and final disposal) associated with an ICT device generate a multitude of material flows which are not obvious to its user [3, 6, 7].

In the following two sections, we will address up- and downstream implications of the average materials composition of EoL) consumer ICT devices (reference year 2010) in Switzerland, focusing mainly on metals.

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[1] ABS: acrylonitrile butadiene styrene; PC: polycarbonate; PC/ABS: polycarbonate/acrylonitrile butadiene styrene blend; PE: polyethylene; PS: polystyrene; SAN: styrene acrylonitrile.

[2] A metal is called geochemically scarce if it occurs at an average concentration below 0.01 weight percent in the earth's crust [4]. In this chapter, we use "scarce" as a synonym for "geochemically scarce."

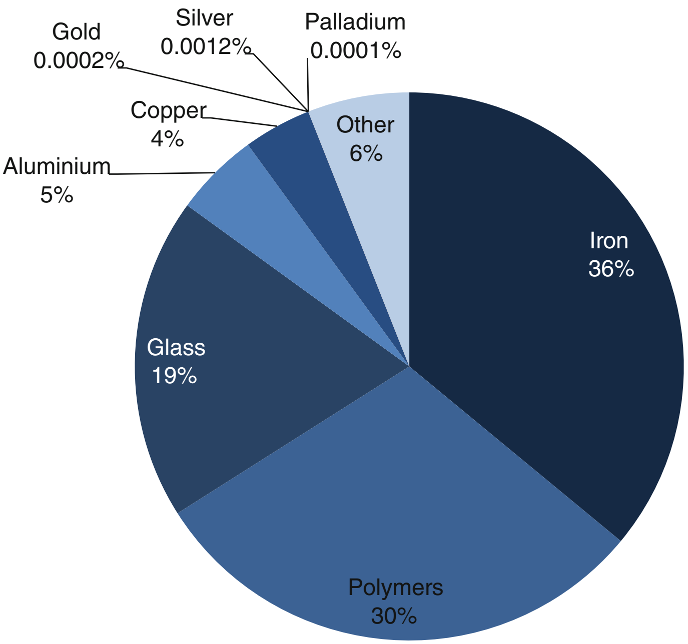

Fig. 1 Relative mass distribution of the materials contained in EoL consumer ICT devices in Switzerland (reference year 2010) [1, 3]

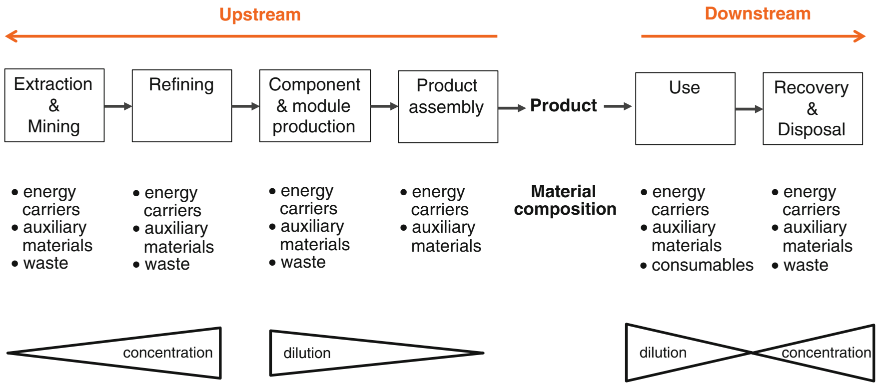

Fig. 2 Processes and material flows (focus: metals) contributing to the material basis of an ICT device, including the perspectives applied in this chapter (upstream and downstream) and metal concentration and dilution phases along the life cycle

2 Upstream Issues

2.1 ICT Raw Material Rucksacks

Each of the materials determining the composition of an average ICT device is associated with a material "rucksack" that includes all material flows connected to their extraction/mining, refining, incorporation into components and modules, and assembly of these components and modules to the final product. The calculation of the material rucksack requires data on the material and energy flows of all processes involved. Figure 3 shows the material rucksack per kg of selected raw materials found in ICT (polymers, the base metals Al, Co, and Fe, and the scarce metals Au, Ag, and Pd) as material input per unit of service (MIPS) scores [8].

In addition to these material rucksacks, Fig. 3 also shows the implications for mineral resource depletion. Mineral resource depletion is one of the issues typically addressed in the ongoing discussion on supply risks of mineral raw materials, which have become a major issue due to emerging technologies' increased demand for scarce metals [9]. The new concept of criticality, which seeks to capture both the raw material supply risks and the vulnerability of systems (e.g., companies, sectors, economies, societies) to a potential raw material supply disruption, emerged only some years ago [10, 11]. The criticality concept has meanwhile been applied in several studies, showing that many scarce metals, among others gallium, germanium, indium, PGM, REE, or Ta, are to be considered "critical." Most of these studies address long-term geological availability, some of them including mineral deposit[3] information. The criticality study commissioned by the European Union [12], which is currently being updated, does not address geological availability because of the time horizon of the study (10 years) as well as reservations with regard to the use of concepts such as "reserve",[4] "reserve base",[5] "resource"[6] and the "static lifetime"[7] as indicators for geological availability.

In Fig. 3, the implications for mineral resource depletion per kg of raw materials found in ICT are represented by the ReCiPe[8] life cycle assessment minerals

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[3] A deposit is any accumulation of a mineral or a group of minerals that may be economically valuable [12].

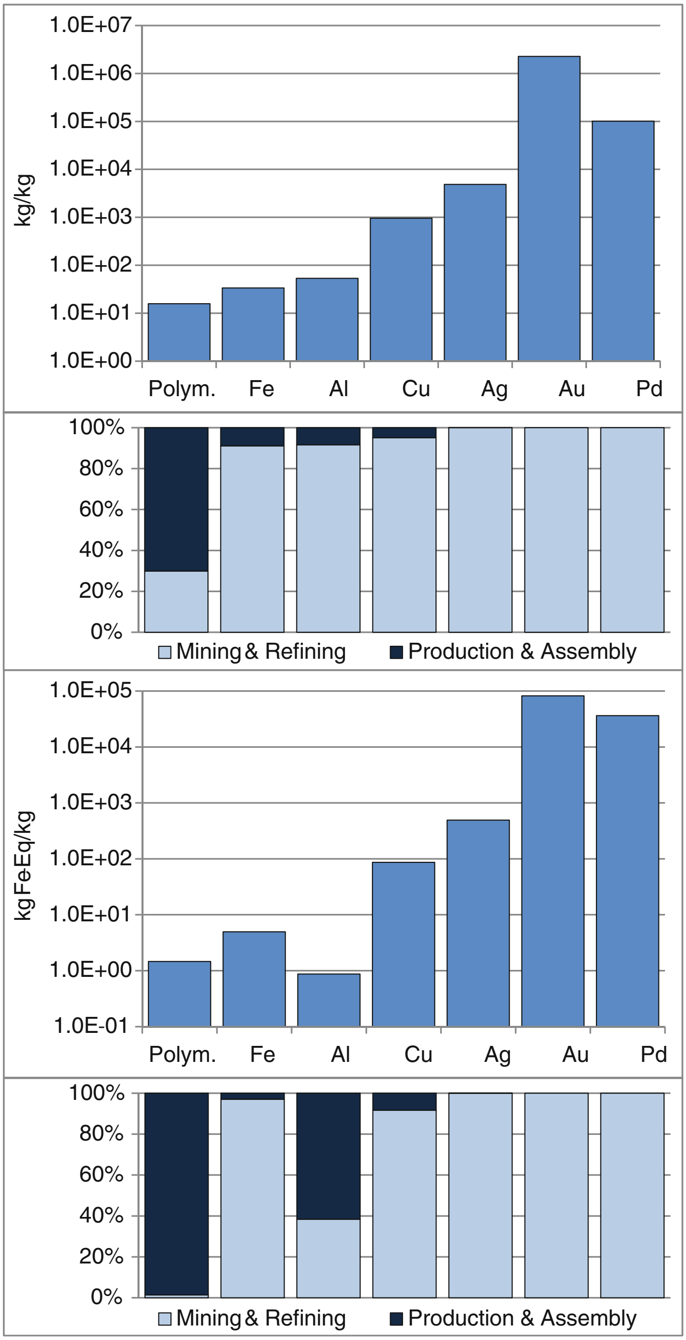
[4] A reserve is the part of the resource which has been fully geologically evaluated and is commercially and legally mineable [12].

[5] The reserve base is the reserve of a resource plus those parts of the resource that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics [12].

[6] A resource is a natural concentration of minerals or a body of rock that is, or may become, of potential economic interest as a basis for the extraction of a mineral commodity [12].

[7] The static lifetime is the ratio between reserve or reserve base and annual mine production [12].

[8] The authors chose the acronym "ReCiPe" because the method is expected to provide a recipe for calculating life cycle impact category indicators and at the same time represent the initials of the institutes that were main contributors to this project [13].


kg/kg
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
Polym.
Fe
Al
Cu
Ag
Au
Pd
100%
80%
60%
40%
20%
0%
Mining & Refining
Production & Assembly
kgFeEq/kg
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
Polym.
Fe
Al
Cu
Ag
Au
Pd
100%
80%
60%
40%
20%
0%
Mining & Refining
Production & Assembly

◀ **Fig. 3** Material rucksack and mineral resource depletion scores per kg of selected raw materials found in ICT. *Upper* two diagrams MIPS scores in kg of total material input per kg of material and corresponding shares of mining & refining and production & assembly. *Lower* two diagrams: ReCiPe mineral resource depletion (primary resources) scores in kg Fe equivalents per kg of material and corresponding shares of mining & refining and production & assembly. *Data source* ecoinvent v3.01 [17]

resource depletion midpoint indicator (primary resources) [13]. This indicator monetizes the energy requirements of resource extraction, with the marginal increase of extraction cost per kg of extracted resource as a base for the model. Other mineral resource depletion indicators used in life cycle impact assessment calculate the ratio between use and deposits/reserves (CML method[9]), the surplus energy required for mining resources with a decreased ore grade at some point in the future (Eco-indicator method[10]), or exergy [16].

Both the MIPS score and the minerals resource depletion indicator in Fig. 3 were calculated with ecoinvent v3.01 data, using the allocation-based attributional system model [17]. As shown in Fig. 3, the material rucksacks per kg of raw materials found in ICT are significantly higher (by a factor of 1,000–10,000) for the scarce metals Ag, Au, and Pd than for the polymers and the base metals Al and Fe; Cu has a score that is closer to the three scarce metals than the two other base metals. Almost the entire material rucksack for the scarce metals is determined by the mining and refining processes (i.e., the process of concentrating them into raw materials for production), while for all three base metals, the material rucksack is partly (5–10 %) and for the polymers mainly (about 70 %) determined by the production and assembly processes (i.e., dilution of the raw materials into products). Ag, Au, and Pd also score highest on the ReCiPe mineral resource depletion indicator. The difference between Au and Pd, the two materials with the highest scores for both indicators, is smaller for ReCiPe than for MIPS. Al has a higher MIPS score than Fe, but a lower ReCiPe score. Compared to the material rucksack indicator MIPS, the relative contribution of the production and assembly processes (i.e., dilution of raw materials into products) as expressed by ReCiPe is considerably larger for polymers and Al and smaller for Fe.

Figure 4 shows the scores for the same materials, however with indicators scaled to their relative mass per kg average EoL consumer ICT device. This provides a completely different picture than Fig. 3 since the mass fractions of the materials in the device are orders of magnitude apart from each other. The

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[9] The CML method is a problem-oriented impact assessment method developed at the Center of Environmental Science (CML) of Leiden University (NL) and described in their “operational guide to the ISO standards.” [14].

[10] The Eco-Indicator ’99 method is an endpoint method that aggregates all impacts into three different damage categories (damage to human health, to ecosystem quality, and to the available resources). The method was developed in the Netherlands and is among the most often used life cycle impact assessment methods in Europe [15].

material rucksack scores are now by far the highest for Cu, followed by Fe, polymers, and Au, while for the ReCiPe mineral resource depletion indicator, the scores are highest for the base metals Cu and Fe, followed by the polymers and Au.

3 Downstream Issues

3.1 Effects of Materials Recovery on Material Rucksacks and Resource Depletion

In this chapter, we do not consider energy carriers, auxiliary materials, and consumables required in the use phase, as our focus is on the implications of the material composition of a consumer ICT device. We therefore skip the use phase in our downstream perspective and address the effects of materials recovery from EoL consumer ICT devices. In particular, we elaborate on the effects of a substitution of primary raw materials with secondary raw materials recovered from EoL consumer ICT devices on MIPS and ReCiPe mineral resource depletion indicator scores, assuming that the recovered materials are used solely for the production of new ICT devices. Two recovery rates are considered: rates currently achieved in Switzerland and technically achievable rates. Concerning the recovery of plastics, it has to be considered that their recycling potential is limited by brominated flame retardants and other problematic additives [18]; when recycling metals, significant quality and dilution losses might occur [19, 20]. The effects of recycling are calculated as the difference between the scores resulting from recycling activities and the (avoided) scores from primary production of the material replaced by recycling. In the case of substitution of primary copper by copper recovered from EoL consumer ICT devices, the scores obtained for the process “Copper market for primary production only” are subtracted from the scores calculated for the process “Metal part of electronics scrap, in blister copper | treatment of, by electrolytic refining.”

As shown in Fig. 5, the recovery of selected raw materials results in a reduction of the material rucksack and resource depletion indicator scores shown in Fig. 4. The environmental benefits are greatest for the base metals, with estimated current recovery rates of 90 % for Fe and 85 % for Al and Cu, followed by scarce metals, with 80 % for Ag, Au, and Pd, and finally polymers with 40 % [21]. Assuming technically achievable recovery rates of 70 % for plastics, 88 % for Ag, Au, and Pd as well as 95 % for Fe, Al, and Cu [21], the improvement potentials are highest for polymers with regard to the material rucksack indicator, followed by Cu for both indicators, and Al, again with regard to the materials rucksack indicator.

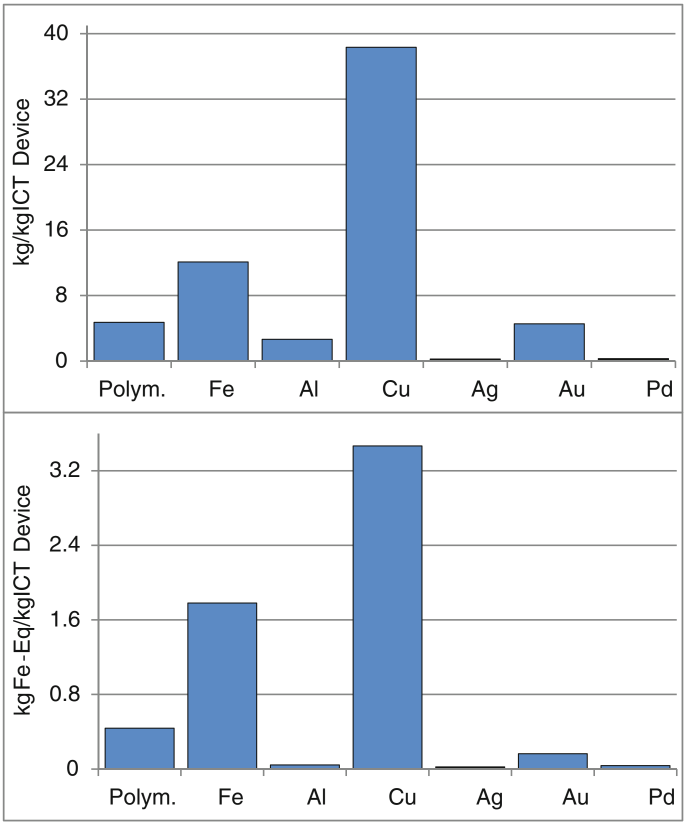

Fig. 4 Material rucksack and mineral resource depletion scores for selected raw materials, scaled to their relative mass in 1 kg average Swiss EoL consumer ICT device. *Top* MIPS scores in kg total material input per kg ICT device. *Bottom* ReCiPe mineral resource depletion (primary resources) scores in kg Fe equivalents per kg ICT device. *Data source* ecoinvent v3.01 [17]

3.2 Scarce Metals Recovery

Despite the concentrations of scarce metals in EoL devices typically being much lower than those of the base metals Al, Cu, and Fe, post-disassembly concentrations can be considered high compared to minimum profitable ore grades [5]. Yet recovery rates of several scarce metals, such as gallium, germanium, indium, REE, and Ta from EoL products have been shown to lie below 1 %, while the recovery rates for “precious” scarce metals such as Ag, Au, Pd or Pt exceed 50 % [22].

Scarce metal recovery rates are a function of the efficiencies of the processes determining the recycling chain, i.e., collection, pre-processing, and end-processing [23].

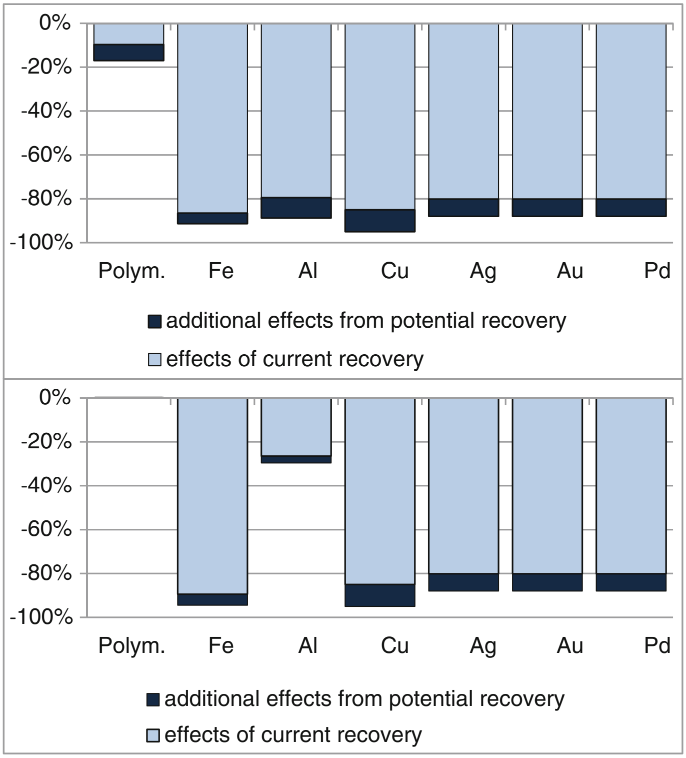

Fig. 5 Effects of the substitution of primary raw materials in ICT devices with secondary raw materials recovered from EoL consumer ICT devices on material rucksack and mineral resource depletion scores with current and potential (technically achievable) recovery rates. *Top* Reduction of MIPS scores relative to primary production. *Bottom* Reduction of ReCiPe mineral resource depletion indicator scores relative to primary production. 100 % corresponds to the scores reported in Fig. 4

Collection efficiency for waste electrical and electronic equipment (WEEE) depends on how well the collection systems in place are adapted to the habits of the owners of the EoL product to be collected and how well they are informed about the collection systems. The *efficiency of pre-processing* depends on the specific implementation and combination of the different steps involved, namely sorting, dismantling, and physical and chemical separation. In order to optimize their costs, recyclers in countries such as Switzerland increasingly pre-process WEEE with automatized, mechanical processes, manual dismantling being limited to separating hazardous materials and disturbing materials before mechanical processing. However, this may lead to mixing materials in a way that negatively affects the recovery rates of certain materials. For example, scarce metals may end up in fine plastic fractions sent to energy recovery processes, resulting in dissipation[11] of the metals [24, 25]. Several projects are currently investigating options to better exploit the potential of manual dismantling of WEEE in view of higher scarce metals recovery rates, including concepts aiming at integrating "best" pre-processing in developing countries and "best" end-processing in international state-of-the-art end-processing facilities ("best-of-two-worlds approach") [26–30]. Other projects aim at optimizing the allocation of output fractions from pre-processing to end-processing [31]. It should be kept in mind for all of them that end-processing is ultimately limited by thermodynamics, which is why certain metal combinations cannot be successfully recycled [20, 32]. Accordingly, not only the actors determining the design of the collection, pre-processing, and end-processing systems will have to take their responsibilities seriously to increase scarce metals recovery, but also product designers.

4 Conclusion and Outlook

ICT is driving the rapid expansion of the material substrate contained in countless devices in use, in terms of both absolute volumes and number of elements, specifically scarce metals. This requires an accelerating intake of primary raw materials, mainly minerals from the lithosphere, which is coupled with rapidly growing material rucksacks. The recovery of secondary raw materials from EoL devices can significantly reduce the need for primary raw materials and subsequently the material rucksacks and mineral resource depletion. However, increased recycling is not a panacea:

- The materials stock in the technosphere is growing rapidly, which entails continuing natural resource depletion. For substitution of primary resources by secondary raw materials to become relevant, steady state conditions have to be reached.
- The recovery rates of the majority of the elements, in particular scarce metals, are very low. Some may be increased considerably, but many cannot, due to thermodynamic limits in the established metallurgic processes of metal refining. Hence, considerable leakage from the envisioned "closed-loop economy" and dissipation to the environment seem unavoidable.
- In a closed loop economy, faster materials turnover due to e.g. shorter residence times of ICT devices leads to increased material losses into inaccessible stocks. Primary raw materials are required to compensate for these losses.

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[11] "Dissipation"—in this context—refers to the dilution of a material in the technosphere or ecosphere in such a way that its recovery is made practically impossible. The "technosphere" includes all objects and associated material flows that have been created by humankind and are under its control [9].

- The material rucksacks for raw materials production tend to increase with decreasing ore grades, which most of the remaining deposits and mineral mines are facing.
- Not only are the primary ore grades decreasing, but the secondary deposits are also becoming less accessible as a result of continued miniaturization, augmenting substrate complexity, and a forceful trend towards "pervasive computing" [33].
- Some of the materials are being phased out from ICT, in particular some toxic heavy metals such as Hg, Pb, and Cd. For example, under the recent UN Minamata Convention on Mercury [34], Hg must no longer be recycled in the technosphere. Therefore, disposal facilities that provide long-term safety are needed, which may require new financing mechanisms.

In view of these perspectives, we draw the following conclusions:

- In the short term, recycling rates should be systematically maximized for the specific elements contained in ICT devices, not just for their total mass. The material turnover in a leaking loop economy needs to be slowed down, i.e., active residence time has to be maximized.
- In the medium term, raw materials production, ICT devices as well as recycling processes have to be designed to achieve minimal material dissipation and minimal material rucksacks.
- In the long term, the material substrates of ICT (as well as all other technologies) need to be changed toward the use of more abundant elements and bio-compatible substances.

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Recycling of ICT Equipment in Industrialized and Developing Countries

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Abstract The increasing penetration of society with Information and Communication Technologies (ICT) is resulting in growing waste volumes. Typical of this waste is the combination of its intrinsic value due to the high content of basic and precious metals with health and environmental hazards caused by the occurrence of toxic substances in combination with inadequate recycling practices. Based on the principle of Extended Producer Responsibility (EPR), industrialized countries have legislated WEEE (Waste Electrical and Electronic Equipment) management. As a consequence, producers established take-back schemes. In developing countries, the absence of a legal framework and formal recycling infrastructure as well as the presence of the self-organized informal sector has complicated similar efforts. In some countries, progress could be achieved through the promulgation of a legal framework and the establishment of basic recycling infrastructure. The environmental and social aspects associated with the improper recycling of WEEE and the sustainable reintegration of secondary resources demands strong efforts from industry, government, and civil society.

Keywords WEEE · E-waste · ICT waste · Formal recycling · Informal recycling · Secondary resources

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1 Introduction

The use of Electrical and Electronic Equipment (EEE) has grown rapidly in recent decades. Expanded functionalities and decreasing prices have influenced consumer behavior. The trend toward embedding Information and Communication Technologies (ICT) into different goods used daily has widened the range of EEE. As a consequence, Waste Electrical and Electronic Equipment (WEEE) has become the fastest-growing waste stream worldwide [1].

This is particularly the case for ICT equipment, where sales of new technologies have outperformed growth in other sectors [2]. In industrialized countries, this phenomenon could be observed as early as the 1990's, while developing countries have been lagging behind. In recent years, however, growth rates of ICT sales in developing countries have exceeded the corresponding rates in industrialized countries. According to the International Telecommunication Union (ITU), the number of mobile-phone subscriptions in industrialized countries grew by 14 % from 2009 to 2013, whereas growth in developing countries reached 48 % during the same period [3]. Similar trends can be observed for computer penetration in households or for per capita use of the Internet.

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal [4] regulates among others the export of ICT waste to non-OECD countries. However, this international treaty could not prevent such exports since not all countries have ratified it, among others the United States as the largest generator of ICT waste worldwide. Furthermore, illegal exports are difficult to detect.

Media reporting on environmental and social conditions witnessed in recycling activities in developing countries has startled the public and led to calls for stricter control and regulation of EEE exports from OECD countries. A working group of the Basel Convention has drafted technical guidelines with the aim of providing clarity on the distinction between EEE and WEEE in order to better prevent their illegal shipment. The guidelines are based on a mandatory functionality test which is to be performed for all equipment designated for export. A similar requirement has been formulated in the recast of the European WEEE Directive [5].

2 ICT Waste: Volumes and Composition

2.1 WEEE and ICT Waste

According to the European WEEE Directive [5], WEEE is grouped into the following ten categories:

1. Large household appliances
2. Small household appliances
3. IT and telecommunications equipment

4. Consumer equipment and photovoltaic panels
5. Lighting equipment
6. Electrical and electronic tools
7. Toys, leisure, and sports equipment
8. Medical devices
9. Monitoring and control instruments
10. Automatic dispensers

The category "IT and telecommunications equipment," mostly also referred to as "ICT," includes end-of-life equipment such as computers, printers, and scanners as well as mobile and fixed communication devices.

2.2 Volumes of ICT Waste

Usage of ICT products in a society and the corresponding stocks and flows are important elements for the design of management systems, both from a waste and from a material management perspective. Quantitative models for predicting WEEE flows incorporating technological substitution and multiple-unit product stewardship have been tested and validated, for instance for the case of cathode ray tube (CRT) TVs being crowded out by flat screen TV sets in Switzerland [6].

Industrialized Countries. Recent statistics estimate the worldwide quantity of EEE put on the market in 2012 at roughly 65 million tons and the corresponding generation of WEEE at almost 49 million tons [7].

In Europe, the share of ICT equipment in relation to total EEE equipment put on the market ranges between 9 % (Norway) and 23 % (Belgium), whereas the share of ICT waste collected in relation to WEEE collected varies between 13 % and 35 % (Table 1). ICT waste collected per capita varies between 0.3 kg/year and 3.5 kg/year (Table 2).

Developing Countries. Due to limited data availability, the quantification of WEEE volumes in developing countries is an iterative process, often based on a combined top-down and bottom-up approach. Figures on imports of EEE equipment can often be derived from statistical data, while consumer stocks and disposal volumes need to be assessed through surveys. Informal waste collection is least documented, for which reason WEEE quantities are often assessed by assigning lifetimes to specific products. Through additional field investigations as well as interviews, meetings, and workshops with stakeholders, valuable information such as transfer coefficients between processes, downstream processes of materials, and information about material quality can be obtained.

Various WEEE assessments performed between 2005 and 2012 have revealed figures on Personal Computer (PC) imports and PC waste as shown in Table 3. The data on PC waste are indicative and are derived from material flow assessments.

Table 1 EEE/ICT put on the market and WEEE/ICT waste collected in 15 selected European countries in 2010 [26]

Country	EEE put on the market	ICT put on the market		WEEE collected	ICT waste collected	
	(t)	(t)	(%)	(t)	(t)	(%)
Austria	165,810	28,656	17	74,256	16,332	22
Belgium	294,530	66,446	23	105,557	18,626	18
Denmark	147,557	27,165	18	82,931	18,325	22
Finland	148,157	20,603	14	50,867	8,034	16
France	1,635,493	201,576	12	433,959	63,407	15
Germany	1,730,794	285,285	16	777,035	217,917	28
Greece	178,260	20,410	11	46,528	7,242	16
Italy	1,117,406	110,221	10	268,216	38,237	14
Latvia	15,290	2,117	14	4,288	562	13
Norway	181,579	16,055	9	107,767	16,496	15
Portugal	157,065	16,316	10	46,673	7,272	16
Romania	151,317	31,944	21	26,247	6,460	25
Spain	746,801	83,215	11	158,100	25,924	16
Sweden	232,403	42,212	18	161,444	31,756	20
United Kingdom	1,534,576	338,838	22	479,356	165,626	35

Table 2 Collection of ICT waste per capita in 15 selected European countries in 2010 [26]

Country	Population (millions)	ICT waste collected (t)	ICT waste collected per capita (kg)
Austria	8.4	16,332	1.9
Belgium	10.8	18,626	1.7
Denmark	5.5	18,325	3.3
Finland	5.4	8,034	3.4
France	65.4	63,407	1.0
Germany	81.8	217,917	2.7
Greece	11.3	7,242	0.6
Italy	60.3	38,237	0.6
Latvia	2.2	562	0.3
Norway	4.9	16,496	3.4
Portugal	10.6	7,272	0.7
Romania	21.5	6,460	0.3
Spain	47.0	25,924	0.6
Sweden	9.4	31,756	3.4
United Kingdom	62.0	165,626	2.7

Table 3 PCs put on the market and estimated PC waste generation in selected developing countries according to various country assessments

Country	Assessment year	Population (millions)	PCs put on the market (t)	PC-waste generated (t)	PC waste generated per capita (kg)	References
Ghana	2009	24.3	16,650	6,400	0.3	[43]
Kenya	2007	40.9	5,200	440	0.01	[1, 52]
South Africa	2007	50.0	32,000	19,400	0.4	[1, 53]
Uganda	2007	33.8	700	1,300	0.2	[1, 54]
China	2007	1,339.2	419,100	300,000	0.2	[1]
India	2007	1,184.7	140,800	56,300	0.01	[1]
Brazil	2005	193.4	no data	96,800	0.5	[1, 55]
Chile	2010	17.1	12,600	5,300	0.3	[56, 57]
Colombia	2006	45.6	13,600	6,500	0.1	[1, 58]
Peru	2006	29.5	7,000	6,000	0.2	[1, 59]

2.3 Composition of ICT Waste

The perception of WEEE has developed over the years from a waste problem which can cause environmental damage and health issues to an opportunity: ICT components, for example, contain a variety of metals for which recovery is economically attractive (Table 4). The metal concentrations often exceed the concentrations found in natural ores [8]. The Kloof gold mine in South Africa, for instance, has gold concentrations of approx. 6 ppm gold [9], whereas in mobile phones this concentration can be up to 100 times higher. Similar situations can be found when comparing Silver and Palladium concentrations in natural ores with concentrations in ICT components.

Compared to annual production volumes, the demand for metals used in EEE reaches significant levels (Table 5). This highlights the relevance of WEEE as a secondary resource. Consequently, inefficient treatment of WEEE may lead to a systematic loss of secondary materials [1]. Hence, the appropriate handling of WEEE both prevents environmental and health issues and contributes to more sustainable use of raw materials.

WEEE also contains toxic and hazardous substances, for example, heavy metals such as mercury, cadmium, lead, and chromium, or Persistent Organic Pollutants (POPs), which can be found in plastic casings or in Printed Wiring Boards (PWB) [10]. Some of these substances have been regulated, and their use has been restricted for new equipment through the European RoHS[1] directive [11]. Other

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[1] Restriction of Hazardous Substances Directive 2002/95/EC.

Table 4 Content of Au, Ag, and Pd in ICT devices [60]

Device	Au		Ag		Pd	
	(mg)	(ppm)	(mg)	(ppm)	(mg)	(ppm)
PC	316–338	21–23	804–2,127	54–142	146–212	10–14
Laptop	246–250	85–86	440	152	50–80	17–28
Tablet	131	215	26	43	no data	no data
Mobile phone	50–69	455–627	127–715	1,155–6,500	10–37	91–336

Table 5 Important metals used for EEE [1]

Metal	Primary production[a] (t/y)	By-product of	Demand for EEE (t/y)	Demand/production (%)	Main applications
Ag	20,000	Pb, Zn	6,000	30	Contacts, switches, solders…
Au	2,500	(Cu)	300	12	Bonding wire, contacts, integrated circuits…
Pd	230	PGM	33	14	Multilayer capacitors, connectors
Pt	210	PGM	13	6	Hard disks, thermocouples, fuel cells
Ru	32	PGM	27	84	Hard disks, plasma displays
Cu	15,000,000		4,500,000	30	Cables, wires, connectors…
Sn	275,000		90,000	33	Solders
Sb	130,000		65,000	50	Flame retardants, CRT glass
Co	58,000	Ni, Cu	11,000	19	Rechargeable batteries
Bi	5,600	Pb, W, Zn	900	16	Solders, capacitors, heat sinks…
Se	1,400	Cu	240	17	Electro-optic devices, copiers, solar cells
In	480	Zn, Pb	380	79	LCD glass, solders, semiconductors
Total			**4,670,000**		

[a] based on demand in 2006; acronyms: PGM = Platinum Group Metals; CRT = Cathode Ray Tube; LCD = Liquid Crystal Display

substances have been banned, but are still allowed for certain applications (for instance, mercury in energy-saving lamps) or are still present in older equipment. WEEE and its components may therefore pose a significant health risk not only due to their primary constituents, but also as a result of improper management of byproducts either used in the recycling process (such as cyanide for leaching gold) or generated by chemical reactions (such as dioxins through the burning of cables). Due to its properties, WEEE is generally considered to be hazardous waste under the Basel Convention.

3 Objectives, Challenges, and Approaches

3.1 Objectives and Challenges

The main services a WEEE management system has to deliver are (a) separate and efficient collection, (b) recovery of secondary resources, and (c) segregation and safe disposal of hazardous components. Although recycling the valuables contained in WEEE may generate income, other processes such as the removal and disposal of toxic components as well as system administration, monitoring, and control to ensure quality may incur expenses.

3.2 Extended Producer Responsibility

Early experiences in industrialized countries showed that municipalities are not adequately equipped and staffed to handle a complex waste stream such as WEEE. New approaches had to be considered, and the concept of Extended Producer Responsibility (EPR) [12], where producers resume the end-of-life responsibility for their products, evolved as a broadly accepted alternative. Based on EPR, producers initiated take-back schemes, either individually, or collectively as a group of producers, or as members of national Producer Responsibility Organizations (PRO), to manage financing of WEEE flows and processing steps. National authorities started to address this concept in their waste regulations.

Formal WEEE management systems adhering to sustainability and extended producer responsibility principles were established approximately 20 years ago mainly in Europe [13–15]. The first European WEEE Directive [16] set the global pace and standard in regulating WEEE management. However, some countries had started to implement WEEE management policies before the EU WEEE Directive came into force. One of the earliest legislative frameworks is the Swiss Ordinance on the Return, Taking Back and Disposal of Electrical and Electronic Equipment (ORDEE) [17]. Its simple principles of mainly defining stakeholders' obligations (see Fig. 1) have led to a consumer-friendly and environmentally sound take-back system with high collection and material recovery rates [18].

In developing countries and emerging economies, the concept of EPR was not adapted until recently. Reports from NGOs on the environmental and health issues related to poor WEEE management as well as various international cooperation projects addressing those challenges [19] increased the priority of WEEE management among environmental issues requiring special legislative attention.

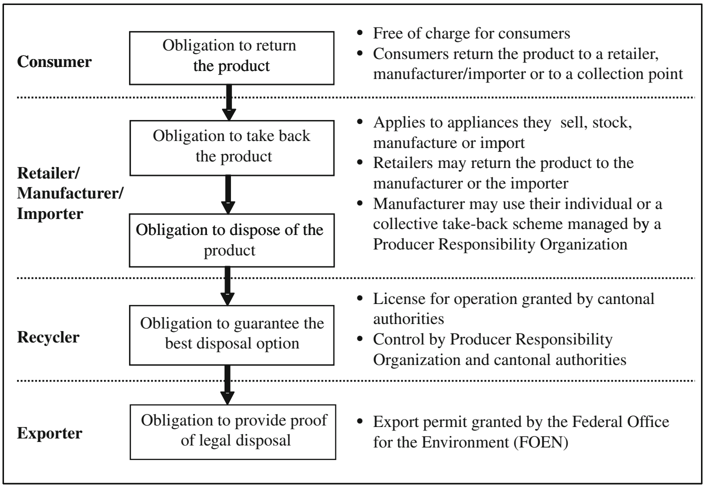

Fig. 1 Flow of WEEE and related stakeholders' obligations according to the Swiss WEEE legislation ORDEE [17]

As a result, WEEE legislation based on EPR has been established in a number of developing countries in recent years. Summaries of rapid developments can be found as global overviews [15, 20] or in publications focusing on specific regions: Africa [21, 22], Asia [23], and Latin America [24]. Since 2011, a few African (i.e., Ghana and Kenya) and Latin American countries (i.e., Colombia and Peru) have introduced EPR as the core principle in their national WEEE legislation. Kenya, for example, published draft WEEE regulations in 2013 for public consultation. In Peru, the "Reglamento de Gestión y Manejo de Residuos Eléctricos y Electrónicos—RAEE" introduced EPR as a new principle in national waste legislation in 2012 [25].

4 Formal Recycling

4.1 Collection

In formal WEEE schemes, municipal collection points and/or retailers' take-back obligations are the backbone of collection. In the European Union (EU), take-back obligations in the previous WEEE directive entailed only municipal collection points. As in some countries take-back quantities are still rather low, the recast of the WEEE directive [5] has defined responsibilities for distributors to take back equivalent equipment they sell on a one-to-one basis (obligation for the customer to buy equipment with an equivalent function) and free of charge. In addition, distributors with EEE sales areas larger than 400 m^2 have to take back WEEE of less than 25 cm external dimension free of charge without the obligation for the customer to buy a piece of equipment with an equivalent function. In 2010, the quantities collected in the EU ranged between 1.1 (Romania) and 15.9 kg/capita (Sweden), with 10 countries still not reaching the required 4.0 kg/capita minimum collection quantity [26]. From 2016 onward, a minimum collection rate of 45 % of EEE placed on the market in the three preceding years has to be achieved by each member state.

4.2 Pre- and End-Processing

Selective treatment of components like printed circuit boards, capacitors, batteries, mercury containing components and others in most cases requires initial manual dismantling steps. In countries with low collection quantities and low labor costs, manual dismantling is a preferred option, since mechanical treatment is not economically viable. In other countries, pretreatment is a combination of manual and mechanical process steps. Mechanical treatment includes crushing and separation of different metal- or plastic-rich fractions or mixtures of the two, which then undergo further segregation steps such as conductivity (eddy-current) or density separation (swim sink). End treatment of metal fractions is a combination of different wet-chemical and metallurgical processes with the aim of obtaining pure fractions that can become secondary commodities. Plastic fractions are separated into those suitable for material recycling and others that have to be finally disposed in incineration plants or landfills.

4.3 Health Hazards and Environmental Impacts

Formal recycling processes have the potential to endanger health and the environment. Direct impacts on health are caused by dust in indoor air generated during dismantling and mechanical treatment processes (e.g., from plastic shredding or treatment of CRT) or nonconformities with occupational health requirements. Indirect impacts on human health may be caused by air pollution related to incineration processes that are not equipped with adequate gas purification systems and dust retention.

Mixed plastics fractions from WEEE still contain regulated Brominated Flame Retardants (BFRs). High average concentrations of BFRs mainly originate from small household appliances for high temperature applications, CRT monitors, and consumer equipment, in particular CRT TVs [10].

Primary production of resources, i.e., mining, concentrating, smelting, and refining, is energy-intensive and hence has a significant carbon dioxide (CO_2) impact. “Mining” of old computers to recover the materials they contain—if done in an environmentally sound manner—needs only a fraction of this energy input [27].

5 Informal Recycling

5.1 The Informal Sector

In developing countries, waste management is mostly performed by a large urban workforce, usually referred to as the "informal sector," making a living by collecting, sorting, recycling, and selling valuable materials recovered from waste [28]. The marginalized poor account for the majority of the informal sector. They often include groups from ethnic or religious minorities or rural migrants. Women and children constitute a significant proportion of the workforce, operating either illegally or in a legal gray zone and with different levels of organization [29].

Even though informality has been the subject of political and scientific discussions for decades [23], there is no clear definition of the informal sector. Yet all definitions point toward similar elements and patterns [30] generally described by the International Labor Organization (ILO) as including all economic units that are not regulated by the state and all economically active persons who do not receive social protection through their work [31].

Collection, manual dismantling, open burning to recover metals, and open dumping of residual fractions are the usual practice in most countries. In smaller and less developed economies, these activities are usually performed by individuals, as volumes are too small to trigger the informal sector to specialize in WEEE recycling on a larger scale. Larger economies, especially countries in transition such as India and China [23, 32, 33], as well as countries subject to intense trade in second-hand equipment and illegal waste shipments, such as Ghana and Nigeria [21], display a substantial organized informal sector. The operations of the informal sector can be grouped into three main stages of the WEEE recycling chain: collection, pre-processing, and end-processing.

5.2 Collection

In contrast to formalized take-back schemes where consumers (indirectly) pay for collection and recycling, in developing countries it is usually the waste collectors who pay consumers for obtaining their obsolete appliances and scrap material [34]. As a result, the informal waste sector is often organized in a network of individuals and small businesses of collectors, traders, and recyclers, each adding value and creating jobs at every point in the recycling chain [35]. Since the valuable components of the products collected usually generate an income higher than the price to be paid to get the product, the informal waste sectors achieves collection rates of up to 95 % of waste generated [21], which is far above what can be achieved by today's formalized take-back schemes [36].

5.3 *Re-use of Computers*

Following a strategy to bridge the digital divide, some developing countries have taken great efforts to provide computers for schools. Initiatives include the provision of low-cost laptop computers as the One Laptop Per Child (OLPC) initiative or the refurbishment of secondhand computers in industrialized or developing countries. A comparative evaluation in Colombia based on Material Flow and Life Cycle Assessment and the application of Multiple Attribute Utility Theory concluded that local refurbishment of secondhand computers is the most favorable solution since it has relevant job creation potential and extends the use of already produced computers, whereas the provision of new computers leads to additional environmental impacts through the manufacturing process [37].

5.4 *Pre- and End-Processing*

As labor costs are low in developing countries and in countries in transition and because of the lack of access to know-how and technology, informal and formal recyclers apply labor-intensive pre-processing technologies such as manual dismantling to separate the heterogeneous materials and components. A comparative study of pre-processing scenarios revealed that material recovery efficiency improves with the intensification of manual dismantling [33, 38]. Hence, manual recycling practices in developing countries do display advantages, such as low investment costs, creation of jobs, and high material recovery efficiency [1].

Subsequent to manual pre-processing, further “refining” techniques, such as de-soldering of Printed Wiring Boards (PWB) and subsequent leaching of gold, silver, and palladium, have been observed especially in the informal sectors in India and China [32]. A pilot project in Bangalore, India, demonstrated that besides being hazardous, informal end-processing or refining practices also have poor recovery efficiency. Improper sorting of printed wiring boards and subsequent wet chemical leaching processes for the recovery of gold, for example, revealed a combined yield of only 25 % [39, 40]. In contrast, today’s state-of-the-art integrated smelters, as used in most formalized recycling systems, achieve gold recovery efficiencies as high as 95 % [41].

5.5 *Health Hazards and Environmental Impacts*

Informal WEEE management often fills the void created by the absence of a legal framework as well as the lack of capacity and resources for a formal waste collection and treatment system.

Fig. 2 Typical recycling processes applied in the informal sector of developing countries (left to right: de-soldering of printed wiring boards, leaching of copper from printed wiring boards, open burning of cables) (Pictures: Empa)

Due to their daily contact with garbage, people working in informal waste management are exposed to various health threats, including injuries, diseases, and both acute and chronic health effects (Fig. 2). Serious health effects and impacts on the environment are likely especially for workers processing waste streams containing hazardous substances, such as WEEE [32, 42]. Emissions stem from (i) hazardous substances which are constituents of the waste, (ii) auxiliary substances used in recycling techniques, and (iii) byproducts formed by the transformation of primary constituents. The activities of WEEE recycling in the informal sector involve sorting as well as separation with the final aim of extracting valuable materials such as copper, gold, silver, and other base and precious metals. The processes applied in the exploitation of metals are of particular concern since they cause a variety of health and environmental hazards. A literature review concerning emissions caused by informal recycling activities has shown high concentrations of lead, Polibrominated diphenyl ethers (PBDE), dioxins, and furans in all environmental pathways (soil, air, water, bottom ash, and river sediments) [32].

Practices for recovering metals such as copper, iron, and aluminum through burning of cables containing PVC insulation have been identified as a major source of dioxin [21]. Dioxin emissions from cable burning, for instance in the greater Accra region alone, are estimated to correspond to about 0.3 % of total dioxin emissions in Europe [43]. In China and India, a review of various studies underlined very high levels of dioxin in air, bottom ash, dust, soil, water, and sediments in informal recycling areas, which sometimes exceeded the reference values generally observed in urban areas by several orders of magnitude [32].

Recent measurements in Accra also indicate increasing levels of BFRs in breast milk, which are associated with the informal recycling of WEEE [44].

BFRs contained in mixed plastics from WEEE are substances of concern due to the existing practices of plastic recycling in developing countries and the potential risk of cross-contaminating secondary plastics in applications where BFRs are not required or banned. A recent sampling campaign in the informal plastic recycling sector in Delhi, India, confirmed that secondary plastic is often contaminated with BFRs. This indicates that mixing of plastics from WEEE with additive-free plastics from other waste types does occur [45].

5.6 Socio-Economic Impacts

Based on the UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products [46], commonly referred to as the S-LCA guidelines, the assessment of socio-economic impacts in WEEE management follows a stakeholder approach based on indicators in the three following stakeholder categories: (1) workers, (2) local communities, and (3) society. Studies in Ghana [47] and Nigeria [48] were based on the framework of indicators shown in Table 6.

Safety- and health-related impacts were observed in both countries, leading to direct effects on the workers and the local communities as outlined in the previous section. As most of the workforce belongs to the informal sector, WEEE recycling does not feature formalized workers' participation mechanisms which results in the lack of worker rights as outlined in Table 6.

In Ghana, child labor was observed for cable-burning activities and for manual dismantling practices such as breaking CRT monitors. Using stones, hammers, heavy metal rods, and chisels to recover copper, steel, and plastic casings from CRT often results in the workers inhaling hazardous cadmium dust and other pollutants [47, 48].

Income levels vary depending on the profit which can be generated by selling the obsolete equipment to recyclers in relation to the price paid for acquiring the equipment. In Ghana, a collector can earn 70–140 USD per month, whereas

Table 6 Allocation of socio-economic indicators to stakeholder categories according to [47, 48]

Workers	Local community	Society
• Safe and healthy working conditions • Freedom of association and right to collective bargaining • Equality of opportunity and treatment and fair interaction • Forced labor • Child labor • Remuneration • Working hours • Employment security • Social security • Professional development • Job satisfaction	• Safe and healthy living conditions • Human rights • Indigenous rights • Community engagement • Socio-economic opportunities	• Unjustifiable risks • Employment creation • Contribution to national economy • Contribution to national budget • Impacts on conflicts

recyclers can earn 175–285 USD a month. In Nigeria, the corresponding figures are 67–100 USD per month for collectors and recyclers. However, these figures are based on calculated incomes based on business profits and do not consider indirect costs and externalities.

In Pakistan, children 6–18 years old search for valuable materials in potentially toxic ash. They work in all stages of the chain, from collecting and dismantling equipment to burning wires and motherboards, separating metals, melting solders, and acid processes [49].

The International Labor Organization (ILO) states that the existing ILO conventions are intended to address the particular situation of WEEE management in the informal sector. A code of practice should cover, among other things, occupational health measures, best practices, formalization of the informal sector, and the formation of cooperatives [29].

6 Trends and Outlook

Rapid innovation cycles and growing volumes of cheap EEE have brought about steep increases in the quantities of WEEE. Technological advances include the switchover to digital-only television in Europe, North America, and other industrialized regions of the world, which will accelerate the disposal of obsolete devices and stimulate trade in used EEE with developing nations. In addition, the material composition of EEE is tending to become more complex and the raw material supply more critical. Technologies to recover them from WEEE streams are needed, but increasingly complex and expensive. In addition, the past and current use of hazardous substances in EEE will shape WEEE management systems for a long time to come.

It is encouraging that legislation for sustainable WEEE management is rapidly being adopted in many countries. However, with the implementation and enforcement of new regulations still ahead, the main challenges are yet to be faced, especially in developing and transition countries. It will be key to ensure a level playing field for all actors in order to make cannibalizing of WEEE solely for valuables impossible and to avoid harmful practices in WEEE recycling. In addition to existing waste policies and legal frameworks, WEEE-related regulations need to be enforced, likewise posing challenges to coordination between different regulatory bodies.

Increased Collection Rates and Improved Recycling Yields. Secondary resources are becoming more and more relevant given the shift of raw materials into products and the increasing demand for new raw materials. As outlined in this chapter, collection rates in industrialized countries are still far below their potential. Besides illegal exports of EEE or WEEE to non-OECD countries, one reason for this is the lack of access to take-back schemes, which results in consumers storing EEE for longer periods of time and/or disposal of EEE through the municipal waste stream or scrap dealers. Higher collection rates need to be achieved in combination with improved recycling rates. In developing countries, most products enter the recycling chain through the informal sector, which is characterized by high collection rates. An international division of labor in WEEE recycling could link geographically distributed treatment options, combining pre-treatment at the local level and end-processing in state-of-the art facilities as outlined in [33].

In the future, the development of WEEE take-back schemes will also need to address technical and operational aspects of recovery of scarce [50] and critical metals [51]. The predominant technology in WEEE recycling is mostly oriented toward the recovery of base and precious metals, whereas scarce metals such as indium, gallium, germanium, and neodymium are lost in today's recycling system.

In addition, a comprehensive international approach is required to ensure sustainable recovery of secondary resources. Among other elements, this might include harmonization of international standards toward fair recovery and trade of secondary resources and applying international financing mechanisms.

International Standards toward "Fair" Secondary Raw Materials. Developing countries are suppliers of primary, but in recent years increasingly also of secondary raw materials. On the demand side, consumers in industrial countries are more and more concerned about production circumstances of imported goods and wish to have transparent product declarations. While quality, social, and environmental labeling is well established for some renewable commodities [e.g., Forest Stewardship Council labeling—(FSC)], it is nearly inexistent for non-renewable commodities (one of the few examples is XertifiX—"natural stone without child labor") and does not exist at all for non-renewable secondary commodities (e.g., precious metals from PWB recycling).

Environmental and social issues linked to informal and formal recycling also cause image problems for producers, usually multinational companies. As described in this chapter, many informal recycling processes involve low material recovery efficiency and risk contaminating commodities with hazardous substances. Hence efficient and sustainable recovery as secondary raw materials is a market opportunity that requires functioning "reverse supply chains" with adequate capabilities for recycling and refining as well as sufficient monitoring of the quality of the recovered material as well as the environmental and social impacts of the related processes. Therefore the harmonization of international standards and the introduction of processes to identify "fair" secondary resources will be instrumental for leveraging these opportunities.

International Financing Mechanisms. Some of the substances potentially released by improper WEEE treatment are classified as persistent organic pollutants (POPs), ozone depleting substances (ODS), or greenhouse gases (GHG) and are regulated under international treaties such as the Stockholm Convention, the Montreal Protocol, and the Kyoto Protocol. Related to these are emission reduction schemes and/or international financing mechanisms, such as UN Environmental Finance Facility programs (e.g. Global Environment Facility—GEF), Cleaner Development Mechanisms (CDM), and voluntary systems (e.g. Verified Carbon Standard—VCS), which may be used for financing parts of processing WEEE properly to capture and destroy POPs and ODS. In addition, recovering secondary resources from WEEE as an alternative to mining primary resources can lower GHG emissions and is subject to the Cleaner Development Mechanism. Such international financing mechanisms might play a crucial role in implementing sustainable e-waste management systems by supporting initial investments as well as by creating market incentives to avoid improper processes and to remove internationally banned chemicals from the secondary resources market.

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The Transition from Desktop Computers to Tablets: A Model for Increasing Resource Efficiency?

Roland Hischier and Patrick A. Wäger

Abstract Sales statistics of computing devices show that users are not replacing units one by one, but rather adding additional devices to their hardware portfolios. This chapter describes the outcomes of a first attempt to quantify the ecological implications of changes in the use of ICT hardware for computing services by using LCA and applying three different perspectives ranging from individual devices to global sales of desktop, laptop, and tablet computers. In particular, it addresses the question of which effect actually predominates: the increase in efficiency induced by the emergence of new technologies or the growing energy consumption due to an increased number of devices combined with a higher utilization rate by individual users. The comparison shows a clear reduction of the environmental impact per hour of active use; and the smaller the device, the smaller the impact due to the active use of the device. However, when the evolution in the use of these kinds of devices is taken into account as well, the picture changes. The calculations show that the higher in-use efficiency of individual devices is fully compensated by the efforts for the production of the increasing number of devices in use, without even considering increased use time. If increased use intensity is assumed as well, a clear increase of the overall impact per day can be observed.

Keywords Life cycle assessment · LCA · Resource efficiency · Desktop computer · Tablet

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1 Introduction

Sales statistics of computing devices show that users are not replacing units one by one (i.e., they are not replacing one desktop computer with one tablet), but are rather adding additional devices to their hardware portfolios. In the United States of America, for instance, ownership of laptop computers increased from 30% in 2005 to 64 % in 2013, while only a slight decrease from 65 to 57 % could be observed for desktop computers [1]. But what are the ecological implications of this growing use of ICT devices in our society? Since the 1970s, a very useful framework for examining this type of question has been established—Life Cycle Assessment (LCA). However, in the early stages of ICT development, data for the ICT sector were very scarce, and such studies were not possible. For example, the first version of the database ecoinvent, published in 2004 and one of the most widely used public LCA background databases worldwide [2], included only a single dataset for the electronics sector (i.e., a general dataset for control electronics in industrial processes). Reasonable coverage of the ICT sector was achieved with version two of the ecoinvent database in 2007 [3], which contained more than 150 specific datasets for the electronics sector. Using these data, it is now possible to measure the ecological implications of, e.g., the growing use of ICT devices in our society.

The objective of this chapter is to give an initial overview of the ecological consequences of changes in the ICT technology used, i.e., the shift from desktop computers to tablet computers. Hence, taking a global view of sustainability, the question is which effect actually predominates: the increase in efficiency induced by the emergence of new technologies or the growing energy consumption due to the increased number of devices combined with a higher utilization rate of the devices by individual users.

2 Methodology

The Life Cycle Assessment (LCA) method was applied to examine the ecological implications of shifts in the hardware used for private computer work. The aim of this LCA study was to evaluate whether ecological savings due to technical developments (a shift from desktop computers to mobile devices such as laptop or tablet computers) are compensated or overcompensated by consumer behavior (e.g., more devices per person and/or longer daily use of such devices), i.e., if the usage patterns of modern ICT equipment result in a rebound effect (more about term rebound e.g. in [4]).

This comparison was made from different perspectives in order to capture the broad diversity in using such devices. The first perspective focused on the devices addressed in this study, using "1 h of active use" as the functional unit for comparison. In a second perspective, a family household with its evolution in terms of its ICT equipment was examined in more detail, looking at the development of the hourly and daily impacts from this usage. Last but not least, in a

Table 1 Key data of examined ICT devices

	Desktop plus CRT	Desktop plus LCD	Laptop I	Laptop II	Tablet
Screen size	17″	17″	12″	14–15.6″	10″
Total weight (kg)	32.3	17.5	3.5	2.8	0.66
Composition					
-Housing (kg)	15.2	8.7	1.71	0.68	0.27
-Screen (kg)	10.9	4.0	0.33	0.56	0.15
-Electronics (kg)	3.42	2.77	0.78	0.47	0.04
-Power supply (kg)	1.47	1.47	0.36[a]	0.36[a]	0.050[a]
-Battery (kg)	0.003	0.003	0.28	0.36	0.14
-Others (kg)	1.34	0.58	0.02	0.45	0.03
Energy consumption					
-Active (W)	150	85	19	17.9	3.16
-Stand-by (W)	45	30	4.0	1.33	0.45
-“Off” (W)	5	3.5	1.5	0.32	0
Lifetime (a)	6	6	4	4	2
Data source(s)	[6]	[6, 7]	[6]	[7]	[5]

[a] Number represents the weight of the external power adapter/charger

Life cycle inventory models of each of these devices were established using the database ecoinvent [8]

third perspective, these data were extrapolated to the total impact (per type of device) in our global society by means of sales statistics, including a projection into the near future (i.e., the year 2016).

The assessment covered a time period ranging from 2004 to 2016 and addressed ICT devices for private computer work that were typically used in the years 2004, 2008, and 2012. For 2004, this is a desktop computer with a 17 inch CRT Screen; for 2008, a desktop computer with a 17 inch LCD screen and a first-generation laptop computer (Laptop I, Table 1); and for 2012, the same desktop computer system together with a newer generation of laptop computer (i.e., Laptop II) as well as a tablet computer. Table 1 summarizes key information for all of these devices—taken from [5–7]. Inventory data of the database ecoinvent—version 3.01 [8]—have been used for modeling these devices. For the use phase, the global average electricity mix (as reported in the market dataset “Electricity, low voltage, RoW (Rest of the World)” of ecoinvent v3.01)—representing average global use of the devices—was applied throughout this study.

On the level of Impact Assessment, one of the most up-to-date methods in this area was applied: the ReCiPe method [9]. ReCiPe is a very convenient way of calculating and presenting the results both on a midpoint and an endpoint level. Its large choice of impact categories allows fulfilling the requirements of the ISO

14,040/44 standards ([10, 11]), which demand a "selection of impact categories that reflects a comprehensive set of environmental issues related to the product system being studied, taking into account goal and scope." In the following section, the results for four ReCiPe midpoint indicators (global warming potential (GWP), freshwater eutrophication potential (FEP), freshwater ecotoxicity potential (FETP), and metal resource depletion (MDP)), three endpoint indicators (one for each of the ReCiPe damage categories Ecosystem Diversity (EQ), Human Health (HH), and Resource Availability (Res)), as well as the overall total (based on the default weighting factor between these three damage categories according to [9])) are reported. No individual indicator for grey energy is shown here, as GWP is directly correlated with the consumption of (fossil) energy resources—and thus leads to similar results as a factor for grey energy (see also the analysis of various ICT devices in the chapter on grey energy [12]).

The whole system was modeled with the LCA software SimaPro 8.0.2 and the integrated database ecoinvent v3.01 [8], and the implementation of the impact assessment method ReCiPe into SimaPro by PRé Consultants (version 1.09) was used.

3 Results and Discussion

3.1 The Single Device Perspective

In a first step, the various devices described in Table 1 were compared to each other, based on the assumption that each device was used for 2 h/day. The results of this comparison are shown in Fig. 1.

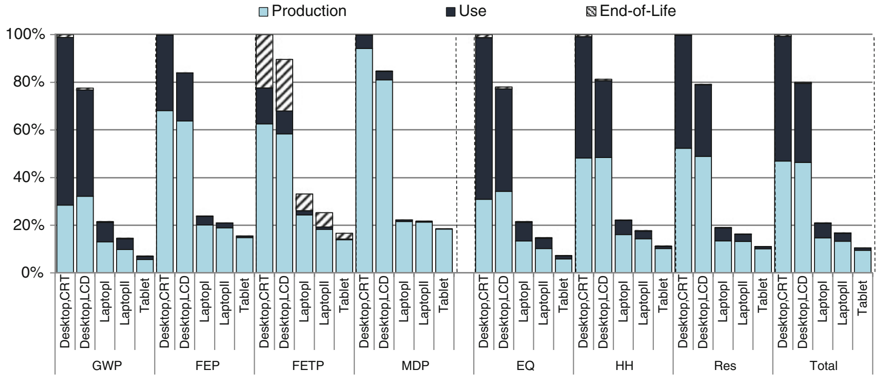

Fig. 1 Environmental impacts of 1 h of use of the computer systems described in Table 1 (relative to the impact of the desktop computer with a CRT Screen, which is set at 100 %). The ReCiPe midpoint impact categories global warming potential (*GWP*), freshwater eutrophication potential (*FEP*), freshwater ecotoxicity potential (*FETP*), and metal resource depletion (*MDP*), and the ReCiPe endpoint damage categories ecosystem diversity (*EQ*), human health (*HH*), and resource availability (*Res*) are shown as well as their weighted total

At first glance, the resulting pattern for the examined environmental impacts of 1 hour of use of these devices are rather similar for all ReCiPe mid- and endpoint impact categories examined here. Based on Fig. 1, it could be concluded that exchanging the screen used with a desktop computer results in a reduction of about 15–20 % of the environmental impact; the first laptop computer is on the order of 20–30 % of the impact compared to the desktop computer with a CRT screen, the second laptop results in an impact on the order of 15–20 %, and the tablet has an impact that is 5–10 times smaller than the one from a desktop equipped with a CRT screen.

A closer look reveals considerable differences, especially on the level of the midpoint indicators. When considering GWP, the use phase is the dominant element for both desktop computers (representing 70 and 60 % of the impact), while mobile devices—due to their much lower energy consumption—are dominated by the impact related to production: only 20 % of the GWP of a tablet computer arises during the use phase, but 80 % during production. The relevance of the use phase decreases more and more for the other midpoint indicators examined and is lowest for MDP, with less than 10 % of the impact resulting from the use phase. The only factor for which end-of-life (EoL) treatment is of relevance is the toxicity factor FETP, with a share of 20 % of the total impact (for all devices). The three damage categories on the level of the endpoint as well as the overall total show a quite uniform picture, which is rather similar to the GWP midpoint indicator.

3.2 The Family Perspective

A second perspective focused on a "model family" with two adults and two children and the evolution of their behavior in terms of ICT equipment consumption. The development of such a family's ICT equipment and the environmental impacts of its active use were modeled for the period from 2004 to 2012 according to the three ICT use scenarios characterized in Table 2.

Figure 2 shows the resulting environmental impacts per hour of use of the family's ICT mix for each of the indicators in 2004, 2008, and 2012, respectively, while Fig. 3 shows the corresponding total daily impacts (taking into account the evolution in the total daily use time of such devices).

With the change from using a desktop computer only (2004) to a combination of a laptop and a desktop computer (2008) and to a tablet, a laptop, and a desktop computer (2012), a clear reduction in the impact per hour of use can be observed. The impact of an hour of ICT use in 2012 is up to 5 times lower than the impact in 2004, and 2 times lower than the impact in 2008 (when considering the GWP and the ReCiPe endpoint indicators). The three midpoint indicators in the figure which are not dominated by the use phase also show a steady reduction of the impact over time; however, the amount of the reduction is less important (with only about 60 % reduction for 2012, compared to the year 2004).

Table 2 Scenarios for ICT use by a family during the period 2004–2012

2004	2008	2012
1 Desktop and CRT × 2 h	1 Desktop and LCD × 1 h	1 Desktop and LCD × 0.5 h
	2 Laptops (Type I) × 2 h	2 Laptops (Type II) × 2 h
		2 Tablets × 2 h
Total use time: 2 h/day	Total use time: 5 h/day	Total use time: 8.5 h/day

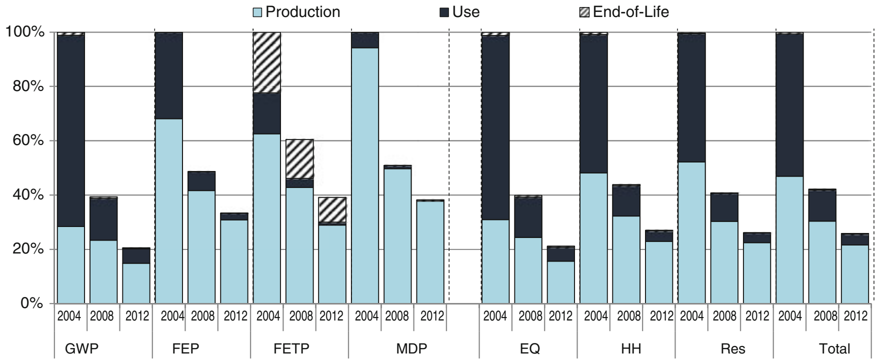

Fig. 2 Environmental impacts of 1 h use of ICT devices (desktop, laptop, and tablet computer, respectively) in a "model family" in 2004, 2008, and 2012 (relative to the impact for 2004, which is set at 100 %). The same ReCiPe mid-/endpoint impact categories are shown as in Fig. 1

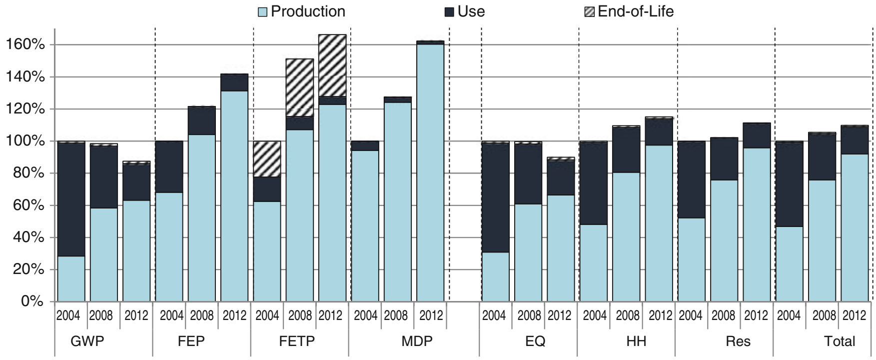

Fig. 3 Environmental impacts of one day of use of ICT devices (desktop, laptop, and tablet computer, respectively) in a "model family" in 2004, 2008, and 2012 (again relative to impact for 2004, which is set at 100 %). The same ReCiPe mid- and endpoint impact categories are shown as in Fig. 1

Because more devices were assumed to be used by a family in 2012 (five compared to only a single computer in 2004), which is expected to lead to a much longer use time (8.5 h/day compared to 2 h/day), Fig. 3 shows the results for all three scenarios based on use per day.

Figure 3 shows a completely different picture than Fig. 2. In the case of the impact categories dominated by the use phase in 2004 (GWP, EQ, HH, Res, and Total), the reduction of environmental impacts for the use phase observed in Fig. 2 is more or less compensated by an increase in environmental impacts from production due to the use of numerous additional (mobile) devices. For GWP, for example, this leads to a reduction of about 15 % for 2012 (compared with the situation in 2004), while the overall total increases by about 10 %. When taking into account the midpoint categories already dominated by the production phase in 2004, a clear increase of the impact per day can be observed—ranging from 40 % (FEP) to more than 60 % (FETP, MDP). When comparing the results for the 2008 and the 2012 scenarios only, a similar development can be found for all examined impact categories: while the GWP shows a reduction, all further midpoint indicators show a net increase.

As the three scenarios for the "family" ICT mix in Table 2 are not based on any kind of statistical information, but are simply assumptions by the authors, we examined the influence of variations of the key figures reported in Table 2 on the overall results in more detail. As a first element, the possible number of mobile devices in use in the model family is varied for the years 2008 and 2012: for 2008, two more scenarios with 1 and 3 laptops are examined, while for the year 2012 all combinations between "1 tablet & 1 laptop" up to "3 tablets & 3 laptops" are included. For each of these devices, a constant daily use time of 2 h is assumed in order to take into account in a simplified way the fact that more devices usually result in a higher amount of daily use. Figure 4 shows the influence of these variations on the hourly impact for 2008 and 2012. The original values from Fig. 2 are indicated by the term "Default" in this figure.

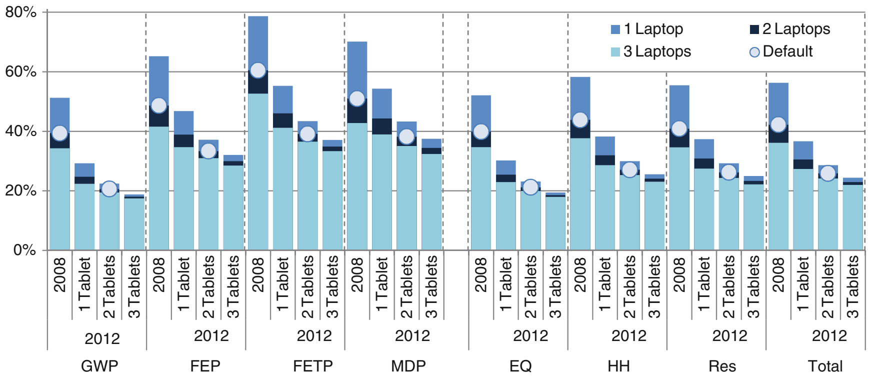

Fig. 4 Influence of the number of mobile devices on the environmental impacts of 1 h of use of ICT devices (desktop, laptop, and tablet computer, respectively) in the "model family" in 2008 and in 2012 (relative to the impact for 2004, which is set at 100 %). The original values from Fig. 2 are indicated by the term "Default." The same ReCiPe mid-/endpoint impact categories are shown as in Fig. 1

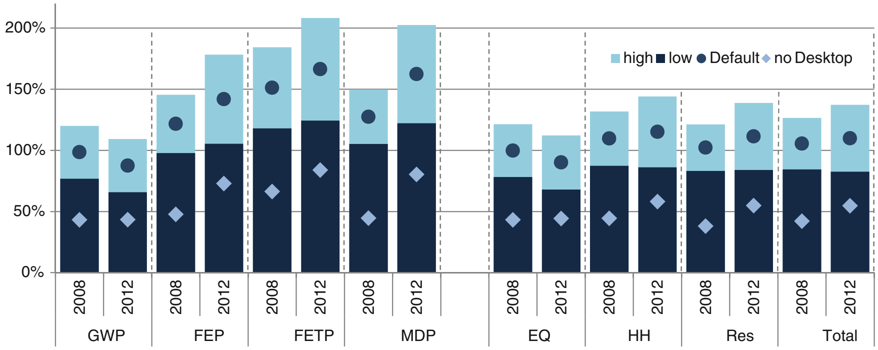

Fig. 5 Influence of the number of mobile devices on the environmental impacts of the use of ICT devices (desktop, laptop, and tablet computer, respectively) in a "model family" per day in 2008 and in 2012 (relative to impact for 2004, which is set at 100 %). The original values from Fig. 3 are indicated by the term "Default." The same ReCiPe mid-/endpoint impact categories are shown as in Fig. 1

As in each of the years examined, the family is also using a desktop computer. The hourly impact of using the family mix in each of the 2 years (i.e., 2008 or 2012) is lower the more mobile devices are in use (and the more time is spent with such mobile ICT devices). Compared to the default values (i.e., 2 laptops in 2008, 2 laptops and 2 tablets in 2012), the hourly impact would be about 30 % (2008)–40 % (2012) higher for all shown impact categories when using a minimum of mobile devices (i.e., only 1 laptop in 2008, and 1 laptop and 1 tablet in 2012), while 3 of these devices would further lower the impact by 12–15 %.

However, as owning more of these devices also means longer active use of ICT devices during the day (e.g., 12.5 h/d in the case of using 3 laptops and 3 tablets for the 2012 scenario), Fig. 5 shows these results on a daily basis as well. For purposes of clarity, this figure contains only the scenario 1 laptop (2008) and 1 laptop and 1 tablet (2012), respectively (designated "low" in the figure), and the scenario 3 laptops (2008) and 3 laptops and 3 tablets (2012), respectively (called "high" in the figure) in addition to the default values shown in Fig. 3 above. Again, the relative changes of the impacts are about the same for all examined impact categories—i.e. ±20 % for the 2008 situation and about ±25 % for the situation in 2012, which in the case of the "low" scenario results in a reduction of the overall impact compared to the situation in 2004.

At the same time, Fig. 5 shows that an even higher reduction would be possible by eliminating the desktop computer and its half hour of daily use. Such a scenario would result (compared to the default scenario, reported in Table 2) in a reduction of the impact by 60 % (in 2008) and 50 % (in 2012).

It is interesting to examine this point (i.e. no desktop computer anymore) and its consequences from the opposite perspective as well—i.e. how long mobile devices could theoretically be used in order to get a similar impact as with the "family" desktop computer in 2004, assuming an equal split (of time) between all mobile

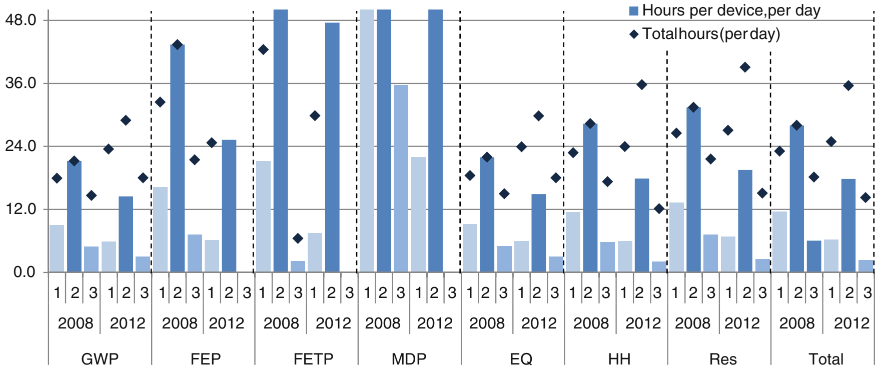

Fig. 6 Theoretical use time for mobile devices (in hours/day) per device and for all devices (laptop and tablet—assuming equal use of this kind of ICT devices) for three different scenarios (1, 2, and 3) in order to get an overall impact equal to the daily impact in 2004. The same ReCiPe mid-/endpoint impact categories are shown as in Fig. 1

devices. Figure 6 shows the results for the three scenarios from above—i.e., the scenarios default (indicated as 1), low (2), and high (3). For the third scenario, three of the factors examined do not show any result, as the impact due to the production and the end-of-life phase of all mobile devices alone is already higher than the total for the system in 2004. In all other cases, the resulting values (in hours of use per day—per device, as well as for all devices) show results quite similar to the preceding figures for all those factors that are dominated in 2004 by the use phase (i.e., GWP and all endpoint indicators). For all these indicators, the daily time amount can be increased quite considerably by the elimination of a desktop system (only used for a short time) for the scenarios 2008 and 2012, with scenario low (i.e., scenario 2 in the figure) showing the highest daily use time (as the impact due to the infrastructure is the lowest in this scenario)—going up to a theoretical value of 30 to 35 h/day for the 2012 scenario. For the remaining midpoint indicators, this time amount is even bigger (up to more than 250 h in 2012 in case of MDP) due to the fact that those indicators are mainly dominated by the infrastructure (i.e., production and/or end-of-life treatment).

3.3 The Sales Perspective

Last but not least, the evolution of the amount of ICT equipment sold globally was examined, using the assumption of a daily default use time of 2 h for each of the devices. Table 4 summarizes the figures for the 4 years (2004, 2008, 2012, and 2016) studied here, using data from different sources.

In analogy to the second perspective, the first figure (i.e., Fig. 7) shows the resulting development of the environmental impact per hour of use of the globally sold hardware mix according to the four scenarios described above.

Table 4 Scenarios for the global sales figures of the computer systems examined here

	2004	2008	2012	2016
Desktop computer	144.6	145.6	145.6	117.9
Laptop computer	48.2	138.1	198.0	194.7
Tablet computer	–	–	134.2	320.5
Total	192.9	283.7	477.8	633.0

Data sources: statistical data from etforecasts, Gartner, IDC and statista [13–16]

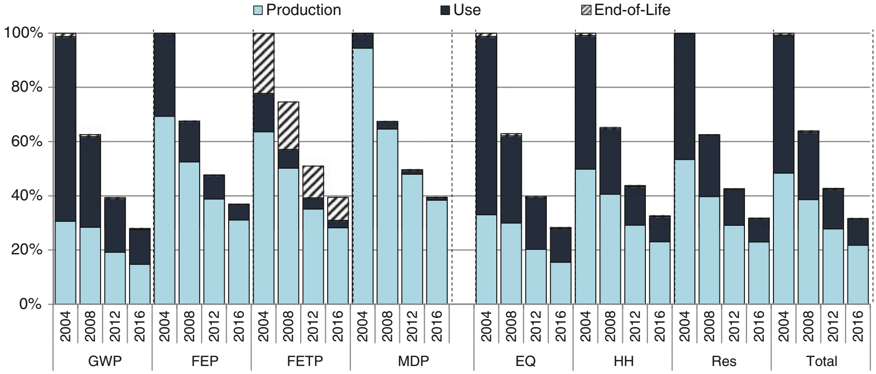

Fig. 7 Environmental impacts of 1 h of use of ICT devices (desktop, laptop, and tablet computer, respectively) for the mix sold in 2004, 2008, and 2012, and the projected mix in 2016 (relative to the impact for 2004, which is set at 100 %). The same ReCiPe mid-/endpoint impact categories are shown as in Fig. 1

As in the second perspective, the mix of ICT devices (i.e., desktop, laptop, and tablet computers) sold shows a constant reduction of its environmental impacts per hour of use from 2004 to 2016. Again, the picture for the various examined impact categories is rather similar at first sight, i.e., all show a reduction from 2004 to 2008 on the order of 30–40 %, a reduction from 2004 to 2012 on the order of 50–60 %, and a reduction from 2004 to 2016 on the order of 70 %.

Examining the daily instead of the hourly impact by using a daily default use time of 2 h for each of the devices throughout the entire time period results in the impacts shown in Fig. 8. The pattern here is rather similar to the daily impact of the family perspective in Fig. 3, i.e., the impact categories dominated by the use phase (GWP, EQ, HH, Res, and Total) show only very small changes throughout the examined time period—changes in the use phase are almost entirely compensated by changes in the production of the various (mobile) devices. When taking into account the remaining midpoint categories dominated by the production phase, the picture leads to a clear increase of the daily impact on the order of 20–25 % for 2012 and 2016.

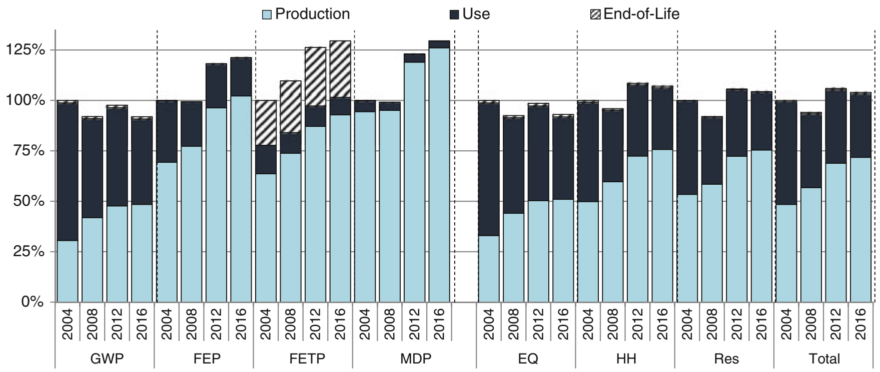

Fig. 8 Environmental impacts per day of use of ICT devices (desktop, laptop, and tablet computer, respectively) for the mix sold in 2004, 2008, 2012, and the projected mix in 2016, assuming a constant daily use time (again relative to the impact for 2004, which is set at 100 %). The same ReCiPe mid-/endpoint impact categories are shown as in Fig. 1

Statistical data also show that the use of these devices is growing over time. An average British citizen, for example, spent about 3.6 h/week on the Internet in 2004, which increased to around 14.1 h/week in 2010 [17]. These data for the UK show that the average time spent on the Internet has doubled more or less every 3 years. As a consequence, we recalculated the daily environmental impact of the use of the ICT device mix sold based on the evolution of the use of mobile devices as summarized in Table 5.

According to Fig. 9, which shows the results of this recalculation, there is no more reduction over time; the use of smaller (and thus less energy-consuming) devices is more than overcompensated by the combination of a growing number of devices and increasing usage time. The development of the use time assumed here results in impacts in 2016 that are about 50 % higher compared to 2004 for the impact categories dominated by the use phase (GWP, EQ, HH, Res, and Total). The impact of the use phase itself is thereby constantly growing from 2008 to 2016, despite the rising amount of (energy-efficient) mobile devices.

Table 5 Assumed development of the daily use times along the four scenarios for 2004, 2008, 2012, and 2016

Hours/day	2004	2008	2012	2016
Desktop computer	0.5	0.5	0.5	0.5
Laptop computer	0.5	1.0	2.0	4.0
Tablet computer	–	–	2.0	4.0

Data sources: authors' estimate based on the reported 3.6 h/week (=0.5 h/day) in [17], assuming that there is an increase of 100 % every 4 years for mobile devices only (while the desktop computer stays constant at half an hour per day)

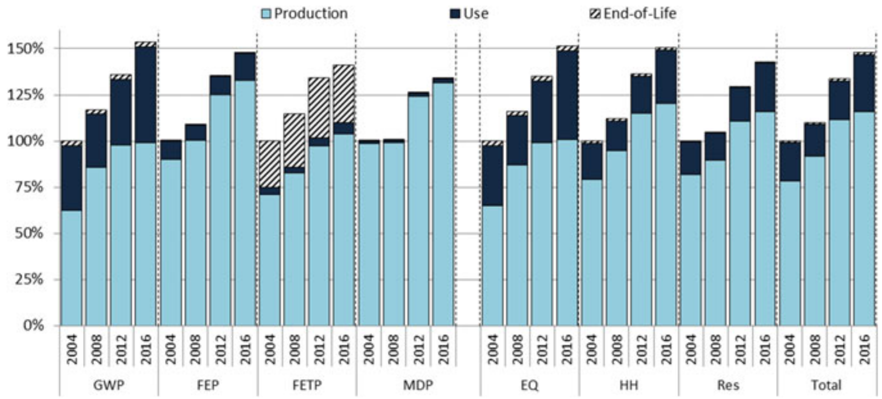

Fig. 9 Daily environmental impact of use of ICT devices (desktop, laptop, and tablet computer) for the mix sold in 2004, 2008, and 2012, and the projected mix in 2016, assuming a growing daily use time as summarized in Table 5 (again relative to the impact for 2004, which is set at 100 %). The same ReCiPe mid- and endpoint impact categories are shown as in Fig. 1

Taking into account the other midpoint categories, which are all dominated by the production phase, the picture is less uniform. While the factor FEP shows a quite similar pattern to the ones listed above, the two remaining factors (FETP and MDP) result in smaller increases through 2016 due to the small influence of the use phase in these two situations. For FETP, the increase through 2016 is still on the order of 40 %, caused however by the production and especially also the EoL treatment of all the devices. MDP, largely dominated by the production phase, rises by only about 30 % in the period examined here.

However, when considering this figure, one must keep in mind that the development of use time is a rather rough estimate based on a single data source (i.e. [17]). Furthermore, it should be noted that all the figures shown here represent only the impacts due to the use of ICT end-user devices; possible impacts from the infrastructure required, e.g., to download a scientific publication from a server at a university is not taken into account. The latter could have a relevant impact, as shown in the chapter on ‘grey energy’ of ICT devices (i.e. [12]).

4 Conclusion

The comparison of different “generations” of ICT hardware for private computing activities shows a clear reduction of the environmental impact *per hour of active use* over time. In particular, it can be observed that the smaller the device, the smaller the contribution of the impact due to the active use of the device (in comparison to the total impact of the device). Consequently, on the use side a very high increase of efficiency can be observed. When the comparison is based on 1 h of active use, these general conclusions are also valid for the development of the mix of ICT hardware in the family perspective as well as for the development of the mix of global sales of these kinds of devices.

However, as soon as the evolution in the use of such devices is taken into account as well, which has been accomplished by shifting the functional unit from "1 h of active use of a single device" to "1 day of use of a mix of ICT devices," the picture changes. In a 4-person-family perspective (that used one computer in 2004 but 5 in 2012), the results show a daily impact that remains more or less constant under the assumed boundary conditions for all those impact indicators dominated by the use phase in 2004 (i.e., GWP, EQ, HH, Res, and Total); the other midpoint categories examined here lead to a clear increase of the daily impact. However, it has to be taken into account that the results and hence the conclusions might be affected considerably by choosing other scenarios.

For example, a change in the daily use intensity of the mobile devices could significantly affect results. In the global sales perspective, when assuming a constant daily use time of 2 h, the results show that the daily impact of the ICT devices sold stays constant during the time period 2008 to 2016 (again for those impact indicators dominated by the use phase in 2004), i.e., the higher efficiency of individual devices is fully compensated by the production efforts for all additional devices in use. If, in addition, increased use intensity for this time period 2008 to 2016 is assumed, a clear increase of the overall impact per day can be observed. This is a typical example of the rebound effect.

Of particular concern in view of reducing or ideally eliminating this rebound effect are desktop computers (with LCD screens) that are still in use, but used only for very short times. As shown in the sensitivity analysis, their contribution to the impact of the use of the ICT mix is relatively high. One conclusion from these investigations is that the number of ICT devices in use should be kept as small as possible. Specifically concerning the future use of mobile devices, two further aspects need to be considered: (i) longer use of these devices and (ii) their more selective use, allowing for reductions in the daily use time overall.

However, it is rather difficult to provide clear limits that should not be exceeded (in the sense of daily use of such devices, but also in the sense of the overall lifetime of a single device). One of the reasons for this is that this study quantified only the impacts of the user's ICT hardware. Neither were the impacts of the Internet and data centers taken into account (a rough estimation of their impact, compared to various types of ICT devices, is to be found, e.g., in [12]), nor was the sector of smartphones included, with growth rates that are even higher than the ones for the mobile devices covered here. Another reason is the fact that modern (especially modern mobile) devices are used increasingly not only to replace traditional personal computers, but also as an alternative to further devices, e.g., radio or television—leading then to even more complex comparisons and scenarios.

All in all, from the sustainability perspective, the results presented in this chapter clearly indicate that the increasing number of devices combined with their higher utilization rate overcompensates the ecological gains from size reduction in ICT hardware components for the moment.

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Addressing the Obsolescence of End-User Devices: Approaches from the Field of Sustainable HCI

Christian Remy and Elaine M. Huang

Abstract The progress of technological development and the resulting rapid replacement of end-user devices has brought increasing issues of electronics waste upon our society. Interaction designers and researchers within the field of human-computer interaction have begun to tackle issues of environmental sustainability in recent years, including the problem of obsolescence. By considering the experiential aspects of obsolescence and the ways in which interaction design could have an impact on experience, the field presents promising approaches with potential to contribute to and complement current materials-focused solutions. In this chapter, we report on a survey of sustainable human-computer interaction research that investigates or addresses issues of obsolescence, presenting challenges as well as opportunities for interaction designers to contribute to solving these issues.

Keywords Human-computer interaction · Sustainable HCI · Sustainable interaction design · Consumer electronics · Obsolescence

1 Introduction

The term obsolescence is used to describe the conditions of objects to become outdated and lose their usefulness—they become obsolete. While the term is often wrongly used as synonym for "planned obsolescence," a concept introduced by marketers in the beginning of the 20th century [1], the traditional meaning of the word does not imply any planned action or bad intent. For the domain of consumer electronics, obsolescence can simply be used to describe the logical conclusion of

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the rapid development of technology. Therefore, we consider obsolescence in its broader definition which includes, both planned obsolescence as well as obsolescence resulting from a more natural loss of functionality. Although the progress of technology is inevitable, as can be observed through the applicability of Moore's Law [2] to decades of development, this does not imply helplessness towards obsolescence: Research in the domain of interactive technology has influenced and will continue to influence the future of technological development, and subsequently have an impact on obsolescence as well.

The field of human-computer interaction (HCI) has become increasingly interested in leveraging the potential of HCI research to make an impact in environmental sustainability [3, 4]. In particular, the proposal of a rethinking of interaction design towards a new paradigm of *sustainable interaction design* (SID) [5] marked the starting point for a plethora of research in the following years. Blevis proposes that "*sustainability can and should be a central focus of interaction design*" [5], and argued that—among other efforts—obsolescence can be addressed if "*things are designed and constructed with sufficient quality and modularity*". In subsequent years, sustainable HCI (SHCI) evolved from an emerging topic to an established, well-published sub-community within the field of HCI, appealing to a variety of environmental sustainability issues, among them the issue of technology obsolescence.

Various researchers working in sustainable HCI have argued to counter obsolescence by tackling the issue by its core definition—making products less prone to obsolescence. For example, this can be achieved by making sure the product itself comprises durable materials [5], lasting for at least ten years minimum [6]. Similarly, another approach that considers the hardware of devices is to enable upgradability [5–9]; a common example is that of modular phones as explored several years ago (e.g., WILLCOM WP004[1]) and again more recently (e.g., Project ARA[2]). This notion of upgradability does not only apply to hardware, but has also been proposed for software [5]. By allowing software upgrades or the installation of new applications, otherwise obsolete devices can even be repurposed for other uses, e.g., by turning PDAs into ebook readers or GPS trackers [10].

All these approaches target the device's hardware or software directly, and as such can be considered as conceptually straightforward, but difficult-to-realize solutions to obsolescence. HCI research, however, considers not only the design of technology itself, but also the implications of the design on the user experience. In the following, we will present an overview of SHCI literature that investigates or addresses issues of obsolescence by focusing on the implications for user experience and how influencing the user experience might change the pathway to obsolescence. We provide a brief overview of important SHCI research streams and elaborate on our literature selection process. The main part of this work

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[1] http://www.engadget.com/2007/04/13/willcom-shows-off-customizable-wp004-handset/.

[2] http://motorolaara.com/.

presents a variety of design considerations that have emerged from work in this field, highlighting the diversity and potential of interaction design to contribute to sustainability and reduce or slow technology obsolescence. By categorizing the obsolescence-related work in the field of SHCI we hope to enable researchers and practitioners from other fields to make use of insights from SHCI research and build upon this work to discover new research avenues that tackle the problem of obsolescence.

2 Sustainable HCI: Background

The field of SHCI is a rather young field, but has seen a tremendous amount of activity in recent years. The SIGCHI conference[3] 2007 is widely regarded as the event that established SHCI as a major area with two highly influential landmark works [4, 5]. In the years since, SHCI has grown into a large research field with several different directions, uncovering a variety of potential pathways via which HCI can contribute to issues of sustainability. In a survey analyzing the existing work in the field, DiSalvo et al. [3] highlighted the potential of HCI research in this area. There are two major streams to distinguish or classify work in SHCI: *sustainability through design* and *sustainability in design* [4].

Sustainability through design denotes the study and development of technology that can be leveraged to pursue sustainable goals. Various approaches have been presented that attempt to influence the decision-making process, induce behavior change, persuade people to engage in sustainable actions, or simply raise awareness through feedback technology, often referred to as *eco-feedback* (for surveys of the research in this field, see [11–13]).

Sustainability in design strives to reduce the material effect of hardware or software itself, making a direct impact for sustainability in the design itself, regardless of its application and use. It is strongly connected with the primary intention of Blevis's seminal paper that fueled the field in 2007, introducing the term *sustainable interaction design* [5]. He argues that it is not sufficient to just apply sustainability to existing solutions or add sustainability principles somewhere in the process of interaction design, but that sustainability has to become the central focus of interaction design to be successful in making an impact for sustainability. The paper concludes with the hope that sustainable interaction design can in fact overcome issues of obsolescence: "If things are designed and constructed with sufficient quality and modularity, people may be inclined to look after them and selectively update them, creating the effect of achieving longevity of use."

Although sustainability in design deals directly with problems of obsolescence, sustainability through design also provides important insights by looking

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[3] http://www.sigchi.org/conferences.

at the issues and proposing solutions from a different perspective. The definition of interaction design supports the diversity of potential opportunities of HCI research: “designing interactive products to support the way people communicate and interact in their everyday and working lives” [14]. Since products can refer to both hardware and software, sustainable interaction design does not only apply to the design of physical objects, but also digital artifacts that support people’s interaction and communication in everyday life to become more sustainable.

In this chapter, we analyze the current state of SHCI research that has dealt with and appealed to the problem of obsolescence for technology. Our approach was to consider all publications related to both HCI and sustainability that address obsolescence directly or indirectly. In the literature review process, our focus was to gather insights through two primary approaches: first, identifying common themes in the solutions proposed for interaction design; second, highlighting challenges mentioned in SHCI research emerging from previous work. In the following sections, we present the results of our analysis of the field, categorized by three themes that emerged as high-level categories in our analysis: values in design, re-use, and longevity. These three categories represent three equally important dimensions along which obsolescence-related SHCI research can be oriented. For each of these themes, we highlight a number of design considerations that have emerged from SHCI research and discuss them in light of their significance to issues of obsolescence and potential challenges in application.

3 Design Considerations in Sustainable HCI Research Addressing Obsolescence

3.1 Values in Design

Many approaches to address obsolescence can be attributed to conveying value in design. The common idea is that an object whose design expresses or comprises a certain quality (e.g., in terms of aesthetics, interaction, or usefulness) is less likely to be replaced, thus creating an innate resistance to obsolescence. In his definition of sustainable interaction design, Blevis incorporates values as one important aspect in design [5], highlighting different aspects of design values as presented in previous literature and design practice. For example, design can be about “features and functions of objects”, “affective aspects of objects”, “interactions between people and environments”, or “choices that lead to sustainable futures”. Similarly, SHCI research presents different concepts of values in design.

Pleasure Engineering. Even before sustainability became a major subject within the domain of HCI, Woolley [8] related the rapid replacement of products with a shift from pleasure (upon purchase) to dissatisfaction (long-term use). He therefore calls out for *pleasure engineering*, creating designs that enable long-term pleasure, and ultimately defer or even avoid the dissatisfaction over time. Four strategies are proposed to achieve such a long-term satisfaction: future-proof design in functionality and appearance; price reduction incentives; no incremental changes but fewer and larger steps in technological advancement (cf. Moore's Law—contracting steps); and as a last resort, governmental regulations. Some of these strategies, e.g., regulations or a product's price, cannot be addressed by HCI approaches directly. The design of services and technology that support everyday work practices of various stakeholders outside of HCI offers opportunities for interaction designers to indirectly achieve an impact on practices that lead to more sustainable actions.

Achieving Heirloom Status. The research of Hanks et al. [15] considers the attitudes of young adults towards sustainability, specifically regarding ownership of objects. Through a survey of college students, they discovered that students did not believe that they would pass electronic devices down to their children. They argue that interaction design should strive to *achieve heirloom status*, turning electronics into objects that are worthwhile not only to keep, but even to inherit. While heirloom status is a design value mentioned by many researchers in SHCI [5, 16, 17], it is difficult to design for and difficult to study as it only develops over time. Studies of objects that people hold on to for a long time can provide hints as to how design technology to achieve a similar impact [18, 19]. In the specific case of electronics, heirloom status might not only apply to physical material, but also the digital dimension of products (see *value of the content, not the device* as reason to keep objects [20]). This interplay of physical and digital properties might create new opportunities for HCI to support the process of establishing heirloom status, if not only the physical product itself becomes a heirloom, but the software, applications, or content on it is perceived so valuable that people want to pass it on.

Ensoulment. By studying people's attachment to objects they would not discard, Odom et al. [18] identified *histories* as one reason for holding on to products—the object helps the owner to preserve a memory. In a study focused around electronic waste, Zhang and Wakkary [21] made a similar observation by highlighting *emotional connections* as one reason why owners do not dispose of their electronics. Those are two examples of *ensoulment* in practice; a term introduced to HCI by Nelson and Stolterman [22] and later on applied to SHCI [23]. It refers to the notion that a product, due to its design, is perceived by the owner as having a soul, establishing an emotional bond that prevents disposal and encourages longer ownership. Related terms are *emotional design* [24] and *attachment* [18–20]. Furthermore, Odom and Pierce [18] suggest to foster such a connection through *narratives* and *character*, and provide the example of an MP3 player resembling a musical passport which, each time the owner enters a new country, allows to virtually “stamp” it, creating a memory and accumulating a travel history over time.

Slow Design. Based on the *slow movement* which proposes a cultural shift towards a new lifestyle with slower pace and increased awareness of one's environment, *slow design* is an approach that targets a people's everyday life beyond just the interaction with one product. Slow design aims to slow the metabolism, resource consumption, and flows of people's life, engendering a positive behavior change. It can be seen as not only addressing obsolescence through the design of products itself, but calling for a change in people's lifestyle in general. Hallnäs and Redström [25] argue that products conveying slow design cause their owners to be more reflective of their interactions and practices, and Strauss and Fuad-Luke [26] pointed out that slow design principles have a positive impact on the design process itself as they open up new perspectives about the potential of designs and their message. A recent slow design case study supported these insights with similar responses from both designers and evaluators [27]. The core idea is that products conveying slow design contribute to a lifestyle resembling more reflection and awareness, ultimately increasing individual wellbeing, both on an individual as well as on a societal and cultural level.

New Luxury. Blevis et al. [9] discuss *new luxury* as an additional opportunity for sustainable interaction design to promote a shift to a more sustainable design of consumer electronics. The concept of new luxury as a contrast to more expensive and exclusive definition of traditional luxury is defined as "*products and services that possess higher levels of quality, taste, and aspiration than other goods in the category but are not so expensive as to be out of reach*" [28]. Blevis argues that this level of quality introduced by new luxury can contribute to SHCI efforts, for example, by promoting "services over new physical materials", "upgrades of existing products", or "concern for secondary markets". Several authors have noted that luxury and material success are obstacles in tackling obsolescence [9, 15, 29] since some consumers—commonly referred to as early adopters—always like to have the most novel technology [15]. New luxury might be leveraged to turn this traditional notion of material success and luxury against itself to promote more a more sustainable behavior, for example, by shifting the societal paradigms such that owning a device for a longer amount of time becomes more desirable than buying a new one.

3.2 Re-use

Another approach to extending the lifetime of electronics—partially or for the whole device—is to design for reuse. These concepts all have in common that some aspect of the relationship between the owner and its device changes, such as changing the owner of the device (transferring), changing the device itself (repairing or recycling), or changing the way people interact with it (repurposing). While the conceptual design of the device itself can encourage and support reuse, observations and studies show that it is often difficult to anticipate what will lead to successful practices. However, interaction designers can also offer support for reusing existing devices, such as by creating tools to share ideas and examples or encourage and support practices of reuse.

Transferability. The lifetime and usage of consumer electronics can be extended if the design of such devices supports and encourages *transferal of ownership*. Hanks et al. [15] propose a rethinking of design such that electronics keep their value of functionality, similar to automobiles. Blevis's rubric [5] also names transferability as an important aspect of sustainable interaction design, calling for "*reuse as is*". In a study comparing mobile phone transferability in three different countries, Huang et al. [30] discovered that there are different attitudes towards transferal of ownership. While in Japan privacy concerns were an issue, leading people to manually destroy and discard their phones rather than selling them, several Northern American participants were unable to transfer their phone due to them being locked to one service or contract. This highlights that depending on context there are different barriers to transferability and different ways of addressing the issue; for example, while the issue of privacy is a matter of decoupling digital contents from a device and making this trustworthy and transparent to people, contract or service issues are an external issue that can only be addressed indirectly by interaction designers. In the same study [30], German participants mentioned that it was economically advantageous and thus often preferred to pass on phones to acquaintances or sell them upon acquisition of a new phone, showcasing an example of encouraging transferal of ownership. Interaction designers can leverage this knowledge by designing services to support these ownership transfers, creating a desire for more opportunities for transferability and thus indirectly making an impact on existing policies and roadblocks to transferability such as contract or service locks. Additionally, designers to support transferability explicitly through the design of devices themselves and their software.

Repair. One of the innate characteristics of obsolescence is that devices break and stop functioning—be it through purposeful design or through unintended malfunctioning. Maestri and Wakkary [31] studied how laypeople repair broken objects, including but not limited to electronics. They argue that interaction design should support the manufacturing of products that allow for them to be repaired without specialized knowledge; a concept they call *everyday design*; the implication is that everyone is a designer or, in the context of their study, a repairer. In an extension to the first study Wakkary et al. [32] provide additional examples and conclude that the material of a product should allow for repair by laypeople based on people's expected competence in repair, and the product's design should allow for repair without the requirement of special tools.

Re-use of Materials. Through an online survey about electronic waste re-use examples, Kim and Paulos [33] developed an extensive design reuse vocabulary for material properties, shape properties, and operation properties of electronic waste. Their framework provides designers with actionable guidelines for the design of electronics that allow for re-use through partial or complete disassembly. But it is not only the materials themselves that are important to consider for re-use of technology; in a study of electronic waste recycling practices, Zhang and Wakkary [21] identify that the disposal of electronics and the information about available electronic waste for re-use needs to be organized. They suggest local recycling information networks to support electronic waste re-use practices. In a framework for sustainability assessment by Dillahunt et al. [6], several criteria call out for a better re-use support as well, such as *modular devices that can be taken apart easily*, materials that can be *replaced*, *reused*, or *recycled*. The latter two criteria also appear in Blevis's rubric [5] as *recycling* and *remanufacturing for reuse*.

Augmentation. A rather difficult design proposal but one that, as studies show, can be very successful to extend the lifetime of a product, is to allow for an object to be augmented beyond its intended use. Odom et al. [18] call this augmentation; further examples for augmentation can be found in the follow-up study by Gegenbauer and Huang [19], e.g., "an alarm clock to which the owners had attached a light" or an embroidered chair. An impressive and exceptional example in the domain of consumer electronics is that of a combination of 30-year-old computer technology currently being used by children in Indian communities [34]; this use is only possible due to the design of the original technology itself that did not prevent or constrain such repurposing of the device. Huh et al. [10] present a similar observation for more recent devices, when PDAs acquired through eBay were used as ebook readers or a cheap alternative to GPS devices. Note that both these examples resemble aspects of transferability as well since they include change of ownership; but the key aspect that enables an extended lifetime is the repurposing and augmentation of devices beyond their intended use.

3.3 Longevity

One theme in SHCI to address obsolescence is that of achieving real durability and longevity. This differs from reusability as it aims for longer ownership without changes in the relationship, tackling obsolescence at its core. Therefore its largest barrier is planned obsolescence, which is the exact opposite of durability; instead of designing a device to break, durability argues that a device should be designed to last longer. Interaction designers can contribute to solutions for issues of obsolescence by laying the foundation of longevity through functionality and motivating longevity of use among consumers.

Longevity of Functionality. Gegenbauer and Huang propose a design principle called *sufficiency*, defined as the "extent to which an object continues to be used or kept because it is capable of serving its intended purpose" [19]. Odom et al. [18]

present a similar notion by defining the design criteria of *perceived durability*, encouraging the design of long-lasting objects due to their functionality, simply inherent longevity, or both. Designing for longevity is particularly challenging as it require thinking about not only whether design is usable and useful now, but also predicting whether it will be in the future. However, the important premise of this approach is to make sure that the core functionality of the object will work in the long-term, as this is a requirement to achieve longevity in the first place.

Intrinsic Motivation for Longevity. Another aspect of longevity is that of raising awareness of the benefits of holding on to one object rather than engaging in a rapid replacement process. The concept of slow design as highlighted by an exemplary design concept study [27] creates an intrinsic motivation for people to continue using a device, as it causes people to reflect on their interaction with technology [26] and ultimately can contribute to a change in lifestyle with regard to their attitude towards technology. Similarly, Hanks et al. [15] argue that some people prefer longevity of use for devices, fully aware of and making reference to the environmental concerns connected with rapid replacement. The combination of awareness of longevity and incentives (often intangible, almost metaphysical) can lead to a strong appeal of longevity.

4 Conclusion

The obsolescence of end-user devices is an issue that concerns many research fields and needs to be tackled on many different levels. The domain of HCI research, due to its focus on user-centered design, can contribute to solutions by addressing obsolescence by considering the user experience, the interaction between the device and its owner, and the influence of these factors on ownership, use, and disposal. We highlighted a variety of design considerations that open up opportunities to engage in new efforts to overcome the rapid replacement of consumer electronics. The categorization of obsolescence-related SHCI research allows us to identify potential solutions to the problem of obsolescence that have been repeatedly found to hold promise. Furthermore, it serves as a design space that highlights under-explored areas that offer new opportunities for research.

Although some of the approaches described in this chapter offer illustrative examples of their application to product design, many of them have yet to be applied in real-world practice. Therefore, future research needs to investigate how these concepts can be applied to the design of end-user devices in practice. We believe that in order to be successful, a concerted effort is necessary that makes use of design knowledge accumulated in SHCI in cooperation with researchers from other domains and stakeholders in practice.

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Part IV
Saving Energy and Materials Through ICT-Enabled Solutions

Software Support for Sustainable Supply Chain Configuration and Management

Andrea Emilio Rizzoli, Roberto Montemanni, Andrea Bettoni and Luca Canetta

Abstract A methodology for the inclusion of sustainability assessment in the design of supply chains is introduced, with the aim of taking into account a sustainability perspective in logistics and industrial allocation choices. The presented approach is based on the initial collection and organization of data related to all stages of the product life cycle and of the possible alternative choices to be made for each production and transport stage. An optimization algorithm is then used to prune the space of alternative solutions and an advanced and flexible graphical user interface allows the exploration of the solution space.

Keywords ICT for sustainability · Sustainability assessment of supply chains

1 Introduction

In the recent past, efforts towards the optimization of the supply chain have aimed at the minimization of costs and time: production had to be fast and cheap. Challenged to effectively balance stacks of strictly interrelated costs (inventory, transport, etc.), many companies decided to leverage on manufacturing costs by offshoring production activities to countries with lower labor costs. A side effect of

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such optimization was the intensive use of transportation to cover larger distances in a shorter time. An undesirable second-order side effect was the exploitation of the workforce, as lower income countries were ready to accept worse conditions for their workers [1] and higher impacts on the natural environment. These countries were not ready for an intensive industrialization from a legislative and an environmental regulatory point of view, even though some studies point to the role of self-regulation in countries such as China [2]. One result was increased CO_2 emissions due to longer transport to cover the larger distances.

Such negative side effects have caused an increased awareness among both customers and companies of sustainability and social responsibility issues in production processes [3], making the planning of production and the design of the supply chain an even more complex process, as new objectives and constraints have had to be taken into account. ICT has always been pervasive in supply chain management, as it has been regarded as an instrument to avoid undesirable oscillations and shocks in the supply chain [4]. Today, ICT can also support the design of complex supply chain processes, addressing the issue of the inclusion of a sustainability perspective. For instance, ICT can support the inclusion of life cycle assessment (LCA) in the performance evaluation of supply chains to deliver a comprehensive analysis encompassing all the activities included in its cradle-to-grave path [5]. Traditional supply chains usually cover the cradle-to-gate part of such a cycle, also called the product beginning of life, i.e. from the gathering of the primary resources to customer purchase. Taking a cradle-to-grave approach implies extending the analysis of the supply chain configuration and analysis to the activities linked to the usage phase (product middle of life), such as repair and maintenance, and to end of life, which comprises reverse logistics and re-use/recycle processes.

In this chapter it is shown how sustainability assessment can be incorporated into supply chain design and management in order to address three main issues: first, including sustainability concerns in the design phase, rather than performing ex-post analyses which cannot change choices that have already been made; second, providing a structured approach to data collection, as the availability of data is the major shortcoming in making informed decisions; and eventually, finally supporting the choice of the better performing solution by providing a tool for the automatic calculation of the more sustainable supply chain among the possible available alternatives.

The inclusion of sustainability concerns in the design phase allows one to provide a real-time evaluation and consequent sustainability-driven product development. This leads to instantaneous sustainability-driven modifications of the design instead of following the classic design loop in which the LCA report is produced at the end of the design phase when it is no longer convenient to implement radical changes.

Secondly, sustainability-related data gathering is a critical issue, as it extends through every process running inside and outside the company, from raw material extraction down to the end of life of the product. This requires companies to widen their perspective in order to encompass not only the activities they directly manage but also to consider and measure the performance of the whole supply chain. To this end, a shared perspective needs to be established, and proper tools for reliable data gathering are also required.

In order to tackle the above described criticalities, this chapter presents a solution capable of supporting real-time sustainability assessment in the design phase of a whole product, production system and supply chain solution space. Achieving the stated objective implies the implementation of the following aspects:

- LCA must be integrated into supply chain design in order to provide feedback on sustainability performance of the supply chain during the design phase, and not only when the supply chain is in place (ex-ante vs. ex-post assessment);
- Data gathering must be assessment-oriented from the very beginning in order to avoid huge efforts at a later stage; this requires a holistic data structure capable of describing a widespread data set and adaptable to highly diverse scenarios;
- Exploration of the solution space, which can be a complex task because of the complex relationships between the involved companies at the various stages of the supply chain and the multidimensional impact of their processes on the various indicators pertaining to the three dimensions of sustainability (economic, social and environmental).

In the remainder of this chapter, we present the data model used to collect, organize and distribute the data related to each step in the supply chain [6]. We then present an approach to the design and configuration of efficient solutions for the supply chain [7]. Finally, we present a case study applying our methodology to the design of low-impact supply chains for the textile sector and demonstrating our techniques of facilitating the exploration of the solution space [8, 9].

2 The Data Model for Cradle-to-Grave Sustainability Assessment

Integrated environments for the assessment of sustainability impact are often composed of many software tools. A shared data model is the first step to effectively support the collaboration of the design tools required to evaluate the sustainability impact of a supply chain [10]. Here the involved design tools can store and retrieve the relevant information on the whole solution space. This sustainability model is conceived of as an extension to the established computational approaches to the LCA problem [11]. The data gathering process is indeed a critical and tricky step as it relies on many different sources, which are seldom harmonized and coherent. A common description language is then called for. To this end, the shared data model covers the three main aspects of a product in a lifecycle perspective: First, the product nature, both in its hierarchical structure and its physical properties; then the production process, which encompasses the whole life of a product from its raw material extraction to its end-of-life treatment; and finally the supply chain, which describes all the involved actors and the actual transport of resources that play a role in the product life.

This coherent and comprehensive description of product-process-supply chain is then used to perform a detailed assessment of its sustainability level. Indeed, the data model becomes the common platform on which all data-providing agents exchange information with the underlining system, thus allowing interaction between them and ensuring consistency of correlated data.

Inside the data model, five macro areas can be identified. The first area is core data entities that provide support to the other areas, providing elementary building blocks and descriptive bridges. Next, three specific areas encompass the corresponding three aspects of the production context, namely product, process and supply chain. The product area represents both the resources that comprise the product's physical structure and how customization choices, carried out by the customer, can change the physical structure of the product itself. The process area represents the operations that are connected by flows of materials as their input and

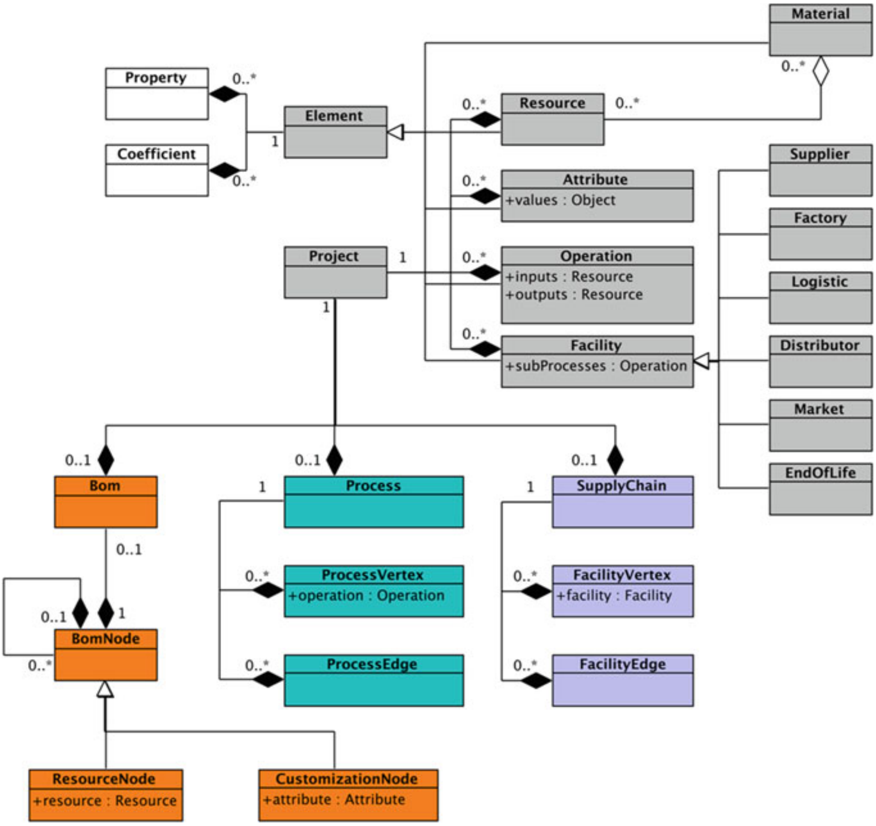


Fig. 1 UML class diagram of the shared data model

transformed output. These operations are themselves specified to reflect modification of the process caused by the application of the customer's customization choices. The supply chain area represents the facilities involved in the solution space. Between these facilities, transport of physical resources takes place that can be achieved following different paths and using a variety of transport means, generating variable sustainability impacts. A last area is dedicated to enabling a large flexibility of properties that are required for an assessment and linked to the various data entities describing the solution space of the product. This flexibility is achieved through a generic definition of assessment properties, representing the physical characteristics of the data entities used by the supply chain designer, described in Sect. 3, for its calculations.

The shared data model areas described above are depicted in Fig. 1, where a high-level class diagram comprising the most relevant classes is shown. For a detailed description, see [6, 12].

It is to be noted that although not strictly related to the data model structure, some limitations apply to this model: (i) single-functional processes only are considered; (ii) loop generation on the graph structure during computation is not allowed.

3 Efficient Design of Supply Chain Alternatives

The environmental footprint of a product can be computed by means of a life cycle impact assessment [13]. Such an analysis can be performed once all supply chain processes have been selected, the production sites have been identified, and the transportation options are set. The drawback of such an *ex-post* analysis is usually the limited capacities for providing any guidance in selecting the best supply. Here, a *supply chain designer* (originally described in [8]) is proposed as the core component for supply chain optimization: for each stage in the supply chain, it evaluates the potential alternatives (e.g. alternative production sites and processes, alternative transportation modes), and it then computes alternative supply chains to production managers according to the importance he or she ascribes to different factors such as economic, temporal, social or environmental aspects.

More specifically, the manager is asked to set the weights of the different factors (e.g. economic costs, impacts) involved in the optimization process leading to the most promising supply chain. In such a way he or she can find the best supply chain design according to the policies of the company. Such a process has to be iterative: the manager can fine tune in subsequent iterations the weights of the different factors based on the results and the expectations, thus obtaining different results until the set goals are met. The input of the optimization comes both from the contracts the company has with the different suppliers/carriers (mainly in terms of production/delivery costs and times) and from more general sources of information such as the environmental databases, in which general environmental impact information is provided for the different steps and processes of the supply chain. This general information is usually refined with first-hand knowledge about the suppliers of the company.

3.1 Mathematical Model

The production process of a product is typically represented in conventional LCA by decomposing it into a sequence of processes, which transform materials in order to obtain the desired output. Given such a sequence of processes, the optimization problem at the basis of the *supply chain designer* can be represented in mathematical terms on a directed graph $G = (V, A)$ where V is a set of nodes representing the stages of the supply chain process, node s is the starting node and node t is the final state (finished product at the destination warehouse). The arc set A contains all possible production/transport steps encountered in the supply chain, and walking arc $a = (i, j) \in A$ (with $i, j \in$ V) means that the product moves from state i to state j through process a. Notice that not all arcs are present (depending on the compatibility of successive production stages) and that the resulting graph is a layered graph, where at each layer there are alternative production histories of the product. A simplified graph is depicted in Fig. 2 (taken from [8]).

A set of labels is associated with each process/arc $a \in A$. They represent the indicators later used by the optimization in a weighted fashion. In detail, for each arc, the following labels/indicators are present: $cost(a)$, $susti$ [1] (a), $susti$ [2] (a), …, $susti[n](a)$ where the last n labels represent the different sustainability impacts considered during the calculation, such as global warming potential, water resource use, damage to ecosystem health, and so on. Labels are real numbers between 0 and 1 representing the indicator normalized between the lowest and the highest possible values for each category. This normalization makes it possible to compare (and weight) quantities that otherwise would have very different definition domains

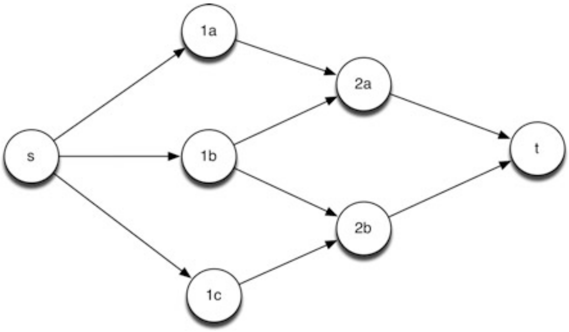


Fig. 2 An example of the graph associated with a supply chain. For each layer (production/transport process) different alternatives are present, with given interlayer compatibility

(ranging between 10^{-4} and 10^{4}). Note that in case the arc $a = (i, j)$ is associated with a production process, the indicators will only depend on the tail node j, and all arcs entering node j will contain the same indicators. Finally, observe that all arcs entering node t have all labels at 0 by construction.

A set of weights w_{cost}, $w_{susti[1]}$, $w_{susti[2]}$, …, $w_{susti[n]}$ has to be specified by the supply chain manager using the application. These weights are positive real numbers summing to 1 and are used to specify the importance of each one of the factors during the optimization.

The problem of finding the best supply chain, according to the weight selected by the user, reduces therefore to the well known *Shortest Path Problem* [14]. Given the weights, the path P from s to t minimizing the following quantity is the best path:

$$\sum_{a \in P} \left(w_{cost} cost(a) + \sum_{k=1}^{n} w_{susti[k]} susti[k](a) \right)$$

Because of the context in which the method is used, however, we prefer to present the user with the best k shortest paths, with k usually on the order of 10–15. In such a way the user is able to visually evaluate the solutions and possibly modify the weights of the various factors thus, aiming to best match the policies of the company, which often cannot be schematized into simple weights. A user interface will embed the optimization procedures previously described (see Sect. 4).

3.2 Optimization Algorithm

The algorithm used to retrieve the k shortest paths according to the given weighted combination of factors is the well known state-of-the-art approach presented in [15]. A detailed description of the algorithm is available in [7], to which we refer readers interested in the technicalities behind the intuitive idea. Note that in the case of supply chains, the required paths are provided with an extremely short computation time, thanks to the limited number of paths requested and to the limited dimension of the graphs associated with average supply chains.

4 Case Study: The EcoLogTex Project

The EcoLogTex project has implemented in a real world case the theoretical and methodological solutions proposed in the previous sections. In this project, a web-based software application for the *environmental design* of the cradle-to-gate supply chain of textile and apparel companies has been realized.

The main components of the EcoLogTeX software application are the following:

- *Benchmarker*: This is a web-based software application in which suppliers (of goods, processes, or services) enter the relevant data for their products and services, attracted by the gains in competitiveness as suppliers to the textile company, and thus providing the data for a holistic supply chain evaluation. The supplier has two advantages in using the tool: first, it can qualify as a potential supplier for the textile company; second, it obtains a quick check of its *sustainability performance* compared to its competitors, leading to an even higher quality of their offer. The data elicited by the benchmarker is then organized in a database structured according to the principles of the data model outlined in Sect. 2.
- *Supply chain designer*: This is a stand-alone software application for the design of sustainable supply chains. The tool can explore the potentially very complex current and alternative supply chain situations and identify the space for design alternatives, based on the background data from the *EcoInvent* database [16] as well as specific supplier data from the EcoLogTex *benchmarker*. This allows for continuous improvements towards a sustainable supply chain. A description of this component has been provided in Sect. 3.
- *Reporter*: This is a stand-alone software application for exploring the solution space and producing reports to be published on the company website regarding its supply chain sustainability. It uses the data provided by the suppliers, stored in the EcoLogTex database and confirmed by an independent party (e.g. the *EcoInvent* database).

4.1 From the Design of the Supply Chain to Exploration of the Results

In this section we briefly present the main features of the graphical user interface of the supply chain designer and offer some examples of the outputs produced by the reporter.

Figure 3 shows how the user sees the various steps of a supply chain, and Fig. 4 shows how the detailed data entry for each node is organized. The supply chain is represented by a tree with the root as the terminal node, as various components can contribute to the assembly of the final product, in this case a mixed wool-cotton shirt. In each node, which represents a process step, the user must select the potential suppliers, i.e. those suppliers who can deliver that particular process, but with different costs, time, and especially environmental impacts.

Once the different process steps, including the transport options, have been selected, the user can launch the optimization algorithm that solves the combinatorial optimization problem described in Sect. 3. Prior to the launch, the user

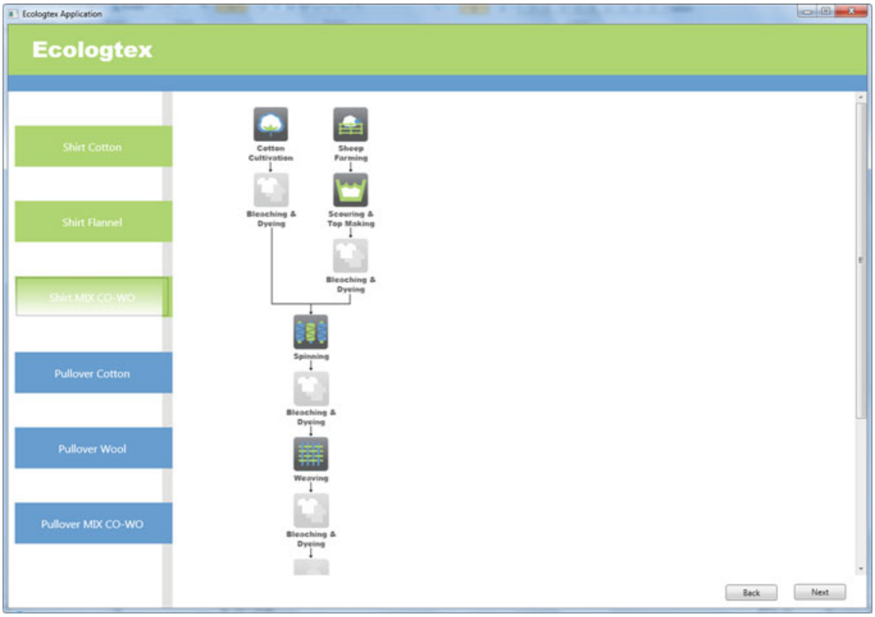
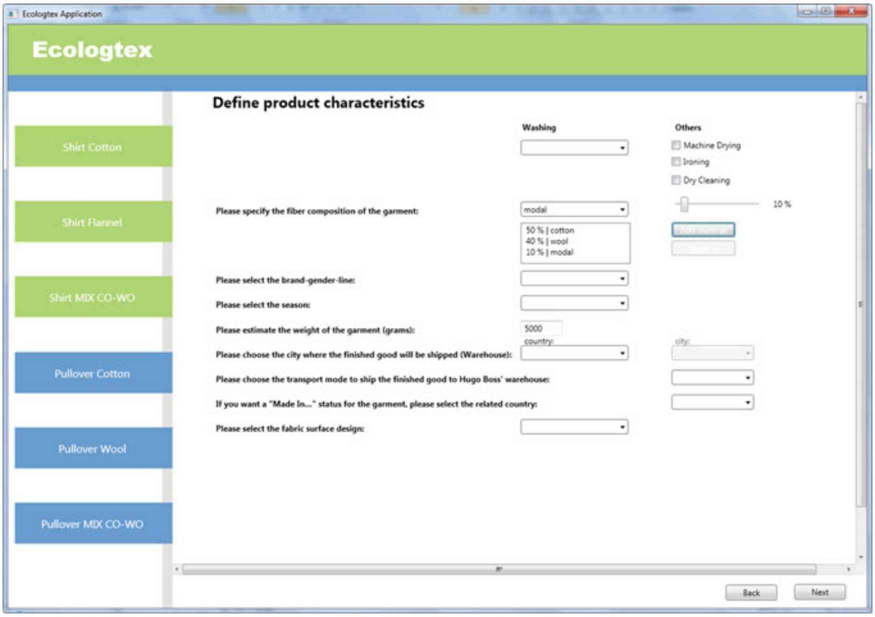


Fig. 3 The representation of the structure of a supply chain



Define product characteristics

Washing

Others

☐ Machine Drying

☐ Ironing

☐ Dry Cleaning

10 %

Please specify the fiber composition of the garment: modal

50 % | cotton
40 % | wool
10 % | modal

Please select the brand-gender-line:

Please select the season:

Please estimate the weight of the garment (grams): 5000

Please choose the city where the finished good will be shipped (Warehouse): country: city:

Please choose the transport mode to ship the finished good to Hugo Boss' warehouse:

If you want a "Made In…" status for the garment, please select the related country:

Please select the fabric surface design:

Fig. 4 The data entry mask for a specific process step must define the objective function by attributing weights to the different indicators, which include both cost and time, but also to the typical LCA indicators such as water depletion, marine eutrophication, climate change and the like (see [17] for the full set of indicators that are used in the objective function).

Computational experiments have been carried out on some realistic artificial scenarios, obtained by considering the characteristic of the real supply chains currently used by Hugo Boss for a few different products. In particular, a typical product has between 8 and 15 production stages, with a number of alternative factories/carriers ranging between 2 and 9 (with typical values below 4) for each stage. The range of values for most of the factors is fairly large: for example, a shipment can be either very fast, expensive, and with large environmental impacts, or slower, cheaper and more sustainable.

Results of the constructed instances proved that a few seconds are always sufficient to rank all possible supply chains (paths) according to the given weighted objective function. Note that in some cases more than one thousand paths are retrieved. As explained in Sect. 3, in the context of our application only a few paths (10–15) are presented to the user for each given combination of weights. This indicates that the algorithm described in Sect. 3 perfectly fits the needs of the project, since it runs in negligible time under the given conditions.

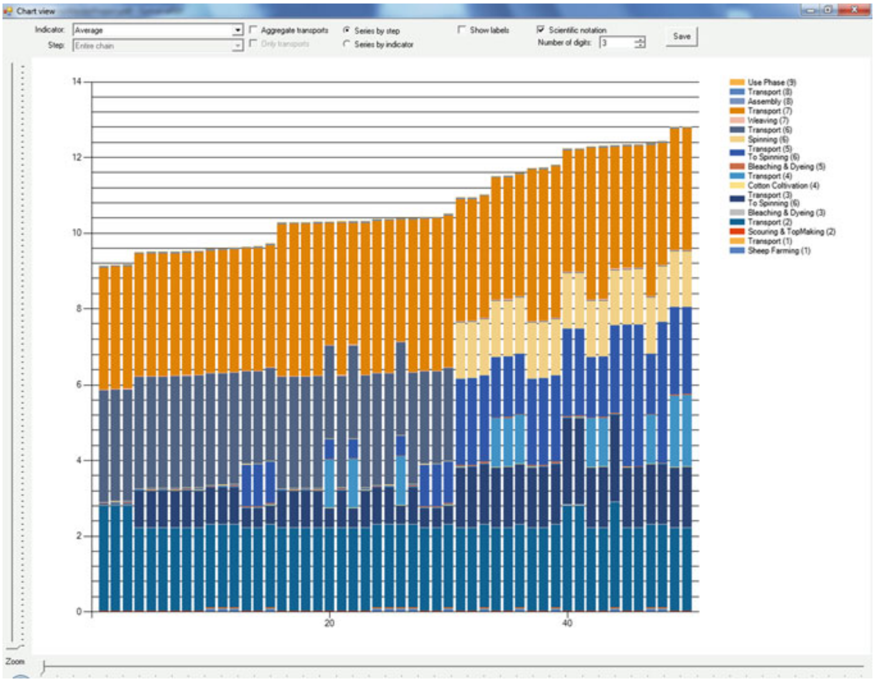
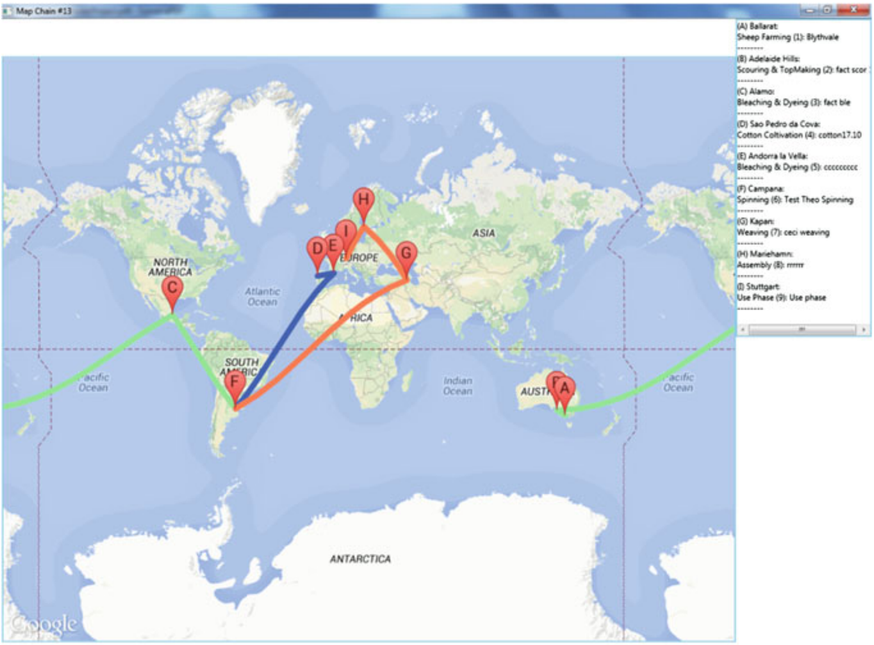

Indicator: Average
Step: Entire chain
☐ Aggregate transports
☐ Only transports
● Series by step
○ Series by indicator
☐ Show labels
☑ Scientific notation
Number of digits: 3

Fig. 5 An example of the chart view in the EcoLogTex reporter. The series (*colored bars*) represent the steps, and the values corresponding to the heights of columns and series are the normalized values of the indicators. Every column represents a chain



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(A) Ballarat:
Sheep Farming (1): Blythvale
---------
(B) Adelaide Hills:
Scouring & TopMaking (2): fact scor
---------
(C) Alamo:
Bleaching & Dyeing (3): fact ble
---------
(D) Sao Pedro da Cova:
Cotton Coltivation (4): cotton17.10
---------
(E) Andorra la Vella:
Bleaching & Dyeing (5): ccccccccc
---------
(F) Campana:
Spinning (6): Test Theo Spinning
---------
(G) Kapan:
Weaving (7): ceci weaving
---------
(H) Mariehamn:
Assembly (8): rrrrrr
---------
(I) Stuttgart:
Use Phase (9): Use phase
---------
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Fig. 6 The map view. In the figure we display a chain with two parallel sub-chains and a final common sub-chain: the *green* path A-B-C-F is the first sub-chain that is executed in parallel to the blue path D-E-F. In F there is the junction of the two paths, and the final common sub-chain is represented by the red path F-G-H-I

Once the algorithm has generated the k-best chains, the EcoLogTex reporter can be used to explore the ranked list of the most promising supply chain alternatives, as shown in Fig. 5. For each solution, the different enterprises carrying out the different working phases can be shown, with the respective value of the weighted objective function. For each production step, the values of the single optimization factors are also shown.

At this point the user can decide whether one of the proposed best chains can be accepted, or whether a re-run of the optimization algorithm, under a different set of weights for the various indicators, is needed.

Finally, the user can also display the whole supply chain on a geographical map to better appreciate its spatial extent, as shown in Fig. 6.

5 Conclusions and Perspectives

Supply chain configuration and management can strongly benefit from the adoption of a product life cycle approach and comprehensive sustainability assessment. On the basis of these considerations, an approach has been developed to address this very current supply chain research topic. In this chapter we presented a tool that integrates in a coherent way various cutting-edge bodies of knowledge, aiming at supporting this activity. The first contribution is linked to the development of a comprehensive data model that allows modeling all stages of the product life cycle and assessing the sustainability impacts of all the processes involved in the product life cycle. The tool also allows representing all the possible alternative choices for each production and transport stage in order to generate a set of potential supply chain configurations. The second contribution is a fast and reliable algorithm based on mathematical programming used for retrieving the most promising solutions for the design of an efficient supply chain, from a sustainability perspective. The algorithm evaluates life cycle impacts based on a shared data model, but they exclude issues related to allocation for multifunctional processes. An advanced and flexible graphical user interface has been developed for supporting the exploration of the proposed integrated tool. The interface allows tuning the optimization parameters dynamically according to the strategic decisions of the company. The optimization process is supported by the possibility of graphically easily comparing the performance obtained by a subset of promising supply chain configurations.

The integrated tool has already been successfully tested in realistic industrial scenarios in the apparel sector, even though it was preferable to start undertaking a partial validation focusing on environmental sustainability and cradle-to-gate supply chain processes.

The proposed tool, developed to provide a comprehensive sustainability assessment and to model all the processes belonging to a cradle-to-grave supply chain, will be further validated, involving a wider supply chain and a set of performance indicators. An interesting perspective is related to the improvement of the graphical user interface to support the optimization of the supply chain performance. This should consider a time horizon over which the supply chain has to simultaneously manage different processes for various product generations, ranging from production and delivery to the customers of the most recent products to reverse logistic activities for old products approaching their end of life stage.

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An Information System Supporting Cap and Trade in Organizations

Brigitte Maranghino-Singer, Martina Z. Huber, David Oertle, Marc Chesney and Lorenz M. Hilty

Abstract We present a software system to create and implement internal markets in organizations that want to limit the CO_2 emissions or the use of scarce resources by their employees. This system can be applied to domains such as business travel by distributing a limited number of permits for business travel-related CO_2 emissions at the beginning of a period and then allowing the permits to be traded inside the organization. The system calculates the CO_2 emissions caused by planned trips and provides the market mechanisms to trade the permits. The approach can be generalized from emission permits to any scarce good that is assigned by the management to units or individual members of the organization, such as parking spaces. Both cases are described by way of detailed examples.

Keywords Cap and trade · Emissions trading · Carbon dioxide · Corporate social responsibility · Corporate environmental management information system

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1 Introduction

The cap-and-trade principle introduced as an instrument of climate policy can be applied at the intra-organizational level when an organization decides to limit or reduce the emissions caused by its activities. The process of trading emission permits among the members of the organization must be supported by an easy-to-use software system to avoid the administrative overhead of such an internal market. We describe such a software system that can be applied, for example, to the domain of business travel, by distributing a limited number of permits for business travel-related CO_2 emissions at the beginning of a period (e.g., the financial year) and then allowing the permits to be traded among the members of the organization, supported by the system, which both calculates the CO_2 emissions caused by planned trips and provides the market mechanism to trade the permits.

One advantage of our approach is that it can be generalized from emission permits to any scarce good that is assigned by the management to units or individual members of the organization, such as parking or office space. Depending on the type of good to be traded, different market mechanisms can be used. The current implementation supports *call market auctions* (in particular, for CO_2 emission permits related to business travel) and *English auctions* (in particular, for the use of parking spaces). The English auction can also be used to create the initial distribution in a call market auction.

We will first describe the cap-and-trade principle (Sect. 2) and then show the application of the system by way of two examples (Sect. 3).

2 Organization-Internal Cap and Trade

According to the IPCC report 2013, the first decade of the 21st century was the warmest in a very long time. Also, most of global warming seems to be due to human activities. Greenhouse gas emissions are changing the global climate with increasingly severe consequences for mankind, the economy, and the environment. For this reason, reducing greenhouse gas emissions is absolutely essential.

One possible tool for accomplishing this task is emissions trading. For example, in 2005 the EU launched the EU Emissions Trading System (EU ETS), which functions according to the cap-and-trade principle, as a cornerstone of its strategy for cost-effective reduction of greenhouse gases. The general workings of such a cap-and-trade system have been described in [1] as follows.

In a cap-and-trade mechanism a quantity of pollution is fixed a priori by the responsible authorities, after a complete assessment of the maximum bearable level of damages. This quantity, called the cap, is set (with great hopes) to replicate the optimal level of pollution as the optimum between the social disutility of pollution and the cost of abatement for the polluting firms. In a way, the agencies that determine the cap can be seen as representatives of a society whose marginal social cost is perfectly elastic: the damages are infinitely sensitive to the smallest variation of pollution.

Once the cap is set, tradable units of pollution are created and allocated to the polluter either for free (grandfathering) or through a compensation scheme. Polluting firms are then allowed to trade those permits among themselves as in the pure market. If many firms have smaller abatement costs than the permit price, they will abate and sell the corresponding permits to firms with higher abatements costs. These seller-initiated trades will progressively lower the permit price. Conversely, if many firms have higher abatement costs than the permit price, they will buy permits on the market. These buyer-initiated trades will push the price higher.

At equilibrium (when all firms are satisfied), using a market ensures that compliance with the capped pollution level is achieved at the lowest possible cost, since the permit price is equivalent to the lowest possible marginal cost of abatement. Moreover, by offering the opportunity to sell permits and generate profits, markets incentivize competitiveness and technology changes towards clean activities.

In the case of the EU Emissions Trading System, however, some problematic aspects of this system have also come to light. Since too many permits were issued from the beginning, the price for a ton of CO_2 settled at a level that was too low. As a result, there was no real incentive to reduce CO_2 emissions. While it is true that from 2008 on, the number of permits on the market was decreased in response, this did not have the desired effect on the price since the demand for CO_2 permits also dropped because of the broadening economic crisis. The price is approximately 5 Euros per ton of CO_2 (February 2014), which does not provide a financial incentive to reduce CO_2 emissions. Yet it certainly would be possible to address this problem by reducing the number of permits on the market to such an extent that it would actually be possible to increase their price and therefore to achieve the climate goals.

But there is another factor hindering achievement of these climate goals. Thirty-one countries including Iceland, Liechtenstein, and Norway, in addition to twenty-eight EU countries, are participating in the EU ETS, which means that more than 11,000 industrial and energy companies are involved, and the program has been expanded to include aviation since January 1, 2012. As a result, the EU is confronted with lobbies from various sectors, in particular aviation, and must stand up to them with the necessary vigor or risk watering down the system in accommodating these various lobbies' individual interests.

Such a cap-and-trade system is applicable not only at the macro level for trading emission permits between different companies but could be put into practice at the micro level within a single private or public institution. Tradable units could be greenhouse gas emission permits as well as rights to use scarce goods, such as parking spaces or conference rooms.

A cap-and-trade system internal to a company might look like the following, using greenhouse gas emission permits as an example: Management defines a maximum yearly permissible cap of CO_2 emissions for business trips at 80 % of expected emissions for the following year, with the goal of actually achieving a reduction in CO_2 emissions. Then, emission permits are created, each of which permits the holder to emit a certain amount of CO_2 (e.g., 100 kg of CO_2 emissions per individual permit), distributed among the individual units within the organization, possibly free of charge, and traded freely on a market internal to the company. If a unit requires more permits than it received for its business trips, it must purchase additional permits on the company-internal market. In the opposite case, it can sell permits it does not need. The price for the permits results from supply and demand on the internal permit market. If, at the end of an accounting period (e.g., at the end of the year), an organizational unit has generated more CO_2 emissions on its business trips than its permits allow, it must attempt to purchase additional permits on the company-internal market. If this is no longer possible because permits are scarce, the unit must pay a fine and purchase the missing permits retroactively at the beginning of the following year.

But if the unit has a surplus of permits because its trips generated a smaller amount of CO_2 emissions, it can try to sell these permits to other departments. The income from such permit sales could be used, for example, in the following ways:

- as a bonus paid to the staff members of the relevant department, which thus creates an additional incentive to reduce CO_2 emissions;
- to increase the discretionary budgets of those staff members whose CO_2 emission reductions made it possible to sell permits;
- to build up the departmental fund available for team-building events;
- to improve the infrastructure of the department in question, whether by reducing CO_2 emissions further and/or improving staff members' job satisfaction;
- as a reserve for future discretionary expenses by the department in question; or
- for a combination of the items mentioned above.

This would make it possible not only to reduce the emissions generated by staff members, but also to utilize the potential for associated cost reductions. The same market mechanism would also enable cost-effective internal distribution of the scarce goods mentioned above.

A software system [2, 3], which will be described in the next section, is required to make good use of the potential of such a company-internal cap-and-trade system.

3 An Information System Supporting Organization-Internal Cap and Trade

3.1 System Architecture and User Roles

The system has a web-based software architecture, which means that each user can log into the system via a web browser from any computer without the need to install software. There are five user roles with different functions and access rights:

- Market participant: An individual or group who owns permits and trades these permits on the internal market. Market participants may have received the permits from their department head in the initial allocation or they may have purchased them on the market. Whenever they use (consume) permits, they must register the consumption in the system (charge their account of permits).
- Agent: An agents has access to the accounts of market participants he or she acts for. Agents are only needed if market participants want to delegate the interaction with the system. A single agent can act on behalf of many market participants.
- Consumer: An individual who belongs to a group owning permits. Consumers can consume permits and debit the consumption from the group account, but cannot trade on their own behalf. Each consumer is assigned to a market participant who is responsible for the trading. For example, the head of group could take the role of the market participant for all group members, because he or she has to approve their business trips anyway.
- Department head: This role is only relevant for the initial distribution of permits at the beginning of each trading period (e.g., the financial year). A department head distributes permits assigned to the department among the groups or individuals within in the department.
- Administrator: The Administrator sets up the market by deciding what can be traded with which market mechanisms and defines the initial allocation of permits among the departments.

As the preferred names of the user roles may differ from organization to organization, the identifiers used by the system can be reconfigured when the system is set up.

3.2 *Business Trip Examples*

Introduction. The following two examples highlight the internal online cap-and-trade platform from a market participant's perspective. To make the examples more concrete, system settings are defined as follows:

- 1 permit equals 1 emitted kg of carbon dioxide (CO_2)[1]
- The period starts on January 1 and lasts 12 months until December 31
- Each employee gets 5,760 permits at the beginning of a period
- The amount of 5,760 permits corresponds to 80 % of 7,200 permits. 7,200 (12 × 600) are emissions expected for the following year assuming that every

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[1] The life cycle assessment data provided by ecoinvent [5], which is used by our system, takes into account all relevant greenhouse gases. The emissions are therefore calculated in kg CO_2 equivalents (kg CO_2eq). For simplicity, however, they are presented to the user as kg CO_2.

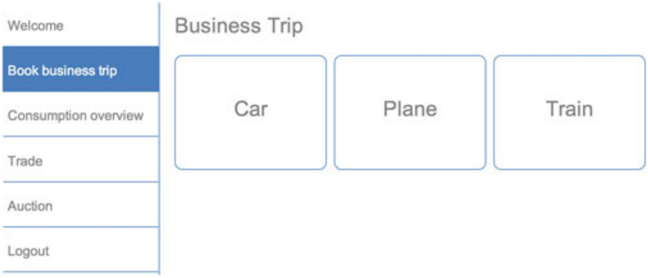


Fig. 1 Selecting means of transportation

business trip that has to be taken by plane is an economy flight and that for all other business trips the small car category is the chosen alternative
- For the examples, we use a virtual currency: Mundo

The (fictional) company *AirPower* is specialized in worldwide consulting for finding the best possible locations for wind farms. The headquarters of *AirPower* is located in Zurich, Switzerland, where currently 200 consultants are employed. For their business trips, consultants can choose among different modes (train, car, plane) and are free to decide which route they want to take.

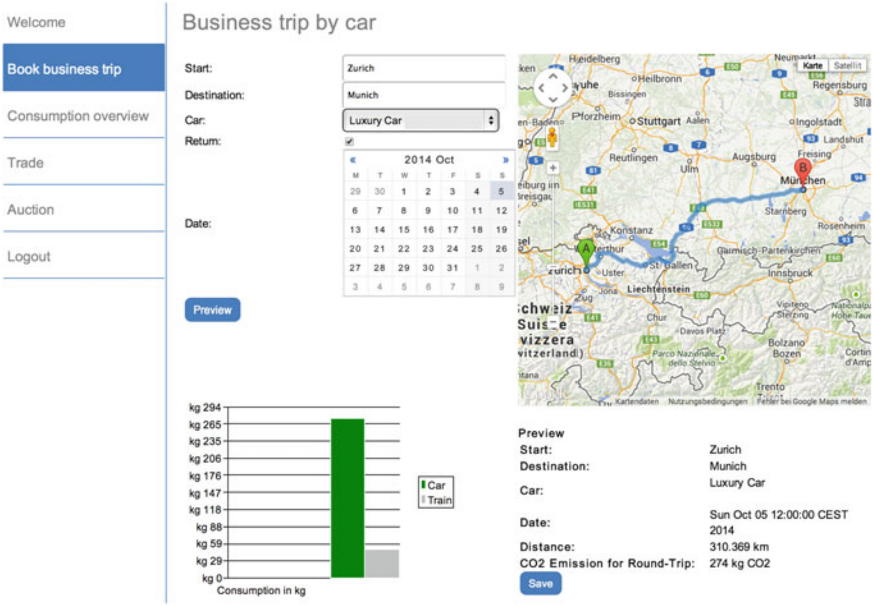
Example I shows Peter's traveling decision process for his next meeting with a possible future client in Munich, Germany. Example II shows Zoe's decision process for her next trip to San Francisco, United States, where she will discuss further steps of the ongoing project with the local authorities.

Example I. As the first step in planning his trip, Peter selects *Car* as his mode of transportation (Fig. 1). After entering the starting point (Zurich) and the destination (Munich), **he selects his preferred car type among a** selection of car types offered by the internal online cap-and-trade platform. The selection is important for the calculation of the CO_2 emissions. Peter checks the category for high-end cars. Next, he checks the box for a return trip and enters the date of his travel (October 5, 2014) (Fig. 2).

Expected CO_2 Emissions by Mode of Transportation. He clicks *Preview* and immediately a sketch of his trip is shown on a map on the right of the screen (Fig. 2). Beneath the map, a summary of the one-way trip shows the starting point, the destination, the car category and the travelling distance [4]. At the end of the list, *CO_2 Emission for Round-Trip* indicates the estimated amount of emitted CO_2 (274 kg) in case the driver returns the same way.

Amazed by the high value and considering the rather short travelling distance, he decides that a smaller car (Minicar) will do just as well. The new result (184 kg; Fig. 3) suits better with him.

By taking the smaller car, Peter would emit 90 kg less CO_2 and save 90 permits. Before clicking *Save* Peter notices the bar chart on the left side at the bottom



Start: Zurich
Destination: Munich
Car: Luxury Car
Return: ☑
Date: 5

Preview

Start:	Zurich
Destination:	Munich
Car:	Luxury Car
Date:	Sun Oct 05 12:00:00 CEST 2014
Distance:	310.369 km
CO2 Emission for Round-Trip:	274 kg CO2

Fig. 2 Calculated CO_2 emissions [5] assuming a luxury car

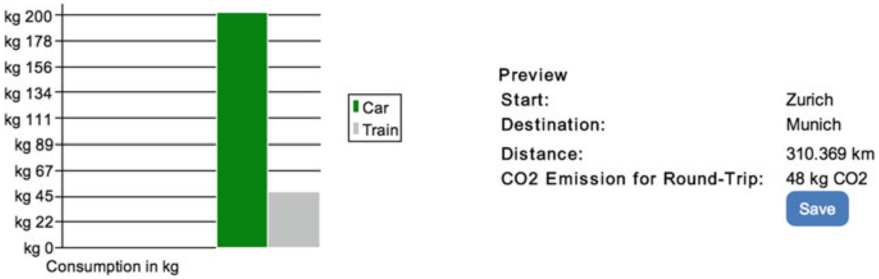
Preview

Start:	Zurich
Destination:	Munich
Car:	Minicar
Date:	Sun Oct 05 12:00:00 CEST 2014
Distance:	310.369 km
CO2 Emission for Round-Trip:	184 kg CO2

Fig. 3 Calculated CO_2 emissions [5] assuming a small car

of the page. The chart shows the total CO_2 emissions of the selected car (left bar) as well as Peter's expected emissions for the same trip if he takes the train (right bar). The difference looks huge.

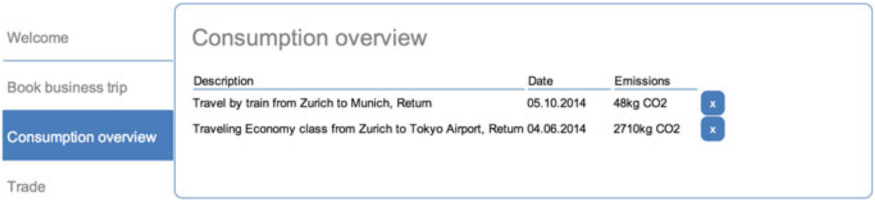
Peter saves the planned car trip but wants to know more details about traveling by train. Therefore, this time he chooses *Train* from the selection provided (Fig. 1). After he enters all relevant information, the preview shows the calculated emissions for a trip by train (48 kg; Fig. 4). Compared to the solution with the luxury car, he would save 226 kg CO_2 (equals 226 permits), while he would save 136 kg CO_2 (equals 136 permits) compared to the solution with the small car. The bar chart now compares the CO_2 emissions from the train with those from an average European car.



Preview

Start:	Zurich
Destination:	Munich
Distance:	310.369 km
CO2 Emission for Round-Trip:	48 kg CO2

Fig. 4 Calculated CO_2 emissions [5] assuming passenger train



Consumption overview

Description	Date	Emissions	
Travel by train from Zurich to Munich, Return	05.10.2014	48kg CO2	x
Traveling Economy class from Zurich to Tokyo Airport, Return	04.06.2014	2710kg CO2	x

Fig. 5 Consumption overview

He decides to take the solution with the train and saves it. Now he has to cancel the prior saved solution in which he had chosen to travel by car. Therefore, he selects *Consumption overview* in the navigation pane (e.g., Fig. 2).

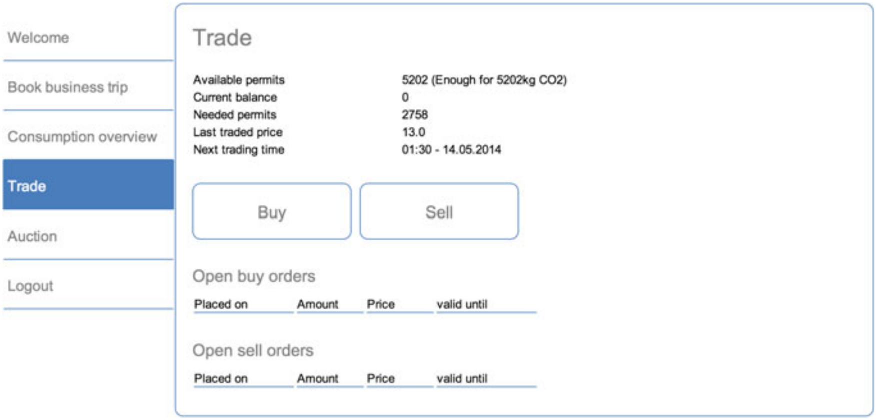
The internal online cap-and-trade platform shows a list of all future trips. After Peter has cancelled the planned car trip to Munich (by clicking the "x" on the right side), the list looks as shown in Fig. 5.

Trading CO_2 Emission Certificates. Peter decides to trade the 136 CO_2 permits he saved by taking the train instead of the small category car over the company's internal market. Therefore, he chooses *Trade* on the left (e.g. Figure 6). The screen shows the overview (Fig. 6). According to the value of *Available permits,* Peter has already used 558 permits (the initially distributed 5,760 minus the currently available 5,202). The value of *Needed permits* results from his flight to Tokyo (2,710) and for his trip to Munich (48) (Fig. 5). *Current balance* shows the amount of money spent (negative balance) or gained (positive balance) by trading permits. Since Peter has not been trading until now, his current balance is 0.

He chooses *sell* (Fig. 6) and a pop-up window appears (Fig. 7). Within the pop-up window he enters the number of permits he intends to sell (136) and the minimum price (13 Mundo) into the corresponding fields. Finally, he selects the date until his offer will be valid (May 30, 2014).

After he saves his order, it appears in the overview as *open sell order* (Fig. 8).

Peter found one buyer and earned 1,768 Mundo (13 × 136). According to the company's policy, the profit he is going to make by the end of the year is given

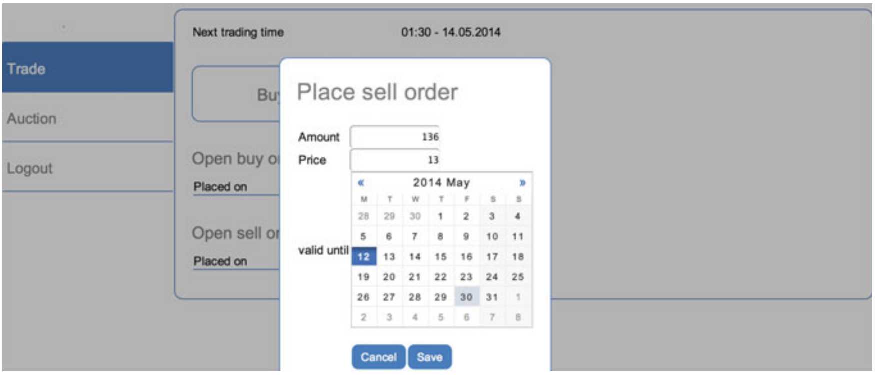


Available permits 5202 (Enough for 5202kg CO2)
Current balance 0
Needed permits 2758
Last traded price 13.0
Next trading time 01:30 - 14.05.2014

Placed on	Amount	Price	valid until

Placed on	Amount	Price	valid until

Fig. 6 Trading CO_2 emissions—overview



Next trading time 01:30 - 14.05.2014

Amount 136
Price 13
valid until

Fig. 7 Trading CO_2 emissions—placing an order

to him as an additional payment to his public transportation season pass. As mentioned above, many policies for dealing with a surplus or deficit that occurs at the end of the year are possible.

Example II. For her business trip to San Francisco, Zoe chooses *Plane* as the mode of transportation (Fig. 1). After filling in all required data and clicking *Preview*, she sees the start and end destination on the map on the right of the screen (Fig. 9).[2]

The button *Show flight route* generates a list of possible outbound or return flights, both direct and with stopovers. Figure 10 shows the list of all outbound

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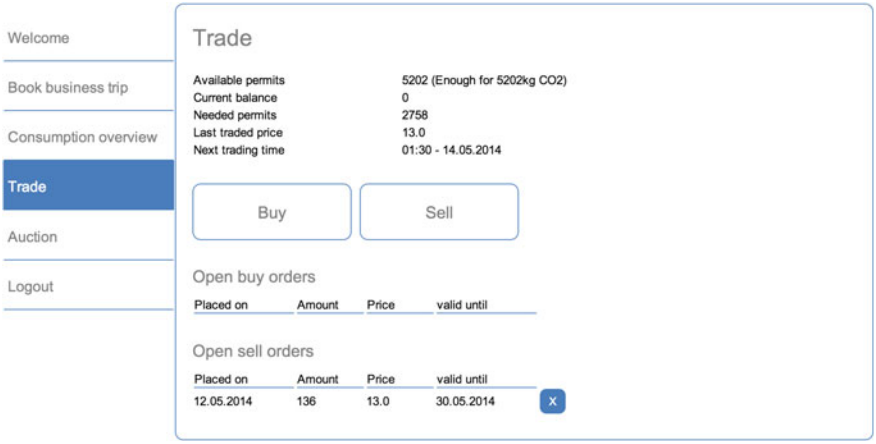
[2] It would also be possible to choose a business class flight, resulting in significantly higher emissions (per person) compared to the economy flight.



Trade

Available permits	5202 (Enough for 5202kg CO2)
Current balance	0
Needed permits	2758
Last traded price	13.0
Next trading time	01:30 - 14.05.2014

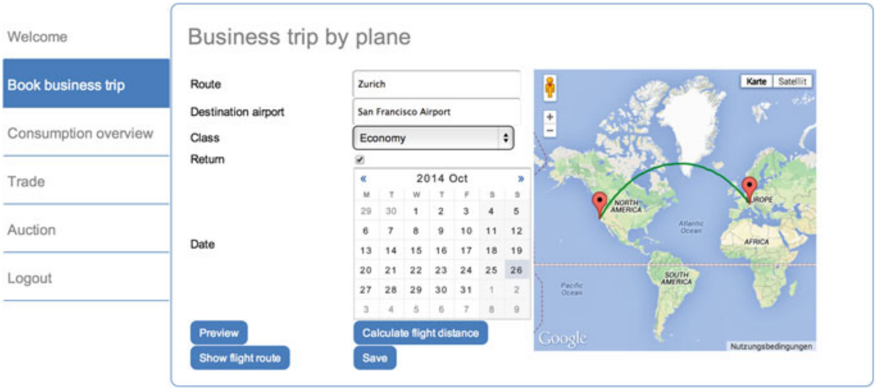
Open buy orders

Placed on	Amount	Price	valid until

Open sell orders

Placed on	Amount	Price	valid until
12.05.2014	136	13.0	30.05.2014

Fig. 8 Trading CO_2 emissions—open orders



Business trip by plane

Route: Zurich
Destination airport: San Francisco Airport
Class: Economy
Return: ☑
Date: 2014 Oct

M	T	W	T	F	S	S
29	30	1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31	1	2
3	4	5	6	7	8	9

Fig. 9 Preview of business trip by plane

flights at the chosen date (October 26, 2014) with specific information on the selected flight about the airline, the travel distance [6] and the amount of emitted CO_2. Different distances for the same flight can show up in case of different routes taken for the second leg of the flight (e.g., due to air traffic conditions). For example, within Fig. 10 the connecting flight AA65 flies from Zurich to New York from which point one can decide between three different connecting flights (#6 and #7 vs. #10).

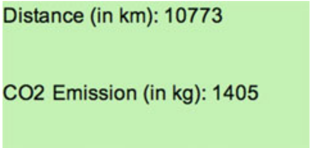
Zoe compares the CO_2 emissions of the non-stop flight #12 with the connecting flight #6 (Fig. 10). The non-stop flight emits 1224 kg CO_2 (Fig. 10) and the connecting flight 1,405 kg CO_2 (Fig. 11). The connecting flight makes a stop in New York, which would give her the opportunity to meet another business partner. However, since she already had to fly overseas this year, she decides to save the

Distance (in km): 9383

CO2 Emission (in kg): 1224

Flight 1	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number UA53	Distance (in km) 10566	Flight type CONNECTION
Flight 2	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number BA709	Distance (in km) 9412	Flight type CONNECTION
Flight 3	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number LH2369	Distance (in km) 9705	Flight type CONNECTION
Flight 4	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number UA135	Distance (in km) 10458	Flight type CONNECTION
Flight 5	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number DL208	Distance (in km) 10471	Flight type CONNECTION
Flight 6	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number AA65	Distance (in km) 10773	Flight type CONNECTION
Flight 7	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number AA65	Distance (in km) 10773	Flight type CONNECTION
Flight 8	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number UA135	Distance (in km) 10458	Flight type CONNECTION
Flight 9	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number UA135	Distance (in km) 10458	Flight type CONNECTION
Flight 10	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number AA65	Distance (in km) 10471	Flight type CONNECTION
Flight 11	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number DL208	Distance (in km) 10471	Flight type CONNECTION
Flight 12	Departure Airport ZRH --> SFO	Start date 2014-10-26	Flight number LX38	Distance (in km) 9383	Flight type NON_STOP

Fig. 10 Calculated CO_2 emissions [5]: nonstop flight #12



Distance (in km): 10773

CO2 Emission (in kg): 1405

Fig. 11 Calculated CO_2 emissions [5]: connecting flight #6

181 permits by taking the direct flight. To communicate with her business partner in New York, she sets up an online meeting, which now will take place during her stay in San Francisco. In this way she has a threefold advantage: She saves CO_2 emissions, saves permits and the time difference between her business partner's location and hers is smaller compared to when she is in Zurich.

3.3 Parking Lot Example

Introduction. The following is an overview of the functionality of the auction mechanism of the internal online cap-and-trade platform. To make the example more comprehensive, it is described from a market participant's perspective. Specific system settings, such as how the amount of money is transferred from one employee to another, depend on companies' regulations and are entered by the system administrator. No further details are provided here.

In the following example the auction is for parking lots; however, in conformance with company regulations any kind of asset (e.g., meeting rooms, coffee machines, printing paper) can be defined.

The (fictional) company *WhiteMoney* is a financial institute whose headquarters, which employs 800 people, is located in Geneva, Switzerland. Around one-third of the staff drives regularly by car to work, but the capacity of the company's parking lot is limited to 150 cars. In the following we spotlight Marianna, lucky owner of a parking space in this lot, who will be on vacation next week; and John, who urgently needs a parking space on a specific date. Both will participate in an English auction organized via the internal online cap-and-trade platform.[3]

Example. Marianna decides to offer her parking space during her vacation to her co-workers. She chooses *Auction* on the navigation pane (Fig. 1), creates a new auction by clicking *Start new auction* and enters all relevant information such as the exact description (Parking 55…), the starting price (4 Mundo) and the date when she wants the auction to end (March 7, 2014 11:00 am), into the pop-up window (Fig. 12). Before saving, she realizes that parking spaces are often only needed on specific days of the week and therefore decides to start an auction per day.

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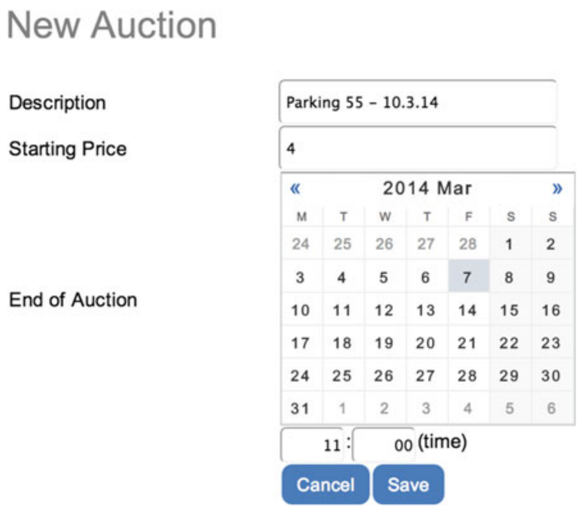
[3] In an English auction the participants bid openly one against another. Each subsequent bid has to be higher than the previous one. When no participant bids further on the auction ends and the highest bidder must pay his bid.

Fig. 12 Auction information



New Auction

Description: Parking 55 - 10.3.14

Starting Price: 4

End of Auction: 2014 Mar, 7; 11 : 00 (time)

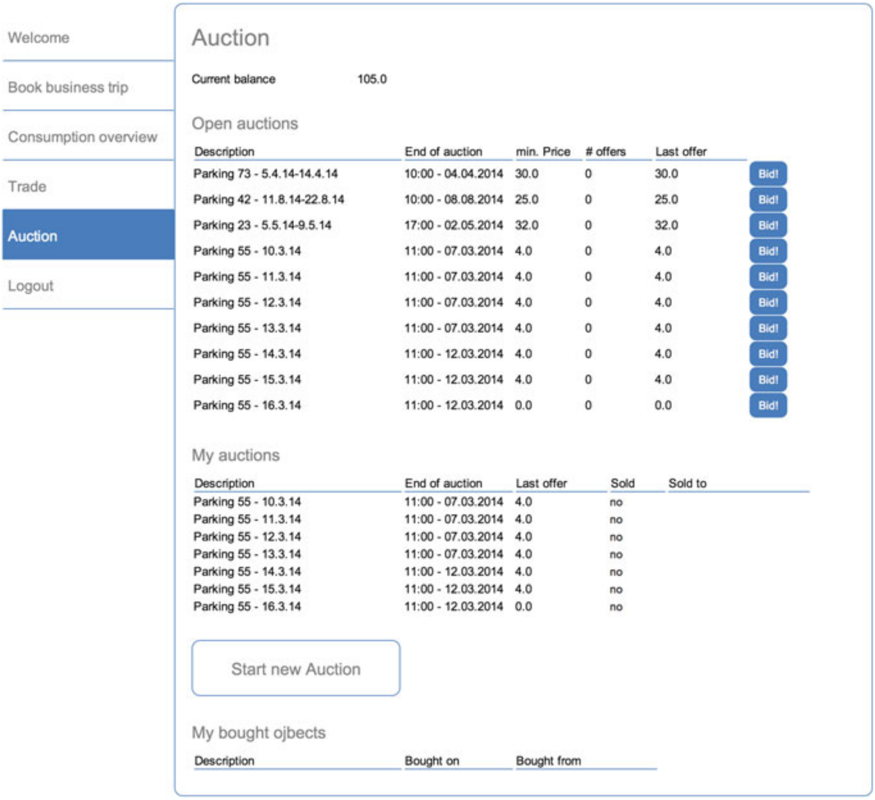
She clicks *Cancel* and inserts 6 auctions according to the previous schema. Since March 16 is a Sunday, she decides to give the parking space for free on that date.

She assumes one week could be too much time in advance for people to know if they need a parking space. Therefore she decides to change the end date for the three last auctions from March 16 to March 12 (Fig. 13). Since the system will end the auction automatically and advise the winner, she does not have to worry about taking care of this while on vacation. After clicking the *Save* button (Fig. 12), her auctions (Parking 55–1x.3.2014) appear together with her co-worker's auctions on the list "Open auctions" as well as separated in "My auctions" (Fig. 13). "Current balance" (105.0) (Fig. 13) shows the amount of money she currently has available for bidding in auctions.

John urgently needs a parking space in the lot for next Tuesday (March 11, 2014) and Thursday (March 13, 2014). He remembers the article about the new internal online cap-and-trade platform in the last issue of the company journal *Transparency* and decides to try it out. After logging into the system, he chooses *Auction* (Fig. 1). On the overview (Fig. 14) he sees all running auctions and is lucky; for both Tuesday (March 11, 2014) and Thursday (March 13, 2014) of next week, an auction for parking space 55 is running. The current price for Tuesday is 8 Mundo; it seems to be a busy day since four offers have already been placed.

On Thursday only one offer has been placed thus far. Consequently, the price is lower (5 Mundo). John still has enough money left on his account to participate in both auctions. He clicks *Bid!* at the right hand side of Tuesday's auction (Fig. 14) and enters a bid clearly above the current price (12 Mundo) into the pop-up window (Fig. 15), hoping to win the auctions. After saving he repeats the same for Thursday's auction.

On March 7 he gets an e-mail generated by the system informing him that he has won the auction for the two dates of interest.



Auction

Current balance 105.0

Open auctions

Description	End of auction	min. Price	# offers	Last offer	
Parking 73 - 5.4.14-14.4.14	10:00 - 04.04.2014	30.0	0	30.0	Bid!
Parking 42 - 11.8.14-22.8.14	10:00 - 08.08.2014	25.0	0	25.0	Bid!
Parking 23 - 5.5.14-9.5.14	17:00 - 02.05.2014	32.0	0	32.0	Bid!
Parking 55 - 10.3.14	11:00 - 07.03.2014	4.0	0	4.0	Bid!
Parking 55 - 11.3.14	11:00 - 07.03.2014	4.0	0	4.0	Bid!
Parking 55 - 12.3.14	11:00 - 07.03.2014	4.0	0	4.0	Bid!
Parking 55 - 13.3.14	11:00 - 07.03.2014	4.0	0	4.0	Bid!
Parking 55 - 14.3.14	11:00 - 12.03.2014	4.0	0	4.0	Bid!
Parking 55 - 15.3.14	11:00 - 12.03.2014	4.0	0	4.0	Bid!
Parking 55 - 16.3.14	11:00 - 12.03.2014	0.0	0	0.0	Bid!

My auctions

Description	End of auction	Last offer	Sold	Sold to
Parking 55 - 10.3.14	11:00 - 07.03.2014	4.0	no	
Parking 55 - 11.3.14	11:00 - 07.03.2014	4.0	no	
Parking 55 - 12.3.14	11:00 - 07.03.2014	4.0	no	
Parking 55 - 13.3.14	11:00 - 07.03.2014	4.0	no	
Parking 55 - 14.3.14	11:00 - 12.03.2014	4.0	no	
Parking 55 - 15.3.14	11:00 - 12.03.2014	4.0	no	
Parking 55 - 16.3.14	11:00 - 12.03.2014	0.0	no	

My bought ojbects

Description	Bought on	Bought from

Fig. 13 Marianna's auction overview

Open auctions

Description	End of auction	min. Price	# offers	Last offer	
Parking 73 - 5.4.14-14.4.14	10:00 - 04.04.2014	30.0	0	30.0	Bid!
Parking 42 - 11.8.14-22.8.14	10:00 - 08.08.2014	25.0	0	25.0	Bid!
Parking 23 - 5.5.14-9.5.14	17:00 - 02.05.2014	32.0	0	32.0	Bid!
Parking 55 - 10.3.14	11:00 - 07.03.2014	4.0	1	8.0	Bid!
Parking 55 - 11.3.14	11:00 - 07.03.2014	4.0	4	8.0	Bid!
Parking 55 - 12.3.14	11:00 - 07.03.2014	4.0	1	7.0	Bid!
Parking 55 - 13.3.14	11:00 - 07.03.2014	4.0	1	5.0	Bid!
Parking 55 - 14.3.14	11:00 - 12.03.2014	4.0	3	12.0	Bid!
Parking 55 - 15.3.14	11:00 - 12.03.2014	4.0	0	4.0	Bid!
Parking 55 - 16.3.14	11:00 - 12.03.2014	0.0	0	0.0	Bid!

Fig. 14 John's Auction overview

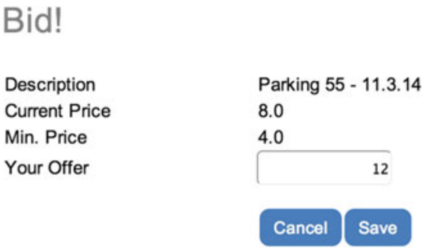


Fig. 15 Auction bid

4 Conclusion and Outlook

In this chapter, we presented a software system supporting the creation and implementation of organization-internal markets for CO_2 emission permits and other limited resources that can in principle be optimally allocated if they can be traded.

Thus far, implementations of cap-and-trade systems have focused on the macro level, with the EU ETS in Europe (The European Emission Trading Scheme) in particular. At a micro level, i.e., at the company level, cap-and-trade systems have a huge potential that has been neglected. They could intelligently complement the EU ETS by providing companies the means to comply with current macro regulations. They would help companies reduce their energy costs and therefore not only to abate CO_2 emissions but also to generate cash flows by selling their extra emission rights.

This system should be of interest for many companies in different sectors. Confronted with a limited number of offices, parking spaces or a limited travel budget, they should try to optimize their decision making process and rely more on solutions such as car sharing, teleworking or online meetings. On the one hand, the system allows the employees to take more responsibility while on the other hand it gives them incentives to make efficient choices.

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Computational Modeling of Material Flow Networks

Andreas Moeller

Abstract Material Flow Networks (MFN) are a modeling instrument in the field of material flow analysis (MFA) that helps to characterize current or future material and energy flows and stocks. Often, efficiency analyses such as life cycle assessments and cost accounting use such models to calculate the relationship between positive outcomes and negative impacts. The systematic integration of stocks makes it possible to analyze infrastructures that provide services, which is necessary in order to assess the effects of replacing material goods by services. The first part of this paper outlines Material Flow Networks as a period-oriented accounting system that systematically integrates stock and flow accounting. The second part is concerned with the question of how to construct the models and calculate data. From this perspective, the instrument becomes a modeling framework.

Keywords Material flow network · Accounting · Steady-state modeling · Dynamic material flow analysis · Process flowsheeting

1 Introduction

Material Flow Analysis (MFA) designates an application domain of a class of accounting and modeling instruments that model and simulate networks of material and energy flows and stocks to shed light on the socio-technical metabolism. Characterized as such, life cycle assessments (LCA) and related instruments such as product carbon footprinting can be interpreted as special MFA instruments. These instruments have the unique characteristic of being efficiency analyses, very similar to cost accounting.

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LCA does not provide insight into all relevant attributes of those systems. In particular, it does not cover the role and time dependency of stocks, the utilization of stocks as infrastructure components, and the synergetic effects of joint supply chains, for instance industrial symbiosis, eco-industrial parks or services of IT infrastructures. Several challenges of sustainable development involve changes in the interplay of flows and stocks: scarcity of raw materials, products in the use phase, and concentration of carbon dioxide in the atmosphere. In such a stock-centered perspective, methods of dynamic material flow analysis and continuous simulation come into play.

However, the number of relevant stocks in the models is small compared to the number of processes. Stocks disjoint the material and energy flow systems into partitions such as production processes with internal recycle streams that converge to steady states.

In this chapter, Material Flow Networks (MFNs) are discussed as an accounting and modeling approach [1] for performing dynamic MFAs as well as steady state MFAs. Moreover, as a period-oriented MFA approach, they can serve as a link between material flow analysis and efficiency analyses such as life cycle assessment and cost accounting. In this regard, the resulting material flow models serve as data providers for life cycle inventory calculations [2].

The main difficulties in applying calculation engines for MFA arise because of recycle loops. Loops prevent a step-by-step procedure: Because of them it is not possible to determine an unambiguous precedence order for the evaluation of all processes within the model. Hence, specifications of MFA modeling approaches emphasize solutions for loops. In this regard, MFA modeling approaches can profit from previously developed approaches to process flowsheeting in chemical engineering.

2 Material Flow Networks as an Accounting System

Material flow analysis can be considered from two different perspectives: accounting and modeling. In the accounting perspective, we can interpret specific MFA instruments as accounting systems. The result data sets provided by the instruments are categorized into flows, transformations, and stocks [3]. The data sets have a specific relationship to predefined interests or outcomes. In life cycle inventories, input and output flows are related to functional units [4], whereas in conventional cost accounting, costs are assigned to cost objects. In period-oriented MFA, the focus is on absolute material and energy flows and their effect on stocks. This is similar to financial accounting, in particular to double-entry bookkeeping [5].

Double-entry bookkeeping in the private sector is used to represent financial flows and effects of these flows on stocks for a given time period (fiscal year). An important feature of double-entry bookkeeping is that it integrates flow and stock analysis. The integration of stocks makes double-entry bookkeeping more powerful than conventional governmental accounting (cameralistics), for example.

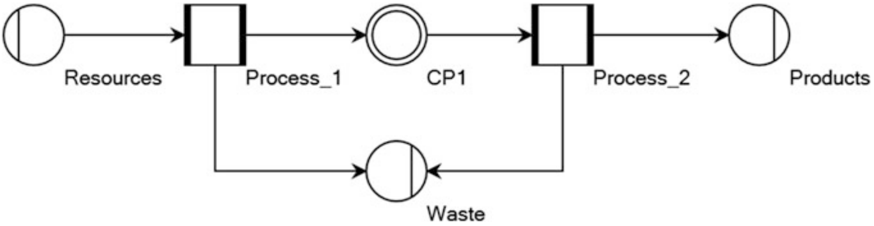

Fig. 1 Net elements of a material flow network

Cameralistics only represents financial input and output flows for a given fiscal year. Cameralistics cannot deal with stocks, for example the total amount of liabilities.

Material flow accounting as an accounting system avoids the shortcomings of cameralistics. Stocks are also an important issue in environmental accounting. Global environmental problems arise from the interplay of flows and stocks: scarcity of raw materials and fossil energy, the concentration of carbon dioxide in the atmosphere, the accumulation of products in the use phase, etc. It should be possible to deal systematically with stocks for model evaluation purposes, for instance the development of stocks over time (multi-period material flow analysis).

An environmental accounting system that supports stocks is the MFN approach [5]. Like double-entry bookkeeping, MFNs consist of two different categories of accounts: flow accounts and stock accounts. To deal with these different categories systematically, the basic approach of Petri nets is applied. Carl Adam Petri developed Petri nets in the early 1960s to represent the dynamics of concurrent calculation processes within computers and computer networks [6]. It has been shown that this approach can be applied in accounting too. Nets specify the static structure of unit processes that specify transformations of material and energy flows, flows and stocks. A net is a triplet N = (P, T, A) that consists of a finite set of places P, a finite set of transitions T with $T \cap P = 0$ and a relation $A \subseteq P \times T \cup T \times P$ which does not allow direct links between places or direct links between transitions [7]. Figure 1 shows typical net elements: the transitions Process_1 and Process_2 as well as the places Resources, CP1, Emissions and Waste. Arcs connect places with transitions and vice versa. The places Resources, Products and Waste specify the system boundary (input and output).

In Petri net theory, the nets are supplemented by components that allow dynamic behavior to be specified. In an accounting perspective, the interests are different. The places are interpreted as stock accounts and the arrows as flow accounts. The triplet is enhanced to a 7-tuple MFN = (P, T, A, TP, M, S, F), where TP represents a finite sequence of time periods, M a finite set of materials (as a general term for substances, materials, energy and services), a mapping S between the set of places and the periods to $R \times R$ (initial stock, final stock) and finally a mapping F between the set of arrows A and the periods to R (flow value).

The 7-tuple MFN has to fulfill the balance equation of the accounting system: For all time periods and materials, the final stocks for the period must be the same as the initial stocks plus the input flows minus the output flows. In a multi-period model, the final stocks for each period except the last one must be the same as the initial stocks for the subsequent period (we assume that time gaps between the periods and overlapping periods are not allowed).

Direct evaluations of MFNs are very similar to double-entry bookkeeping [8]. If the focus is on flows, we can derive a period-oriented input/output balance which aggregates and compiles the input and output flows for a given part of the net (more precisely, for a given transition-bordered subnet [9]) and a given time period. Changes in stock can be interpreted as internal inputs (decreasing internal stocks) or outputs (increasing internal stocks), respectively. If all unit processes fulfill the law of mass conservation, the input/output balance including internal input and output fulfills it too.

The input/output balance can be combined with a compilation of stocks and their changes over time. In this regard, multi-period analyses are important. More sophisticated evaluation methods, in particular efficiency analyses, are examined later in this chapter.

3 Material Flow Networks as a Modeling Framework

The second part of this chapter discusses the question of how the accounting system can be filled with data. This requires past-oriented accounting, manual or computer-based data collection and data processing. Nowadays, Enterprise Resource Planning (ERP) systems are used to a large extent. In future-oriented accounting, data collection must be replaced by a model that serves as a data provider. In the field of MFA, these models can be called material flow models. (Even if material flows are mentioned, these models include in addition stocks, energy and where appropriate immaterial goods.)

The core component of a corresponding modeling framework is a calculation engine or solver which uses the specifications in the form of algebraic or differential equations as its data input. Its purpose is to calculate all flows and stocks.

As described above, an important challenge is to deal with recycle loops. The solver applies proved and tested standard algorithms such as root finding or integration methods to determine a solution. The following discusses various possible approaches to determining steady states of material and energy flow systems. After a warm-up period, all flows and stocks no longer change over time and become constants. Thereafter, this kind of modeling can be embedded into a simulation approach to dynamic material flow analysis.

The modeling procedure consists of three steps: (1) the construction of the network, (2) the specification of unit models for all unit processes (transitions) and (3) data entry for scenario parameters: manual flows and stocks including their properties and components; planned product output and reference flows; future developments of product demand, prices and other factors; design specifications; and constants which characterize the scenario.

The most important modeling task is the specification of unit processes (transitions). The purpose of these specifications is to allow the calculation of all input and output flows for each process for a given set of fixed flows and parameters. This can be done in two ways: (1) The unit processes provide equations, which are used by a calculation engine for the whole MFN (equation-based approach) or (2) the unit processes are treated as black boxes which contain their own calculation engine (modular approach). Each approach has its advantages and disadvantages.

The equation-solving approach assumes that the model "is represented by a collection of nonlinear equations, which must be solved simultaneously" [10]. The unit models provide model equations, the flowsheet connecting equations and previously fixed scenario parameters such as reference flows and feed streams ("equation generation").

A solver is applied to calculate the results directly and simultaneously and consists of two steps: block decomposition and the application of root-finding methods [11].

(1) Block decomposition divides the system of algebraic equations into strongly connected components, and it specifies a precedence order between them. This makes it possible to calculate the equation variables step-by-step.
(2) General-purpose root finding algorithms (Newton's method and in particular Broyden's method) are applied to determine the equation variables of each strongly connected component. Root finding algorithms come into play because the equations of each component depend reciprocally on equation variables of other equations within the component, largely because of loops.

The equation-based approach is "clearly the more elegant and intellectually satisfying" [11]. The equation-based approach provides the highest flexibility, one of its main advantages: for given design specifications, flows and stocks are calculated as well as the process parameters under which the process meets the specifications.

The number of algebraic equations the solver has to deal with can be very high. Westerberg et al. estimate for chemical processes that "the number could become 50,000–100,000 or more" [12]. Reliable algorithms which can deal with those systems of nonlinear algebraic equations are not available. The time complexity of underlying algorithms can be very high and a solution is not assured. Normally, the solvers need assistance from the modeling expert, for instance first estimations.

Another problem of the equation-based approach is model validation. This approach does not support "sequential modular thinking" [13] of modeling experts, because of the rearrangement of equations in the block decomposition step, among other possible reasons. Error messages may be confusing ("the equations of strongly connected component x are over-determined"). This makes bug fixing more difficult and has a negative impact on the transparency of the model.

Another disadvantage of equation-based strategies is the interface to unit models. From a computing science perspective, the overall solver defines a grammar for the equations that the unit models have to provide. Such a grammar makes the interface between the flowsheeting systems and the unit processes more complex and excludes some calculation engines for unit processes, for instance widely used spreadsheet tools like Microsoft Excel® ("Excel interface").

Modular approaches distinguish between two different levels of calculation: the calculation within each unit process and an overall calculation engine which calculates all results for the material flow model. Such an approach results in very flexible software solutions. Of course, software tools provide calculation procedures for both levels, but it is possible to implement the calculation of unit processes as remote function calls: Microsoft Excel® as mentioned above, remote servers, and the like.

The calculation engine within the unit processes checks the completeness and consistency of fixed input parameters and calculates a vector of output parameters (modular approaches). It is not necessary to know how the calculation procedures are implemented (black-box).

The outer calculations can be performed in two different ways. In the sequential modular approach, the outer calculation is a straightforward, step-by-step procedure, which calls the calculation engines of the unit processes if necessary. A bundle of concepts deals with recycle loops: tearing of loops, first estimations and convergence methods.

In the simultaneous modular approach, all data inputs of the unit processes are fixed flows or first estimations of the process levels. The fixed flows and first estimations allow the unit models to be calculated simultaneously ("all-stream tear strategy" [14]). The input and calculated output parameters of all unit models are used as input parameters of a convergence method, which calculates the next estimations as long as a steady state is detected.

Often an approximately linear behavior of the modeled unit processes is assumed [15]. The inputs and outputs of all unit models constitute a linear specification (process coefficients) of the unit processes, as in life cycle assessment. These linear unit models allow formulating the solution as a system of linear equations (for details with regard to life cycle inventory calculations, see [16]). As a solution, all flows are calculated and the process levels are determined. These levels normally differ from estimations. All unit processes are recalculated with aid of a convergence method and the calculated process levels, and the results are compared. If there are no relevant differences, the iterative procedure is finished. Otherwise, the calculations must be repeated.

The simultaneous modular approach [17, 18] is a successful strategy when the process levels of all non-linear processes are known beforehand [19]. However, good first estimations are necessary for non-linear processes only. Linear processes are common in material flow analysis, both because of overlapping research fields with life cycle assessment and because of the availability of life cycle inventory databases, which do not provide non-linear unit processes. For purely linear process specifications, the simultaneous modular approach requires one iteration only to determine the steady state (and a second iteration to check the results), making the simultaneous modular approach as powerful as matrix methods in life cycle assessment [20].

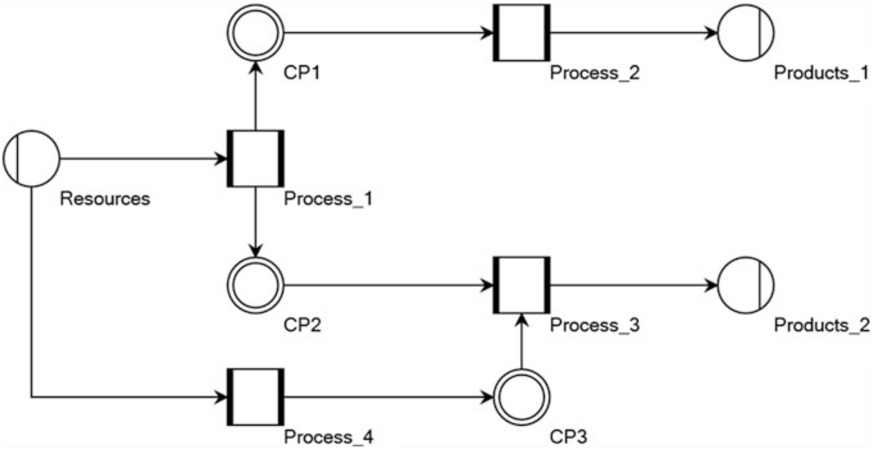

Fig. 2 Material flow network without loops

The sequential modular approach is—as mentioned above—a straightforward calculation procedure, which calculates the unit processes step by step, starting with feed streams and other scenario parameters. Model calculation is a sequence of function calls of the calculation engines of the unit processes. The result of such a subroutine call is a set of new flows, for instance the output flows, which feed other unit processes. The calculation procedure is successful when all unit processes are calculated in a consistent manner. Figure 2 shows an example. Starting with a feed stream between place Resources and transition Process_1, the transitions Process_1, Process_2, Process_3 and final Process_4 can be calculated step-by-step. Note that the transitions can be specified in a way that makes it possible to calculate them downstream or upstream (Process_4).

When the models contain recycle streams (loops), the approach requires additional specifications. In fact, recycle streams occur very often in chemical processes. Reference models of chemical processes normally include recycle streams [21] because the conversion rate of most chemical processes is less than 100 %. And recycling is an important topic in material flow analysis; it is a central strategy to reduce the demand for virgin raw materials (Fig. 3).

The specifications to deal with loops are based on the idea of tearing all loops and estimating virtual feed streams (tear streams) so that the loops no longer occur [22]. In such a case, the straightforward calculation procedure can calculate all values. Figure 3 shows the feed stream, the tear stream and the calculation steps. However, this yields two values for the torn stream between CP3 and the Mixer process: the estimated and the calculated value. When the two are more or less equal, the steady states of the loops have been determined; otherwise, it is necessary to calculate the loops again, with modified estimations. So-called convergence methods are applied to calculate the next estimation.

Convergence methods interpret the torn loops as a sequence of functions. In total, the sequence specifies a function f between the estimation $x \in R$ and the

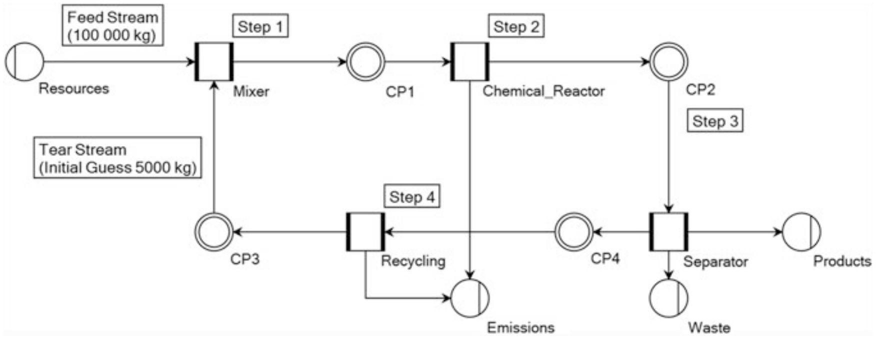

Fig. 3 Material flow network with loops

calculated value f(x). The calculation procedure has to determine for all loops fixed points x* with f(x*) = x*. The simplest convergence method is direct substitution. When f(x)! = x, the calculated value f(x) is used as the estimation for the next iteration. A more enhanced convergence method is Wegstein's method [23]. The Wegstein algorithm uses the estimation of the current iteration and the estimation of the earlier iteration to calculate the next estimation. In many practical cases, the Wegstein algorithm is very efficient, making Wegstein's method the default algorithm in several flowsheeting tools.

Other common procedures are Newton's and Broydon's methods [24]. These methods can be applied by transforming the fixed-point problem into a root finding problem. The solver tries to solve the problem g(x) = 0 where g(x): = f(x)−x as specified above. Whereas simple fixed-point iterations try to calculate all loops independently, methods like Newton or Broyden calculate next estimations simultaneously. The root finding algorithms deal with functions of the form $g:R^n \rightarrow R^n$ and use in particular the inverse of the Jacobian matrix of g to calculate the next estimation simultaneously. These methods are often efficient when the steady states of several nested loops must be determined.

Software implementations of the approaches have become core components of MFA tools. The purpose is to determine the process levels of all loops as well as all material and energy flows and stocks, including their properties (for instance temperature, pressure and specific volume of gaseous mixtures) and components. First implementations of the sequential modular approaches in the field of material flow analysis started in the early 1990s, and many modeling experts in practice and academia use its software tools to perform material flow analyses.

The equation-based approach is discussed in the field of material flow analysis in connection with process optimization and operations research solvers [25]. The simultaneous modular approach is remarkable when material flow analyses serve as data providers of life cycle assessment and cost accounting. Apart from the selected approach, successful calculations result in a material flow model for a given time period.

4 Integration into a MFA Modeling Framework

In the following, the integration of MFNs and respective calculation engines into an MFA tool-chain is briefly examined. Such an MFA tool-chain includes simulation approaches on the input side and, in particular, efficiency analyses on the output side of period-oriented material flow models.

A direct evaluation of period-oriented material flow models is the input/output balance: the input and output flows for a given subnet. The flows do not remain in relationship to functional units or reference flows; rather, they are absolute flows for the given period, which means that an input/output balance is not a life cycle inventory.

Input/output balances are often used to validate material flow models. Nevertheless, the most important evaluations of the material flow models are rather life cycle assessment and cost accounting. A special input/output balance serves as the main data input of life cycle inventory calculations [26]: the input/output balance of single transitions. The inputs and outputs of the transitions are interpreted as production coefficients of unit processes. The functions of each unit process can be identified with aid of Dyckhoff's categorization of goods, bads, and neutrals [27]. For multi-function processes, allocation rules must be applied. As a result, it is possible to derive life cycle inventories from MFNs.

The most important difference compared to direct LCA instruments is that more than one life cycle inventory can be derived from a single material flow model. Furthermore, period-oriented MFNs close the gap between those efficiency analyses and simulation. In the MFA field, two different simulation approaches can be distinguished: continuous simulation and discrete-event simulation. Both approaches can be supported [28, 29].

5 Conclusions

Two decades after their invention, MFNs are still in development. The first part of this paper interprets MFNs as an accounting system. In adopting an accounting viewpoint, the basic characteristic of material flow analysis instruments can be identified: the handling of flows as well as stocks. For a given time period, the material flow models provide data on initial stocks, the flows within the period and the final stocks in the end. In multi-period analyses, the dynamics of stocks can be assessed. The period-oriented material flow models serve as data providers of efficiency analyses such as life cycle assessment and cost accounting.

The second part of the chapter interprets MFNs as a modeling framework that supports steady-state modeling of material flows and stocks. The approaches to steady-state MFA, discussed here, are already in use in chemical engineering. Process flowsheeting tools help to design complex chemical processes with several unit processes such as mixer, chemical reactors and flash units. Very often recycle streams have to be modeled, for instance between separator units and mixers. Tearing strategies and convergence methods together allow the levels of processes to be estimated. The torn loops make it possible to apply sequential modular approaches. But it is necessary to converge the ends of the torn loops with the aid of fixed-point iterations or root finding algorithms.

The approaches have become the core algorithms of a calculation engine of steady-state MFA tools, which are helping to close data gaps in the accounting system. In future-oriented analyses, the resulting material flow models should be derived from scenario parameters, possibly with aid of a simulation approach; in past-oriented analyses, the scenario parameters and preferably all stocks and flows are replaced by actual data.

The convergence methods are discussed here in detail because these methods provide solutions for some of the key issues in material flow analysis: recycling and reuse of used products and waste. The MFNs in general are not focused on single products or services, which makes it possible to apply them in the conceptual design of complex production systems and eco-industrial parks. Moreover, the relationships between stocks and flows can be analyzed in detail. This is important for IT infrastructures and their services: Models of sustainability in the Information Society.

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Toward the Next Generation of Corporate Environmental Management Information Systems: What is Still Missing?

Jorge Marx Gómez and Frank Teuteberg

Abstract This paper outlines the development as well as the technical features of a corporate environmental management information system (CEMIS) and explains how integrated system-oriented information systems can facilitate environmental sustainability in business organizations. Furthermore, the paper discusses implications (lessons learned) of the IT-for-Green project. The paper also discusses further requirements of traditional CEMIS toward a next generation of CEMIS focusing on a more strategic level instead of a compliance approach and on an interactive exchange of information between stakeholders, as well as the realization of synergy effects using green services.

Keywords Corporate environmental management information systems · Sustainability reporting and dialogue · Green IT · Green production and logistics

1 Introduction

Despite the heightened concern of business organizations for environmental sustainability, strategic decision support systems have failed to prevail in practice. Environmental Management Information Systems (EMIS) have been designed for operational data storage and documentation purposes to support compliance with environmental directives. However, the increasing demand for comprehensive environmental reporting as well as proactive environmental management imply new challenges for the integration of EMIS into the established corporate Information

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Technology (IT) landscape. The joint IT-for-Green project [1] aims to develop a new, integrated, and service-oriented type of EMIS called Corporate Environmental Management Information System (CEMIS). The resulting information system supports practitioners with the implementation of environment-related workflows, such as life cycle assessment, environmental monitoring, and Sustainability Reporting (SR), by obtaining, processing, and disseminating information.

The ideas of environmental and sustainable development started to influence development of and research on Information Systems (IS) at the beginning of the 21st century on a wider international base. The first conferences on the topic, such as the International Conference on Information Technologies in Environmental Engineering (ITEE), the International Symposium Informatics for Environmental Protection (EnviroInfo), and the International Symposium on Environmental Software Systems (ISESS), took place in the years 2001–2003. Melville [2] and Watson et al. [3] published the first contributions to the concept of environmental sustainability in one of the leading IS journals, the MIS Quarterly. But even though a huge number of information systems have been successfully implemented for the operational level, strategic decision support systems have failed to be disseminated into business practices. This contradiction motivated us to investigate the following research question:

How can information systems successfully enable sustainable strategic decision-making within business organizations by collecting, storing, and processing information with appropriate means?

We answer this question by designing, implementing, and evaluating our CEMIS and by giving an example. Furthermore, we derive a reference architecture from the example. Our system is built in a modular manner, with service orientation as a major conceptual design element. In this context, service orientation means that the smallest units of the modules are realized as services (called Green Web Services); these services are published in the Green Service Mall (service registry). Following the service-orientation approach, functionality will be established and expanded via the integration of new or modified services to add any kind of functionality. The design science approach [4] is applied for realizing the software.

This chapter is structured as follows: In Sect. 2 a brief description of the IT-for-Green project is given. The status quo of environmental management information systems (EMIS) is described, based on a systematic literature review (Sect. 3). The results (IS artifacts) of our research are outlined in Sect. 4, followed by a discussion of design considerations of CEMIS in Sect. 5. A CEMIS reference architecture is presented in Sect. 6. Lessons learned are discussed in Sect. 7, and conclusions are drawn in Sect. 8.

2 IT-for-Green Project

The ubiquity of IT in modern society and the progressive merging of digital and physical systems have created the basis for companies contributing more systematically to sustainable development. Common objectives of sustainability-oriented management include a fundamental redesign of business processes, a general increase in transparency, and more efficient handling of energy and material resources.

The IT-for-Green project supports companies in increasing their resource and energy efficiency with the help of information technology—that is, by means of Corporate Environmental Management Information Systems (CEMIS). However, formerly conventional CEMIS merely serve to ensure compliance with environmental laws and regulations and hence fall short of the full potential that IT holds for environmental management. The new generation of CEMIS (CEMIS 2.0) needs a stronger strategic focus and is intended to provide more direct support to decision-makers within companies.

The project IT for Green aims at modeling the entire product life cycle supported by a CEMIS, including the input side (measuring the energy efficiency of a company's ICT), the transformation phase (production/logistics and sustainable product development), and the output side (corporate communications and Sustainability Reporting, SR). To this end, three interlocked modules are developed as reference implementations for an innovative CEMIS 2.0. Participating companies may also procure the modules in the form of services via a Cloud Computing Mall.

Researchers of the IT-for-Green project are members of the innovation network ertemis [5], which consists of researchers from the Universities of Oldenburg (Prof. Jorge Marx Gómez and Prof. Wolfgang Nebel), Osnabrück (Prof. Frank Teuteberg), and Göttingen (Prof. Jutta Geldermann). The University of Lüneburg (Prof. Andreas Möller, Prof. Burkhardt Funk, Prof. Peter Niemeyer) is also involved as an associate partner. Industry partners include CeWe Color, Hellmann World Wide Logistics, Nowis, and erecon. Furthermore, over 30 companies contribute their practical expertise to IT-for-Green.

Ertemis aims to facilitate knowledge transfer between research and practice and to advance interdisciplinary research on CEMIS 2.0.

3 CEMIS Status Quo: A Literature Review

A common definition explains CEMIS as an organizational and technical system with the ability to collect, process, and supply environmentally relevant information in a company [6]. This definition omits the bigger picture since it does not incorporate any information from supply-chain partners or publicly available information which is needed to make well-founded decisions regarding environmental sustainability. By following the proposed holistic approach using the three modules described in a later section, Green IT measures can be enabled and leveraged.

Present CEMIS follow a rather operative approach with tasks such as legally required reporting [7], therefore there is little assistance when it comes to strategic decision support [8, 9]. Integration with other systems (e.g., ERP, CRM, and publicly available data) and automated sustainability reporting have been broadly discussed in the literature, but are yet to be implemented [10]. These are key components of the future CEMIS, since a contribution to sustainable development can be realized only if the causes and effects of ecological, social, and economic key performance indicators (KPI) are recognized and an efficient way of handling relevant data is developed.

An analysis of third-party funded projects in the field of corporate environmental management from the last decade has shown a need for action and research in the interest of society, politics, business, and science. None of the projects scrutinized aimed at supporting all parts of the environmental management cycle, including input (energy and material efficiency), transformation processes (production integrated environmental protection), and the output side (sustainability reporting and strategic decision support) in a holistic and integrated way. However, a cross-corporate inspection of the sustainability of entire supply chains (sustainable supply chains) has been a relevant topic in scientific literature, but has—as yet—not found its way into business practice. For one of the most advanced approaches to sustainable supply chains, see the chapter by Rizzoli et al. [42] in this volume.

The research network ertemis and the project IT-for-Green will, in contrast to other projects, focus on exactly these aspects (integration of the strategic level and sustainability needs) of the next generation of CEMIS. The new CEMIS systems will provide advantages for business users by enabling them to:

- develop environmental production and reverse logistics processes,
- develop hybrid products (integrated and associated services) focusing on sustainability ideas in order to open up new markets for sustainable products,
- realize an interactive exchange of information between different stakeholders in the field of sustainability reporting based on new Internet technologies (blogs, wiki, semantic web, podcasts, etc.),
- realize synergy effects, cost-cutting effects, strategic advantages etc. by offering or using green services from the cloud (green clouds/Green Service Mall) or based on service-oriented architectures, and
- pinpoint complementary cause-effect relationships and their effects on different targets from a strategic perspective. Complementary in this case means that, for example, pursuing economic targets concurrently supports ecological ones.

Whereas traditional CEMIS might be regarded as rather isolated, function-oriented information systems [8], new CEMIS will take a holistic approach that guides organizations to a strategic orientation. In this way, next-generation CEMIS are—from our perspective—information systems that deal with material and energy efficiency, emission and waste minimization, reverse logistics, stakeholder support, legal compliance, and especially with strategic environmental management. As yet, such systems only exist as concepts within academic discussions and have not found their way into business practice. Therefore, research and knowledge transfer especially into small and medium enterprises (SME) is an important prerequisite for putting such systems into action. Ubiquitous ICT and continuous integration of digital and physical systems allow for a fundamental renewal of business processes regarding sustainable business development, for increased transparency as well as for better control of material and energy usage.

In order to map the entire life cycle of a product, we see a need [11] for three modules that in sum interact as a reference implementation and proof of concept for a next-generation CEMIS. These three modules are Green IT (focusing on energy efficiency in a data center), Green Production and Logistics (focusing on the transformation phase of the product life cycle), and Sustainability Reporting and Dialogue (focusing on sustainability communication). In order to build our research on a strong base of existing literature in the field, we conducted a systematic literature review [12, 13]. The literature review represents the "essential first step and foundation when undertaking a research project" [14], ensuring relevance by avoiding reinvestigation as well as rigor by effective use of existing knowledge [12]. In order to efficiently integrate the knowledge base, we followed the approach of a systematic and concept-centric review [13]. The literature search yielded 18 publications discussing the topic of EMIS/CEMIS in international peer-reviewed journals. The concept matrix depicted in Fig. 1 was developed on the basis of these contributions.

We can see from the matrix that sustainable reporting systems (discussed in 9 publications) as well as key performance indicator based systems (7) and output-oriented systems (7) are the types of EMIS/CEMIS receiving the most attention within the scientific community. This result leads to the assumption that EMIS/CEMIS are increasingly applied within the stakeholder dialogue, i.e., to generate sustainability reports and information on the environmental output of business organizations.

The large number of key performance indicator based systems is evidence for the increased application of EMIS/CEMIS within decision-making, which is also documented by the fact that process data (11) are the main data sources of current EMIS/CEMIS. This evidence correlates well with processes being the most common boundary of the systems (9). Roughly the same number of publications studied refer to each of the environmental media (9–12), reflecting the need for comprehensive EMIS/CEMIS that do not focus on single-scope solutions. Emissions (14), energy (13), waste (10), and material flows (7) are the most frequently mentioned objects of EMIS/CEMIS. This can perhaps be explained by increased application of the systems within the context of energy and material efficiency, which also indicates that EMIS evolve into strategic control instruments rather than operational systems. Model development and simulation (10) as well as active data warehouses (8) are the most common software tools among EMIS/CEMIS. Whereas model development and simulation tools are evidence of a more predictive or proactive use of EMIS/CEMIS, active data warehouses display a continuous demand for documentation systems. The most intensively discussed application areas for EMIS/CEMIS are reporting (10) and logistics (9), followed by procurement (8), production (7), waste management (7), and life cycle assessment (6), indicating the diffusion of EMIS/CEMIS to business domains beyond the classical scope of environmental management. Even though EMIS/CEMIS are predominantly stand-alone solutions (9), integrated systems are increasingly discussed and implemented (6). This brief outline of the observations gained from the literature forms the basis for formulating the following objectives for the implementation of EMIS/CEMIS:

	type						database					environmental medium				object						methods/ tools							application area							integration level			system boundary				
	key performance indicator based	environmental accounting systems	sustainability reporting systems	input-oriented systems	process-oriented systems	output-oriented systems	material master data	structural data	process data	data on energy flows	organizational data	soil	air	water	waste	material flows	waste	emission	energy	hazardous material	facilities	active data warehouses	model development and simulation	environmental databases	knowledge-based systems	document management	artificial intelligence (e.g. neuro-	meta-information	procurement	environmentally friendly production	Distribution/ eco-logistics	recycling planning	waste management	life cycle assessment	reporting	stand-alone	add-on	integrated	product	process	department	company	inter-corporate level
Angeles 2013	x			x			x	x				x	x	x	x	x	x	x	x	x			x							x				x	x			x	x				
Beermann 2011		x		x		x			x	x		x	x	x	x			x	x	x	x		x	x						x				x		x				x			
Carvalho et al. 2012			x		x						x	x	x	x	x	x	x	x	x	x	x	x			x	x									x	x			x			x	
Erlandsson & Tillman 2009	x			x			x					x	x	x	x		x	x	x						x	x			x	x								x	x		x		
Fracchia et al. 2012				x			x	x				x			x	x	x	x	x		x				x				x		x					x				x			x
Govindan et al. 2013	x		x				x					x	x	x	x					x		x						x	x		x	x			x								x
Green & Zelbst 2011			x					x	x		x	x	x	x	x		x	x		x		x			x				x		x				x								x
Hilpert et al. 2013		x				x			x				x					x					x								x			x		x				x			
Green et al. 2011	x		x				x		x	x						x			x			x							x	x	x		x		x			x		x			x
Liu et al. 2011			x					x	x					x			x	x		x		x	x										x		x	x				x			
Loos et al. 2011	x		x		x										x		x	x				x	x						x	x	x	x	x		x								
Meacham 2013			x		x				x		x					x	x		x			x							x		x		x		x			x					x
Méline et al. 2013			x			x			x				x					x					x								x				x	x				x			
Myhre et al. 2011	x					x			x				x		x		x	x					x									x	x	x		x				x	x		
Page & Wohlgemuth 2010	x	x			x		x		x	x		x	x	x	x	x	x	x	x		x		x							x				x						x			
Protogeros et al. 2011		x		x		x						x	x	x	x		x	x	x			x																x				x	
Sarkis et al. 2013		x	x			x	x		x	x					x	x	x		x	x			x	x		x			x	x	x		x	x	x	x		x				x	x
Tian et al. 2011						x			x					x			x	x					x										x			x				x			
SUM	7	5	**9**	5	4	7	7	4	**11**	4	3	9	11	10	**12**	7	13	**14**	10	7	4	8	**10**	2	4	3	0	1	8	7	9	3	7	6	**10**	**9**	0	6	3	**9**	2	3	6

Fig. 1 Concept matrix of EMIS literature

- supporting the realization of eco-friendly production, logistics, and disposal processes,
- enabling analysis of cause-effect relationships between economic and environmental objectives via energy and material flow management to enable sustainable strategic management,
- promoting interactive exchange of information with various stakeholders via reports and documentation of product- and process-related environmental impacts,
- integrating process databases and applications of different departments and locations, e.g., using web portals or cloud computing, and
- enabling model development and simulation as well as storage of data by means of an active data warehouse.

The software prototypes developed and presented in the papers analyzed were not evaluated formally and quantitatively. Besides, it can be seen that the systems developed in the realm of corporate environmental management are for the most part operative rather than strategic. There is still a lack of integration measures, for instance, for integrating CEMIS with accounting and production. In addition, there is a shortage of reference and maturity levels for CEMIS that can be parameterized and configured. So far, the results of the analyzed contributions are basically concepts and prototypic implementations whose comprehensive introduction in companies is still lacking. The market situation of software designed to support corporate environmental protection is relatively fragmented and confusing. Despite the growing importance of the topics environment and sustainability in political, social, and commercial environments, isolated applications are still more common in practice than integrated CEMIS [8].

Within the context of a market study in advance of this contribution, the authors were able to identify 110 software products in the range of corporate environmental information systems. Thus, the structure of the covered application areas is very heterogeneous. The systems can mainly be assigned to the categories

- environmental and environmental law databases,
- environmental management,
- environmental accounting, and
- material flow analysis and compliance management.

According to a research report by the Fraunhofer Institute of Labor Economics and Organization (IAO), approximately 60 % of the respondents use software to support their corporate environmental management [40, p. 90].

According to another study, software support is so far mainly limited to the application of Microsoft Office Excel™. The majority of the companies have not yet installed specific CEMIS [15]. All surveyed companies have environmental management systems in place, in accordance with EMAS or ISO 14001, thus they systematically conduct environmental protection.

Although CEMIS could be an adequate approach to support environmental activities in companies, it must be emphasized that the present concepts have not been able to establish themselves in corporate practice. Rather, they are predominantly used as poorly integrated solutions [16].

Various research projects aim to integrate CEMIS and ERP systems and develop reference models. Such reference models are, for instance: ECO-Integral [17], production and recycling planning as well as monitoring [18], organizational models and information systems for production-integrated environmental protection (OPUS) [19], and the reference model for CEMIS in the realm of in-plant logistics [41]. Despite these efforts, the present reference models have not yet been implemented by the providers of commercial CEMIS software, or at best only to some degree [41, p. 24].

CEMIS have been broadly discussed in the literature for the last two decades from varying perspectives; therefore the above literature review was conducted to identify preliminary work that aids the development of the authors' research. The results can be reviewed in Table 1 below.

4 IT Artifacts Developed in the IT-for-Green Project

The IT-for-Green project, funded by the European Regional Development Fund (EFRE), concentrates on the design of ICT artifacts for corporate environmental and sustainability management. In this development project, the three universities Göttingen, Oldenburg, and Osnabrück collaborate closely with cooperation partners from the region Lower Saxony. The envisaged research results are constructs, methods, models, and instantiations in terms of design research [4]. In order to ensure the relevance of the research, the approach of consortium research was selected. The ICT artifacts resulting from current developments are displayed in Table 3. Since the beginning of the project in 2010, 30 artifacts have already been

Table 1 Overview of related works

References	Contribution(s)
El-Gayar and Fritz [8]	Conceptual overview of CEMIS
	Analysis of supply of and demand for environmental information
	Detailed examples of the stakeholders' influence on environmental reporting
Teuteberg and Marx Gómez [9]	Analysis of the various challenges faced by next-generation CEMIS
	Proposal of a reference architecture
Teuteberg and Straßenburg [10]	Literature review of the scientific progress in the field
	Highlighting of unsolved problems
Melville [2]	Highlighting of the role IS can play in sustainability and environmental performance of organizations
	Research agenda spanning ten research questions, application of the belief-action-outcome framework
	Literature review

developed, and 21 papers on design research have been published. It can be seen that instantiations, the operationalized form of an artifact, as well as models make up the largest share of the development output. The disproportionally high number of instantiations (12) and the small number of methods (2) correlates with the observations in view of related works. The small number of constructs (2), as a highly formalized form of artifacts [4], indicates that research is distinctly applied and industry-oriented. Thus, the strong application and industry orientation of the external investors (EFRE/EU) is mirrored in the scientific project output. What is striking is the high number of models (14). A specific feature of models is the inherent description of the relationship between problem and problem solution [4]. Despite their relatively high degree of formalization, they can be of significant practical relevance [27]. The high number of models in connection with the high number of instantiations thus points to a practice-related approach as the primary focus of the research project. The artifacts construct (2) and method (2) account for only a minor share of development output. Numerically, publications at scientific conferences (12) constitute the largest proportion of all publications. Publications in magazines (1) and books (1) are less frequent (cf. Table 2).

5 Design Considerations of CEMIS 2.0

Both scientists and practitioners were invited to participate in a survey in order to determine properties of next-generation CEMIS (CEMIS 2.0). A total of 33 responses were completed within a timeframe of 3 weeks in August 2011 and subsequently analyzed by the authors using PASW Statistics 18 and Microsoft Excel 2010.

Table 2 Artifacts produced in the IT-for-Green project

Medium	Designation of ICT artifact and source	Artifact according to [4]	Context
Conference	Framework for agent-based, adaptive business applications [20]	Model	Logistics
Conference	Service-oriented architecture [21, 22]	Model, instantiation	CEMIS
Conference	Event engine for automated processing of pre-defined control tasks [23]	Model, instantiation	CEMIS
Magazine	Framework for quality assessment of sustainability reports [24]	Model	SR
Conference	Instrument for process benchmarking [25]	Model, instantiation	Green BPM
Conference, magazine	Ontology, profiling tools, graphical editor, simulation framework [26, 27]	Construct, model, method, instantiation	Green IT
Conference	Conceptual framework [28]	Construct	Eco-balance
Conference	Practice-oriented development of application software [29]	Method, instantiation	Eco-balance
Book	Architecture and functionalities of a tool for web-based sustainability reporting [30]	Model, instantiation	SR
Magazine	BAO Model [31]	Model	SR
Conference	Web portal and maturity model [24]	Model, instantiation	Corporate environmental management
Magazine	Web platform for registration, automated classification, and assessment [32, 33]	Model, instantiation	Cloud services
Conference	Structured catalogue of criteria [34]	Model	BPM applications
Magazine	Design and implementation of an augmented sustainability report [35]	Instantiation	SR
Conference, magazine	Multi-criteria decision model [36, 37]	Model, instantiation	Decision support
Conference	Evaluation framework [38]	Model	SR
Conference	Design and simulation of a balanced scorecard [39]	Model	Sustainable supply chain management
n/a	Online visualization of a CEMIS market study [not published]	Instantiation	CEMIS
n/a	Online visualization of a sustainability report [not published]	Instantiation	SR

57.6 % of the respondents replied that they were scientists, the remaining 42.4 % indicated that they were practitioners. Additionally, practitioners were asked about their company's business sector. The most frequent sectors are chemical, plastics, mining, or energy (41.7 %), printing (16.7 %), and services (16.7 %).

63.6 % of all participants are directly affiliated with the project; 3.0 % are affiliated with the research network carrying out this research, but not with the project itself; and 33.3 % are affiliated with neither the project nor the research network.

Respondents were asked to rate the importance of each design property on a scale from 1 (high) to 5 (low). In the analysis, the design properties were ranked in ascending order by their arithmetic mean, i.e., the sum of all prioritizations of each property, divided by the number of votes. Table 3 shows the ranks of the prioritized properties broken down by votes by researchers, by practitioners, and totals (R); arithmetic mean (AM); standard deviation (SD); differences in mean values (Dif); and the statistical significance of differences among the perceived importance of the properties between practitioners and researchers according to a t-test using independent samples and unequal variance (Sign). As mentioned above, each property was rated on a scale from 1 to 5, resulting in an expected mean of 3. However, the results show that the overall mean score is 2.17 (2.27 for researchers, 2.03 for practitioners); in fact, only 2 of the 47 properties received a total mean higher than 3. The lower the arithmetic mean, the higher the priority. For better legibility, means under 2 are highlighted in bold and means equaling or above 3 in italics; statistically significant differences are highlighted in bold as well. In addition, the means of the top five criteria of each group (researchers, practitioners, and total) are underlined.

Table 3 shows differences in perceived importance for researchers and practitioners. For example, the difference in the arithmetic means for researchers and practitioners for the property "Consistency and traceability/transparency of calculations, information, and reports" (#29) is 0.63 points. It ranks 7th for researchers and 1st for practitioners. According to a t-test, this discrepancy is statistically significant, whereas discrepancies for most other properties are not. The discrepancies can be partially explained by the observation that researchers generally rated properties as being more important than practitioners did. These circumstances illustrate how important feedback from practitioners is to scientists.

Figure 2 visualizes the top design properties (i.e., those with an arithmetic mean lower than 2) and groups them by the goal that is pursued by their fulfillment.

These design properties form the functional and non-functional top-level requirements on which basis we designed the reference architecture of a CEMIS 2.0 (cf. Sect. 6).

Table 3 List of all design properties ordered by arithmetic mean

Design property		Researchers			Practitioners			Total				
No.	Category/Description	R	AM	SD	R	AM	SD	R	AM	SD	Dif	Sign
29	[T] Consistency and traceability/transparency of calculations, information, and reports	7	**1.78**	0.808	1	**1.15**	0.376	1	**1.52**	0.724	**0.63**	**0.008**
22	[T] Export to common file formats	3	**1.67**	0.767	2	**1.36**	0.497	2	**1.53**	0.671	0.31	0.178
25	[T] Flexible and transparent interfaces for integrating existing data and isolated applications	1	**1.53**	0.612	10	**1.64**	0.745	3	**1.58**	0.663	0.11	0.637
11	[O] Assistance with operative and strategic decisions	2	**1.63**	0.831	8	**1.64**	0.929	4	**1.64**	0.859	0.01	0.972
33	[T] Diverse user roles with corresponding rights	4	**1.68**	0.820	7	**1.57**	0.646	5	**1.64**	0.742	0.11	0.662
44	[T] Easy to use and comprehend; promotes enjoyment of work	14	**1.89**	1.049	3	**1.36**	0.633	6	**1.67**	0.924	0.53	0.078
40	[T] Good documentation/manuals/context and online help	6	**1.74**	0.562	12	**1.64**	1.082	7	**1.7**	0.81	0.10	0.77
20	[T] Automated calculation of KPI	5	**1.68**	0.749	20	**1.79**	1.122	8	**1.73**	0.911	0.11	0.772
46	[T] Adaptability to existing software and enterprise infrastructure	8	**1.79**	0.631	14	**1.64**	1.151	9	**1.73**	0.876	0.15	0.671
39	[T] Selection of level of abstraction (“drill-down”)	12	**1.84**	0.765	11	**1.64**	0.745	10	**1.76**	0.751	0.20	0.459
6	[O] Integration of environmental management in business processes	17	2.00	0.667	5	**1.5**	0.65	11	**1.79**	0.696	**0.50**	**0.039**
7	[O] Data, process, and workflow integration	13	**1.89**	0.832	15	**1.69**	0.855	12	**1.81**	0.833	0.20	0.529
28	[T] Timeliness of data/warning if data are outdated	15	**1.94**	0.802	16	**1.71**	0.726	13	**1.84**	0.767	0.23	0.403
4	[E] Measurable economic, social, and ecologic advantages through software use	16	**1.95**	1.079	17	**1.79**	0.975	14	**1.88**	1.023	0.16	0.656
5	[E] Assistance with monetary valuation of KPI and data	25	2.21	1.084	4	**1.5**	0.519	15	**1.91**	0.947	**0.71**	**0.019**
13	[T] Comprehensive and configurable KPI-dashboards	21	2.11	1.150	9	**1.64**	0.745	16	**1.91**	1.011	0.47	0.172

(continued)

Table 3 (continued)

Design property		Researchers			Practitioners			Total				
No.	Category/Description	R	AM	SD	R	AM	SD	R	AM	SD	Dif	Sign
16	[T] On-demand (ad hoc) sustainability reporting (automated generation of sustainability reports)	20	2.00	0.745	18	**1.79**	0.975	17	**1.91**	0.843	0.21	0.498
37	[T] Avoidance of informational overload; only display the needed information	19	2.00	0.943	21	**1.79**	0.893	18	**1.91**	0.914	0.21	0.511
10	[O] Avoidance of organizational efforts for management reporting	18	2.00	0.943	23	**1.86**	1.167	19	**1.94**	1.029	0.14	0.71
30	[T] Automated check for erroneous data entry using historical data	28	2.22	0.808	6	**1.57**	0.646	20	**1.94**	0.801	**0.65**	**0.017**
27	[T] Minimal manual data entry	9	**1.79**	0.787	31	2.21	1.424	21	**1.97**	1.104	0.42	0.326
31	[T] Access via browser	10	**1.83**	1.043	30	2.15	1.405	22	**1.97**	1.197	0.32	0.494
43	[T] Handling follows established standard software	26	2.21	1.084	13	**1.64**	0.929	23	**1.97**	1.045	0.57	0.117
45	[T] Adaptation to corporate growth (scalability and modular design)	27	2.21	0.918	22	**1.79**	0.802	24	2.03	0.883	0.42	0.168
19	[T] Display of cause-effect relationships, sensitivity analysis	11	**1.84**	0.501	35	2.36	1.008	25	2.06	0.788	0.52	0.096
9	[O] Analysis of processes and functions	24	2.21	1.032	24	**1.93**	0.997	26	2.09	1.011	0.28	0.435
14	[T] Greenhouse gas emission calculation and management	22	2.16	0.834	28	2.14	1.292	27	2.15	1.034	0.02	0.97
2	[PL] Usage of legally non-mandatory standards and corresponding KPI(-systems) (e.g., GreenScor, CoBIT, ISO 14000)	23	2.16	0.958	32	2.23	0.725	28	2.19	0.859	0.07	0.808
1	[PL] Attention to the dynamics of regulatory requirements	32	2.37	0.831	25	2	1.038	29	2.21	0.927	0.37	0.284
21	[T] Good predefined reports	29	2.32	0.946	27	2.07	0.917	30	2.21	0.927	0.25	0.461
15	[T] Preparation of documentation for audits	33	2.42	0.692	26	2	1.109	31	2.24	0.902	0.42	0.225
17	[T] Generation of an input-/output-balance	38	2.68	0.885	19	**1.79**	0.699	32	2.3	0.918	**0.89**	**0.003**

(continued)

Table 3 (continued)

Design property		Researchers			Practitioners			Total				
No.	Category/Description	R	AM	SD	R	AM	SD	R	AM	SD	Dif	Sign
26	[T] (Automated) logging of fine-granular consumption data from sensory networks	37	2.50	0.707	29	2.15	0.899	33	2.35	0.798	0.35	0.261
8	[O] Adequate mapping of organizational and process structures of the enterprise	35	2.47	1.073	33	2.29	0.825	34	2.39	0.966	0.18	0.574
18	[T] Forecasts, assistance for simulations	34	2.42	1.071	36	2.38	0.87	35	2.41	0.979	0.04	0.916
12	[O] Inter-company networking along the supply chain	31	2.37	0.895	43	2.64	1.082	36	2.48	0.972	0.27	0.446
38	[T] Rich offering of information and KPI for each enquiry	36	2.47	0.772	40	2.57	0.938	37	2.52	0.834	0.10	0.753
34	[T] Anonymous benchmarking with other organizations/organizational units	30	2.32	1.057	47	3.15	1.144	38	2.66	1.153	**0.83**	**0.046**
24	[T] Coverage of the requirements of material flow management	40	2.88	1.111	37	2.43	0.938	39	2.68	1.045	0.45	0.228
42	[T] Process-oriented models of CEMIS, e.g., predefined processes and/or workflows	39	2.74	1.147	42	2.62	1.193	40	2.69	1.148	0.12	0.776
3	[PL] Attention to privacy issues beyond legal requirements	41	*3.00*	1.291	34	2.36	1.151	41	2.73	1.257	0.64	0.143
23	[T] User-specific consumption information for personal benchmarking	44	*3.17*	1.249	39	2.5	1.286	42	2.87	1.289	0.67	0.152
41	[T] Training functionality (e.g., embedded tutorial videos)	43	*3.11*	0.937	41	2.57	1.342	43	2.88	1.139	0.54	0.215
47	[T] Usage of energy efficient infrastructures (e.g., virtualization, cloud computing)	42	*3.05*	1.471	44	2.77	1.235	44	2.94	1.366	0.28	0.56
36	[T] Storage of process instructions, work instructions, safety sheets, environmental statements, and (supplier) certificates	45	*3.33*	1.085	38	2.46	1.45	45	2.97	1.303	0.87	0.081
32	[T] Access via specialized applications for mobile devices (smartphone, tablet)	46	*3.50*	0.786	45	*3*	1.414	46	*3.28*	1.114	0.50	0.249
35	[T] Mapping of inventory lists and inventory cycles	47	*3.53*	1.179	46	*3*	0.853	47	*3.31*	1.072	0.53	0.172

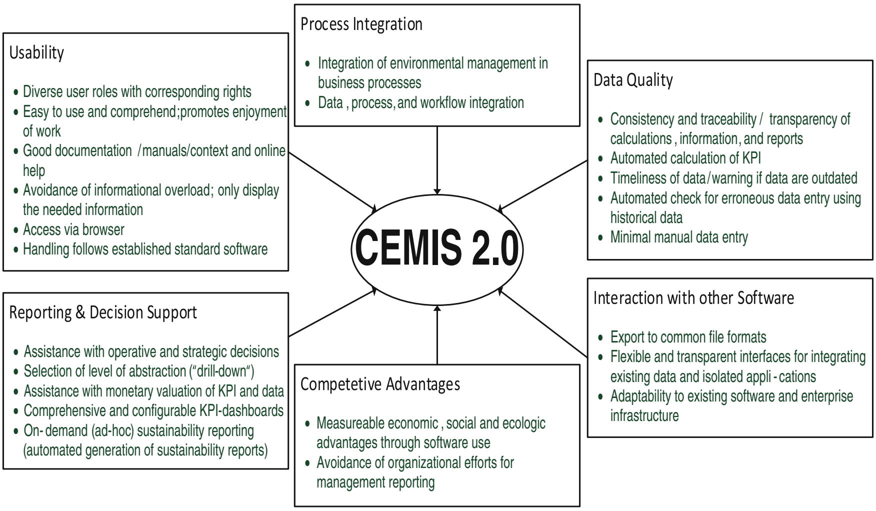

Fig. 2 CEMIS 2.0 top design properties in categories

6 Next-Generation CEMIS 2.0 Reference Architecture

Figure 3 is a schematic diagram of the CEMIS under development in the IT-for-Green project. The runtime environment forms the backbone of the system. It is organized in a modular and service-oriented manner and contains the following core building blocks: Green Service Mall, Workflow Engine, databases, Event Engine, and user interface.

The smallest functional units of the system are realized as Green Web Services and are available via the Green Service Mall. The Green Service Mall provides a service repository that supports all service phases from discovery to invocation and is accessible online.

The registration of external and internal services at runtime permits the development of services that are not available in the stock version of the CEMIS. It is also possible to change or update services at runtime without changing non-involved services and without the need to shut down the whole system. This concept features high flexibility paired with a highly integrative character. Moreover, embedding environmental considerations into any desired business processes allows for intermixed usage by self-hosted services, non-environmental services (such as transforming data into reports), and external service providers.

The Workflow Engine allows users to combine services and processes to create workflows using a graphical editor and manages the execution of workflows. "Execution" means starting, pausing, and stopping workflows, including the persistence of data and the actual workflow state. The engine enables internal business processes of an organization to discover and invoke Green Web Services, regardless of their origin (internal or external service provider). Due to various heterogeneous data, the architecture supports different kinds of database technologies,

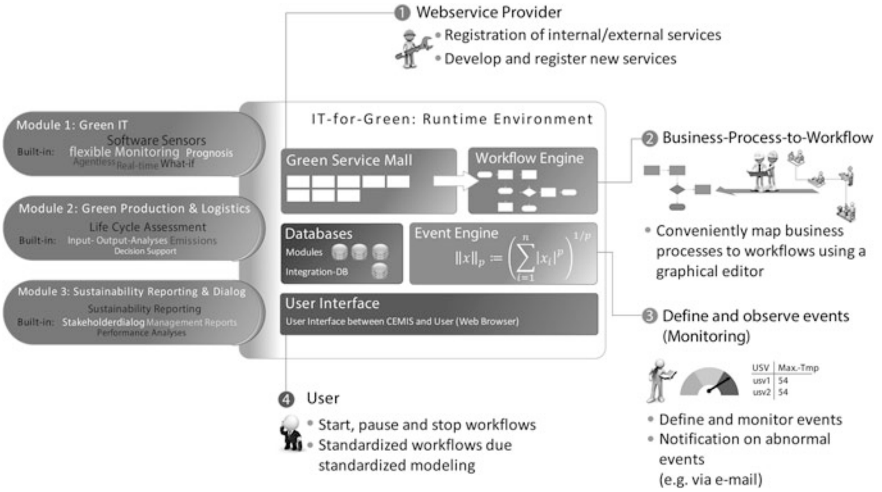

Fig. 3 CEMIS schematic diagram

such as relational databases or document-oriented databases (such as XML based databases). The Event Engine allows monitoring and ad hoc reporting of events by continuously comparing current states of user-selected indicators with “regular” behavior. Regular behavior in the current implementation is inferred from historical data, but can also be inferred from more complex methodologies (implemented as Web Services). If a collected data point varies significantly from historical means, predefined events may be triggered (e.g., sending a text message to a decision maker if the carbon footprint of a specific product is too high).

The user interface of the runtime environment visualizes the software and allows user interaction via a web browser. This means that the interaction is platform-independent and also that integration of an optimized mobile-device interface is possible. Interaction between a user and the runtime environment can be divided in two parts: the interaction between a user and the runtime environment itself and the interaction between a user and workflows. The interaction between a user and the runtime environment was implemented as a web application. The interaction between a user and a workflow needs more flexibility and is even more complex. We integrated a state-chart-based annotation language (SCXML) and extended the language with custom interaction elements (interaction states). Workflows are technically SCXML Documents which define service calls and the custom interaction elements. These custom interaction elements provide the possibility to render client-side HTML elements (or scripts such as JavaScript). This offers the opportunity to combine service calls with user-driven interaction in a flexible manner. Authorizations for specific functions (e.g., service calls, workflow execution) can be granted by using the rights and role system that is responsible for issuing permissions. The rights and role system does not restrict access to individual services, it hides the information from the unauthorized users (or groups) instead.

Table 4 Statements on the success factors and problem areas in consortium research

Success factors and problem areas	Central statements of the interviewees
Time arrangements	Major concern prior to the project, time problems especially with high-ranking dialogue partners
Cooperation based on mutual trust	Trust through: insight into one's own data, business processes, mutual benefits, secrecy, addressing of problems, anonymization
Goal setting/objective	A cooperative attitude on the part of project management is of central significance The importance of the various ways of transferring knowledge (publications, programming/development of artifacts, organization of conferences) within different groups (professors, employees, practitioners) must be respected The heterogeneity of the partners leads to different expectations, goals, and needs Practitioners prefer solutions to a specific problem, they are not interested in abstractions Scientific goal-setting should be viewed in an abstract way; the main focus is not on the identification of solutions for individual problems, but on finding universal solutions valid for a defined group of objects The central idea and the milestones for the achievement of the goals need to be recognizable Goals should be categorized in "must-be", "should-be", and "optional ("nice-to-have")"
Scope of action/access to resources	A realistic assessment of the partners' resources is difficult (software environment, external service provider, access to data) Projects that are classified as business-critical (e.g., hazardous materials) are more likely to be avoided. Especially in the realm of sustainability, practitioners are careful with respect to their company's image Restrictions of the practitioners' scope of action and creativity must be taken into account
Disclosure of results	Especially in the field of sustainability, companies highlight cooperation with universities in their external communications Publication of the scientific results must be enabled by means of agreements with regard to confidentiality
Participants'skills	The varying skills of the participants, especially of programmers, moderators, and employees working conceptually, need to be recognized and valued. The choice of partners should be addressed systematically Support provided by moderators, external partners, service providers such as management consultancies, networking, and a moderation partner who can, as a person from outside, offer constructive criticism and express recommendations are all valuable Particularly among heterogeneous partners, skills and knowledge gaps can easily be detected
Application of methods	The scientific partners should complement each other in terms of methods (e.g., prototyping, evaluation research, empirical

(continued)

Table 4 (continued)

Success factors and problem areas	Central statements of the interviewees
	research) and share a common basis in terms of high-level scientific quality Practitioners should be integrated in the scientific work by means of practical methods (action and evaluation research)
Conceptualization and implementation	Purely scientific conceptualization is often not applicable in reality Practitioners should be integrated as early as the design phase by means of a proactive contribution of real data
Research capacity	Scientific research projects are sometimes given low priority by companies, which may lead to delays Practitioners reduce capacities in case success is not apparent (warning sign) Development of case studies by practitioners and application of the prototypes in reality. This is indeed a problem as action research consumes staff/resources and interferes with daily business
Communication/organization	A central success factor is task-sharing among the partners There must be a two-way textual communication Clarity about communication even before the start of the project shapes expectations Contact persons need to be designated and reachable. A communication structure needs to be recognizable
Personal success and motivation	Intrinsic motivation for the project on the part of the practitioners is an important factor The benefits of the project results (e.g., business models, licensing models, spin-offs) should be discussed early on to enhance personal motivation Heterogeneity of the partners allows for creative problem-solving A project depends on the individual commitment of the participating parties Create personal successes for employees: newly acquired methodological and technical skills, experiences in cooperating with practitioners, an opportunity to get away from the everyday routine at the university and the company

7 Lessons Learned and Implications for Theory and Practice

Prior to this contribution, 11 researchers of the IT-for-Green consortium research project were surveyed as to their experiences, and as a result, 11 success factors and problem areas for consortium research were identified. Table 4 shows the interviewees’ central statements. The success of the project is reflected in particular by positive statements made by the practitioners.

8 Conclusions

The results of the literature reviews, the expert interviews, and the industry workshops in the project IT-for-Green made clear that there is a shortage of scientifically sound and practically tested concepts as well as maturity and reference models (best practices) that support sustainable corporate development on the basis of CEMIS 2.0. The currently available CEMIS almost exclusively serve to establish conformity with the environmental legislation relevant in a particular case (end-of-pipe solutions). Economic, ecological, and social performance factors (key performance indicators), that is, the environmental performance of companies, are accordingly documented only ex-post.

In addition, there is a lack of adequate control mechanisms in practice that render transparent and monitor the cause-effect relationships between economic, ecological, and social key performance indicators and that control the measures for the realization of the objectives of sustainable corporate development on the basis of CEMIS 2.0.

A first step toward realization of CEMIS 2.0 has been taken by means of the reference architecture at hand.

The experiences, success factors, and problems (lessons learned) discussed in this paper show current challenges of consortium research for future projects in the realm of CEMIS 2.0.

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Smart Sustainable Cities: Definition and Challenges

Mattias Höjer and Josefin Wangel

Abstract In this chapter, we investigate the concept of Smart Sustainable Cities. We begin with five major developments of the last decades and show how they can be said to build a basis for the Smart Sustainable Cities concept. We argue that for the concept to have any useful meaning, it needs to be more strictly defined than it has previously been. We suggest such a definition and bring up some of the concept's more crucial challenges.

Keywords Smart city · Sustainable city · Sustainable development · Definition of sustainability · ICT

1 Introduction

Increasing environmental awareness and concern, urbanization and technological development have together resulted in an urgent need and opportunity to rethink how we construct and manage our cities. Over the last decades, these interlinked issues developments have started to converge under the new heading of Smart Sustainable Cities.

This chapter aims to provide an introduction to and discussion of the concept of Smart Sustainable Cities. The chapter also aims to suggest a definition of Smart

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Sustainable Cities and to present some core challenges involved in operationalizing the concept. While there are a numbers of definitions of smart cities and sustainable cities, the combination of these two has been less explored. Moreover, given the diversity in definitions of smart cities and sustainable cities, making such a combination is not an easy task. A definition of Smart Sustainable Cities is nevertheless needed to provide a joint understanding of the concept and to function as a basis for further discussions on what Smart Sustainable Cities aspire to deliver.

Following the introduction, the chapter continues by presenting five different developments that form the basis of the concept of Smart Sustainable Cities. This historical backdrop is important since it provides an understanding of how the concept has emerged. The chapter then proceeds to a somewhat more detailed examination of two closely related concepts, namely smart cities and sustainable cities, and what can be learned from these in developing a definition of Smart Sustainable Cities. In the final part of the chapter a number of challenges for Smart Sustainable Cities are presented and discussed. The chapter concludes with a discussion relating directly to the aims formulated above.

2 Five Developments

In the following, we look into five developments that can be seen as the seeds from which the concept of Smart Sustainable Cities has grown.

2.1 Globalization of Environmental Problems and Sustainable Development

A series of UN conferences over the last 40 years have highlighted the increasingly global character of environmental problems. Until the Stockholm conference in 1972, environmental problems were mainly seen as local issues. They were created locally and had local effects. But over the last 40 years, it has become increasingly clear that this is not the case. The Brundtland commission report from the World Conference on Environment and Development [1] put the concept of sustainable development on the agenda, and the subsequent conferences in Rio and Cape Town kept it there. Under the slogan “think global, act local,” the Agenda 21 action plan clearly pointed to the importance of local implementation and action to abate global environmental and social problems.

One of the most evident examples of global environmental problems is climate change. Ever since 1988, the Intergovernmental Panel on Climate Change (IPCC) has explored the causes and potential effects of climate change and has in subsequent reports sharpened their conclusions: climate change is real, and it is being driven by human activities (see e.g. [2]). Moreover, there are a number of other, perhaps equally important global issues that need to be addressed. The rapid decline in biodiversity, the imbalance in the cycles of nitrogen and phosphorous, and the acidification of oceans and changes in land use are other examples of issues where humankind has exceeded global thresholds or is on the verge of crossing them [3].

2.2 Urbanization and Urban Growth

When the 20th century began, about 12.5 % or 200 million people lived in cities [4]. A 100 years later those numbers had increased to 52 % or 3.6 billion people [5]. According to these statistics, more than half of the world's population now lives in cities; a share that is only expected to increase. According to UN DESA, "urban areas of the world are expected to absorb all the population growth expected over the next 4 decades while at the same time drawing in some of the rural population" [5, p. 1]. In 2050 the urban population is estimated to account for 67 % of the global population, albeit with large regional differences. In more developed regions, 86 % of the population is expected to be urban dwellers in 2050, while in less developed regions the urban proportion is expected to be 64 % [5]. According to UN DESA, most of the urbanization will take place through the growth of already existing urban areas. However, contrary to what one might think, the largest part of the growth is expected to take place in relatively small cities.

2.3 Sustainable Urban Development and Sustainable Cities

With more than half of the world's population living in urban areas, this is also where the use of energy, land and other resources is increasingly originating. The ongoing concentration of the global population in urban areas thus implies that these are increasingly important when it comes to addressing issues of sustainable development. In other words, sustainable urban development has become a prerequisite for sustainable development [6].

Combining sustainable development and urbanization issues, the area of sustainable cities has become of interest for research, education, policy making and businesses—an interest that has been manifested in all parts of society. In academia it can be seen in scientific journals, university education, research programs and university departments specifically devoted to addressing sustainable urban development.

In the public sector of policy making and planning, the perceived need for sustainable urban development can be seen in international forums, charters and organizations, in national programs and targets, as well as in local comprehensive plans and environmental programs. Combining the local and the international, networks such as ICLEI (Local Governments for Sustainability), C40 Cities climate leadership group and the Clinton Climate Initiative—Cities program (CCI) aim for mutual learning and sharing of experiences on how to best advance sustainable urban development in practice.

The concept is now also increasingly used by actors in the private sector, especially by consultancies and companies in the construction of buildings, city districts, or entire cities. In Sweden, one example of this is “SymbioCity” a marketing platform developed and run by Business Sweden with the explicit aim of promoting Swedish eco-profiled companies on the international eco-city market [7]. Business Sweden is however not entirely private but jointly owned by the Swedish Government and private businesses [8].

In policy making, planning and the private sector, the concept of sustainable cities has tended to focus mainly on infrastructures for urban metabolism—sewage, water, energy and waste management within the city.

2.4 Information and Communication Technologies

While the increased interest in sustainable development comes from an understanding of the pressure that humanity imposes on global ecosystems, and urbanization is a consequence of people moving to conurbations, the ICT development is commonly understood to be a technological development. Townsend [4] on the other hand depicts the development of Information and Communication Technologies (ICT) and urban growth as a symbiosis. Townsend argues that writing, as the first information technology, was invented to keep track of increasing market activities in the Middle East some 6,000 years ago, and that this made it possible for cities to grow. Much later, the emergence of more advanced communication technology in the form of the telephone and the telegraph supported urban growth by making it possible to keep track of the increased complexity in the industrializing cities.

The development of ICT has had an enormous impact on how people live their lives and on how work, leisure and society are organized. The reduction in the cost and size of computing capacity has facilitated a number of new products, services and business models. From an environmental perspective, the development thus far has been double-edged. On one hand, ICT has made it possible to dematerialize music and books for example and has made it possible to communicate without travelling (see the chapter by Coroama et al. [9] in this volume). On the other hand, it seems that the ICT development has increased productivity, leading to even cheaper products and fuelling the consumption society. Moreover, despite the opportunities for substituting travel with telecommunication, global air travel is increasing [10].

Townsend [4] points out two recent changes in global ICT development and uses those to provide a basis—but also a challenge—for cities to become smart. The first is the transition from wires to wireless, including both telephones and Internet access. The second development concerns the increasing number of devices being connected to the Internet, the transition towards an “Internet of Things”.

2.5 *Smart Cities*

The origin of the concept of Smart Cities can be traced back to at least the Smart Growth Movement of the late 1990s [11]. Gabrys [12] find the roots of the concept earlier, namely from what they call the "cybernetically planned cities" of the 1960s, in proposals for networked or computable cities in urban development plans from the 1980s onwards.

To a great extent, Smart Cities is today a concept advanced by the business sector. It is a catchword that draws enormous interest from companies involved in ICT and infrastructure. Townsend [4] chooses to highlight a few of them, and describes their different interests as: "[i]f Siemens and Cisco aim to be the electrician and the plumber for smart cities, IBM's ambition is [to] be their choreographer, superintendent and oracle rolled into one" [4, p. 63]. From the business side, repacking ICT solutions in a "smart city" framework holds the potential of launching a kind of wholesale concept, and to direct this to the public sector of city administrators.

Most of the ICT included in the smart city concepts already exist. The novelty is thus not so much the individual technologies, products or services but the interconnection and the synchronization of these and the systems they include, so that they work in concerted action. This is also where the challenge is and what makes the market so interesting for the big companies that have the potential to develop those broad solutions.

3 Developing a Definition for Smart Sustainable Cities

There are essentially two approaches to crafting a definition of Smart Sustainable Cities. The first is based on an inductive (bottom-up) approach, by which the definition is developed by looking at and synthesizing how others have defined the concept in theory and/or in practice. Depending on how congruent the identified definitions are, this process may result in one definition or a typology of definitions. The second way is based on a deductive (top-down) approach whereby the process of developing a definition starts out with a hypothesis or a normative statement about what Smart Sustainable Cities should be, on the basis of which a definition is then elaborated. In practice these "ideal types" of approaches are typically combined, either consciously or unconsciously, but with one of them being the dominant approach.

3.1 *Sustainable*

In this chapter we have chosen to develop a normative and deductively crafted definition of Smart Sustainable Cities. A key reason for this derives from an understanding of the word "sustainable" as a normative and socially constructed concept with the purpose of pointing out a desired state or trajectory of development. This means that the definition of sustainable development (or sustainable or sustainability) cannot be based on an inductive approach. The concept has to be defined top–down.[1] For the purpose of this chapter, we depart from the classic definition of sustainable development, as coined by the Brundtland report in 1987 [1]. Since this definition has been both misinterpreted and misused, we also want to highlight that we adhere to the full definition, including the clarification of needs and the limitations to development:

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- the concept of ‘needs’, in particular the essential needs of the world’s poor, to which overriding priority should be given; and
- the idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs” [1].

The definition of sustainable development by Brundtland has a global perspective. In applying it to anything less than the whole world, some kind of addendum is needed. The Swedish government has solved this by defining a so-called “generational goal” stating that “the overall goal of Swedish environmental policy is to hand over to the next generation a society in which the major environmental problems in Sweden have been solved, without increasing environmental and health problems *outside Sweden’s borders*” [13, our emphasis]. Such an addendum can be useful not only for nations but also for smaller units such as cities.

3.2 Smart

The word “smart” is seen here as an instrumental rather than a normative concept. Moreover, smart is understood here as a feature rather than a sign of performance. This means that the opposite of “smart” is not “dumb” in this chapter, but rather “without the use of advanced information and communication technology”. This means that smartness per se is not seen as holding any value. As an instrumental concept, smart is seen here as a prefix denominating an empirical category of products, services and product-service systems in which ICT play a major role. However, it should be stated that not everybody would agree with this interpretation. Hollands [14], later echoed by e.g. Kitchin [15] and Allwinkle and Cruiskshank [16], sees smart not as instrumental but as an intended outcome, which makes smart just as normative as sustainable. On the other hand, Neirotti et al. [11] remark on the importance of not being misled by the word smart: “the

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[1] Top–down here refers to the conceptual and cognitive process of developing the definition and should not be confused with the extent of participation in the process.

number of ‘smart’ initiatives launched by a municipality is not an indicator of city performance, but could instead result in an intermediate output that reflects the efforts made to improve the quality of life of the citizens” [11, p. 25].

If, instead, we had used an inductive approach, we would have concluded that smart is as much a normative concept as a sustainable one, an idea that we will return to in the following section. This would also have led us towards looking at a partly different literature, e.g. including many kinds of innovative city planning. In our view, it is somewhat unfortunate that “smart” has to some extent become interchangeable with “ICT-supported”. But at this point, we find that the concept of Smart Cities has grown so strong that it is better to use it and sharpen its definition than to let it mean everything and therefore nothing. We base this on a belief that connecting “Smart” in “Smart cities” to advanced ICT is the most constructive way forward. Thus, it is a normative choice to use the concept instrumentally.

3.3 Cities

“Cities”, as the object to which both smart and sustainable are attached, is also an empirical category. Here it is used to designate the types of human structures and environments where smart solutions for sustainable development may be found. In contrast to smart, the concept of cities is however not seen as instrumental. The reason for this is that the existence of cities is not seen as optional but is taken for granted. Thus, rather than looking at whether or not cities as such are beneficial to sustainable development, the focus is on how cities can be made more sustainable.

The empirical basis for an inductive definition of Smart Sustainable Cities is weak. Indeed, it is the combination of smart and sustainable that is missing; considering smart or sustainable cities separately offers more material to draw on.[2] Still, the material on smart cities and sustainable cities is relevant for a deductive definition in that it provides a basis for filling the concepts of smart and sustainable with meaning that is related to and thus relevant for cities. Therefore, we explore how these concepts have been defined by others (Sects. 3.4, 3.5), before presenting our own definition of Smart Sustainable Cities (Sect. 3.6).

3.4 Definitions of Smart Cities

Most of the literature on smart cities focuses on either specific types of ICT (e.g. e-services or travel planners), specific opportunities and challenges (e.g. big data),

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[2] A search for “smart cit*” in Title, Abstract or Keywords in SCOPUS gave 683 hits. A search for “smart cit*” AND “sustainable*” gave 100 hits, and a search on “smart cit*” AND “green*” gave 33 hits, 12 of which also appeared in the search on “sustainab*”. A search on “smart sustainab* cit*” gave 1 hit only. Searches made in February 2014.

or specific domains of application (e.g. smart transportation or smart land use planning). Still, a number of examples of smart city definitions can be found:

- "places where information technology is combined with infrastructure, architecture, everyday objects, and even our own bodies to address social, economic and environmental problems" [4, p. 15];
- "when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance" [17, p. 50];
- "are characterized by a pervasive use of Information and Communication Technologies (ICT), which, in various urban domains, help cities make better use of their resources" [11, p. 25];
- "A 'Smart City' is intended as an urban environment which, supported by pervasive ICT systems, is able to offer advanced and innovative services to citizens in order to improve the overall quality of their life" [18, p. 169];
- "a city seeking to address public issues via ICT-based solutions on the basis of a multi-stakeholder, municipally based partnership" [19];
- "A Smart City is a place where the traditional networks and services are made more efficient with the use of digital and telecommunication technologies, for the benefit of its inhabitants and businesses" [20]; and
- "effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens" [21, p. 4].

In further specifying the concept, many researchers such as [17–19] refer to the work carried out at the Centre of Regional Science at the Vienna University of Technology [22], which sees the smart city concept as including six axes or types of action:

- Smart economy
- Smart mobility
- Smart environment
- Smart people
- Smart living
- Smart governance

Neirotti et al. [11] present a slightly different approach, based on a conceptual framework comprising a number of application domains and sub-domains that they see as classifying a smart city. However, with few exceptions, the applications domains are essentially the same as the six axes:

- Natural resources and energy
- Transportation and mobility
- Buildings
- Living
- Government
- Economy and people

3.5 Sustainable Cities

As mentioned above, initiatives on "sustainable cities" have typically focused on technical solutions for a more efficient urban metabolism. The sustainability of a city has typically also been focused on sustainability impacts occurring within the city's administrative boundaries. Together, these two practices result in a situation in which only parts of the challenges and solutions related to sustainable urban development are identified.

The main reason for this is that few (if any) cities are self-sufficient. To support the life of its citizens, the city is dependent on a hinterland, from which resources are taken and to which pollutants and waste are disseminated. In the historical past, this hinterland was located in close proximity to the city, more or less starting on the other side of the city wall. However, due to the processes of industrialization, urbanization and globalization, an increasing share of the goods consumed in the city is produced further and further away. This means that the environmental impacts of the consumption taking place in a city are scattered over the globe, and, consequently, that the environmental impact of a city cannot be delimited to the urban metabolism within the city boundaries. Thus, a better understanding of the concept of sustainable cities requires a global perspective in which sustainability assessments and urban developments are made in a way that takes into account the global consequences of local action or inaction.

A global perspective can be taken in essentially two different ways. One is to use a production-based accounting approach with a full life-cycle assessment, meaning that the impact of a city is determined by the production taking place within the city boundary, including all impacts upstream and downstream of the production. The second way is to use a consumption-based accounting approach by which the impact of a city is determined based on the consumption of a city's inhabitants, no matter where the production of the consumed goods takes place [23]. A consumption-based account thus builds on a relational understanding of space and emphasizes both intra- and inter-generational justice. As a result, the system boundary delineating where ICT solutions can be used includes not only the infrastructures, technologies and everyday life in the city, but the entire life-cycle of products and services consumed by the citizens.

To abate global environmental problems as well as the distributional inequities of environmental and social costs and benefits, a consumption-based accounting perspective is the only feasible way forward.

The issue of system boundaries is also relevant when looking at the social aspects of sustainability. Here, all of the Smart City concepts found focus entirely on the use phase of ICT, completely disregarding the quality of life of people involved in the other phases of ICT's life-cycle (e.g. working in mining, production and disassembly). While this way of drawing the system boundaries for the analysis might make sense at the level of urban governance and planning, it is important that these other aspects are not forgotten.

3.6 What Could We Mean by Smart Sustainable Cities?

Smart Sustainable Cities (SSC) should be seen as an aggregate concept. As shown in Fig. 1, this means that all three parts need to be present for an entity to qualify as a smart sustainable city; if not, the entity is instead a smart city, a sustainable city, a case of smart sustainability—or something else.

In some of the identified definitions of a smart city, sustainability is an integral part. Thus, one might argue that the smart city is the smart sustainable city, and that the word 'sustainable' can be left out without further ado. However, there are a number of reasons why it should be kept.

Firstly, while some smart city concepts include sustainability, this is not the case for all of them. In a literature review of smart city concepts, Kramers et al. [24] found that few of these included explicit environmental sustainability objectives. In contrast to this study, a recent mapping of smart city initiatives in the EU found that "smart environment" and "smart mobility" are the most common types of actions, with 33 and 21 % of all smart initiatives respectively [20]. This also correlates well with the findings of Neirotti et al. [11] in which "Transportation and Mobility" and "Natural Resources and Energy" were found to be the two most common types of application domains for smart city initiatives across the 70 investigated cities. One potential explanation for why the studies by Kramers et al. [25], on the one hand, and by Neirotti et al. [11] and commissioned by European Parliament [19], on the other hand, lead to different conclusions is that there is a divide between how smart cities are interpreted in theory and how they are carried out in practice.

Secondly, none of the identified smart city concepts set up any baseline for sustainability or define what sustainability (or a sustainable city or sustainable urban development) is. And while a smart city concept might get away with not defining sustainability, this is more problematic for a smart sustainable city. A definition of sustainability is important to know what to strive for, i.e. to know for what purposes the smart technologies should be used. It is also important to assess whether the smartness delivers the intended outcomes or not. And it is crucial when it comes to dealing with conflicts between two or more sustainability objectives. None of the smart city definitions identified provides a hierarchy or prioritization of smart aspects or types of applications, which in practice means that smart economy, smart mobility, smart environment, smart people, smart living, smart governance, and such are all assigned the same value.

As a first attempt to define Smart Sustainable Cities, we have chosen to base the concept on the Brundtland definition, while taking the above discussion into account:

A Smart Sustainable City is a city that

- meets the needs of its present inhabitants
- without compromising the ability for other people or future generations to meet their needs, and thus, does not exceed local or planetary environmental limitations, and
- where this is supported by ICT.

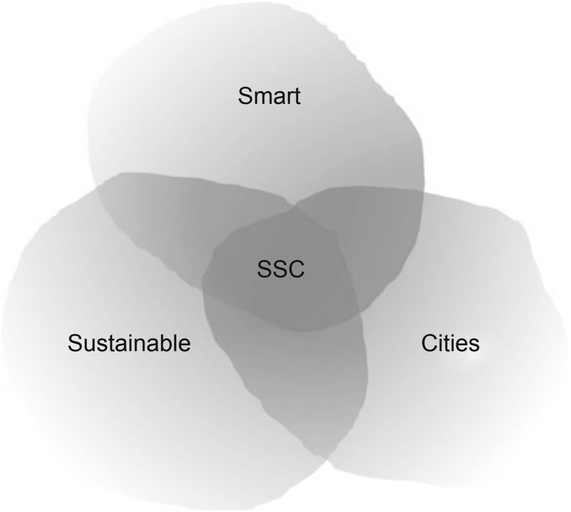

Fig. 1 Cities can be made sustainable without the use of smart (ICT) technology, and smart technologies can be used in cities without contributing to sustainable development. Smart technologies can also be used for sustainable development in other cases than cities. It is only when all these three aspects are combined, when smart technologies are used for making cities more sustainable, that we can speak of smart sustainable cities (SSC)

The definition is a rewrite of the Brundtland definition, complemented with "for other people", in order to emphasize the global responsibility of any city with sustainability claims, and ICT as an instrument to achieve sustainability. With this definition, we assert that ICT in a Smart Sustainable City is used to solve local and global environmental problems while supporting a good life for its citizens as well as intra- and inter-generational justice.

The definition has commonalities with a recent preliminary definition from the International Telecommunication Union's (ITU[3]) Focus Group on Smart Sustainable Cities. Their definition,[4] or a close variant, is likely to become the UN standard definition of Smart Sustainable Cities later in 2014.

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[3] ITU is the United Nations' specialized agency for information and communication technologies.

[4] "A smart sustainable city uses information and communication technologies (ICTs) to provide enhanced quality of life to its citizens, improved efficiency of services and sustainable development. Such a city meets the needs of today without sacrificing the needs of future generations with respect to economic, social and environmental aspects" [22].

4 Five Challenges for Smart Sustainable Cities

Smart Sustainable Cities is an underdeveloped concept. In the previous section, we suggested a definition for it. In this section we present five challenges that need to be addressed for smart sustainable cities to materialize.

4.1 Strategic Assessment

Once Smart Sustainable Cities are defined, it is evident that assessments in relation to that meaning become necessary. Methods and practices need to be developed and implemented. Methods are required that can be used to identify which solutions are needed, and that take a systems perspective on evaluating the effects of the proposed solutions. Without this, "Smart Sustainable Cities" risks becoming just a label without validated content. In developing assessment methods, it is important to keep in mind that in practice it is the assessment, or the indicators included in an assessment, that defines the important characteristics of a smart sustainable city. As mentioned, it is also important to consider how to prioritize between different objectives in case of conflicting interests. Such conflicts may arise between sustainability dimensions (e.g. the conflict between biofuel and food production) or within them (e.g., the conflict between biofuel production and biodiversity).

4.2 Mitigating Measures

Historically, infrastructure development and investment have led to substantial improvements in wellbeing and wealth. Through the implementation of systems for transport, power, water and sewage management, life for billions of people has been improved. As a part of this, infrastructures have also made it possible to create and develop more efficient systems for trade and businesses of various kinds. Infrastructure development is in many ways a backbone of modern society. However, infrastructures have also made it possible to ruin ecosystems and exploit natural resources to an extent that threatens the existence of that same modern society. ICT is in this sense functioning in the same way as other infrastructures; today it plays an increasingly important role in maintaining and developing society and has the potential to support a resource-efficient sustainable society. But it also has the capacity to be used to make modern society an even more efficient machine for over-exploiting the earth. An example of this is using ICT to increase traffic flows in cities. If measures are implemented that make it easier to travel, travel will increase along with its negative environmental impacts. Therefore, the improvements in traffic might need to be paired with other measures. Similarly, counter-measures may be needed to realize the sustainability potential of ICT in other cases as well. Cities must craft mitigating measures at the same time as they encourage technology for efficiency improvements, and they must closely follow how ICT is shaping society.

4.3 Top-Down and Bottom-up

The actual products, services and systems of the smart sustainable city may originate as large-scale suggestions from big companies such as Cisco, Ericsson, IBM or Siemens. One potential benefit of such top–down solutions is that these giants have the economic capacity to fully implement the assessments called for above, and they can function as concrete suppliers of the tools and services that city administrations may want to implement. However, there is also a risk that the strength of the corporate giants can enable them to monopolize smart sustainable city development to the extent that it kills creativity. The bottom–up approach can be represented by hacker communities and other types of grassroots or small-scale initiatives. Many cities have great expectations on the potential for innovation through involving people in formulation and solving of problems. A weakness of this approach is that it can be very difficult to take the solutions to the next level, thus leading to many fragmented small-scale solutions without the power to actually make a big change. Another weakness of this approach is that it can be very difficult to assess the actual outcome. It may be argued that supporting many initiatives will increase the chance of yielding successful ones. This may be true, but it is also likely that others will turn out to be bad from a sustainability perspective.

4.4 Competence

As mentioned in the previous challenge, initiatives from big enterprises can be very effective. They may also be efficient ways of implementing good solutions. However, currently ICT knowledge among companies is so much higher than among city governments that the cities become weak customers. They do not have the capacity to adequately specify their needs or to properly evaluate the offers they receive. This can lead to either bad investment decisions or paralyzed decision making. It is probably in the interest of both city administrations and ICT companies to increase city administrations' competences with regard to ICT solutions for Smart Sustainable Cities. This need has been recognized by the EU Smart Cities Stakeholder Platform, which has developed guidelines for public procurement for smart cities [26].

4.5 Governance

The smart sustainable city calls not only for interconnecting devices but also organizations, requiring a reconsideration of which actors need to be involved in the planning and governance of the city [27–30]. Moreover, for the diverse ICT in the city to work through concerted action, a coordinating body must play a role. This is also important from the perspective of sustainability because of the aforementioned need to strategically assess and evaluate the effects of ICT investments. Lee et al. propose a "[d]edicated smart city team formed with diverse roles and skills to promote smart city development [that is] also recognized by other city's agencies" [30, p. 6]. With a focus on Smart Sustainable Cities, this team could then be given the assignment to promote smart sustainable city development. Over time, such a body could also develop the competence needed to scrutinize offers from ICT companies as well as play a role in balancing top–down and bottom–up approaches.

5 Concluding Discussion

Smart Sustainable Cities is an aggregate concept. In this chapter we have shown that each of the constituent concepts—smart, sustainable, and cities—is important in its own right. Cities can be made sustainable without the use of smart (ICT) technology, and smart technologies can be used in cities without contributing to sustainable development. Smart technologies can also be used for sustainable development in venues other than cities. It is only when all three aspects are combined, when smart (ICT) technologies are used to make cities more sustainable, that we can speak of Smart Sustainable Cities (SSC).

Indeed, the concept of Smart Sustainable Cities is not relevant for all actors and perspectives. For example, from a sustainability perspective it could be argued that whether or not a city uses ICT is a rather unimportant issue as long as it becomes more sustainable. Therefore, the concept of a sustainable city would be enough. And from an ICT industry perspective it could be argued that industry works with smart solutions, while the sustainability part is not their business, and therefore the concept of the smart city is appropriate and sufficient. Those standpoints are valid, but from a more holistic perspective, the concept of Smart Sustainable Cities is needed, exactly because of the two standpoints above.

Connecting the concepts of sustainable cities and smart cities may also raise awareness about the potential of using ICT to promote urban sustainability among planners, IT companies and policy makers. The concept of Smart Sustainable Cities can thus be used as a common framework or joint vision for elaborating new collaborations, business models and ways of carrying out urban development. This in turn highlights the need to avoid getting caught up only in the technological challenges of developing Smart Sustainable Cities and rather taking a proactive approach to actor-networks, governance, and policy innovations.

Defining Smart Sustainable Cities is also important because of the ongoing competition on how to interpret this concept. It has become a concept with positive connotations, and thus it is seen as good to be associated with it. In practice, this can lead to a loss of power for the concept the concept losing its power. By focusing the definition, ICT development based on sustainability concerns can get a competitive edge. By simultaneously emphasizing both smart and sustainable, ICT development could be driven more by sustainability problems, instead of by a pure technical development in which newly developed "solutions" may not actually be solutions to any specific problem.

In this chapter we developed this definition of Smart Sustainable Cities:

> A Smart Sustainable City is a city that
>
> - meets the needs of its present inhabitants
> - without compromising the ability for other people or future generations to meet their needs, and thus, does not exceed local or planetary environmental limitations, and
> - where this is supported by ICT.

However, even if such a definition were to gain broad acceptance among private and public actors, a number of challenges for the practical use of the concept would remain:

- Assessment methods need to be developed and used in order to ensure that cities identified as Smart Sustainable Cities are in fact sustainable;
- Mitigating measures will most likely be needed for implementing policies for Smart Sustainable Cities. Otherwise, rebound effects may well cancel out the positive effects;
- The relationship between top–down and bottom–up initiatives needs further exploration;
- Strategies for strengthening city governments' competences are needed; and
- Governance models for smart sustainable city development must be considered.

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Social Practices, Households, and Design in the Smart Grid

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Abstract Considerable effort is put into the design and development of cleaner and more efficient energy systems. In this paper, we describe the problems arising when these systems are designed from a top-down technological perspective and when much development fails to account for the complex processes involved since people and their practices are key parts of transitioning to new systems. The transition to a smart grid not only demands new technologies, but is also fundamentally dependent on households taking on a role as co-managers of the energy system. The chapter illustrates how the emerging research field of "sustainable interaction design" may play a role in supporting these roles and in shaping sustainable practices.

Keywords Smart grids · Energy use · Sustainable practices · Sustainable interaction design

1 Introduction

Most people do not even realize that they use electricity until the bill arrives. We just use things—we work and play on computers, switch on the lights, make coffee, and watch TV. Even though these things require electricity to work, it is not

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the electricity as such we think about, but the activities. Usually, we do not pay much attention to how our habits and practices rely on electricity use. This is something most people in industrialized countries may agree on. However, in many other areas of the world where the supply of electricity is not as reliable, people's everyday life looks different. For instance, in a country suffering from political and economic instability, the population is affected not least with regard to electricity supply. People may have long power cuts every day in their homes. When this happens, they are painfully reminded about having used electricity. The absence of electricity becomes the evidence for its existence. The lack of electricity is reflected in their lives in a way that radically contrasts their everyday practices from those in the Western world. The unpredictability of then electricity will be available affects households in that they have to learn which activities they need electricity for, and plan to do these when electricity is available. Thus, they might be forced to seize the opportunity to wash, iron, cook, and charge their computers when electricity is available, since they know that that might change from one moment to the next.

The above example describes a scenario where the energy system mediates practices in a way where the relationship between politics and people's household activities is very clear. The instability of the political situation leads to unsystematic delivery of electricity, which in turn has direct consequences for households' access to electricity. In Western society, the relationship evidently also exists, but here, the supply of electricity is taken for granted and conceived of as one of the cornerstones of a modern society. The energy system has traditionally been characterized by centralized production and distribution of electricity and clear institutional borders between the producers and users of energy. However, major changes are taking place in this system that forms the very core of modern society. New "smart" technology is directed toward making the energy system more efficient through peak load management, energy conservation, and local production of renewable energy. The term "smartness" denotes the integration of information and communication technology into the power system. Considerable effort is being invested into the design and development of cleaner and more efficient energy systems. However, these systems have often been designed from a top-down technological perspective, and much development thus fails to account for the complex processes involved since people and their practices are key parts of transitioning to new systems. Society faces a challenge in caring for technical, social, and psychological needs in the development and implementation of the future energy system. This challenge may and must be approached by combining competences from different fields. In this paper we highlight the approaches of social practices and interaction design.

The expected future of the electrical grid is usually referred to as a "smart grid." Although there is no unified concept of what a smart grid is, the transition to smart grids will involve the whole energy conversion chain from generation to consumers (SG3 Roadmap).[1] The power flow will change from being unidirectional to bidirectional between generation, transmission, and end users.

The transition to a smart grid not only demands new technologies, but is also fundamentally dependent on households taking on a new role in relation to the energy system. One aspect of this new role derives from the need for more active consumers who are encouraged to change their energy use patterns in response to supply conditions, e.g. through pricing mechanisms. The second aspect concerns households' involvement in the micro-production of energy, i.e. shifting from being consumers of energy to being prosumers. Prosumer is a term used to denote the dual role of a person being both a producer and a consumer of a certain commodity. Inherent to both of these aspects is the active participation of energy users as co-managers in the energy system.

Few smart grid visions and initiatives have, however, succeeded so far in recognizing and including the social side of energy use in a satisfactory way. Rather than embracing the socio-material complexity of energy use, end users are typically depicted as consumers/producers/prosumers driven only by environmental concern and/or potential economic benefits. Moreover, the willingness and possibilities of these end users to shoulder the role as prosumers and to adapt to the required changes in technologies and practices is rarely made a topic of discussion. Regardless whether ICT is considered as an option for dematerialization, demobilization, or smart operation, see, e.g., [1] end users are a fundamental cog in the wheel of energy production and consumption [2–4].

The aim of this paper is twofold. First, it aims at exploring how the vision of the smart grid fits with sociological insights on the constitution of everyday life and its energy use. Secondly, it discusses the role of interaction design for the formation of sustainable habits and everyday practices in relation to the smart grid.

2 Practicing the Smart Grid

2.1 From Technological Fixes and Behavioral Change…

How planners and policy-makers perceive citizens and behavioral change is decisive for the measures proposed and implemented [5–7]. In current sustainable development agendas, technological fixes and behavioral change often constitute the standard pair of solutions [4]. While technological development (i.e., energy efficiency) is left to market forces or promoted through supra-national or national standards, behaviors are typically tackled through economic incentives and educational campaigns to "empower citizens, as consumers, to make sustainable environmental choices" [26, p. 3]. This is because "only consumers who are aware

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[1] IEC Smart Grid Standardization Road Map, June 2010, Edition 1.0.

of the benefits of energy efficiency and are empowered to make informed choices can be drivers for change" [27, p. 50]. Smart grid initiatives are no exception to this.

Indeed, it has repeatedly been shown that both information and incentives have an effect, but it is also clear that the extent of change is limited concerning the number of people influenced, the scope of the change, and the duration for which it persists (see e.g. [3, 4]). Such shortcomings are typically explained by a deficiency in knowledge, understanding, or commitment [8, 9]. This "deficit model" is typically based on the assumption that if people only knew better, they would change their attitude (A), their behavior (B), and the (consumer) choices (C) they make [10]. However, this "ABC model" of policy intervention receives little support in empirical studies on how information affects behavior [11–14]. One proposed alternative explanation is that many incentives and interventions have been too focused on making technical and economic sense while disregarding the social logic of energy use [4, 12, 15, 16]. This explanation is underpinned by numerous studies clearly showing that technical, social, cultural, and institutional dimensions also need to be taken into consideration in order to understand patterns of consumption [13, 14, 17, 18].

2.2 …to a Social Practice Approach

Warde [19], Shove and Pantzar [20], Hargreaves et al. [21], and Strengers [22], among others, have drawn attention to how practice theory may be used to understand transitions to sustainability. In contrast to the deficit-based explanatory models, social practice theory highlights that understanding energy use requires replacing the idea of individual consumers and instead focusing on practices (what people do) and communities of practice (in which socio-material environments those practices are played out). Accordingly, what people do, and why and when they do it, is not to be seen as the result of individual decision-making, but as both an outcome and a part of an intricate multi-dimensional ecology of everyday life practices, each sustained by a specific mix of materials, images, and skills [20]. The materials dimension comprises technologies and other matters needed to perform a practice. The images dimension comprises the meaning of performing a practice related to a desired image, and the skills dimension comprises both the knowledge and the know-how needed to manage a technology and perform a practice.

In the contemporary smart grid discourse, the materials are at the core; it is through the dissemination and connection of solar panels, smart meters, interfaces, and automation and control devices that the energy system is to become smart. But besides these ICT materialities, transition to a smart grid is also dependent on the dissemination of other types of consumer goods such as electric cars and smart washing machines, see, e.g. [23–25]. The proposed image related to the smart grid is that of the prosumer: an environmentally engaged and economically driven person with a benevolent view of technology; or, to use the wording of the

European Commission [26, 27]: an “empowered” and “informed” type of citizen-consumer. The smart grid also demands a certain set of skills from its users who need to be able to, first, select the “right” types of home appliances and other household technologies needed to make the smart grid function and, second, be able to use and control these technologies in the “right” way.

Drawing further on social practice theory, altering practices requires all three types of elements, i.e. materialities, images, and skills, to be taken into consideration, and not separately, but as a consistent whole: “new practices consist of new configurations of existing elements or of new elements in conjunction with those that already exist. From this point of view, innovations in practice are not simply determined by the generation of new products, images or skills. What really matters is the way in which constituent elements fit together” [20], p. 61.

Thus, in order for smart grid practices to emerge, the materialities need to be related to existing or created images with an appealing connotation, such as in Fig. 1 below, which portrays the smart home in an attractive way, but also to the set of skills needed to perform the practice. In some communities of practice these skills are already in place, in others they need to be developed.

From a social practice perspective, it becomes apparent that an introduction of smart grids does not only imply a change of technologies (from knobs and switches to interfaces, and from old appliances and machines to new and smart ones), but also of practices, which renders it crucial to take into account the entire socio-material context of the proposed change.

2.3 Smart Grid Practices

For the expected potentials of smart grid technologies to be realized, a number of prerequisites need to be fulfilled. Firstly, the smart grid entails a set of new technologies, competences, and meanings that need to be adopted by households. Secondly, the technology must not only be adopted initially, due to curiosity or a flair for novelties, but must be used continuously. In other words, it must become embedded into the practices of the households, which happens only when the technology is linked to both meaning and competence; “products (‘things’) alone have no value. They do so only when integrated into practice and allied to requisite forms of competence and meaning” [20]. If a smart meter is not meaningful to me, I will not use it.

The smart grid concept not only includes new technologies, but also entails a change in roles, namely adjusting energy use to the supply at critical times or in response to energy market prices, which might in turn involve a desired change in householders’ everyday practices in relation to optimal conditions for using electrical appliances. This is usually referred to as load balancing or load management and peak shaving. It might be controlled by the energy companies, or it might entail a change in consumers’ roles, depending upon which strategy is selected. As Nyborg and Røpke [28] observe, the smart grid concept is

Fig. 1 An example of an image of smart technology, also featuring materialities and skills. From: http://www.komsa.com.cn/en/product/product.asp?BigclassID=78

characterized by a high level of *interpretative flexibility* (see also [29]). This is a term from the social construction of technology research denoting how technological artifacts can have different interpretations for various social groups. The smart grid concept sometimes possesses conflicting interpretations of how technological solutions should be designed [28]. For instance, a major issue concerns load management in the household in order to provide flexibility. Should this be up to the households themselves or to the electricity companies? At least two major strategies seem to prevail. One strives for automatic design of dwellings and appliances, whereas the other is directed towards applying instruments to motivate householders to contribute to load balancing and peak shaving. The predominant instruments for motivating consumers to adjust their energy use are dynamic price models and visualization of energy use based on frequent measurements at the household level as well as the level of appliances. The latter will be treated in depth in Sect. 4.

In the following section, we will discuss how interaction design can be used as a tool to these ends, but first we will approach these challenges from a practice perspective.

Peak Load Management Through Laundry. Peak load management is a way to cut or shave peaks in energy use and/or to align them with peaks in energy production. Today, energy use in most households peak at the same time(s). The first peak occurs in the morning when people get up and get ready for school or work. The other, bigger peak occurs in the early evening when people get back home, cook dinner, watch TV etc. Proposals for cutting these peaks include shifting (some of) the energy demanding activities in time, for instance by having "smart" laundry machines take care of the laundry at night instead of in the evening—or during the day when the energy use is high in industries and other work places. However, such a shift relies not only on people being willing to change their laundry routines, but also on household having access to their own laundry machines, which is not always the case. Moreover, it is practically impossible to shift some practices (or the use of material components of practices) in time, such as lighting, cooking dinner, or watching TV. In these cases, the focus must be on energy efficiency rather than on peak load management.

Decreasing Energy Use Through Smart Metering. Another common proposal for smart technology (in the smart grid) to render the energy system more efficient and sustainable is the introduction of smart metering. Smart metering is a both automating and persuasive type of ICT through which the user can control and/or be informed about energy use at home. Much research has explored what effect smart meters actually have on energy use, and the results differ, from realized savings to an actual increase in energy use due to the increased possibility of controlling indoor climate, see e.g. [30, 31]. Clearly, economic or environmental gains do not always carry more weight than comfort.

3 Empirical Studies of New Types of Roles for Households

3.1 Changing Energy Use Patterns

In recent years, a few empirical studies have been carried out to analyze household behavior in a smart grid context. In [32], Christensen et al. explored how differences between Denmark, Norway, and Spain influence the understanding of the role of households in the smart grid. The study also points to challenges and discrepancies in existing approaches to integrating households in the smart grid. The authors especially emphasize the importance of understanding the interaction between smart grid technology and everyday practices.

Another study along a similar path is [33], where Nyborg and Røpke discuss lessons to be learned from smart grid experiments focusing on consumers and the role this type of experiments may play in the construction of smart grids. The experiment studied is the first relating to smart grids in Denmark. The potential of consumers' flexibility was the focus of the study. One question dealt with whether certain groups of consumers are more flexible than others. Another question discussed the nature of consumer groups that were *not* flexible.

The study identified five user profiles: the technical, the economical, the curious, the participating, and the comfortable. The first three are categorized as enthusiastic and the latter two as interested, signifying a lower degree of engagement. The profiles were segmented according to their use of the smart grid equipment installed in their home, their life values, professional background, knowledge of and relationship to "the electricity world," and their motivations for being part of the experiment [33].

The study also identified factors influencing user flexibility. These were: willingness, family composition, life situation, household infrastructure, and smart technology in the home. Some other interesting insights were that there was a significant flexibility potential in the use of heat pumps, that the householders displayed openness towards being controlled by an external stakeholder, and a relatively small experience of loss of comfort.

3.2 Micro-Production of Energy

The second change in practice concerns the shift inherent in the term "prosumers"—in the smart grid, the end users of energy will not only be consumers of energy, but also producers. Private production of solar power is already a reality [34, 35]. When end users become producers, this entails a change of the power landscape of energy provision, trading, and use. Thus, the smart grid implies a new wave of electrification [36] and new networks of power, in the very same dual sense of the meaning used by T.B. Hughes in his seminal book on the electrification of the Western society [37]. This change in the system boundaries of the energy system is positive, as it brings the previously black-boxed end use of energy out into the open, and in the bigger-picture types of energy systems analysis as well. In other words, the increasing interest in smart grids in policy and research holds the potential to make real a long-sought change in perspective on the energy system, from being seen and treated as a mainly technical system managing resources to a socio-technical system managing services [38].

4 Designing for Sustainable Practice

As observed above, materials are at the center of the current smart grid discourse. It is through the dissemination and connection of solar panels, smart meters, interfaces, and automation and control devices that the energy system is to realize its "smart" potential. Users, customers, and citizens emerge as vital links between the vision of the smart grid, technology, and new services. These are the end users of technology, and the way they use it depends on the context. Businesses as well as households may be users. The point is that people are carriers of practice, and their various skills in dealing with technology are part of a social practice.

We know from research in the behavioral sciences that the design of people's physical and technical space has a strong impact on their behavior. In the context of the smart grid, people must be regarded primarily in their roles as human beings, who are busy with their everyday activities and practices, rather than merely being users of electricity. The design of new technology relating to the smart grid needs to take this into consideration at every point of contact between people and the smart grid. It needs to take into account the users of the technology.

The design of this technology, including interface, information, etc., plays an important part in realizing the smart grid ideas in a way that also fits the users it is targeting.

4.1 Sustainable Interaction Design

The emerging research field referred to as "sustainable interaction design" [5] focuses on how interaction design may play an important role in shaping sustainable practices. So far, contributions in the field have mostly dealt with eco-feedback devices, i.e., devices providing feedback on certain types of energy-related behavior [39, 40]. The feedback usually consists of information on electricity consumption and conservation. Major research issues concern the relationship of the design of this feedback to comprehension, engagement, and behavior of users. Most studies target household practices [39, 41], but a few are also directed to workplace practices [41, 42]. Although applying design to engage people in the subject of sustainability is still in its infancy, some of the first experiments using interaction design for visualizing energy use were carried out around 2004—the Power-Aware Cord (Fig. 2) being an early prototype to illustrate how electricity feedback could be provided without detailed information represented in numbers or graphs [43]. The Power-Aware Cord is an ambient display in that its presence may be perceived with our peripheral senses, providing continuous information without being distracting or obtrusive. The Power-Aware Cord is a redesigned electrical power strip in which the cord is designed to visualize the energy rather than hiding it. When electricity is used, this is represented through glowing pulses, flow, and intensity of light. Expressing the presence of energy through light can inspire people to explore and reflect upon the energy consumption of electrical devices in their homes (Fig. 2).

Studies in human-computer interaction (HCI) focusing on the design of feedback to make users aware of environmental factors are sometimes referred to as studies of "eco-feedback." Froelich et al. [44] present a comparative survey of the literature in this area, which relates the framework of human-computer interaction to models within environmental psychology relevant for everyday life. The survey addresses behavior change and criticizes eco-feedback studies in that they do not attempt to measure behavior change. Some eco-feedback studies have designed games for teenagers as a platform [45] and studied the use and engagement of the rest of the household in energy conservation. Other examples of the design of domestic eco-feedback applications, which have been studied in households, include the Energy AWARE Clock (Fig. 3) [11] and EnergyCoach [41]. The clock is a portable energy display that can be hung on a wall, placed on a table, or carried around freely. It uses a time (i.e., analogue clock) metaphor to visualize electricity consumption in a home. One intention is to use the clock metaphor in order to depart from the concept of a meter and technological references to the discourse used in the domain of electricity. Another is to facilitate transfer of some desired

Fig. 2 The power-aware cord (designed by the Interactive Institute)

behavioral patterns, such as regularly glancing at an ordinary wall clock. The overall idea of the Energy AWARE Clock is to make electricity use more concrete in relation to ordinary activities as well as being a tool that could encourage discussions about electricity consumption in the home. Recent overviews of the field of sustainable HCI and interaction design are presented in [46–48].

4.2 *Private Energy Production*

User aspects of private and micro production of energy have recently attracted attention. Existing research literature on the user group is quite scarce. Only a few published studies around domestic solar power generation focus on the user groups per se [34]. Tengvard and Palm [34] interviewed 20 households and analyzed their decision-making regarding the adoption of small-scale photovoltaic panels and wind turbines. According to the analysis, environmental concerns are the main motive for these households. Some live ecological lifestyles in which the adoption of photovoltaic panels or wind turbines represents a way to take action in the field of energy. Yet for others the adoption is symbolic in displaying environmental consciousness. Finally, some are motivated by the opportunity to protest against the system with its large dominant actors.

The above results are supported by currently unpublished work from a study carried out by the Interactive Institute. It is important to note that the interviews reported above concern current private producers of wind and solar energy. However, research also needs to focus on the next generation of producers ("prosumers"). The motive of environmental concern identified by Tengvard and Palm [34] is also found in a consumer survey of 2,000 Dutch households [35].

Fig. 3 The energy AWARE clock (designed by the Interactive Institute)

Respondents were asked to report on their *intentions* to produce their own electricity. About 40 % of Dutch households have the intention to generate their own power, with an overrepresentation of young households. Results show that environmental concerns are the largest driver of households' intentions to generate their own electricity. Other motives were affinity to energy and to a lesser extent to technology. However, results did not point to financial motives for households to generate their own power.

Although some research has been carried out on the target group of private producers of energy, design aspects of the field are in their infancy. One issue to be addressed is how to enhance the experience of producing one's own electricity. Another is how to show users how their production relates to their consumption of electricity. This does not appear to be the main concern for manufacturers of solar panels. Some solutions for visualizing domestic energy production are available on the market. These are marketed by the manufactures of the inverters connected to the solar panels, and most of them target a technical user group.

5 Interaction Design for the Smart Grid

In the future electrical grid, people's consumption of electricity will have to be managed in response to supply conditions. This entails, for example, adjusting electricity use to supply at critical times or in response to market prices of energy. In turn, this will involve a change of everyday practices in relation to information communicated about optimal conditions for using electrical appliances.

To address issues oriented toward user aspects of the future electrical grid, research needs to focus on the role of design and design research in the transition to new behavioral patterns and social practices. We need to learn more about implications for people as users of the future energy system. Central issues concern how sustainable practices may be formed in relation to the future electrical grid, what kind of information is needed to attract and maintain people's attention, and how to provide engaging interaction models. Automation and intelligent technology play a role in the area of smart homes, but user aspects need more attention. However, some interesting research on the use of intelligent thermostats has recently been published [49].

Other important aspects are privacy, automaticity of household appliances and systems, and private production of energy. Research in design has a central role for developing concepts and prototypes for communicating relevant information with the purpose of engaging households in the changing energy systems. Questions need to be addressed concerning how design may integrate feedback, aesthetics, and playfulness to influence people's motivation and engagement to change their practices relating to electricity consumption.

In order for people to understand, trust, and make effective use of these new systems, careful attention must be paid not only to the more technical properties, but also to how their use is developed, introduced, and sustained over time. The transition to a smart grid and a sustainable society thus has to recognize the complexity of social practices.

6 The Social Practice Perspective Revisited

Although researchers of social practices use different types of theoretical frameworks, there is a consensus that a social practice perspective may open new opportunities to understand and potentially change everyday practices in a more sustainable direction [50]. This perspective implies that human activities are part of an ecology rather than isolated phenomena. They are viewed as parts of a system. This may facilitate the reformulation of the question "how can we change people's behavior?" into more fruitful formulations in terms of relations and dependencies such as those between everyday practices and power companies, producers of white goods, etc. Regarding electricity use and sustainable lifestyles from a social practice perspective facilitates the discovery of patterns in the analysis of empirical data. There is currently a lack of this type of empirical research. Hargreaves et al. [21] and Christensen et al. [51] provide exceptions.

Strengers [22, 52] approaches the Australian energy system from a practice-oriented standpoint according to which the power grid is seen as a technical system mediating social practices. Including material infrastructure as an element of everyday practices marks a clear contrast to the division between demand and supply characterizing the energy sector. Technology and human activity are clearly divided and approached by different disciplines. However, according to the social practice perspective, technology, infrastructure, and human action are all involved in constituting the practice. Instead of changing individual behavior, social practice theorists refer to a change of elements constituting the practice. This also entails a view of change as something emergent, dynamic, and uncontrollable [52]. The "problem" is about *transforming* technologically mediated social practices. Strengers [52] shows how social practice theory may refocus and reposition roles and practices of professions charged with the responsibility and agency for affecting and managing energy demand.

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Gamification and Sustainable Consumption: Overcoming the Limitations of Persuasive Technologies

Martina Z. Huber and Lorenz M. Hilty

Abstract The current patterns of production and consumption in the industrialized world are not sustainable. The goods and services we consume cause resource extractions, greenhouse gas emissions and other environmental impacts that are already affecting the conditions of living on Earth. To support the transition toward sustainable consumption patterns, ICT applications that persuade consumers to change their behavior into a “green” direction have been developed in the field of Persuasive Technology (PT). Such persuasive systems, however, have been criticized for two reasons. First, they are often based on the assumption that information (e.g., information on individual energy consumption) causes behavior change, or a change in awareness and attitude that then changes behavior. Second, PT approaches assume that the designer of the system starts from objective criteria for “sustainable” behavior and is able to operationalize them in the context of the application. In this chapter, we are exploring the potential of gamification to overcome the limitations of persuasive systems. Gamification, the process of using game elements in a non-game context, opens up a broader design space for ICT applications created to support sustainable consumption. In particular, a gamification-based approach may give the user more autonomy in selecting goals and relating individual action to social interaction. The idea of gamification may also help designers to view the user’s actions in a broader context and to recognize the

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relevance of different motivational aspects of social interaction, such as competition and cooperation. Based on this discussion we define basic requirements to be used as guidance in gamification-based motivation design for sustainable consumption.

Keywords Gamification · Sustainable consumption · Persuasive technology · Technology paternalism · Collaborative software

1 Introduction

The goods and services consumed in industrial societies are the main cause of global environmental impact. Sustainable consumption and production aims at changing “unsustainable patterns of consumption and production” and requires “fundamental changes in the way societies produce and consume” in order to “achieve global sustainable development” [1, p. 12].

ICT applications have been developed to support users in this imperative change towards sustainable consumption. Specifically, eco-feedback technologies and so-called Persuasive Sustainability Systems (PSSs), which are Persuasive Technologies (PTs) in the field of sustainability, aim at inducing users to more sustainable behavior. Whereas eco-feedback technologies have primarily focused on raising awareness by providing information on measurable aspects of sustainability, PSSs go beyond this and suggest predefined actions typically designed to achieve a rational goal. Within current implementations these two technologies usually merge, as in the cases of UbiGreen [2], a mobile phone application supporting “green” choices of transport modes or features in Toyota cars which encourage eco-friendly driving [3]. Recently, community-based approaches encouraging environmentally friendly actions, particularly in regard to reducing residential electricity usage have increasingly been discussed within the field of ICT. Eco-feedback and PT have been expanded to the Internet, sharing usage data and comparing it with predefined benchmarks and social norms. Examples include WattsUp [4], which focuses on social norms and StepGreen.org [5], which additionally suggests actions that “may save money or energy” (p. 2).

In spite of the widely acknowledged desirability of encouraging sustainable behavior, PT has been criticized for several limitations. These involve, in particular, an oversimplified and isolated view on behavior due to focusing on clearly measurable aspects, the inherent technology paternalism and the lack of solution building [6, 7]. These limitations will be explained in more detail later.

The design of ICT solutions to support people in behavior change needs to be approached in a more comprehensive way. Instead of focusing only on predefined solutions, the context of the process causing the consumption has to be analyzed. This requires additional engagement strategies, the (social) context of an action and the user’s cognitive, emotional and social capabilities. Research has shown that games have a high potential for engaging people in a wide variety of ways.

Games tap into the world of "fun", affect emotions and have the ability to involve users more deeply. At the same time they have the potential to motivate users toward a specific course of action without dogmatism [6]. *Gamification* is the use of game or game design elements in *non-game contexts* and has recently become of increasing interest within ICT. "Assuming that people like to play but are confronted in their everyday life with non-motivational activities, gamification is the process that induces motivation in those activities" [8, p. 3]. Gamification does not say anything about how to use game elements in the non-game context or what the non-game context has to be. As a result gamification-based approaches can be found in a wide range of applications. Approaches include loyalty programs (e.g. collecting miles in frequent-flyer programs or stamps in super markets), systems encouraging customers to share information (e.g. showing progress bars and scores such as in LinkedIn [9] and ResearchGate [10]), or motivating consumers to eco-friendly driving behavior (e.g. providing information on average consumption as Toyota does [3]) or to reduce electricity consumption (e.g., by enabling normative comparison as done by Opower [11]).

As a matter of fact, all of these gamification-based approaches are rooted in PT-based design. Depending on the perspective, it could also be argued that recent PT-based approaches include gamification-based ideas (see for example [2–4]). Regardless of where the line between PT and gamification is drawn, all the examples previously mentioned inherit the limitations of PT-based design.

In this chapter, we elaborate requirements intended to guide the design of a gamification-based approach, which motivates sustainable consumption while overcoming the present limitations of PT. Sustainable consumption is embedded in, and influenced by, a complex structure of regulations, communities, large enterprises, and other stakeholders. All of these entities affect a consumer's decision-making process and in their turn may be influenced by it. We believe that in order to achieve sustainable consumption it is important to take into account the influences of all these entities. Our research focuses on the potential role of gamification in this context.

The chapter is organized as follows: Sect. 2 provides some background on PT and discusses the major limitations of PT; we focus on limitations we consider to be relevant, at least in the context of sustainable consumption. Section 3 gives an overview of gamification. Section 4 provides examples of first attempts to introduce gamification into the field of sustainable consumption. Section 5 elaborates basic requirements for gamification-based approaches to sustainable consumption that can guide designers who want to overcome the limitations of PT-based approaches. Finally, Sect. 6 provides preliminary conclusions and identifies open research questions.

2 Persuasive Technology

2.1 Background

The concepts we introduce below are based on Fogg's work on *captology* [12]—the study of computers as persuasive technology.

Persuasion. Fogg defines persuasion as "an attempt to change attitudes or behavior or both (without using coercion or deception)" (p. 15). Thereby, *intention* to change attitudes or behaviors is seen as a necessary condition for persuasion. The goal of persuasion is to generate *intentionally planned* attitude and behavior changes [12, 13]. "Self-persuasion" is a specific form of persuasion in which a person already agrees with the values directing the behavior change and the persuasive system is used in order to "overcome a weakness of the will" [14, p. 645].

Persuasive Systems. Based on the definition of "persuasion", PT can be defined as an "interactive computer system [technology] designed to change people's attitudes and behaviors" [13, p. 1]. Thereby, PT "focuses on the attitude and behavior changes *intended* by the designers of interactive technology products" [13, p. 17]. As an example, Fig. 1 shows a speed monitoring system. The underlying goal is to raise drivers' awareness of their speed and implicitly suggesting driving at the maximal indicated speed limit. Specific applications of PT are usually called "persuasive systems". The application of PT in the domain of ecological sustainability has created the special case of "persuasive sustainability systems" (PSSs). Contemporary PSSs are described as "technologies that sense, interpret, and respond to human activity by providing information intended to change the behavior of individual consumers according to a metric selected in a top-down fashion usually defined as reducing resource consumption" [6, p. 950].

Eco-feedback Technology. Eco-feedback technology provides information (e.g. by mobile phones, ambient displays, or online visualizations) about individual or group behavior and its environmental effects. These applications are based on the

Fig. 1 Information comparison as a persuasion technique (*Source* [59])

assumption that their users lack awareness and understanding of the environmental effects of their everyday behavior [15, p. 1999]. Research on eco-feedback has its roots in environmental psychology and—as some authors claim—may improve PT research [15]. Whereas eco-feedback systems have the character of raising awareness, PSSs tend to persuade consumers to change their behavior in order to achieve a specific system goal.

Communicating with versus Communicating through Computers. Persuasive and eco-feedback technologies are important in human-computer interaction (HCI) research. In HCI, the focus is mainly on people's interaction *with* computer systems [13]. Fogg makes a distinction between this view and the paradigm of computer-mediated communication (CMC). In the first case, the system is viewed as a "participant in the interaction and possible source of persuasion", able to "proactively seek to motivate and influence users, drawing on strategies and routines programmed into it [e.g. by incentives or negotiations]." [13, p. 16].

In the second case, the focus is on people's interaction *through* computer systems, which are used "as a channel that allows humans to interact with each other (e.g. instant messaging and electronic whiteboards for collaboration)" [13, p. 16]. While captology—the study of computers as persuasive technology—investigates how people are persuaded when interacting with computers, we consider that both aspects are equally relevant to a gamification-based approach.

The Scope of Consumption. Consumer behavior has been a subject of research in the fields of evolutionary psychology, anthropology and sociology. In a nutshell, there is high evidence that consumer behavior is mainly influenced by

- Symbolic roles and cultural meanings of consumer goods (e.g. McCracken in [16])
- Social and sexual competition (e.g. Penn in [17])
- Continual process of constructing and reconstructing personal identity (e.g. Soron in [18])

Individual decisions and actions are rooted in routines and based on affective and emotional bursts. They evolve from the complex structure of socio-cultural and socio-economic influences and rely on restrictions due to constraints (e.g. regulations) or current unavailability of possibilities (e.g., due to low income).

PT is usually based on the implicit assumption that information causes behavior change—or at least a change in awareness and attitude that will then cause behavior change. Against the background of the views cited, this looks like a reversion to the era of psychological behaviorism.

2.2 Limitations of PT-Based Approaches to Sustainable Consumption

In this subsection, we present an overview of aspects of PT-based approaches discussed in the literature with a focus on issues we consider particularly limiting in the context of sustainable consumption.

Focus on Measurable Effects. PT-based approaches applied in the field of sustainability usually rely on measurable effects declared as sustainability indicators, for example how much of a resource such as electric energy has been used. The measured data, typically in regard to a benchmark, usually works as a trigger for system actions (e.g. a list of predefined "solutions" such as turning off the lights), with the intention of persuading consumers to move toward the system goal (such as reducing energy consumption).

Measurements are becoming more and more fine-grained, allowing more tailored interventions by PT. In the domain of residential electricity consumption, an approach called Non-Intrusive Load Monitoring (NILM) is becoming popular. The goal of NILM is to recognize household appliances based on their "energy signature". Machine learning algorithms applied for this purpose have been improved over the last years. However, accuracy is still an issue, especially if appliances are new and/or have similar signatures [19] (e.g., dryer and oven [20]). Furthermore, satisfactory answers to privacy concerns are still missing [21].

Despite improvements in such technologies, with a too narrow focus on measured output, even with 100 % accuracy in NILM, interpretation of the meaning attached to an action (e.g. reason, intention and kind of action) and analysis of the process causing the consumption become very difficult or even impossible.

Assumption of Rational Choice. PT-based approaches are often based on the implicit assumption that consumers are rational actors whose only goal is to optimize their activities based on their preferences and knowledge [6]. "Rational choice models assume that human behavior is regulated by a systematic process of evaluating expected utility." [15, p. 2000]. Under this assumptions rational actors in any given situation only take actions that provide the biggest personal gain at the least personal cost. Evidence shows that "ordinary people in ordinary situations are simply not capable of processing all the cognitive information required for so-called 'rational' choices." [22, p. 36]. Benkler [23] argues that under the *homo economicus* assumption, volunteer work for peer-production projects such as Wikipedia [24] would not exist. Even though there are people who show a behavior based on purely selfish choices—a limited form of rational choice—, research has shown that this applies to only one third of the population [23].

Feeding back data from measurable aspects of sustainability makes sense under the assumption of purely rationally motivated consumers. However, consumers are diversely motivated, and the interpretation of change in measured output under the isolated assumptions of rational choices loses sight of the broader motivational aspects of human behavior, and may lead to ineffective action triggers produced by the system (e.g. predefined "solutions" which have no meaning to consumer).

Insufficient Account of Individual Differences and Social Context. PT-based approaches are for the most part built on a foundation that information will trigger a predetermined interpretation and action in all consumers. This assumption can only be made if consumers are seen as identical and isolated agents. In reality, though, consumers come with a "variety of backgrounds, desires, and skillsets" [25, p. 225] and their decisions are influenced by their individual and collective identity. Identity in this context is "the meanings one has as a group member, as a role-holder, or as a person" and part of the self which emerges from social interactions [26, p. 8]. According to Greenwald and Pratkanis [27], the self consists of three different aspects:

- public: 'people [parents, peers, authorities] think I…',
- private: 'I [my inner audience for behavior] think I…',
- collective: 'my family [reference group] thinks I…'.

The development and influential power of these aspects depend on cultural variation, specifically on the *complexity, the level of individualism, and the looseness of a culture*. Based on this view of humanity, it can be assumed that the more all three dimensions are developed, the more likely it is that people will express their private self [28]. No individual self can exist without *social relations*. Mead views the self as "something which has a development; it is not initially there, at birth, but arises in the process of social experience and activity (…)" [29, p. 1]. Baumeister and Leary point out the importance of the need to belong, which "can be considered a fundamental human motivation" [30, p. 521].

Within the design structure of PT-based approaches, while focusing on measurable aspects of sustainability and assuming consumers are purely rationally motivated, it makes sense to consider consumers as uniform agents. However, ignoring the complex interaction between the individual, groups and society locks out major consumer segments and may not lead to solutions that can sustain motivation over a long period.

Paradigm of Raising Awareness and Changing Attitudes. PT-based approaches are typically designed following the paradigm that raising awareness and changing attitudes are the main drivers for behavior change. Research, however, has shown that behavior change does not necessarily come from raised awareness [31], nor from a change in attitude [32]. In fact, the actual influence of awareness on any change in behavior is usually unclear since other factors may also have played a [unknown] role [6]. Empirical results suggest that some behaviors are induced neither by attitude nor intention; on the contrary, observations have shown that "although the attitude-to-behavior connection is not very substantial, the behavior-to-attitude link has been shown to be quite strong" [32, p. 253]. For example, "people may recycle simply as a result of changes in municipal waste collection services, without ever having decided that recycling is a good thing" [22, p. viii].

A too narrow focus on awareness and attitude, assuming purely reactive consumers, misses the power on consumer's decisions deriving from a broad field of various influences. As pointed out before, influences derive from structures into which consumers are integrated such as communities, major corporations, rules and regulations. Moreover, purely focusing on awareness and attitude misses the motivational power given by pro-active engagement opportunities.

Inherent Technology Paternalism. PT-based approaches applied in the field of sustainability are mostly based on the implicit assumption that the designers of the application start from objective criteria for "sustainable" behavior and are able to operationalize them in the application context. The evaluation of the consumer's actions according to these criteria is delegated to the system in order to automatically rate the impact of an action and to recommend alternatives. In this process, "the designer seems to be de facto more knowledgeable about sustainability than the users of PSSs" [6, p. 953]. This attitude is referred to as "technology paternalism". Paternalism is a concept used in ethics, describing an attitude involving imposition of solutions to assumed problems on other persons even without their consent.

The underlying ethical dilemma arises from the fact that an imposed solution on one side clearly "violates the autonomy of the other person". On the other hand, "by not imposing [the solution] one may not do the best possible in the interest of the other" [33].

2.3 Potential for Improvement

PT persuades people rather than creating opportunities for negotiation, reflection and self-conviction. Thereby, the question arises "where to draw the fine line between persuasion and manipulation." [14, p. 634]. Furthermore, PT assumes "that the user has already understood and accepted the larger reason that the technology inscribes" [7, p. 61].

Consequently there is room for innovation to tap a much greater potential for motivating and supporting sustainable consumption through ICT- based solutions.

3 Gamification

In the field of residential energy consumption, systems with the goal of motivating pro-environmental behaviors have evolved from eco-feedback technologies for electricity consumption such as early ambient displays (e.g. The Power Aware Cord [34]) and sophisticated remotely accessible In-Home Displays (IHD) to more actively persuasive systems such as EcoIsland, "a system for persuading users to reduce CO_2 emissions" [35, p. 59]. Recently, especially because of the motivational and engaging character of games, gamification-based design has become of increased interest in this field.

In the following we are going to outline basic design requirements to overcome the limitations of PT to sustainable consumption. Gamification-based approaches have been developed in different fields. The requirements may not be transferable to all of them e.g. approaches to prevent adolescents from substance abuse and relationship violence [36] or to encourage engagement in online debate systems [37].

In Sect. 3.1 we give background information on gamification with a focus on motivational aspects of games being of interest for gamification-based approaches to sustainable consumption. To give a better understanding in how to apply the theoretical background in the physical world Sect. 4 provides first examples to introduce gamification into the field of sustainable consumption. Finally, Sect. 5 follows with an outline of basic requirements for these systems to overcome the limitations of PT.

3.1 Background

Whereas the field of gamification has already been implicitly introduced over the last decades, its terminology is new [38]. One of the most conclusive and most frequently cited definitions of gamification is given by Deterding et al.: “Gamification refers to the use (rather than the extension) of design (rather than game-based technology or other game-related practices) elements (rather than full-fledged games) characteristic for games (rather than play or playfulness) in non-game contexts (regardless of specific usage intentions, contexts, or media of implementation).” [39, p. 13].

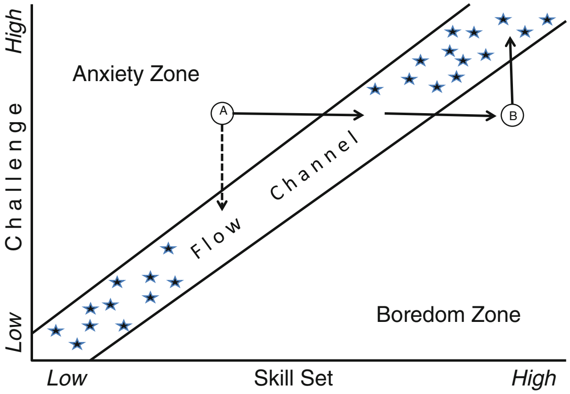
This definition gives a formal understanding of gamification, it does not restrict the aim or scope of a gamification-based system. So far more common in loyalty programs such as frequent flyer programs, recently, the field of gamification has expanded beyond such programs and gained interest in another area: motivating and engaging consumers.

The goal of gamification in this newer area is to engage consumers in the *process of developing their own behaviors*, and it does this by “the process of using game thinking and game mechanics” [38, p. 9].

Gamification does not necessarily require interaction with an ICT system, as the examples of frequent flyer programs and discount stamps show. However, in the following, we will implicitly refer to gamification as an *ICT-based* approach.

Playing or Gaming? According to Deterding and colleagues, playing (from the Greek term “paidia”) refers to a free form of expression, allowing improvisational recombination of different behaviors and meanings, in contrast to gaming (from the Latin term “ludus”) [39]. However, there are no generally accepted definitions of these concepts, even after millennia of thinking and talking about them [40]. In the words of Lehman and Witty: “The whole truth’ regarding play cannot be known until the whole truth regarding life itself is known, for play is; not an

Fig. 2 Flow (*Source* author, based on [46])



isolated phenomenon." [41, p. 7]. We will rely on the following tentative definitions of the concept of game:

- "A game is a problem-solving activity, approached with a playful attitude'. Thereby, 'play' is defined as 'manipulation that satisfies curiosity." [40, p. 37].
- "A game is a rule-based formal system with a variable and quantifiable outcome, where different outcomes are assigned different values, the player exerts effort in order to influence the outcome, the player feels attached to the outcome, and the consequences of the activity are optional and negotiable." [42, p. 5].

Game Elements. Schell, based on various definitions of games, identifies ten elements of a game: "Games are entered willfully, have goals, have conflict, have rules, can be won and lost, are interactive, have challenges, create their own internal value, engage players and are closed, formal systems" [40]. Similarly, McGonigal proposes four defining traits which all games have in common: "a goal, rules, a feedback system and voluntary participation" [43, p. 20].

The Motivational Power of Games. Despite there is no consensus on how to define "game", there is a wide consensus about the motivational power of games [44]. Motivational aspects are manifold, their power depends on diverse influences such as context, interface design and genre, and they can be introduced by different means. We will elaborate on crucial motivational aspects in the following subsections.

Flow. According to McGonigal, the power of a good game is that it "motivate[s] us to participate more fully in whatever we're doing" [43, p. 125]. In fact, researchers in the area of neuropsychology have found evidence that playing video games can release Dopamine, a neurotransmitter, which "may be involved in learning, reinforcement of behavior, attention, sensorimotor integration and activation of the pleasure circuit" [45, p. 266]. This intense neurochemical activation in our brain and body while playing a good game [43] has been referred to as *state of flow*. *Flow* expresses a state of being completely absorbed in what one does [46].

Table 1 Illustration of bartle's player types (based on [60])

Original player types [61]	New implicit types [58]	New explicit types [58]
Achievers want to gather as many points as possible and level up	**Opportunists** look around for things to do and if they see an opportunity, they take it. They avoid obstacles	**Planners** set a goal and aim to achieve it. They perform actions as part of a larger plan and work around obstacles
Explorers prefer to expose the game's internal machinations	**Hackers** seek to discover new phenomena by going where their fancy takes them and have an intuitive understanding of the virtual world	**Scientists** actively form theories and test them. They methodically acquire new knowledge and seek to explain phenomena
Socializers like to connect with other people	**Friends** "interact with people they know well already, have a deep understanding of them, and accept their quirks and foibles"	**Networkers** make an effort to find people with whom to interact, learn from, and hang out
Killers like to impose themselves on others	**Griefers** love to attack and get in your face. Their vague aim is to acquire a substantial bad reputation	**Politicians** manipulate people subtly through forethought and foresight. They want to contribute to the community and get a substantial good reputation

It can be experienced within a small channel between anxiety and boredom and depends on personal (player) skills in regard to a challenge (Fig. 2). *Flow* is individually experienced and can happen in any kind of situation, including non-game activities.

According to this concept, a person (player) in position A (Fig. 2) will try to improve her or his skills in order to reach the channel of flow for the chosen challenge. This is illustrated in Fig. 2 by the solid arrow pointing from position A to the right. A second possibility would be to choose an easier challenge (illustrated by the dashed arrow pointing from position A downwards (Fig. 2)), but in practice this solution seems to be less likely [46]. By further improving the skills, a challenge might be mastered and become boring. In this scenario, the person (player) moves away from the flow channel and ends up at position B (Fig. 2). To go back to the channel of flow, a harder challenge has to be chosen, indicated by the solid arrow pointing from position B upwards (Fig. 2).

Player Types. Based on the observation that different players find different things fun, Bartle developed an extended concept of different player types. In his basic model he hypothesizes that four different player types do exist. In the extended model he specified the player types by each two sub-types (an implicit and an explicit one) (Table 1) and by the possibility that a player will change type over time. Originally defined for players of Multi-User-Dungeon (MUD), a multiplayer real-time virtual world, his framework is useful for various kinds of games.

Model of Skill Acquisition. Based on the model of skill acquisition [47, 48], people seek mastery in whatever they do (e.g. losing weight). The underlying assumption is, that by “acquiring a skill by means of instructions and experience” people “normally pass through five developmental stages”—*novice*, *competence*, *proficiency*, *expertise* and *mastery* [47, p. 0].

Cooperation and Competition. Intra-group solidarity (cooperation) and inter-group competition are two key aspects of human behavior [22] and two basic mechanisms used in game design [49]. Whereas, in competition, “individuals or groups seek to outplay others in accordance with the game rules” [50, p. 7], cooperation encourages participation and collaboration; “the goal is not to win as a player but as a team of players” [51, p. 253]. Both goal structures “can be widely implemented in a non-gaming context” [49, p. 2005]. Moreover, it is also possible to compete with oneself in order to become better now and in the future, compared to the past.

The high relevance of cooperation in motivating players has been demonstrated by Massive Multiplayer Online Role-Playing Games (MMORPG) [52], cooperative games [51], and collaborative game-based learning [50]. An online survey related to player motivation provided data from 3,000 MMORPG players and identified teamwork as an important social component for player motivation [52]. Results of a background questionnaire showed that if they had to choose between cooperative and competitive games, 55 % of the 60 % 6–16 years old kids preferred cooperative games, while 77 % preferred games with both elements [51].

Learning. Learning, whether deliberately or inadvertently, is a key factor in behavior change. “In the social learning system, new patterns of behavior can be acquired through direct experience or by observing the behavior of others” [53, p. 3]. Together with modeling our behavior on what others do, this is suggested by research to be a more promising way for achieving behavior change than raising awareness is [22]. People learn most effectively from models who are seen as more successful by them [53], attractive to them, influential to them or alike them [22]. Collaborative game-based learning builds on social learning and is described as a game that “involves more than one player in gameplay with the pedagogical intention to promote cooperative learning between those engaged in the game.” (p. 4). Key factors for motivating collaborative learning are cooperation and a sense of belonging [50].

4 First Attempts to Introduce Gamification into the Field of Sustainable Consumption

Early approaches including gamification-based ideas have mostly been developed as prototypes with aspects from PT, eco-feedback technology, game design and other related fields. The dominating application domain for these systems is found in the home context, in particular with regard to domestic energy consumption.

In the following, we introduce two examples of prototypes, which often are referred within literature and one example from the industry, all containing gamification-based aspects.

4.1 Domestic Energy Consumption

EcoIsland [35] is a "game-like application" addressing the final goal of reducing domestic energy consumption within a household. In regard to a target CO_2 emission level, which is set by each family, rising energy consumption is correspondingly visualized on an IHD by a rising sea level eventually threatening a virtual island. Avatars representing the household members inhabit the island. Two possibilities for stopping the sea level from rising are provided; either through reduction of energy consumption or by acquiring emission rights. In order to reduce energy consumption, household members can select actions from a list of actions predefined by the system designer (such as turning down the air-conditioning). A lower sea level makes it possible to sell emission rights to other islands (neighboring households). The virtual earnings can be use to decorate the island. All neighbors are able to see all islands and all taken actions.

4.2 CO_2 Emission Caused by Transportation

UbiGreen [2] is a mobile phone application which semi-automatically senses means of transportation and provides corresponding information on the behavior indicating CO_2 emissions caused by taken choices. Small rewards are given to those who take "green" choices (e.g. taking public transportation, carpooling or walking). Feedback is provided over two different interfaces between which users can choose. One shows a tree and the other a polar bear on a small iceberg. Both tree and iceberg indicate green choices. Progress is shown by a sequence of images. At the beginning the tree has no leaves and the iceberg, on which the polar bear is standing is very small. When green means of transportation are chosen, the tree gets more leaves and in the final stage bears apples. Correspondingly, the iceberg gets bigger and harbors more animals (fish, seals, other polar bears), finally the last picture shows northern lights above a large group of polar bears.

4.3 Eco-Friendly Driving

Toyota built a special feature into their Prius line [3], a miles-per-gallon meter, showing the average miles per gallon since the last fill-up. This feature is claimed to be the beginning of a trend called hypermiling [54], a competition where car drivers try to drive as many miles as possible on one gallon. To do this they use different techniques, such as adjusting their driving style, driving behind trucks or driving when it's not windy.

5 Requirements for a Gamification-Based Approach to Sustainable Consumption

By "[attempting] to harness the motivational power of games and apply it to real-world problems" [55, p. 1], gamification offers opportunities for overcoming limitations of PT in the domain of sustainable consumption.

Gamification by itself neither guides the designer through the identification of relevant game design elements nor teaches how to use, apply, and combine these elements (among themselves and within the context). "Yet despite the parallel increase in research on fun, entertainment, and motivation in video game play, we are still in want of theoretical models of the motivational pull of game elements" [56, p. 2].

In fact recent gamification-based approaches have been criticized for just randomly applying game elements, neither considering the application context nor the user's background. This is why they "will fail to drive participation and sustain user engagement" [57, p. 6]. Moreover, as pointed out in the previous section, current gamification-based approaches usually inherit some fundamental limitations of PT-based approaches.

We therefore define four requirements that can help constraining the search space for good design in the field of gamification-based approaches to sustainable consumption. This set of requirements is derived from the results and perspectives discussed in the preceding sections.

5.1 Requirement 1: Respecting Consumers as Individuals

Respecting consumers as individuals by enabling skill acquisition and multiple levels and types of challenges in order to provide multifaceted user experiences.

The *model of skill acquisition* [47, 48], the *concept of flow* [46] and the *framework of different player types* [58] together picture the dynamics and diversity of individual consumers. Put in simple terms, consumers include different player types who acquire different skills by different means. Consumers choose these means according to their desired level of challenge with the goal of maintaining themselves in the state of flow.

This dynamic is a driving force of engagement within individuals, and has to be taken into account by gamification-based approaches for sustainable consumption.

Such an approach considers societal, cultural and demographic aspects (e.g., regulations, knowledge, restrictions, location of living, number of children, non-availability of alternatives…) influencing consumers' decisions. This means that consumers should not be treated as users to be merely informed, but as social actors who are engaged in the process of sustainable consumption.

5.2 Requirement 2: Respecting the Consumers' Autonomy

Respecting the consumers' autonomy by designing game dynamics that authorize users to define their own sub-goals and the avenues for reaching their goals (e.g. according to time, place, action, device, brand).

Direct experience is one important factor in learning, which itself is a powerful factor in changing behaviors. Developing more sustainable behaviors with regard to consumption by allowing consumers to design their own routes and choose their own speed (e.g. by defining sub-goals) instead of following predefined paths and system structures, thus respecting consumers' autonomy, is an important part of gamification-based approaches for sustainable consumption.

This approach enables consumers to obtain experience alongside the core (offering an indirect path to sustainable consumption) and gives individual meaning to actions (and to their output). Moreover, consumers are part of the process of solution building. This is both a powerful motivational element and a bottom-up approach generating knowledge for the whole field of sustainable consumption.

5.3 Requirement 3: Introducing the Social Level

Enabling social interaction by providing possibilities for (normative) comparisons of individual achievements and the opportunity to share own experiences and suggestions with others in order to enable social learning.

Gamification-based approaches to sustainable consumption only make sense when taken to the social level. By doing so, the isolated view of actions can be expanded by relating them to the context in which they are carried out.

This overcomes the rational approach of measurable aspects by adding meaning to specific actions. Normative comparisons expand multifaceted user experiences by introducing additional game elements, such as competition. Moreover, the sharing of suggestions and experiences might trigger more solutions and strategies for sustainable consumption and lead to spillover effects.

5.4 Requirement 4: Enabling Collective Action

Enabling group experiences by introducing game elements on a group level in order to expand user experiences and providing more possibilities for engagement, particularly intra-group cooperation and inter-group competition.

This requirement differs from requirement 3 by specifically addressing the experience of collective action. By introducing the possibility of collective actions, gamification-based approaches enable the achievement of group goals. The combination with requirement 2, e.g. reaching group goals while setting individual sub-goals, widens the user experience and provides an additional motivational aspect. Moreover, by taking collective actions, synergetic effects become visual to individuals. This is relevant because single actions taken by individuals are often perceived as a drop in the ocean.

6 Conclusion and Future Work

We have discussed limitations of PT we consider relevant in the field of sustainable consumption, particularly

- the focus on measurable effects,
- the assumption of rational choice,
- an insufficient account of individual differences and social context,
- the paradigm of raising awareness and changing attitudes,
- the inherent technology paternalism.

Gamification-based solutions have great potential for engaging consumers in sustainable consumption, but are not per se immune to the limitations of PT. For this reason, a design framework for gamification-based solutions is needed. Based on existing evidence from the literature in the fields of PT, eco-feedback technology, game design, psychology and related fields, we defined four basic design requirements for gamification-based approaches supporting sustainable consumption. The four basic design requirements are:

1. Respecting consumers as individuals
2. Respecting the consumers' autonomy
3. Introducing the social level
4. Enabling collective action

These requirements are intended to provide guidance to the designer who wants to go beyond the limitations of PT. The definition of these basic requirements is a first stepping-stone toward a design framework for gamification-based approaches to sustainable consumption.

A complete framework will provide more guidance to the designer in selecting features depending on the application context, including cultural factors. Empirical research will be needed to develop aspects of such a design framework by developing and testing hypotheses about the effects of specific types of gamification on motivation in a sustainability context. The most central issue for a process that could be called "motivation design for sustainable consumption" is how to create a link between the physical and social reality. Sustainable consumption is rooted in physical reality, it is about using energy or buying material goods, while these actions are embedded in existing social practices. Gamification adds a virtual world that creates a new link between the two spheres and supports the transformation of practices by using elements of games. Future research based on empirical studies will help to reveal the success factors of such an approach.

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Supporting Renewable Power Supply Through Distributed Coordination of Energy Resources

Michael Sonnenschein, Christian Hinrichs, Astrid Nieße and Ute Vogel

Abstract Renewable Energy Sources (RES) are considered a solution for a sustainable power supply. But integrating these decentralized power sources into the current power grid designed for a centralized power supply is a challenging task. We suggest distributed, agent-based and self-organized control algorithms for distributed units in a “Smart Grid” as a promising but challenging solution. Dynamical Virtual Power Plants (DVPP) are introduced as a first prototype of distributed controlled components of a Smart Grid. Tools and methods for a comprehensive evaluation of such new Smart Grid control methods in terms of technological indicators as well as sustainability indicators will be the next challenge in research and development for computer scientists in this domain.

Keywords Renewable energy · Distributed control · Multi-agent systems · Virtual power plants

1 Motivation and Introduction

Since the work of Schellnhuber [1], research on the integration of renewable energy resources in power systems has proceeded from a sustainability perspective with the goal of reducing the usage of fossil energy resources. This goal refers

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mainly to environmental sustainability with both global and regional aspects along the whole chain of primary energy resource extraction (land-use and mining devastation, toxification due to mining processes) and energy usage (local pollution, greenhouse gas emissions). A transition path towards a reliable and sustainable future energy grid based on a significant share of decentralized renewable energy resources was defined in [2].

According to the 2013 IPCC report on climate change [3], it is absolutely necessary to reduce CO_2 emissions from all human activities to avoid global warming at a level that entails uncontrollable environmental impacts. A significant share of global CO_2 emissions can be explained by the combustion of fossil fuels for power production. Hence, it has become widely politically widely accepted in Europe, to reduce national shares of fossil fuels in power production significantly: The EU aims to generate 20 % of its energy from renewable energy sources (RES) by 2020. In 2050, this share is meant to increase to 85 % for the German electricity supply [4]. Such a politically driven evolution of the power system faces not only economical and societal challenges, but it must also address several technological challenges of ensuring a highly reliable power supply [5]:

- The fluctuating supply from such RES as photovoltaic systems or wind energy converters must be matched to the demand at all times. This requires rapidly controllable power plants such as gas turbines, storage systems, and demand side management.
- Power supply from RES is distributed in the grid; the power flow from large power plants on high voltage levels to consumers on low voltage levels, its current configuration, might become inverted. The grid infrastructure must be adapted to this new operational mode.
- To integrate a large set of small, rather unreliable power plants into the market, new market structures and new business models are needed.
- Distributed power plants, controllable loads and storage systems must also provide so-called ancillary services to contribute to voltage control and frequency control in the power grid.

1.1 Smart Grids

In order to address these challenges, new concepts for power grid operation—especially for the distribution grid—are needed; the notion of “Smart Grids” has been introduced for this purpose. The European Technology Platform (ETP) defines a Smart Grid as an “electricity network that can intelligently integrate the behavior and actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supply” [6]. An overall architecture of a Smart Grid is provided by the European version of the SGAM [7]—originally introduced by the NIST in 2009—as a reference design (see Fig. 1) highlighting interoperability aspects.

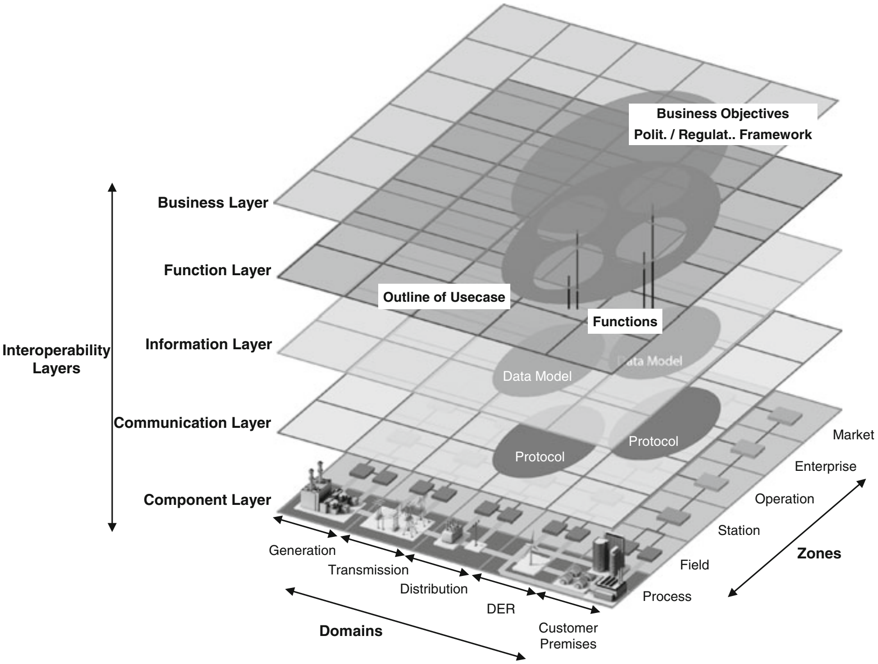


Fig. 1 Smart Grid Architectural Model (SGAM), *source* [7]

On the domain dimension in the SGAM, the energy conversion chain from bulk generation down to the customer premises is depicted, integrating the domain of distributed energy resources (DER) on the distribution level. The management systems for each level form the second dimension, emphasizing the different hardware, IT systems and actors involved from market down to field and process zone. The plane formed by these dimensions is combined with the different abstraction levels from the business level to the communication and component layer as an interoperability dimension. Information security in Smart Grids is an important part of the reference architecture [8], but it is a complicated topic of the subject of ongoing research. A state of the art overview of this topic can be found in [9].

Throughout this contribution we focus on the *function layer in the operation zone* of the SGAM, discussing *services to integrate Distributed Energy Resources (DER) into the power system*. The function layer is based on an information layer and a communication layer offering such information models and communication services as the CIM (Common Information Model) and the IEC61850 standard.

In the operation zone are located for example energy management systems, micro-grid management systems, electrical vehicle charging systems, and virtual power plants. From an ICT perspective, these services to integrate DER and RES into the power grid face several challenges [10]:

- Scalability: Integrate a huge amount of distributed power producers and consumers.
- Aggregation: Support aggregation forms such as virtual power plants.
- Restructuring: Allow transparent integration, segregation and substitution of new components in the ICT-based control system.
- Real time: Guarantee reaction within given time boundaries when using distributed components for system stability issues.
- Robustness: Disseminate critical system functions to redundant and distributed ICT components.

1.2 Virtual Power Plants

One of the most important approaches to efficiently integrate the large amount of DER and RES into the power grid's management system is to aggregate these resources. For this purpose, the concepts of *micro-grids* and *virtual power plants* (VPPs) are convenient. A comparison of both concepts can be found in [11]. Microgrids are physical parts of the power grid that are able to match demand and supply on their own—they can disconnect from the grid if necessary. VPPs were introduced in the late 1990s as a derivation of the *virtual utility* (VU) concept, which is defined as a "[⋯] flexible collaboration of independent, market-driven entities that provide efficient energy service demanded by consumers [⋯]." [12] In addition to this consumer-driven service definition, VPPs may have operational targets such as aggregating energy (commercial VPPs) or delivering system services (technical VPPs) [13]. But unlike microgrids, VPPs are not bound to physical parts of the grid—they are ICT-controlled aggregations of DER acting like large power plants in the market. A number of successful VPP realizations can be found in [14].

However, such VPPs usually focus on the long-term aggregation of generators (and sometimes storages and flexible consumers) only and are each still operated in a centralized manner. For an implementation of automatic restructuring, a more flexible concept is required. In the last years, a significant body of research has emerged on this topic. In this context, autonomous agents and the concept of self-organizing systems are key elements in order to intelligently use the inherent flexibilities of distributed generators, power storage systems and power consumers. For instance, [15] surveys the use of agent-based control methods for power engineering applications. Further exemplary applications can be found in [16–19] (also see the references therein). Finally, a research agenda in this context was proposed recently in [20].

This chapter focuses on the aspect of distributed control of distributed energy resources as an example of how advanced ICT methods can support an efficient, flexible integration of RES into the power grid. In Sect. 2, we give a short introduction to the basics of distributed systems, multi-agent systems, and distributed optimization. The subsequent section introduces a vision of distributed control in power systems. This vision is the framework for our current research in Dynamic Virtual Power Plants (DVPP). In Sect. 4, we discuss challenges in assessing sustainability indicators of such control methods by simulation studies.

2 Modeling of Distributed Systems in Computer Science

After the motivation of distributed control as a promising attempt to integrate RES into the power system, this section introduces the basic concepts of distributed, multi-agent based systems for readers not familiar with.

2.1 Coordination Paradigms

The transformation of the electrical power system towards an integration of renewable energy resources requires a system model able to incorporate a huge number of independent and heterogeneous units, e.g. photovoltaic systems, wind energy plants and combined heat and power plants (CHP). Moreover, these system nodes are not reliable. For diverse reasons, these plants can be temporarily unavailable making demands on robustness and reconfiguration of failing or additional components. Modeling, simulation, and control of such complex systems has been a research topic in Computing Science since the advent of concurrent systems. The main question in the system's design concerns the coordination within the system: the possibilities range from centralized systems, which gather and process all information in a central component, up to completely distributed systems, which solely rely on the self-organized interaction of local components [17].

These diverse system designs have different advantages and disadvantages which must be assessed in relation to the application case. Important evaluation criteria are fault tolerance, i.e. the system's fulfillment of its function even in the presence of faults, and performance, i.e. the system's need for resources (incl. time) to execute its task. Beside this, organizational and application-specific aspects have to be considered: in comparing centralized to distributed systems, important issues are whether sensitive information has to be exchanged and whether the organization of the system reflects the organization of the real world system and its needs. Furthermore, in the power grid domain, the geography has to be considered: power is generated at specific geographical locations and has to be transported via the power network. Hence, the locality of power production and consumption and of information processing has to be considered an important quality criterion.

The traditional power supply system can be seen as a *centralized system*: it consists of a small number of controllable power plants. A "control room" acts as a central component that knows the operational constraints of the plants and stipulates the plants' reactions when deviations from the original operating plans occur. The advantage of this organization is that the system's structure is very simple and easy to control. All information is collected at a central component and decisions can be based on complete knowledge about the system. The disadvantage is that all this (mutually sensitive) information has to be communicated, which creates a source of risk. Furthermore, as the system's goal usually is an optimal usage of its units, the search space of the underlying combinatorial optimality problem grows exponentially with the numbers of units. The amount of information that has to be processed in a single component is mainly responsible for the scalability of the system design. Hence, such a centralized solution is only possible in systems with a low number of units.

Compared to centralized systems, *decentralized systems* also own a central component, that contains all the information about the optimization objective function, but the central component does not have internal knowledge about the units' controllability, which reduces the potential risk of misusing information. In this paradigm, the central unit informs the local units about the objective aspired to. Each local unit determines its contribution to solving the delegated objective and communicates it to the central component. This reduces the combinatorial search space for the centralized component, but the question arises how the global system's objective can be broken down to complementary delegated goals. Here, the contribution of local, decentralized units can be seen as a partial solution. The number of messages that have to be sent increases if the diverse local solutions do not complement each other perfectly and further iterations are necessary.

The continuation of this idea leads to *hierarchical systems* in a tree topology, where each inner node acts as a central component for the units in its subtree. Hence, the communication effort is reduced, as information is only allowed between central components and a small number of assigned local components. Such a hierarchical approach suffers if an inner node of the tree fails. In case of a breakdown, the transmission of information to the root of the tree is disrupted and the unit cannot be incorporated in the optimization process. Besides, the problem of finding delegated but complementary goals for the subtrees causes the global optimum usually only to be approximated in an iterative process.

The hierarchical organization allows the system to reflect the main organization of the power network, which distributes power from the high voltage level to the low voltage level of customers. But for the future energy management it has to be taken into account, that photovoltaic systems and wind turbines feed electricity into the system at the low- and medium voltage level, respectively, such that a temporary reversal of the electrical power flow from top-down to bottom-up becomes possible. In addition, small CHPs, controllable loads and batteries of electrical vehicles are also located in the low and medium-voltage level of the power grid. Thus, approaches are researched that reverse the direction of control: PowerMatcher [21] is a well-known example of a hierarchical bottom-up control approach based on local auctions. It also allows local demand-supply matching in the power system. Of course, all general benefits and drawbacks of hierarchical control systems apply for this approach—static hierarchies in particular are not able to adopt structurally to significant changes in the system e.g. to significantly different behavior of RES and CHPs in the seasons of a year.

Distributed systems are decentralized systems that also allow the direct communication between local components, and *completely distributed systems* are additionally characterized by the absence of a central component. These systems are highly dynamic, as a failure of one node can be compensated for by other nodes. The operation of such a completely distributed system relies on the concept of self-organization, which is defined by Serugendo et al. [22] as a "mechanism or process enabling a system to change its organization without explicit external control". The direct communication also allows contracts between subsets of the systems and, hence, the forming of coalitions, which guarantee partial solutions. Solutions can be constructed bottom-up, starting with the contribution all components can deliver for solving the problem.

The desired characteristics scalability and robustness of distributed systems are gained in return for an increased effort in the coordination and control and in the engineering of dependable algorithms. In terms of the organizational structure, distributed systems reflect the requirements of Smart Grids best. Section 3 will introduce current approaches for the distributed control of dynamic virtual power plants.

2.2 Multi-Agent Systems and Self-Organization

In the previous section the renewable energy resources have been depicted as if their system components themselves were able to act, i.e. to communicate and to gather and process information. As the physical units usually lack such "intelligent" behavior, software components, so-called agents, adopt this task and act behalf of the physical unit. According to Wooldridge [23], such an (intelligent) *agent* is characterized by the following aspects:

- Autonomy: Each agent controls its inner state and is able to perform autonomous actions.
- Social ability: Agents observe their environment and are able to interact with other agents.
- Reactivity: Based on its perception of the environment and its own state, each agent can respond to changes in order to pursue its delegated (local) goal.
- Pro-activeness: Each agent can act in order to fulfill its goal.

A *Multi-Agent System* (MAS) is a distributed system, in which each agent has only incomplete information or capabilities for solving the problem, and the communication as well as the computation are asynchronous [24].

Due to the agents' restricted view of the environment, the system's state is distributed over all the agents, and the behavior of single agents is based on only partial knowledge of the system. But even if the global objective is not known to the agents, such systems can evolve in goal-oriented fashion and exhibit emergent properties that are not intrinsic to the agents' behavior. The challenge of designing distributed systems is to model local agents who receive, process, and distribute as little information as possible, and to define their local goals so that the local behavior of all agents causes the system to converge to the aspired global goal, i.e. to design a "self-organizing" system. Gershenson [25] describes this goal-oriented interaction of elements towards a global goal as a practical notion of self-organizing systems.

For the interaction of agents, diverse protocols have been established that rely on negotiations between agents [26]. The *contract net protocol* describes a self-organizing process that relies on collaborative agents (rather than competitive agents): An agent that decides that it will not achieve its local goal on its own, informs other agents about the subtasks which have to be achieved. These agents decide whether they are willing or able to solve such a subtask and answer with bids on the subtasks. After collecting these bids, the announcing agent chooses contract partners and informs the bidders of his decision. As the bidders themselves can also announce their subtasks and initiate sub-contracts, contract nets can evolve.

In addition, protocols for multi-agent systems have been developed that are based mainly on local decisions of agents regarding their controlled units. These agents interact by communicating their own decisions and their knowledge on the decisions of other agents in the systems. A reference to such a protocol is given at the end of the next subsection.

2.3 Distributed Algorithms

As mentioned before, the system's objective is a combinatorial optimization task, e.g. the minimization of the distance between energy production and usage over time. This optimization objective is the global goal of the system. In distributed MAS, the system's state is distributed over the agents who communicate via messages. The reaction of an agent as well as the transportation of messages needs time. Thus, several basic problems need to be solved. First, it is difficult to determine a consistent system's state, i.e. a snapshot of the system: If an agent is charged with collecting all information of all other agents, the delay time of messages causes the agents to answer the request at different times. Second, as the system evolves towards an optimization goal, the optimization process should stop when the goal is reached. The termination detection is quite difficult too: even if all agents have reached their local goals and are inactive, any pending message could trigger further activities. Thus, the distributed optimization has come to an end when there are neither active agents nor pending messages left.

These basic problems occur in many distributed systems—possible solutions have already been published, e.g. in [27]. Besides these basic algorithms, application-specific algorithms for the distributed optimization have to be developed that ensure the units' operational constraints and the system's convergence towards an optimum. An example of a combinatorial optimization heuristic for distributed agents can be found in [28].

3 Dynamic Virtual Power Plants

In Sect. 1.2, the aggregation of distributed resources into VPPs was identified as an important approach to efficiently integrating large amounts of DER and RES into the power grid's management system. Traditional VPP concepts are usually based on a rather static set of aggregated units under centralized control. However, for an implementation along the transition path towards a reliable and sustainable future energy grid based on a significant share of decentralized RES, a more flexible approach is required. First, the difficulty of long-term forecasts for RES and their seasonal variation in power supply requires highly dynamic aggregation mechanisms that can adapt to changing behaviors, e.g. due to updated forecasts. A second source of variation is varying ambient conditions in the power system such as the current demand in a power market. Third, individual DER are usually owned by self-interested entities. Hence, an aggregation approach that leaves as much freedom of action as possible to the participants is a reasonable choice in this regard. In view of those three presumed properties, variability inside aggregations, variability at the ambient level, and self-interested entities, approaches for the aggregation and management of RES and DER that are based on self-organization principles are a viable option. As described in Sect. 2, such approaches offer the needed dynamics and adaptivity for this case, while in turn requiring an increased effort in the coordination of the participating units at run-time, as well as increased preparatory engineering expenses to construct a dependable system. In the following, we give an example of such an approach and present the concept of dynamic virtual power plants (DVPP).

The DVPP concept is characterized by the use of self-organized control algorithms to integrate decentralized energy units into present active power markets as well as prospective markets for ancillary services. Active power schedules (henceforth referred to as *active power products*) and ancillary services (e.g. primary/secondary control reserve) can be offered on a market by a set of decentralized power producers, local storage systems and controllable loads after having been aggregated *dynamically* to coalitions. Aggregation takes place in a fully distributed and temporally flexible fashion, meaning that the organizational binding resulting from common product procurement is restricted to the provision of a provided product only and coalitions dissolve after their fulfillment. Compared to VPPs, which are constructed as a static set of units acting as an aggregated entity with predefined long-term goals, DVPPs are thus characterized by a large flexibility regarding the pool of aggregated units. Because of the distribution of

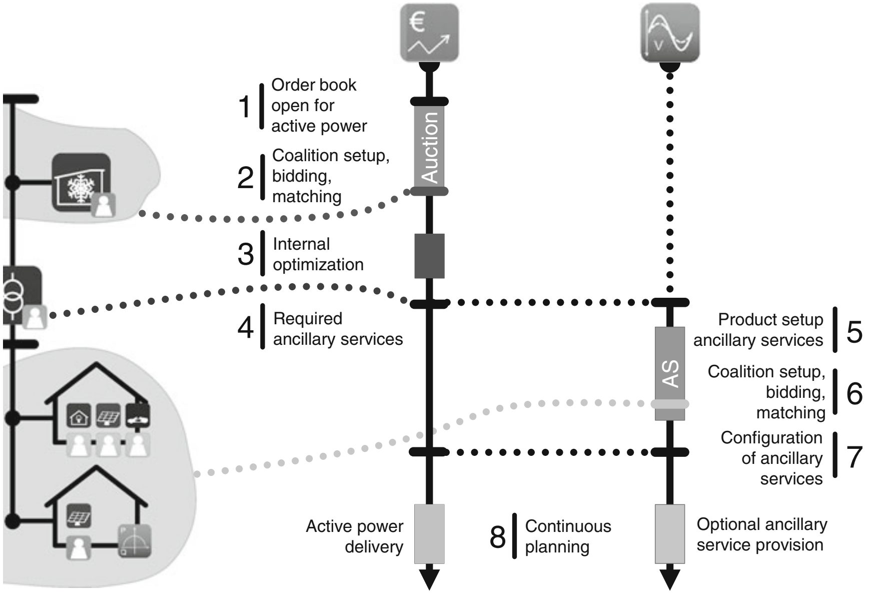


Fig. 2 Conceptual steps for formation and operation of dynamic virtual power plants

both knowledge and control in the system, this flexibility leads to an ongoing adaptation to the system's environment, i.e. the current situation in the market.

A detailed description of the concept, including differentiation from related approaches, was given in [10]. It is important to notice that this concept provides only a vision of how DVPP can be integrated in the current energy market and system. Concrete implementations of this concept have to define the details regarding the use case considered. If for example voltage stability is considered as a system service to be delivered using active and reactive power, or frequency control using balancing energy, different constraints have to be taken into account along the whole process compared to the supply of active power. To illustrate the concept for non-experts in energy systems though, we pinpoint the general characteristics, omitting the details and dependencies needed for specific use cases. Figure 2 shows the conceptual steps involved in the formation and operation of DVPPs within a multi-agent setting (cf. Sect. 2). In this setting, each energy resource is represented by a *unit agent*. Additionally, *market* and *grid agents* serve as communication interfaces for the respective services (e.g. product announcement by the market agent, and grid admissibility check of operation schedules by a grid agent). The visualized timeline (from top to bottom) depicts eight different steps:

- **Step 1—Order book open for active power:** Based on a prognosis for load and supply of uncontrollable consumers and renewable power plants, for a specific period of time in the future (e.g. next day 8 h ahead), a market agent defines active power products and starts an auction for these products.

- **Step 2—Coalition setup, bidding, matching:** The published active power products are used as target functions for building coalitions of controllable loads, storage, and generators. The coalitions are formed in a self-organized process [29] through communication between agents based on the contract net protocol (cf. Sect. 2). Subsequently, an elected representative agent for each coalition bids for products on the market. The bids of all coalitions are matched at the market, thus forming DVPPs out of successful coalitions. Moreover, the operation schedule of all energy resources in a DVPP is checked for local admissibility (in terms of feasible voltage levels and line loadings) by a grid agent behaving as a local arbitrator [30].
- **Step 3—Internal optimization:** After market matching, the schedule of all units in a DVPP is optimized with respect to the accepted product such that the overall benefit for the units of the coalition is maximized, while all constraints of controllable energy resources are still respected [28]. A required compact representation of feasible schedule sets is shown in [31].
- **Step 4—Required ancillary services:** A grid agent responsible for a grid section and thus for a successful product-coalition combination calculates the maximal needed amount of ancillary services within that particular section of the grid [30] and reports it to the market agent.
- **Step 5—Product setup ancillary services:** The needed ancillary services (e.g. short-term real-time changes in active or reactive power necessary for feasible operation) is divided into ancillary service products with local impact and effects. These products are then announced by the market agent.
- **Step 6—Coalition setup, bidding, matching:** Similar to step 2, DVPPs are formed with respect to the announced ancillary service products [32].
- **Step 7—Configuration of ancillary services:** After market matching for ancillary service products, the units within DVPPs have to be configured in order to react autonomously with stabilizing load changes (e.g. to frequency instabilities) for the respective contracted ancillary service product of the DVPP.
- **Step 8—Continuous planning:** Finally, all DVPPs enter the delivery phase, i.e. the period of time of the contracted products from step 1. Note that an energy resource may be part of both an active power DVPP and an ancillary service DVPP. Hence, a rescheduling in technical DVPPs delivering ancillary services as well as prognosis errors for RES or failures of units in DVPPs might affect the delivery of active power products. Therefore, an online adaptation mechanism is employed, that continuously evaluates reliability values and the operating status of each unit and is able to perform a reactive scheduling while respecting grid admissibility [33]. Rescheduling

of active power delivery of a DVPP is based on a variation of the distributed optimization algorithm referenced in step 3.

DVPPs dissolve after product fulfillment (i.e. the end of the delivery phase), and the energy resources may participate in the next trading phase beginning with step 1 again. The approach uses distributed algorithms for formation and operation of dynamic virtual power plants throughout the whole process, thus meeting the requirements identified in Sect. 1.

4 Challenges in Assessing the Sustainability of Distributed Energy Resources Control

Dynamic virtual power plants as defined in the last section are considered to serve the goal of reducing fossil energy dependence by aggregating small distributed energy resources—both renewable generation and controllable loads—to virtual units with a reliable active power profile. With DVPP, flexibility in distribution grids should be used to reduce the overall consumption of fossil fuels, bring renewables to markets and deliver system stability services.

Simulation is a well-established means for evaluating distributed systems' behavior. Usually, in energy systems at least two systems are coupled: On the one hand, the energy system itself has to be simulated; on the other hand, the coordination system as an ICT-based system has to be co-simulated to evaluate the effect of the coordination system on the energy system's components. Up to now, very little work has been done to evaluate sustainability indicators of distributed coordination in energy systems. Assessments usually focus on single aspects of sustainability for specific applications, such as enlarged local usage of renewables in e-mobility [34] or CO_2 reduction gained by end-user decision support [35]. Some studies discuss sustainability on a broader scale, i.e. including provision and systemic effects as well (see e.g. [36] for an assessment regarding greenhouse gas emissions of ICT systems in general). In distributed coordination of energy resources, however, such an assessment is still missing. Therefore, we cannot compare the existing concepts (see Sect. 3) in terms of their sustainability characteristics.

What is impeding the evaluation of the distributed coordination approaches with respect to the main motivational background, i.e. the sustainability performance on a broader scale? Distributed coordination systems can hardly be analyzed following an analytical approach, and experiments in the field cannot sufficiently show the system's behavior on a large scale. Therefore, an evaluation is performed based on simulations to analyze the distributed coordination system in terms of defined evaluation criteria. When sustainability indicators are taken into account in such a simulative evaluation, special requirements have to be fulfilled to answer the main question of whether the coordination scheme under evaluation really helps in reducing the fossil fuel share in energy delivery. In

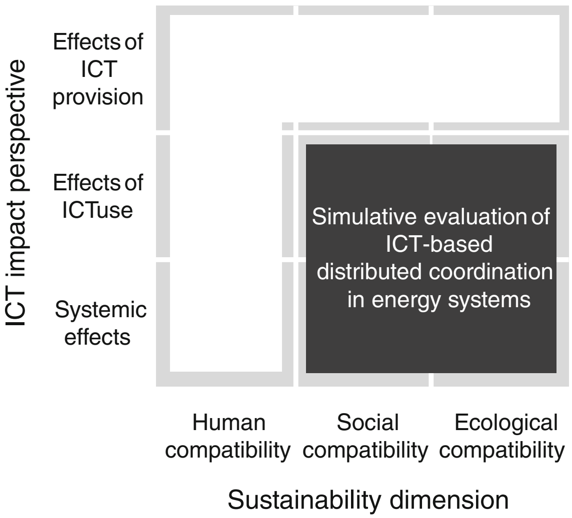


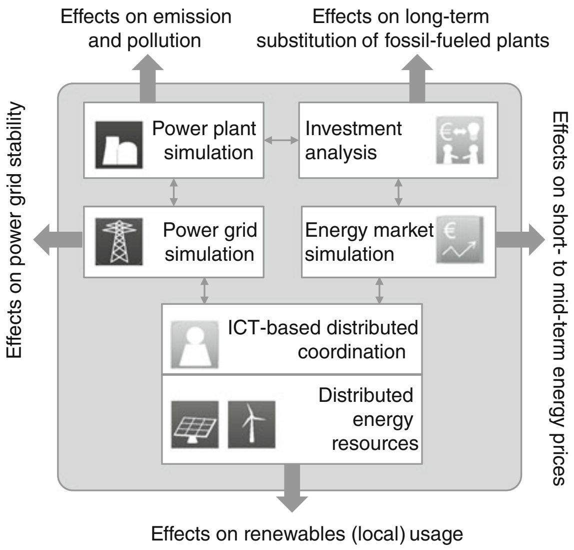
Fig. 3 Sustainability assessment for ICT-based distributed coordination in energy systems following the conceptual framework from [37] (reduced scope)

Fig. 3, a classification of such a sustainability assessment is given following the integrated sustainability model as described in [37] (see Part I: ‘‘Introduction’’ in this book for an overview of this framework [38]). As can be seen, evaluating the substitution effect of ICT-based coordination in energy systems will only cover a small part of the plane formed by sustainability dimensions and ICT impact perspectives.

In the following, we elaborate some challenges in this context and suggest how the substitution effects of (distributed) coordination schemes for the integration of renewable energy resources can be evaluated for a sustainability assessment with such a reduced scope:

- **Effects on emissions and pollution:** In coupled energy systems, a time resolution of less than one hour is needed for the simulation of the system to evaluate which kind of fossil fuel has been substituted in detail. In Germany, for example, the typical mid-time load peak has been covered by gas-driven power plants. On sunny days, this peak is cut off quite often by solar power. If the effect is compared to substituting coal-fired plants, quite a different emission reduction can be found. This can only be analyzed by taking into account both time resolution in supply and demand and the merit-order of conventional power plants. To analyze the effect of distributed coordination in energy systems, we therefore have to couple market information and power system information with a time resolution of 1 h or below.
- **Effects on long-term substitution of fossil-fueled plants:** Taking the example of solar power cutting the mid-day load peak, it can be seen that this has a relevant effect on the revenues generated with gas-fired power plants. To analyze the effects of distributed coordination in energy systems on the overall generation system, we therefore have to couple our simulation

Fig. 4 Hypothetical sustainability evaluation system for distributed coordination in energy systems with the reduced sustainability scope as defined in Fig. 3



results with an analysis of the revenues and investments made in power plants.

- **Effects on power grid stability:** A distributed coordination scheme in energy systems must not lead to violations of operational constraints in the power grid, as this would endanger system stability. Therefore, we have to analyze the effect of distributed coordination on the power grid itself using a power grid modeling and analysis tool and to take into account the results gained from this analysis within the coordination schemes.
- **Effects on electricity prices:** Renewable energy resources have a remarkable effect on the electricity prices at the European energy exchange. This effect, known as the merit-order effect, is dependent on both the current prices for fossil-fueled power generation and the mid- to long-term investment in these power plants. Although the actual price reduction is still subject of discussion it is clear that a price reduction can be expected and has already been valuated on the energy exchanges as a consequence of renewable feed-in. It remains unclear though, when and to what extent these effects will appear on the consumer level—considering social compatibility, this is a highly relevant aspect.

In Fig. 4, an overview of a hypothetical evaluation system is given that would be able to fulfill these requirements and deliver the needed indicators. As can be seen, even for a reduced scope of a sustainability assessment of distributed coordination in energy systems, these requirements cannot be met within a single simulation framework: We would have to couple market simulation, power plant simulation, investment analysis, distributed energy system simulation and ICT-based control. We do not show the circular references in such an evaluation system that additionally hinder setting up such a sustainability assessment system for distributed control in energy systems.

What then is a way out of this trap of complexity? How can we analyze the sustainability of distributed coordination in complex systems like the electrical power system? We give some suggestions for a first approximation:

1. Define the sustainability indicators needed from each simulation framework for an integrated sustainability assessment.
2. Define a common scenario and parameter base for all simulation frameworks used. As the control scheme connects all layers by defining the operation scheme of energy units from different actors' perspectives, the parameter settings for all simulators have to be aligned. Although this sounds self-evident, this is one of the most demanding tasks in the process, as the different simulators work on different abstraction levels, and parameter settings for e.g. the market simulator seem to be independent of the power grid simulation.
3. Define input-output relations to reuse results from one simulator for the next, paying attention to the differences in time resolution and abstraction level of each simulator.
4. Ignore the circular references to separate the different simulators during runtime by flattening the simulation frameworks' runs to a sequence. The injected error can be mitigated by following an iterative approach. Define the minimum number of iterations, taking into account the different possibilities of sequencing the frameworks.

5 Discussion and Open Questions

Integration of large shares of renewable energy sources into the power grid is an essential task to reduce anthropogenic greenhouse gas emissions from the combustion of fossil fuels. This task requires a reorganization of the power grid not only by substituting e.g. fossil fired power plants by wind energy converters or photovoltaic systems, but it also demands for a substantial change in the operation mode of the power grid.

We have shown that distributed, self-organized control methods are an adequate choice to support integration of decentralized power supply into the grid operation—they are a promising research area. For the development of such control algorithms we propose Smart Grid algorithm engineering [39], a methodology integrating simulation-based evaluation of algorithms. Prototypical control methods for dynamic virtual power plants are a first result of applying this methodology.

Control algorithms in this application domain have to be evaluated with respect to several technologically motivated performance indicators, such as robustness, adaptivity, and scalability. Societal aspects such as privacy or data protection have to be integrated into the algorithms “by design”. We discussed issues that currently hinder the evaluation of these control approaches for their effects on the reduction of fossil fuel dependence, namely the needed integration of various simulation models, coupling Smart Grid simulation models, control algorithms, energy market simulation and investment analysis. To this end, we proposed some guidelines on how to reduce the complexity of the evaluation framework needed.

The development of ICT-based distributed coordination approaches in the energy sector has a large potential, but a detailed evaluation with respect to sustainability indicators remains an ambitious task where complex evaluation frameworks still need to be developed.

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Dematerialization Through Electronic Media?

Vlad C. Coroama, Åsa Moberg and Lorenz M. Hilty

Abstract While the traditional roles of the computer as a machine for scientific calculations, text editing, and graphic design are still significant, computers are increasingly perceived as means of accessing information and interacting with other people—i.e., as electronic media. The aim of this chapter is to analyze digital electronic media and their effects on environmental sustainability. Two fields of application are addressed: electronic media that may replace or augment traditional print media such as newspapers or magazines, and videoconferencing as a potential substitute for traveling to a face-to-face meeting or conference. In both cases, the environmental costs of the electronic media are compared to those of their conventional counterparts. The examples show that electronic media can represent an energy-efficient alternative to traditional activities such as long-distance travel. But they can also be added on top of existing activities instead of replacing them. In such cases, a net increase in the environmental impact results. The availability of small, energy-efficient devices being used as electronic media does not guarantee dematerialization. The overall resource use and emissions throughout the life cycle of the media product systems and, more importantly, at the macro level of total global

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production and consumption need to be considered. To achieve the dematerialization potential of new electronic media solutions, their efficiency needs to be combined with sufficiency; thus additional measures are necessary to turn the dematerialization potential of electronic media into environmental relief.

Keywords Electronic media • Print media • Videoconferencing • Virtual meeting • Life cycle assessment • Environmental assessment

1 Introduction

Today's electronic media are the result of a convergence of three lines of technological evolution. The first one is the development of technologies bridging space, i.e., extending the spatial range of communication, from flags and fires used for transmitting messages over some distance to the wires and electromagnetic waves we use today. The second one is the development of technologies for bridging time, i.e., extending the temporal range of communication, from carving messages to future generations into stone, writing and printing on paper to today's digital electronic storage. The third line, finally, runs from making calculations by moving limestone pebbles on a board (calculi in Latin, the origin of the verb calculate), using the abacus and mechanical calculators to the digital computer.

The final convergence of these three lines to digital Information and Communication Technology (ICT) created a new form of media we use to communicate, characterized by the possibility to transport information at almost zero cost through space and time. Before the convergence (roughly, before the emergence of the World Wide Web that made the Internet spread to every home), computers were machines we used for many other purposes, from solving numerical problems to playing chess and editing texts, but not for transporting messages through them to other people. The older role of the computer that dominated the pre-Internet age is of course still relevant but seems to be losing ground in the public perception. Most of the electronic media devices used today, such as smartphones or tablets, although they are computers with certain specific built-in peripherals and software, are no longer even perceived as computers by their users.

In this chapter, we will address two fields of media application:

- The media sector as the traditional domain of unidirectional media, delivering content in one direction, usually from one sender to many receivers.
- Videoconferencing as an application of bidirectional (or multidirectional) media, connecting two or more people in either direction.

The division into uni- and bidirectional as used here is also under transition and the media sector is today moving towards more bi- and multidirectional communication as well, with social media leading the way and more traditional media trying to make the best use of the possibilities provided.

In both cases we will investigate the environmental cost involved in the use of ICT-based media compared to that of their conventional counterparts (such as print media and face-to-face meetings). This cost can be assessed by investigating the life cycle of each medium, from the extraction of material resources and production of the consumer devices and the communication infrastructure used, to their use and disposal, including the effects of providing the energy needed in each phase.

The convergence to digital ICT has dramatically changed media use and has created opportunities for, as well as threats to, sustainable development. Careful analysis of the current situation and future options is necessary to steer the development in the direction of sustainable (in particular dematerialized) media use.

2 Electronic Media and the Media Sector

2.1 ICT Solutions for the Media Sector

The media sector is an early adopter of ICT solutions. Over the 20th century, TV and radio were the major electronic media, but now a considerable increase and diversification of electronic distribution of content can be seen through desktop and laptop computers, followed by tablet computers and smartphones. These consumer devices are forming media content in new ways and also have considerable impact on people's media use practices. The yearly statistics for Sweden 2012 [1] show that one-third of the population (9–79 years) accesses newspapers, magazines, radio or TV (so-called traditional media) via the Internet on an average day [1]. In addition, almost 50 % use social media and 21 % watch video clips on the Internet [1].

In 2001, during the evening (7–10 pm), 73 % of the Swedish population (9–79 years) watched television and 9 % used the Internet; in 2012 the figures were 63 and 33 % respectively, which clearly illustrates ongoing changes in media use practice (see Fig. 1).

Changes taking place may offer opportunities for transitions towards sustainable media use practices. With the fast introduction and development of new ICT solutions for the media sector, an opportunity—and a major challenge—is to yield from this transition a positive result from an environmental perspective. The potential for ICT solutions to facilitate sustainable media practices needs to be actively developed. This implies that we learn about what the potential actually is and also about the possible disadvantages of an increased use of ICT solutions.

2.2 Environmental Impacts of Electronic Media

Several Life Cycle Assessment (LCA) studies of print media (e.g., [2–4]) and music on CDs [5] indicate that pulp and paper production for print media as well as the distribution of media products and potential personal transport needed to

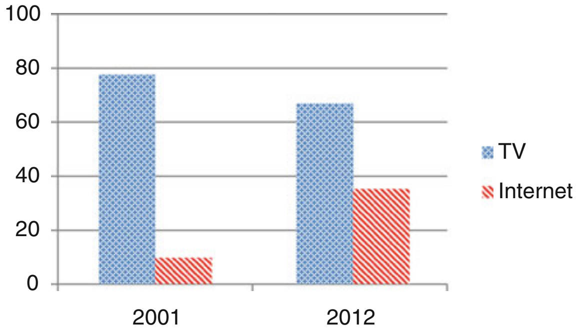


Fig. 1 A change in media use practice is illustrated here by the share of the Swedish population aged 9–79 who watched TV and used the internet (based on [1]) between 7–10 pm

purchase or collect them are important contributors to their overall environmental impact. With the introduction of new dematerializing solutions where printed copies and CDs can be avoided, easily achieved environmental benefits could be anticipated by changing to electronic media. However, early comparative studies of traditional printed and new electronic media solutions indicated that the picture was more complicated (e.g., [6–9]). In spite of data gaps and rough assumptions, these assessments have offered analyses of the potential environmental impacts related to electronic media, which are in some sense less visible than those of traditional print media where the content needs its own physical substrate for distribution and the waste papers accumulate. The negative environmental impacts of electronic media were shown to be relevant as well and in some cases comparable or even larger than those of the traditional print media. This was an eye-opener to the media sector.

The direct environmental impacts of the electronic media solutions are to a large extent due to the manufacturing of the end-consumer devices and/or their usage [10]. These direct impacts, their magnitudes and their main causes are changing with the rapid development of ICT hardware. For the media sector, this is clearly illustrated by large and energy-demanding desktop computers with Cathode-Ray Tube (CRT) screens having been a common setting in the early 2000s, while only 10 years later we carry one of the typical devices used for media content, the smartphone, in our pockets. Desktops, laptops and screens on the market in 2005 had the following electric power consumption in idle mode: desktop 78 W; laptop 32 W; CRT screen 70 W; and LCD screen 31 W [11]. Some illustrative figures for the current 2014 consumption are for tablets around 3–5 W and laptops 6–17 W [12]. The consumption of e-readers lies in the sub-Watt region, as they only consume 3 W while "turning the page" (i.e., while refreshing the screen) and have zero consumption most of the time while text is being read. Even though the effect varies and can be higher or lower than in these examples, a trend can be observed towards lower input power for electronic devices used for accessing media, as they are to a greater extent mobile devices facing demand for longer battery life, while the energy density of batteries is limited. Furthermore, the manufacturing of smaller devices is generally causing less impact per device produced (see also the chapter by Hischier and Wäger [13] in this volume.)

However, the lifetime of devices is also a very important parameter, and the trend in this case is less beneficial. Remy and Huang ([14], in this volume) analyze the possibilities for the research field of Human-Computer Interaction (HCI) to provide solutions addressing obsolescence, which could be one way of counteracting this negative trend.

The trend towards decreasing lifetimes of products is in line with the overall increase in consumption in society, and a major problem with electronic media lies in the increasing diversity of devices being put on the market. We use several different electronic devices for consuming media content; in many cases we may use them for the same purpose/content, but in different locations or related to different activities. Together with decreasing lifetimes this leads to increased production and higher amounts of e-waste that have to be processed using methods that minimize environmental and social impacts (see the chapter by Böni et al. [15] in this volume). This makes the benefits less clear cut.

In assessing the direct environmental impacts of new electronic media solutions, these can be compared to those of traditional media products which they may substitute, such as printed books, newspapers and magazines. Some devices are specially designed to substitute for these, for example e-book readers which cannot be used for surfing the Internet. Others, such as smartphones and tablets, are multi-functional, and consuming media content is only one of several options for use. In the latter case the environmental impacts related to manufacturing and disposal are consequently allocated to several different activities. Also, the traditional media products have different characteristics, which are relevant to their environmental impact. Newspapers are printed on thin, low-weight paper, in contrast to magazines, which often have thicker and sometimes even glossy paper grades. Not all of the content in daily newspapers is read; the reader skips parts that are not interesting or for which he has no time, whereas in a book the reader tends to read the entire text.

Comparative environmental assessments have shown that different types of media products and different circumstances may imply a greater or smaller benefit, or drawbacks, from the introduction of ICT solutions. This can be, at least partly, explained by the characteristics mentioned above, e.g., a difference in total paper utilization in relation to overall reading time for printed media. The environmental impact related to electronic media increases as the use time increases, unlike printed media whose environmental impact is independent of reading time (if the light needed when reading is not accounted for).

Using the example of a daily newspaper, printed versions generally result in higher environmental impacts than the electronic version (e.g., [4, 7, 10]). A newspaper that is purchased or subscribed to implies a certain environmental impact related to the manufacturing, distribution and disposal of that newspaper. This impact is caused irrespective of whether the reader spends 1 or 45 min reading the paper. However, in considering the amount of time spent on printed or

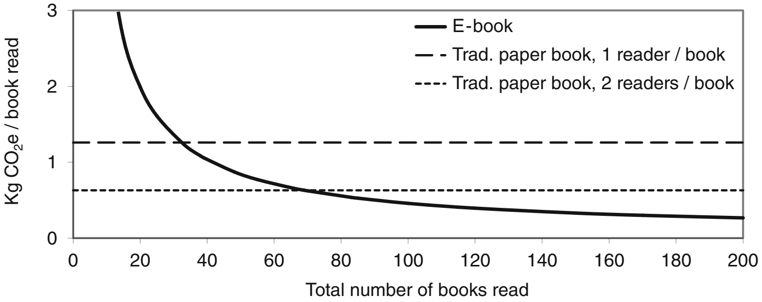


Fig. 2 Estimated greenhouse gas emissions per e-book as a function of total amount of e-books read on an e-book reader [9]. The books assessed are a 360-page hardcover novel and a 1.5 MB PDF file, respectively. The books are bought, read and disposed of in Sweden. The impact of the paper book is shown for one and two readers per book

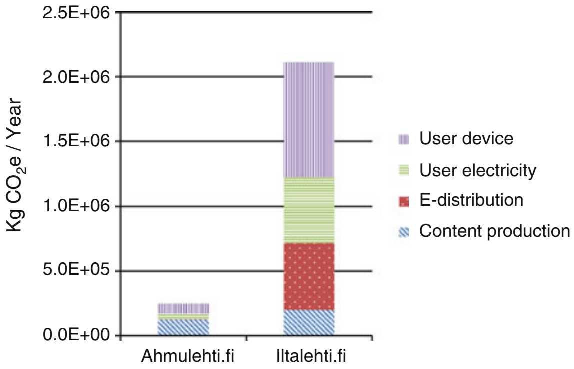
electronic newspapers, the environmental impacts of an electronic version may come close to or even be larger than those of the printed version, at least if the online newspaper is read from a desktop computer [4].

Similarly, in a study that compared the reading of e-books on an electronic reader with e-ink versus hardback literary books, the results clearly indicated a draw between the two options [9]. In this case, the reading time per book would be similar in both cases. As illustrated in Fig. 2, the result is very much dependent on the number of printed books that are being substituted by the electronic reader.

Other studies of scholarly books have yielded quite contradictory results, with Enroth [8] presenting results in favor of printed books and Kozak [3] the opposite. The assessments differed in geographical scope as well as the characteristics of the books' studied. Enroth assumed each printed scholarly book to be used by five different pupils, and thus to be compared with 400 h of the use of a laptop or a desktop computer for reading an electronic version. With the assumption of only one pupil using the printed book, Kozak compared it with 32 h of reading the electronic version. Furthermore, in Kozaḱs case it was read from an e-reader device with LCD screen. This aptly illustrates the variation in the potential benefits or drawbacks from introducing ICT solutions for media content.

An LCA of two newspapers published by a Finnish media company clearly illustrated a source of difference between electronic newspapers [16]. One newspaper, with an emerging online version with rather few readers, showed that content production was important for the overall environmental impact. The other newspaper with a rather mature online version had higher downloads. Thus, the electronic distribution proved to influence the environmental impacts together with the manufacturing and the use of end-consumer devices, while the content production in this case was a minor factor [16]. Figure 3 shows the cumulated impact for all copies of the emerging and the mature online newspapers. For the mature e-paper with more copies, content production is roughly the same in absolute terms, but less important relative to the other sources of impacts.

Fig. 3 Greenhouse gas emissions caused by two different Finnish online newspapers (based on [16])



Studies that distinguished between emerging and mature versions of electronic media [16, 17] pointed out that when electronic media is produced for a small number of consumers, the environmental impacts related to the content production become more important. This is because the impact is allocated to only a few consumers, and because at the same time the electronic end-user devices are getting smaller and more energy-efficient. With new media solutions making it possible to produce and distribute more diverse types of media to smaller audiences, the relatively large weight of the content production phase may become commonplace [16, 17].

As devices become more efficient and if they are used sensibly, the environmental impacts from the electronic storage and distribution of the content may well become important too. In a study of a tablet magazine, the size of the electronic version was comparatively large and the average reading time per copy low; thus, the environmental impact of the electronic storage and distribution had a large influence on the overall environmental performance of the average tablet magazine [17]. In their comparison of this tablet magazine and its printed version, Ahmadi Achachloui and Moberg [18] illustrate that even with an efficient end-consumer device such as a tablet, the environmental impact may be higher for the electronic version than the printed one. This was the case when the overall number of readers of the tablet version was low. Large file size and low overall use of the tablet in this study also resulted in a higher impact for the tablet version compared to the printed one [18].

In addition, the early and widespread implementation of ICT solutions in the media sector may represent positive learning in terms of social practices and structural change, which may also be seen as a positive impact related to emerging technologies [19]. The introduction of new electronic devices triggered new media content and new media producers. Media content diversified and media content platforms are additionally used for communication. As Westlund [20] indicates, a smartphone today is used for personal and mass communication as well as to access information distributed personally or to a mass of people. If the use of ICT-solutions for media content encourage the use of ICT-solutions for other purposes and in other sectors (as people become comfortable with the tools and activities), many effects may ensue, both positive and negative. In this wider sense that includes induced behavior [21], the long-term environmental effects of the new media solutions and media practices are therefore difficult to foresee.

2.3 Assessment Challenges

Thus far, most of the existing environmental assessments focused on product-level direct impacts, challenging future studies to cover longer-term effects as well. For product-level assessments, many studies of electronic media have used rather uncertain inventory data due to lack of specific data [10, 22]. This means that available, often generic, data are used and assumptions need to be made. This can result in both the underestimation and overestimation of impacts. Hischier et al. [23] distinguish between a "lab based" and a "desk based" strategy for modeling an ICT device. The former is based on dismantling the device and treating each component individually, while the latter makes use of available information on the component composition. Hischier et al. conclude that the "lab based" approach provides a more complete description of components. Still, if the data availability is insufficient for the components identified, estimations and assumptions will need to be made in any case in the next step. In a study of an e-magazine read from a tablet device, for example, the dismantling of an iPad2, identification of components, and connection to data available in the ecoinvent database lead to a result of 36.2 kg CO_2-eq. per device, while Apple reported 63 kg CO_2-eq. per device [17].

Assessments thus far have focused to a large extent on greenhouse gas emissions and energy use [10]. Energy-related resources and emissions are in general better covered in LCAs than are process-specific and material-specific impacts. This is an important limitation in the use of LCA for ICT solutions, where there are many different processes throughout the manufacturing of devices and components and where there are in many cases special requests for high purity of raw materials [24]. Assessments often note the high uncertainty or data gaps surrounding the disposal of the obsolete devices. Specific processes are used to handle e-waste, and a substantial part is handled informally in developing countries with considerable negative human and environmental impacts (e.g., [25, 26] and Böni et al. [15] in this volume). Generally, toxic emissions are relatively poorly covered in LCA [27], as are impacts related to biodiversity and land use, for example. This is a general difficulty in LCA, and one that is highly relevant to the assessment of electronic media solutions. This means extra efforts are needed to get a more complete understanding of the environmental impacts related to, for example, toxicological impacts, which are relevant for electronic media solutions.

Despite flaws and limitations in assessments of electronic media, especially when compared to paper media [22], increased knowledge has been gained. Drawbacks identified in the existing data have also encouraged the development of improved data sources, even though this development needs to be continued and intensified. One example where data is becoming more easily accessible and transparent is the energy intensity of the Internet (see the chapters by Coroama et al. [28] and Schien et al. [29] in this volume).

Some of the difficulties in assessing electronic media are related to user practices. The challenge here is inherent, as user practices cannot be foreseen and vary among users. This can be handled for example through sensitivity analyses or by presenting results for different persons. In so doing, the variation of environmental performance related to user practices can be made visible. This may also be one way of trying to illustrate how the potentials of new ICT solutions can be achieved and trying to encourage the development and use of devices facilitating sustainable practices.

3 Virtual Meetings Substituting for Physical Meetings

3.1 Transporting Bits Instead of Atoms

The technological convergence mentioned in Sect. 1 also opens the possibility of replacing physical meetings with virtual ones. From a sustainability perspective, it seems immediately plausible that sending images and sounds over fiber optics across the world is energetically more efficient than having people travel via cars and airplanes. Moving bits is easier than moving atoms.

This substitution effect is thus prominently mentioned as one of the main promises of ICT-induced energy efficiency and reduction of anthropogenic greenhouse gas (GHG) emissions. An optimistic industry vision, for example, predicted in 2008 that ICT could induce by 2020 a worldwide GHG reduction of 7.8 Gt CO_2e, which corresponds to 15 % of humankind's estimated business-as-usual emissions in 2020 [30]. These reductions were to stem mainly from three domains: (i) as a result of improved energy efficiency in the domains of smart engines, buildings, and logistics; (ii) due to ICT-supported novel paradigms for the generation and distribution of electricity (i.e., smart grids); and (iii) due to substitution effects, where ICT partly replace energy-intensive activities. Within this third domain, substituting data transfer for transportation to meetings (i.e., videoconferencing) and to work (i.e., telecommuting [31], not considered in this chapter) is seen as the substitution with the highest reduction potential. Studies on the energy intensity of the necessary data transmission have shown that such a substitution (apart from possible rebound effects) usually leads to dramatic energy and related GHG emission savings, as argued below.

Given the fact that the cost of virtual meetings is lower in terms of energy, the question should be asked if the benefit is the same as that of face-to-face meetings, in particular in terms of what may be termed "quality of communication." Varying qualities of communication between virtual and physical meetings, as well as among different technologies used for virtual meetings, could explain people's varying preferences for the types of meetings and the technologies used.

Takahashi et al. [32] analyzed the environmental effects of replacing business trips with videoconferencing, complementing the LCA of the two with a "value factor" for the quality of communication. Assuming that a virtual meeting is not a perfect replacement for a face-to-face meeting, they assigned a value factor of 0.6 to it, while using 1.0 for the face-to-face encounter. Even under this condition, the virtual meeting was only responsible for 20 % of the emissions of the business trip for which it was substituted (400 kg instead of 2000 kg CO_2). The assessment of Toffel and Horvath [33] came to an even stronger conclusion, estimating that CO_2 emissions for a business meeting held via teleconferencing are lower by 1–3 orders of magnitude compared to physical meetings. For obvious reasons, the number of participants and geographic distance are sensitive parameters in all studies of this type, and they largely account for the variation of the results.

Which ICT equipment is deployed for teleconferencing, how this equipment is used, and whether the use actually leads to less overall travel are nevertheless crucial factors for the net environmental effects. Borggren et al. [34] compare six teleconferencing scenarios (three different technologies combined with two usage intensities) with three types of physical travel (plane, car, and train). While for most cases, substituting videoconferences for travel leads to net energy and GHG savings, when high-end telepresence technology is used to substitute relatively short train travel (in Sweden roughly 450 km one-way), the energy use and greenhouse gas emissions may increase. This effect, however, only appears in two cases: First, in the low-usage scenario, when the telepresence system is used for only 2 h per week and the production phase burden is thus distributed over a low usage for the entire lifespan.

Secondly, the effect also appears for the more intensive usage scenario of the telepresence system, but only in a sensitivity analysis using an Internet energy intensity value of 3.5 kWh/GB instead of the 0.42 kWh/GB from the baseline scenario. With this 3.5 kWh/GB assumption (adapted from [5, 35] for 2010) the use-phase energy needed for data transmission dominates the Cumulative Energy Demand (CED) of the teleconference. As [36] shows, however, the top-down estimates in [5] and [35] include not only Internet network devices, but also data centers and LAN network devices in their calculations. The Internet energy intensity value used for the sensitivity analysis in [34] was thus unrealistically high.

Other studies examined the effect at the macro level for entire countries or regions. For all of Australia, for example, a replacement of one-third of the business trips by high-quality telepresence systems was estimated to reduce emissions by 2.4 Mt CO_2e or around 0.4 % of Australia's total emissions at that time [37]. If 30 % of business trips worldwide were replaced by teleconferencing, it would lead to an estimated reduction of 500 Mt CO_2e [30]—roughly 1 % of global emissions.

These macro-level estimates usually assume that a 1:1 substitution takes place, i.e., they do not take into account rebound effects that may (partly) compensate for the substitution effect, because people will spend the time or money saved on trips either for additional trips or for other activities with relevant environmental impacts (see also Gossart [38], in this volume).

3.2 The Case of Large International Conferences

Hischier and Hilty [39] looked at the case of large international conferences. As a compromise between a traditional conference and a totally virtualized conference with participants sitting at their computers without the opportunity to enjoy the social aspects of conferencing, they suggested dividing a large international conference into several conferences, in particular with the aim of reducing the number of intercontinental flights.

This type of international conference was then organized in 2009, simultaneously in Switzerland and in Japan, and investigated with regard to its impact on participants and emissions [40].

Attendees could choose to travel to either one of the two venues: Davos, Switzerland, or Nagoya, Japan. Due to the time difference between the two regions, only part of the program could be shared; the morning workshops in Japan and the afternoon workshops in Switzerland were used for activities of more local interest. In the common 4-h slot, however, all plenary sessions were shared among the two locations during the three conference days. The locations were connected via four high-definition "telepresence" streams, which included real-time audio, video, and slide sharing of the speaker, the audience of the other site, coffee break areas, and a small conference room that could be used, for instance, for workgroup meetings. This organization mode enabled not only the talks to be followed on the remote site, but also cross-continental Q&A sessions, the creation of small workgroups across both sites, and informal chats during coffee breaks [40]. Figure 4 shows how the remote audience was seen by the local audience and the speaker. Figure 5 depicts how participants engaged in discussions during the breaks.

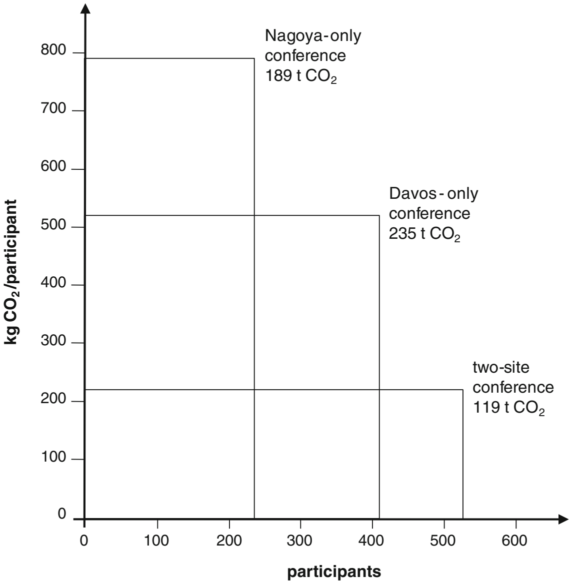
After the conference, all attendees were invited to participate in a survey. They were asked about their satisfaction with the conference format (see [40] for the results) and the means of transportation they took to the conference. In order to assess their travel emissions, they were requested to precisely describe the legs of their journey and the respective means of transportation. A typical description was, for example, "airplane New York—Paris; airplane Paris—Zurich; train Zurich Airport—Davos." For each participant, the distances traveled on each leg and the resulting emissions could thus be computed. The participants were further invited to estimate whether they would have attended the conference had it been organized in a traditional mode only at the remote site (the site they had not traveled to). The hypothetical emissions for the travel to the remote site were computed conservatively assuming that attendees would have taken a train from their point of departure to the closest international airport, from there a direct flight to Zurich or Tokyo, respectively, and finally a train to Davos or Nagoya.

Three alternatives could thus be compared: the two-site conference as it was held and the two hypothetical alternatives "Davos-only" and "Nagoya-only." The results are summarized in Fig. 6:

Fig. 4 The speaker engaging the local and the remote audience at a 45 ° angle each

Fig. 5 Typical cross-site interaction during coffee breaks

Fig. 6 Number of attendees and average per-capita emissions in the three possible conference scenarios. The surface of each *rectangle* represents the respective scenario's overall travel emissions. The multiple-site conference saved travel emissions as compared to both traditional alternatives, despite more overall attendees



- The Davos-Nagoya multiple-site conference had a total of 531 participants, 372 in Davos and 159 in Nagoya. Their travel caused 119 t of CO_2 emissions, 84 t for Davos and 35 t for Nagoya.
- In the 'Davos-only' scenario, 448 attendees (the 372 from Davos plus another 76 from the Nagoya public) would have induced 235 t CO_2
- (84 t from the former participants plus a disproportionate 151 t from the new attendees), almost double the CO_2 emissions of the real scenario.
- In the 'Nagoya-only' scenario, a considerably reduced number of 238 attendees (159 'Nagoyans' and another 79 from Davos) would have produced 154 t CO_2, still more than those of the real scenario. Next to the 35 t that would continue to be caused by the 159 Nagoya participants, the 79 new attendees would be responsible for another 154 t. This disproportionate impact would be due to their mainly international travel.

Compared to traditional organization modes, the distributed conference allowed on average quicker and less expensive travel for attendees. A significant rebound effect in terms of the number of participants was the unsurprising effect. Despite this rebound effect, the overall CO_2 emissions caused by the travel of attendees were significantly reduced compared to the single-site alternatives. The relatively few avoided intercontinental flights (of participants in Europe or Asia who would have traveled to the remote site as well but had an alternative close to home) more than made up for the short trips of the many new participants who only took part because they had a venue close to home.

Allowing more attendees to take part while lowering the overall energetic costs meant that the reductions per participant were even higher—by a factor of 2.3 and

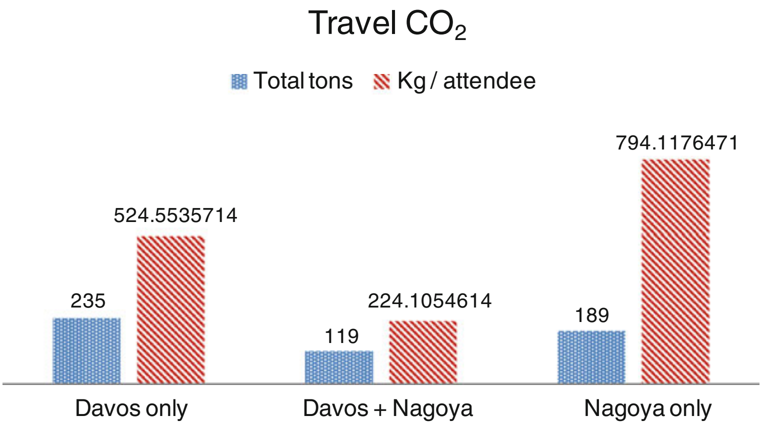


Fig. 7 Per participant and overall travel emissions in the three scenarios

3.5 as compared to a ‘Nagoya-only’ and ‘Davos-only’ conference, respectively. Figure 7 summarizes the emissions per participant as well as the overall emissions for the three alternative organization modes.

4 Conclusion and Outlook

In introducing electronic media as a possible means of reducing environmental impact, it is important that these new solutions replace some other product or activity whose environmental impact can then be avoided. Even with some substitution taking place, numerous electronic media solutions are just added to what was there before. New types of media and new devices are continuously being created that can be used to consume media content as well as to communicate with others. More energy-efficient devices and communication networks need to be combined with sufficiency, not with increasing consumer demands [41].

Some new media solutions seem to inherently fulfill this condition. As it turns out from the field experiment presented in Sect. 3.2, the GHG emissions caused by an international conference can be reduced substantially by organizing it at multiple sites and thus reducing the average travel distance of the attendees. Even accounting for the rebound effect of increased participation, the overall CO_2 emissions caused by the travel of attendees were significantly reduced compared to traditional alternatives.

For other types of new media (e.g., alternatives to print media), the picture is more complex. Even with increasingly energy-efficient devices, it is clear that considerable substitution is necessary to gain benefits, as well as increased utilization of devices over their lifetime and a decrease of the fast obsolescence of ICT gadgets. It is also important to consider environmental impacts other than greenhouse gas emissions.

As the main aim of a transition to new electronic media solutions is not to achieve more sustainable practices, the opportunity that this provides needs to be seized and actively managed. Action needs to be taken at different levels of society to achieve this, as “consumption choices are based not only on individual choices but also on existing and available infrastructure and on established social norms” [41, p. 21]. In order to foster environmental benefits from electronic media based on their dematerialization potential, the overall resource use and emissions throughout the life cycle of media product systems and more importantly at the macro level of total global media production and consumption need to be lowered. Adequate incentives are necessary and a variety of actors need to engage through policy-making in society and industry. Conscious design choices for hardware and software as well as increased awareness and informed choices among actors need to be encouraged. Electronic media is not a straightforward solution for dematerialization, but it can facilitate it if its potential is actively sought and unleashed.

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Part V
Models of Sustainability in the Information Society

The Interdependency of Energy, Information, and Growth

Daniel Spreng

Abstract This contribution is based on the talk I gave at the conference on ICT for Sustainability, February 14–16, ETH Zürich [1], in which I reopened the discussion on the impact of ICT on energy consumption [2]. The chapter has four sections. The introduction connects my topic to the conference theme. In part two, I discuss energy conservation; the mutual substitutability of energy, time and information; and some fundamental aspects of the nature of these three quantities. In the third part I present two empirical case studies of this mutual substitutability. Finally, in the fourth section, I conclude by speculating on what these results may mean in term of ICT's effects on sustainability, mindful of the role of time and of economic growth in this interaction.

Keywords Substitution · Rebound effect · Energy · Time use

1 Introduction

ICT holds great potential to contribute to sustainable development. Doing things in a more controlled and intelligent manner can be an essential ingredient for a long-term viable future.

Often energy consumption is used as a proxy for sustainability. Many people would consider the use of this proxy to be a terrible simplification. There is no room here to go into much detail here, but I would argue as long we do not assume a linear relation but some sort of convex relationship, the energy consumption per capita is good a proxy for sustainability as one can find.

For energy use per capita below 1 or 2 kW/capita sustainability increases (extreme poverty decreases) with increasing energy consumption, however for

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energy consumption per capita above a few kW/capita, and this is the case we are interested in here, sustainability decreases with increasing energy consumption (compare [3, 4]). Therefore, it is not inappropriate to narrow down the theme of the conference to the effect of ICT on energy consumption.

2 Mutual Substitutability of Energy, Time and Information

In the 1970s I thought about energy conservation and postulated that in order to conserve energy, either time or information or both were needed. To produce any given good or service, perform a task, some amounts of energy, time, and information are required. Reducing the energy input is achieved by increasing the time and/or information input for the task.

In order to save energy one can either perform a task smarter or slower:

- more time reduces friction, losses in heat-transfer, etc.
- more information reduces unnecessary safety margins, trial-and-error operation, and—this is most important—useless and unused energy services.

A trip from A to B can be made more energy efficient

- by choosing a slow mode of travel, by not speeding
- by taking the best route, and best (high-tech) vehicle.

Thus, the inputs to produce a good or service can be characterized by the three quantities energy, time and information. My hypothesis is that these inputs are partially substitutable. The graphical representation of the hypothesis is an equilateral triangle. The various ways of perform a task are then represented by points in the triangle, the distance to the sides measure the amounts of the three inputs applied to the job (Fig. 1).

The triangle, sometime called Spreng Triangle, applied to energy conservation then looks as follows (Fig. 2):

This mutual substitutability is often, but by no means always, observed in processes and equipment on the technical plane.

The mutual substitutability of energy, time and information can, however, also be seen on a micro-economic plane. It is possible to position economic sectors within this equilateral triangle by calculating for each sector the cumulated energy and cumulated time (labor) input to produce a good or service worth a dollar and then examining what the relative, cumulative information input is, assuming no other input is necessary [5]. Standard economic theory would suggest that besides labor, capital is the most important input, supplemented perhaps by additional resources other than energy. However, focusing on physical inputs at the level of the triangle, one can argue that energy is reasonably good proxy for *any* resource and that capital is money earned at some earlier time period and therefore not much different from cumulated labor. Marx called capital “geronnene Arbeit,” labor hardened like blood.

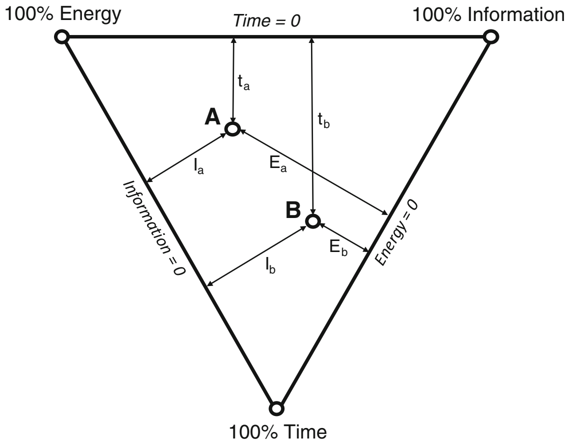

Fig. 1 A good or service can either be produced by the inputs E_A, t_A and I_A or the inputs E_B, t_B and I_B,—i.e., by the input relationships *A* or *B*

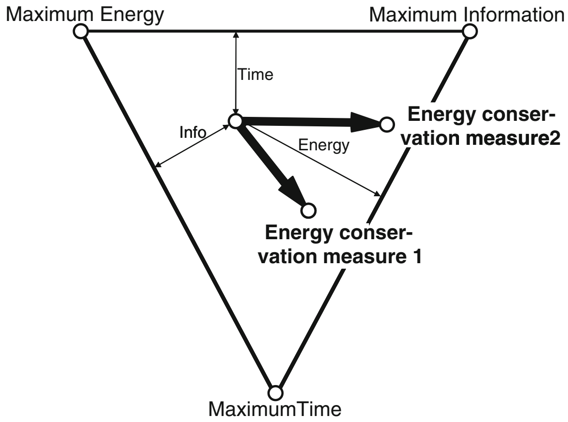

Fig. 2 From the substitutability hypothesis follows that there are various ways to save energy. Both using more time and using more information can have the desired effect

A good worth a dollar can be produced and a service worth a dollar can be rendered in various sectors with different characteristic ratios of the energy, time and information. The result of plotting economic sectors in such an energy-information-time triangle (Fig. 3) is supportive of the idea of substitutability and also hints at the meaning of cumulated information (see footnote 1 in [5]). Cumulated information turns out to be high in modern, high-tech industrial sectors. For energy and time (measured in working hours) the cumulated inputs are calculated. The information input is the plausible result of the plotting procedure.

On the macroeconomic plane, the triangle allows to speculate about the direction of the future development of nations. ICT pushes nations powerfully in the direction of the top right corner of the triangle. Whether this leads to less time, a society of harried men and women, or less energy, a society of starving philosophers, depends also on other factors, such as price level of labor and resources (Fig. 4).

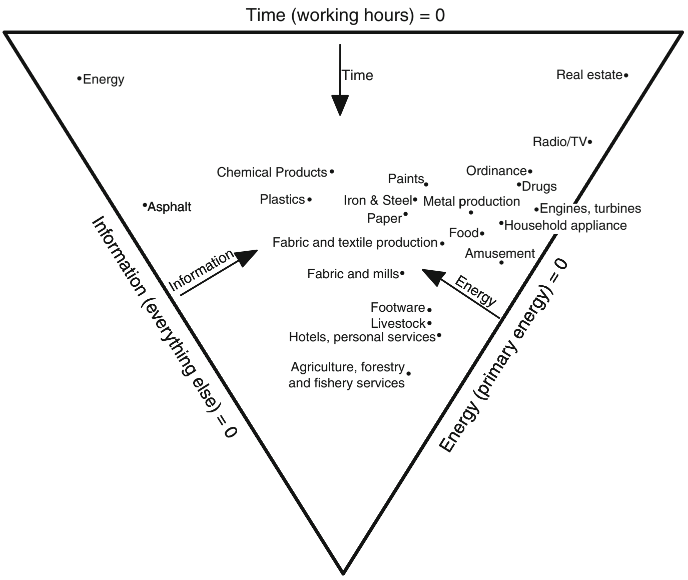

Fig. 3 Industrial activities require energy, time and information inputs in various proportions [5]

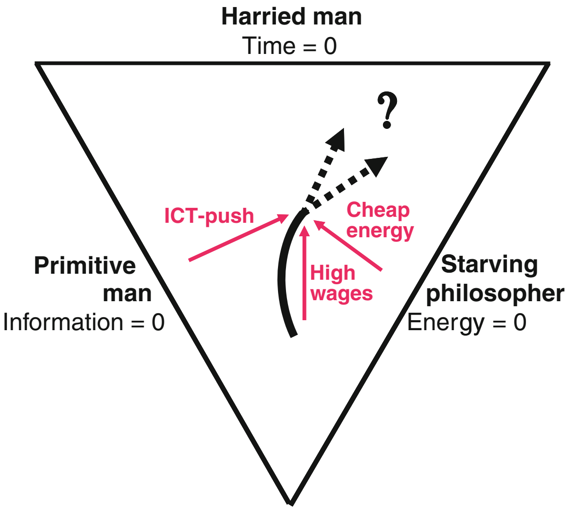

Fig. 4 ICT pushes nations powerfully in the direction of the *top right corner*; information input becoming more and more important

The concept of the triangle may seem to be a bit simplistic. However, by being careful about the exact meaning of the three inputs, the concept gets rather complex and subtle.

Characterization of the energy input: Even though there are

- four thermodynamic potentials (as well as energy),
- many commercial and non-commercial forms,
- although time and location matters a lot in terms of usefulness,

the definition is rather straight forward.

It is important to note, that energy is an extensive quantity (i.e. it depends on quantity). The quantitative relationship between energy on the three levels (technical, micro and macro) is the topic of many models (bottom-up, top-down etc.).

Time, on the other hand, is a mysterious quantity. Time is

- both extensive (time period) and quasi intensive (time availability: 24 h a day, life time),
- an irreversible flow,
- both linear (in the technosphere) and cyclical (in nature),
- chronos and kairos.

However, time is easily measureable on the technical level and labor (one aspect of time) or free-time, can be measured on the micro and macro level.

Information (as applied to a task) includes many aspects, depending on how close it is to being applied and also whether it is static or dynamic. Figure 5 is drawn to illustrate this complexity.

To some degree information has an elusive meaning, differently specified (and measured) on various levels. On the technical level it can have the specification as given in Fig. 5. On the microeconomic level it would refer more to the choice of technologies (in particular ICT), the skill of personnel, the choice of products and services by consumers.

On the macroeconomic level the penetration of ICT in national economies is important, as well as the education of the labor force, the concentration and clustering of high-tech firms and demand for quality rather than quantity of products and services.

In summary, the meaning of energy is rather straight forward, although one has to be careful of not mixing-up the technological, microeconomic and macroeconomic planes; time is a mysterious quantity, but neglecting it leads to serious errors; and information is what changes our societies and lives these days, it has different meanings in various and varying settings. Substitutability of energy, time and information is not a law of physics, but is

- often a fact on the technical level (old saying: haste makes waste), but there are many exceptions,
- on the microeconomic level, substitutability is often plausible (see triangle with economic sectors), but the elusiveness of energy, time and information makes quantification difficult and
- on the macroeconomic level it is an intuitive truth that nations with much stability (giving change the time it requires) and high innovative capacity (putting a high value on information) seem to be more sustainable (using energy and other natural resources sparingly).

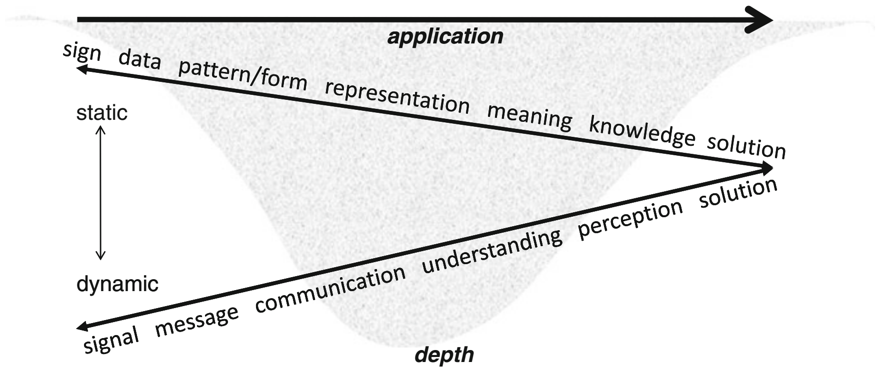

Fig. 5 Various aspects of information on the technical level (as applied to a task)

3 Two Empirical Case Studies of the Mutual Substitutability

Research, my group did in the 1980s, particularly the two following case studies, was based on the triangle.

Case Study I. In the first project we looked carefully at the energy effects of the introduction of computers in various parts of textile industry. The heart of the research, the PhD thesis of Rolf Bergrath, was an examination of the energy conservation potential of electronics used for air conditioning spinning mills. As it turned out, the energy conservation potential was huge.

The automated control in all corners of the mill allowed the safety margins to be reduced and thus the temperature at which the climate had to be set could be increased. As the electricity requirement for air conditioning is a large part of the cost of spinning, this reduction in the cooling requirement proved to be economically important.

However, as it turned out, electronics also improved the spinning machines. The much more tightly controlled spinning process allowed higher speeds without increasing the frequency of yarn ruptures, a decisive factor for the productivity of the mill. The higher speed caused much more heat, and thus the energy requirement for air conditioning did not decrease. The energy requirement per yarn may have decreased, but the energy requirement in the now more productive mill increased rather than decreased.

Similar effects could be observed in all parts of the textile industry. However, with the introduction of computers everywhere in the industry, including the commercial side, the industry as a whole could react more quickly to the wishes and whims of the market, thus greatly speeding-up fashion cycles and increasing demand. The overall effect of the early introduction of modern IT in the textile

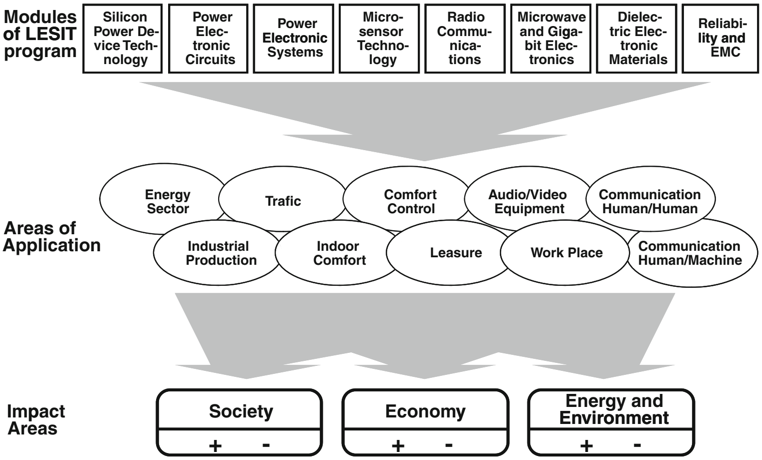

Fig. 6 Advances in power electronics were pursued, within the LESIT program in various modules (*top row*), all of these could potentially lead to improvement of power electronics implementations in a myriad of applications (*middle row*). All of these would then have impacts on societal, economic and energy/environmental developments (*bottom row*)

industry was so profound that it could not be rigorously quantified. It was difficult to isolate the effect from changes that occurred in the global economy as a whole [6]. The only definite conclusion was that IT greatly amplified the potential for both increases and decreases in energy consumption; IT enabled both significant energy conservation measures, on the one hand, and new business opportunities and new ways of speeding-up production and demand on the other.

Case Study II. This case study was a technology assessment project. We were asked to find out how much energy was saved with the creation and introduction of improved power electronic components and devices. In particular we looked at a large research program, called LESIT, supported by the Swiss government, which had as its goal to advance the technology of power electronics. The program comprised the 8 modules listed in the top row of Fig. 6.

Like in case study I, our research came to the conclusion that although the use of newly developed power electronics did reduce the energy requirement of a given application, on the macroeconomic level the effect was more likely a speeding-up of industrial production, travel and consumption and thus an overall increase in economic activity and energy demand, even if energy efficiency had been improved at many points. Although the technology assessment we conducted was a sizable undertaking, involving several research groups and disciplines,[1] we could not study all possible effects (see Fig. 6), but we concentrated

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[1] The assessment was done by a multi-disciplinary team including F. Varone, B. Aebischer, W. Eichhammer, E. Gruber, St. Kuhlmann, D. von Wichert-Nick and is described in [7].

on three topics, typical for the three stages of the innovation process involved (see Fig. 7).

In my opinion, discussions of the rebound effect often do not pass a reality check. Pure energy conservation measures are rare. Most technological innovations called energy efficiency innovations are innovations that *among other things* improve energy efficiency (Fig. 8).

Energy efficiency innovation almost always includes some co-benefits. In the case of the train engines, smoother traction, faster acceleration, smaller engines etc.

Stages of the innovation process	**Focus**	**Topic**	**Object of the analysis**
Applied research and technology development	1	Perceptions of researchers on impacts on energy consumption	Selected products and research methods
Technology transfer and production	2	Research co-operation industry and academia / Technology transfer	Energy considerations when choosing industry partners
Sale and use of new products	3	Impactof "intelligent buildings" on users	Marketing situation for new energy optimal products

Fig. 7 The technology assessment was conducted by focusing on three topics

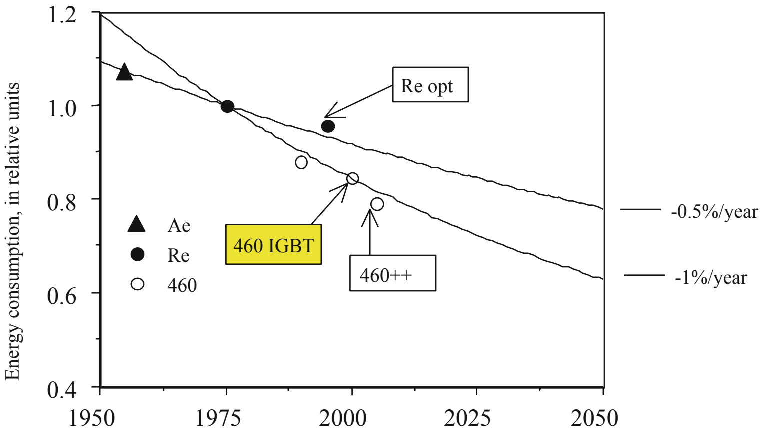

Fig. 8 Energy consumption of several train engines (Ae 6/6, Re 6/6, 460) is plotted in function of their first year of service. 460 IGBT (incorporating much LESIT-technology) shows reduced energy consumption exactly in line with the business-as-usual trend

were economically more important to take advantage of than fully exploiting higher energy efficiency. Generally, co-benefits of energy efficiency innovation, like reduced cost and higher convenience (e.g., time savings for the user) are economically attractive and will often generate economic growth.

More often than not, as with ICT in the textile industry or power electronics, the energy efficiency effect, clearly evident at the level of one application, does not lead to energy conservation on the macroeconomic level. Energy conservation is a cultural achievement, but is not natural to us (Westerners), it requires valuing leisure, where as energy efficiency often increases without special effort and does not necessarily lead to energy conservation.

4 Conclusion

The disappointing results of the case studies show that ICT is mostly used to accelerate processes, markets and national economies: time is money. As long as time costs more than energy, ICT will likely be applied to save time rather than energy. The time saved may be labor on the production side or it may be time saved, i.e. greater convenience, on the consumer side. Economic growth is often regarded as the remedy for unemployment. However, promoting ICT applications indiscriminately is not a good way to combat unemployment. ICT, although very suitable to push economic growth, often contributes to economic growth by saving labor.

Only if ICT is applied discriminately to do things smarter, wary of automation and higher speeds, will its increased use lead to higher economic growth, without reducing the labor intensity of products and services. This type of growth has the potential to be less resource intensive as well. The debate on aiming at qualitative growth rather than quantitative growth, conducted in the 1980s, has almost been forgotten but needs to be revived.

If time (an important fraction of labor) and cumulated time (an important fraction of capital) cost more than energy (and other natural resources) and if consumer preferences remain unchanged then more ICT leads over all to

- no energy conservation, but instead to
- time savings, faster production and economic growth,
- i.e. higher labor and capital productivity (likely more unemployment and cheaper products).

ICT could easily lead to more sustainability, if

- leisure,
- quality of products and services and
- energy as well as other natural resources would be more highly valued.

Policy design should take into account both the

- massive transformative power of ICT and
- the necessity to correct present incentives on all levels (from international to personal) to steer ICTs application, and with that ICTs effects, in the desired direction.

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Rebound Effects and ICT: A Review of the Literature

Cédric Gossart

Abstract This paper presents a critical review of the literature on the rebound effects generated by information and communication technologies (ICT). Following a discussion of the types of general rebound, including direct, indirect, and economy-wide, the literature on ICT-related rebound effects is critically assessed. The chapter suggests ways of overcoming rebound and lays out promising avenues of research to better understand and tackle rebound effects in ICT.

Keywords Rebound effects · ICT · Resource efficiency

1 Introduction

Between 1982 and 2012, while final energy intensity in France decreased by one third, final energy consumption increased by 15 %, from 134 to 154 Mtoe [1]. The transportation sector also witnessed important energy efficiency gains. For example, the fuel consumption of a medium-range car dropped from 8.3 to 6.7 l/100 km between 1990 and 2012, and CO_2 emissions of new average cars also dropped from 175 to 124 gCO_2/km. In the same period, the mileage per medium range car remained stable at around 13,000 km/y. These results should have delivered energy savings to the French economy, but the exact opposite happened: the final energy consumption of road transportation increased from 32 to 36 Mtoe, and its CO_2 emissions increased by 10 %. Despite energy efficiency improvements, overall energy consumption and pollution increased, notably because the number of cars increased from 24 to 32 million, providing evidence of a “rebound effect.” One would not be blamed for questioning, like Herring [2–3], whether energy efficiency measures do in fact deliver energy savings. As explained in the

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next section, information and communication technologies (ICT) are often used to improve energy efficiency but are subject to rebound effects. Large public and private investments are made every year to leverage ICT to improve energy consumption and other types of efficiency such as labor productivity. But if the rebound effects associated with ICT are high, those gains will be absorbed and the environmentally-driven investments will fail to meet their objectives.

The purpose of this paper is to clarify the rebound effects related to ICT, including energy-related effects. To this end, Sect. 2 defines rebound effects, and Sect. 3 presents the rebound effects that are associated with ICT. The conclusion offers some ways for avoiding ICT-related rebound effects and points to future lines of research.

2 What are Rebound Effects?

2.1 Definitions

In the 19th century, the industrial revolution supported England's economic wealth and political power. Domestic coal was key to maintaining this power and there were great fears regarding the growing scarcity of this cheap local fuel. England was consuming massive amounts of coal, and much of it was wasted by inefficient mining and processing. To prevent this core resource from being prematurely exhausted, engineers invented solutions to reduce coal waste by improving mining and processing efficiency. Would English coal resources last longer thanks to these energy efficiency innovations? A negative answer seldom heard at the time was voiced in a book entitled *The Coal Question*, in which the economist William Stanley Jevons claimed in that "technological efficiency gains (…) actually increased the overall consumption of coal, iron, and other resources, rather than saving them" [4, p. 9]. In his formulation of the "Jevons' paradox," Jevons demonstrated that contrary to their primary objective, efficiency policies were actually counterproductive and were leading to resource overuse [5]. Jevons believed that "the present generations are allowed to use intensively ore resources to the extent they transform them in wealth for future generations" [6, p. 100].

It was more than a century before energy economists coined the expression "rebound effect" to characterize the negative side effects of efficiency policies and strategies that ended up taking back the environmental gains they had permitted. For them, the term "rebound effect" dates back to Khazzoom [7] and characterizes "improvements in the technical efficiency of energy use" that had a smaller energy-saving effect than predicted by engineers [8]. Indeed, efficiency gains achieved when manufacturing a product or providing a service reduce their costs. As a consequence, its price decreases and demand for it increases. If efficiency gains are indeed reported at the micro level of single products, the macroeconomic picture suggests that more resources have actually been used, for example because the lower price of single products has boosted their sales or because the more efficient single product has been used very intensively. For example, a company using energy-efficient servers will reduce its data storage costs, which will enable it to buy more servers and to use them more intensively, directly impacting its electricity bill. In analyzing the relationships between ICT and the environment, Hilty emphasizes that they can enable positive environmental changes but also negatives ones [9]. Based on an OECD report [10], the author distinguishes three levels of effects of ICT on the environment: 1st order effects (direct effects of ICT caused by their physical production, use, and disposal), 2nd order effects (impacts of ICT on other sectors), and 3rd order effects (structural ones), which include rebound effects.

Rebound effects have also been discussed in other disciplines such as psychology, as in the case of "stereotype rebound."[1] Another psychological rebound effect occurs when ecotechnologies make consumers feel good and encourage increased consumption of greener products [12]. From an economic perspective, consumers buy a given product because it "maximizes his/her utility": it serves a purpose or need, which makes the consumer happy and satisfied for a given amount of money. The various needs that people seek to satisfy have been described in a simple manner by Maslow's "hierarchy of needs," which represents people's needs in a pyramid starting with basic needs at the bottom: physiological needs, safety needs, love and belonging, esteem, self-actualization. Once the first two basic needs have been satisfied, people seek to satisfy more elaborate ones such as the need to belong to a community or to be esteemed by their peers. Consuming greener products can contribute to these needs because it makes individuals feel that they belong to a community of people who care about the environment, and that they are esteemed by other people because they adopt responsible consumption patterns.

2.2 Categories of Rebound Effects

In a seminal paper in which he recalls the history of the concept and clarifies its categories, Sorrell explains the three categories of energy-related rebound effects [8], which were already present in Jevons' book (as underlined by Missemer [6]). They are "typically expressed as the percentage of potential savings taken back from the maximum efficiency improvement expected" [12, p. 6].

The first category includes *direct rebound effects*, which have been extensively analyzed by economic theory [13–15]. In this case, lower energy cost induces price reductions that trigger an increase in the demand for the cheaper good (e.g. if washing machines need less power, consumers can afford to wash more

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[1] "Stereotype rebound refers to the ironic finding that active efforts to avoid thinking about people in a stereotypical manner can backfire and subsequently lead to increased stereotypical thinking and prejudiced behavior." [11, p. 111].

frequently). From earlier work, Sorrell cites the example of the Bessemer process, which enabled metallurgical companies to achieve their greatest energy savings of all times, while at the same time leading to large increases in steel demand that would not have been seen before that innovation [8]. Here, the money saved thanks to energy efficiency gains was reallocated to consume more of the same product. For example, throughout the second half of the 20th century, in the US manufacturing industry there is evidence of a 24 % rebound effect, meaning that energy efficiency gains had gone hand in hand with a 24 % increase in energy demand [16]. It is hard to compare evaluations of rebound effects since they vary with the methodology and data employed. Hence, some authors disagree with Jevons' standpoint, claiming that rebound effects have been small over the 1970s and 1980s, and that during this period "most of the improvements in energy efficiencies led to reductions in energy intensities" [17, p. 367]. Others underline that if total resource consumption grows while efficiency improves it "does not necessarily demonstrate that resource consumption grows because of improvements in efficiency" [18, p. 21]. However, Bentzen suggests an order of magnitude for the rebound effect that ranges between 0 and 50 % in relation to consumers, with a smaller effect for firms [16]. At the upper margin, this would imply that if technological energy efficiency gains are predicted to be 100 MW by engineers, they are actually only 50 MW. Half of the expected energy savings are absorbed by rebound effects. The author also reports a study showing that in the Netherlands, up to 30 % of projected efficiency gains could be absorbed by an increased demand for energy services [13]. Although these estimates are not very precise and vary across time, countries or sectors, they may be useful to firms and policy makers as an indication of how much they should reduce their expectations of the savings generated by energy efficiency measures. For example, in calculating the return on investment of an insulation program, a government agency could use a discount rate of 30 % to account for potential rebound effects in order to obtain more realistic energy saving figures. This rate would vary across sectors; for example, rebound effect estimates in the UK industrial sector are about 15 %, and they range between 20 and 60 % for US energy-intensive sectors [18].

The second category concerns *indirect rebound effects:* When a resource is used more efficiently and its price goes down, it induces the consumption of other commodities (e.g., consumers buy extra DVD players for the money they saved due to an energy-efficient product). In this case, households use their increased remaining income to buy other energy-consuming products or services. For example, if a family saved money by insulating its apartment, it might use the savings to fly to a remote holiday location instead of taking the train to a closer one. Overall, the financial gains from insulation-driven energy savings would not generate environmental benefits.

A third category concerns *economy-wide rebound effects,* which appear when declining energy prices induce a reduction in the prices of intermediate and final goods throughout the economy and cause structural changes in production patterns and consumption habits. For example, cheaper gasoline enables people to live further away from their workplace by making it less expensive to drive longer distances to work. These effects are the aggregated result of both direct and indirect rebound effects and can be expressed as a "percentage of the expected energy savings from an energy-efficiency improvement" [8, p. 1457]. If this percentage reaches 100 %, it means that "the expected energy savings are entirely offset, leading to zero net savings for the economy as a whole" (ibid.). These savings "backfire" when the rebound exceeds 100 %, which means that the overall energy consumption actually increases after energy saving measures (ibid.).

The rebound effects defined here refer to "pure" energy efficiency gains; i.e., energy efficiency productivity, with no gains in other resource productivities and no gains in labor and/or capital productivity (including convenience). One must be careful speaking of a rebound effect in these cases. In practice, technological change generally produces a bundle of improvements, of which the energy efficiency gain is just one such improvement. Indeed, such a change can become so popular that it produces other improvements that can be considered "collateral benefits." Hence, these benefits can give the demand for the improved technology a huge boost and lead to economy-wide rebound effects higher than 100 %. As a consequence, a technology that leads to efficiency gains on the micro level might actually lead to efficiency losses on the macro level. In order to avoid this confusion, a distinction can be made between pure energy efficiency improvements and technological changes that include energy efficiency improvements.

3 Rebound Effects and ICT

3.1 ICT and Efficiency

ICT include both hardware and software technologies. Historically, they are among the most prominent general purpose technologies, such as steam, electricity, and internal combustion, since they generate wide-ranging impacts across all sectors, including economic, social, and environmental effects [19–20]. General purpose technologies are pervasive (spreading to most sectors), improve over time, spawn innovation (making it easier to invent and produce new products or processes), and continually lower costs for their users [21]. Therefore, the efficiency gains enabled by ICT diffuse across all sectors, as do their related rebound effects. There are many ways in which ICT can contribute to energy efficiency [22]. They can reduce their own energy consumption, enable energy savings in other sectors such as buildings, transportation, and lighting control, contribute to energy saving awareness, and so on. Consequently, they are the focus of ad hoc policies that seek to support these contributions, such as the European energy efficiency plan [23] or the *Smart 2020* initiative [24]. The former does not mention rebound effects, but the latter underlines that in the case of ICT, "prevention of the rebound effect requires an emission-constraining framework," suggesting that energy efficiency technologies alone are not enough to foster energy savings [24, p. 2].

In order to avoid rebound effects that would absorb the positive contributions of ICT to energy savings, rebound effects related to ICT must be identified and evaluated. Unfortunately, few studies have measured rebound effects related to ICT. For example, *Energy Policy*'s 2014 special issue on "Energy efficiency for a more sustainable world" does not contain a single paper on rebound effects, and the term is not even mentioned in its editorial [25]. A study on Korea even shows that when they are not geared towards reducing energy consumption, ICT investments can contribute to increased electricity intensity, because they induce the replacement of less labor-intensive inputs with more electricity-intensive ones [26]. This is consistent with Binswanger who argued that when production costs are dominated by wages and energy prices are low, labor will tend to be replaced by machines [27]. Since machines usually consume more energy than human workers doing the same task, low energy prices will encourage increases of firms' energy consumption. Sorrell argues that this is also the case with household appliances such as washing machines or dishwashers [28]. It might also be true for ICT that replaces manpower, as in the case of electronic messaging that partly substitutes for written letters sent by mail. The comparison of traditional paper-based media with electronic media with regard to sustainability is discussed in detail in the chapter by Coroama et al. [29] in this volume.

3.2 Direct Rebound Effects

Direct rebound effects appear when technological change enables an improvement in the efficiency with which some output can be produced from a resource, whose demand then increases as prices go down, thereby absorbing the resources saved by efficiency gains. As a consequence, *more of the same resource* is consumed.

In ICT, the optimized output is information: Moore's law formalized efficiency gains enabled by technological change in microprocessors. This generated rebound effects related to key resources such as time and raw materials. For example, since microprocessors are getting continuously smaller, each of them requires less material to be built [9]. But as a consequence, their prices drop, their demand explodes, and new models quickly offset slower ones. This contributes to the obsolescence of computers, for example, since only new ones are powerful enough to host heavier operating systems. Many users would notwithstanding have been satisfied with a PC fitted out with an older processor, since they do not need quadruple core processors to write emails and surf on the Internet. Because of efficiency gains at the level of ICT components, ICT products are made obsolete, which wastes the resources that could have been saved thanks to these efficiency gains. In the end, consumers find themselves with over-equipped machines whose processors remain in a "busy waiting" state most of the time [9]. The historical development of the power consumption by ICT components is discussed in detail in the chapters by Aebischer and Hilty [30] and Kaeslin [31] in this volume.

Moreover, even if a product is small its energy intensity is often higher than that of larger products such as cars or refrigerators [32]. And this is likely to worsen with ubiquitous computing that will connect a multitude of objects to the Internet such as household appliances, wearable devices, and other smart labels, since this makes intensive use of network infrastructures by automatically generating data transfer [33]. New cars will also contribute to information overload, since "high-end functions like autonomous driving or driver assistance systems are likely to have even higher requirements for data throughput and quality" [34, p. 281].

Rebound effects caused by ICT miniaturization are exemplified by the case of Switzerland, where between 1990 and 2005 the average physical mass of a mobile phone was reduced by a factor of 4.4, while the total mass of all phones in Switzerland increased by a factor of eight, because the number of users exploded. This is an example of what has been termed the "miniaturization paradox" [9]. The underlying mechanism here may be that while ICT shrinks, MIPS per dollar increase even faster: "processing power is getting cheaper faster than it is getting smaller!" [9, p. 95]. One might argue that smaller devices require smaller batteries, yet this type of efficiency gain might be offset because devices multiply (pervasive computing enables a large number of components to be used in parallel), but also because those devices are never turned off and use energy-consuming Internet services. Another example of direct rebound effects caused by miniaturization is small RFID readers, which enable wireless short-range communication. As their price declines they multiply, which "will result in a growing stock of always-on radio transmitters whose transmitting power of up to 2 W must be powered by mains adaptors" [33, p. 835].

Miniaturization also helped increase data centers' efficiency, enabling servers to grow in size and functionality. Such efficiency gains, also achieved through virtualization,[2] helped reduce the costs of information storage and enabled the deployment of cloud services, which permitted multipoint information access. As a consequence, demand for data storage space skyrocketed: in 2011, all recorded data in the world amounted to 1.8 ZB (1.8×10^{21} bytes) [35], and from 1986 to 2007 worldwide computing capacity grew five times faster than economic growth [36]. These developments, largely enabled by miniaturization, required a lot of energy. Indeed, "A modern supercomputer usually consumes between 4 and 6 MW—enough electricity to supply something like 5,000 homes" [37, p. 50].

Finally, direct rebound effects were also identified by archivists. Confronted with increasingly large collections, they had to use increasingly sophisticated archival practices and technologies, which eventually led to higher costs in terms of time and resources. For example, archiving innovations did enable repositories to solve their backlog problem. But "once this newly found efficiency has been put into practice, it follows that the repository will seek out even more acquisitions to further its mission as a collecting repository and the new efficiency would actually cause an overall increase in the holdings of a repository" [38, p. 44].

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[2] Virtualization enables one server to host multiple virtual servers by using computing resources that are not being used at their maximum capacity.

3.3 Indirect Rebound Effects

Indirect rebound effects appear when a resource is used more efficiently and the prices of the goods or services produced from this resource go down, which induces an increase in the consumption of other resources. Because ICT are general purpose technologies, this type of rebound is particularly documented for several sectors where "savings from efficiency cost reductions enable more income to be spent on other products and services" [12, p. 6]. As a consequence, *more of other resources* is consumed.

In the area of e-learning, Herring and Roy have studied the environmental impacts of three higher education delivery systems [39]. They concluded that "electronic delivery does not result in a reduction in energy or CO_2 emissions compared to print-based distance learning, due to rebound effects, e.g. in use of computers and home heating." (ibid., p. 525) As for Caird et al., their study of 30 higher education courses in campus-based and distance education systems in 15 UK institutions revealed that, despite rebound effects, online teaching did lead to dematerialization [40].

Because it uses ICT intensively, telework is also subject to rebound effects. For example, telework can also lead to longer commutes when physical presence in the office is required, since employees might decide to live further away from their workplaces if they know that they will be able to telework. According to Hoogeveen and Reijnders, "the indirect effects associated with increased buying power and the rebound effect on transportation following from freed travel time greatly exceeded direct energy efficiency gains" [41, p. 542].

Other indirect rebound effects can occur with e-commerce. But although some authors mention rebound effects as one of the side-effects of e-commerce, they do not mention any evaluation [42–43]. Only one of them argues that "teleshopping generates additional delivery transport" [44, p. 296].

In the case of transportation, Hilty et al. see strong rebound effects "whenever ICT applications lead to time or cost savings for transport" [45, p. 1618]. For example, ICT can help drivers find a parking place more quickly [46, 47]. Although this avoids wasting gasoline, it also makes it easier for people to use their car in the city and might increase overall traffic in the long run. The same consequence can ensue from ICT-based traffic management systems that reduce traffic jams. Fluidifying traffic might provide incentives for non-drivers to start using a car because it is less time-consuming and tiring to do so.

Indirect rebound effects have also been observed in relation to ICT services that seek to reduce transportation. For example, in the cases of teleshopping, telecommuting and teleconferencing "a substantial part of the transport savings are nullified by increased transport for other purposes such as shopping and increased transport by other family members" [48, p. 132]. Case studies suggest that the highest rebound is found in Denmark (73 %): although 105 km could be saved in weekly commuting, 77 extra kilometers were driven. In the Netherlands, 42 extra kilometers were driven compared to 98 saved (hence a 43 % rebound effect). The lowest rebound effects were found in Italy (14 %, 242 km saved vs. 33 km extra) and Germany (19 %, 283 km saved vs. 53 km extra).

In the logistics sector, electronic vehicle management systems are supposed to improve capacity utilization. Studying their impact on the load factor of heavy trucks, authors find evidence of a rebound effect on fronthaul movements, measured by a reduction of the load factor by about 8 % [49].

Other indirect rebound effects related to ICT are plausible, although they have not been empirically studied thus far. Examples are those related to information and knowledge. Since ICT enable more efficient ways of handling information, "individual efforts to access and exchange information is lower than before" [9, p. 91]. This decreases companies' internal price of information work, and increases demand for information, causing people to waste time filing reports. This increased efficiency of distributing information also benefits researchers: thanks to online databases, the number of journal articles has boomed. For example, it was estimated that by the end of 2008 about 50 million articles had been published in the world [50]. Digital technologies also eased the creation of journals, including open access ones, making it harder for researchers to follow up scientific discoveries. It even impacted academic evaluation procedures: "The Internet has not only reduced the cost and effort of conducting peer review through highly automated Web-based management systems, it has provided a great deal of flexibility in how peer review can be conducted" [51]. This phenomenon has gone hand in hand with the diffusion of procedures to evaluate researchers based on the quality and number of publications. Studies show that when such measures are put in place, the impact factor decreases [52], for example because instead of publishing one single paper in a very good journal with a longer evaluation process, researchers tend to send several papers to journals with shorter publishing times but lower impact factors. As a consequence of this overflow of knowledge diffusion, although the efficiency of carrying out research has increased tremendously it has become more difficult to assimilate knowledge because there is so much of it. Indeed, "a growing number of available and potentially interesting goods and pieces of information shortens the span of time that can be devoted to each particular object," and as a consequence "the amount of time we can allot to the dutiful perusal of an academic journal decreases in lockstep with the increase in the number of relevant journals" [53, p. 125]. To conclude on information-related rebound effects, as Hilty puts it: "Acceleration is certainly the most significant effect of ICT, the very heart of its potential for societal change" [9, p. 69]. Within companies, ICT enabled people to process information more efficiently, but at the same time "the demand for internal reporting has increased with the development of IT infrastructure in many organizations to a degree that affects the productivity of the organization" [54, p. 27]. Paradoxically, "although we constantly save time by using better and speedier technology, in the end we do not have more time than before, even less perhaps" [55, p. 295]. Hilty conducted an experiment on the use of PCs in order to understand whether new versions of operating systems had generated rebound effects. He concluded that "changing over to a faster computer running newer software does not necessarily lead to higher work efficiency" [9, p. 89]. This can be explained by new functionalities added by software developers, who tend to overlook software efficiency, and by "software bloating." Besides, "technological change of a time-saving nature can have a large influence on energy use as many time-saving devices (for example, faster modes of transport) require an increase in energy consumption that is frequently reinforced by a 'rebound effect with respect to time'" [27, p. 119].

3.4 Economy-Wide Rebound Effects

Economy-wide rebound effects appear when declining costs of a key resource induce a reduction in the prices of intermediate and final goods throughout the economy, and cause structural changes in production patterns and consumption habits.

Unfortunately, to our knowledge no study has sought to evaluate those effects in the case of ICT. An interesting discussion in relation to the economy-wide rebound effects caused by ICT is proposed by Sorrell [8]. In a critical assessment of the work of Brookes and Saunders, he suggests that they do not "distinguish the energy-efficiency improvements associated with general purpose technologies and other forms of energy-efficiency improvements" [10, p. 1467]. According to Sorrell, economy-wide rebound effects are likely to be large in the case of energy efficiency improvements associated with general purpose technologies. On the other hand, for technologies with smaller economy-wide effects, "Jevons' Paradox seems less likely to hold," as in the case of dedicated energy-efficiency technologies (ibid.). Therefore, if ICT are indeed energy-efficiency technologies, because they are general purpose technologies their environmental benefits are likely to be absorbed by economy-wide rebound effects.

Finally, as a suggestion for future research we would like to propose a new type of economy-wide rebound effect that has not been investigated yet. As general purpose technologies, ICT have had positive economic impacts in many economic sectors. The diffusion of ICT has also taken place in the financial sector. Without ICT world financial markets would not be interconnected and speculative activities such as high frequency trading would hardly be possible. The diffusion of ICT in the financial sector is having economy-wide effects that can offset the economic benefits of ICT. For example, ICT contribute to the financialization of our economies that deters innovation [56], including environmental innovation {Bohl 2013 #3227}. Given their importance in the financial sector, ICT also played a role in the financial crisis, which according to some estimates caused economic losses of "at least a year's worth of U.S. economic output" (more than 14,000 billion dollars) [57]. We can thus argue that the economic benefits of ICT are offset by the losses caused by their diffusion in the financial sector, which represents an economy-wide rebound effect.

4 Conclusion

In this paper we have discussed the rebound effects related to ICT. Although the number of academic papers evaluating rebound effects in other sectors such as transportation or buildings has increased greatly over the past few years, the ICT sector remains underinvestigated. This is despite the fact that existing papers all point out that ICT are subject to important rebound effects of all kinds (energy, time, and knowledge-related), notably because ICT are general purpose technologies that can generate high resource savings throughout the entire economy and society. Although more research is needed to evaluate those rebound effects, some lessons can be learned about how to overcome them.

First, efficiency strategies should not rely exclusively on technological change. As Hilty puts it: “In general terms, an efficiency strategy must always be accompanied by a sufficiency strategy” [9, p. 72]. Other authors have also argued in favor of such behavioral changes on the consumer side [58–61]. Also, general awareness of rebound effects should be increased [62], including limitations of the concept, especially at the macro level. Van den Bergh suggests carrying out systematic “energy/environmental rebound assessments” of important energy conservation projects or strategies, just as any large investment project requires an environmental impact assessment [63]. Integrating rebound effects in energy efficiency evaluations is one solution [64], and integrating them in life cycle assessments is another [65], as has been attempted by Andersen for renewable energy [18]. Finally, efficiency evaluations need to stop focusing on individual products and look at the broader picture, even if the difficulty of finding data makes this challenging. In the case of spam, massive information pollution due to low email costs, Mike Berners-Lee (the brother of Tim who founded the World Wide Web) suggests taxing by one cent per email, since in terms of energy intensity “e-mail is great individually, but it’s terrible in the aggregate because there’s so much of it” [66, p. 65]. Combining technological efficiency measures with pollution capping would “create incentives that would spur demand-side efficiencies to match those already realized on the supply side” (ibid.). Besides, policies and strategies could be developed to support energy-aware ICT by design, as suggested by Ricciardi et al. for the Internet [67]. This would enable ICT to control for their energy impacts from the design stage, in a similar fashion to what has been done with “privacy-by-design” technologies [68].

Beyond the technicality of their evaluation, rebound effects should be perceived as indicators of destructive contradictions in our socioeconomic systems. Studying them enables us to better understand these contradictions, and to imagine means to overcome them. Some argue that if they are controlled, technologies could support the absolute decoupling between increased wellbeing and worsening ecological impacts [63]. Otherwise, only partial decoupling might be achieved, at best [69]. Solutions to combat rebound effects are outside the scope of this chapter. Yet we can sense that they require profound changes in our production systems and consumption patterns in order to achieve a sustainable transition of human societies.

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Modeling the Effects of ICT on Environmental Sustainability: Revisiting a System Dynamics Model Developed for the European Commission

Mohammad Ahmadi Achachlouei and Lorenz M. Hilty

Abstract This chapter revisits a System Dynamics model developed in 2002 with the aim of exploring the future impacts of Information and Communication Technology (ICT) on environmental sustainability in the EU, which then consisted of 15 countries. The time horizon of the study was 20 years (2000–2020). We analyze the results in light of empirical data that is now available for 2000–2012. None of the three scenarios that were developed by experts to specify the external factors needed to run the model were realistic from today's point of view. If the model is re-run with more realistic input data for the first half of the simulation period, however, the main results regarding the impact of ICT remain qualitatively the same; they seem to be relatively robust implications of the causal system structure, as it is represented in the model. Overall, the impacts of ICT for mitigating greenhouse gas emissions and other environmental burdens for 2020 tend to be slightly stronger if the simulation is based on the empirical data now available.

Keywords Information and communication technology · Environmental impact · Sustainable development · Information society · Socioeconomic modeling and simulation · System dynamics · Prospective technology assessment

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1 Introduction

In 2002, the European Commission's Institute for Prospective Technological Studies (IPTS) commissioned a study to explore the current and future effects of ICT to a consortium led by the Institute for Futures Studies and Technology Assessment (IZT), Berlin, Germany. The aim of the study was to estimate positive and negative effects of the ongoing "informatization" of society on environmental indicators with a time horizon of 20 years. The method applied was to develop future scenarios, build a model based on the System Dynamics approach, validate the model, and use it to run quantitative simulations of the scenarios. The results were published in 2003 and 2004 in five interim reports [1–5], one final report [6], and several articles [7–10]. This study was, to our knowledge, the first attempt to simulate the future positive and negative environmental impacts of ICT at a macroeconomic level.

In this paper, we will revisit the results and the methodology of the study—in the following called "the IPTS study"—in light of the developments observed during the past decade. We will critically examine the simulated scenarios from today's point of view and investigate how the predictions made by the study match current empirical data.

A background report published by KTH serves as supplementary material to this chapter [11]. We will refer to it whenever the data to be presented would exceed the space provided for this chapter.

2 Development and Application of the Simulation Model

2.1 Context of Model Development and Application

The aim of the model was to estimate the following environmental indicators (which relate to those reported to the Spring European Council in March of each year) for the year 2020 and to isolate the effect of ICT on them:

- Total freight transport
- Total passenger transport
- Modal split (private car transport vs. public transport)
- Total energy consumption
- The share of electricity generation from renewable sources
- Greenhouse gas emissions
- Municipal solid waste not recycled.

The idea of the model was to enable simulation experiments in which one could "switch on" and "switch off" ICT trends such as telework, mobile work, virtual meetings, Intelligent Transport Systems (ITSs), intelligent heating, etc., and observe how this affects the indicators. The model as such can be viewed as an instrument of integrated impact assessment [12]. The project consortium consisted of the following organizations:

- Institute for Futures Studies and Technology Assessment (IZT), Germany,
- Forum for the Future (FFF), Great Britain,
- Swiss Federal Laboratories for Materials Testing and Research (Empa), Switzerland,
- International Institute for Industrial Environmental Economics (IIIEE) at Lund University, Sweden.

IZT was responsible for the overall coordination and data collection, FFF for scenario development, Empa for model development and simulation, and IIIEE for the policy recommendations derived from the results.

2.2 Basic Terminology and Method

The terminology and method used in the original study are described in detail in Chap. 2 of the fourth interim report [4]. We will briefly recapitulate the most basic concepts: model, simulation, scenario, and System Dynamics.

We define a *model* as a system S’ that an observer uses in the place of a system S in order to answer questions that interest him/her about S. The method of simulation (as opposed to the analytical use of models) is a specific way of using S’ to generate answers, namely experimentation. In a simulation experiment, the model is exposed to experimental conditions, represented by the simulation input data, and shows an observable reaction by producing simulation output data. A simulation model is a model specifically designed to be used for simulation.

The *simulation experiment* makes a prediction of the form “if…then,” where the “if” part is represented by the input data used to feed some of the model variables and the “then” part by the output data generated by calculating other (dependent) model variables. It is the conditional nature that makes a prediction different from a forecast, which calculates future values of *all* model variables based on their initial values only [13]. Strictly speaking, a forecast is a special case of a prediction.

The simulation experiments were based on *scenarios* of the type called “What-if” scenarios in the typology of Börjeson et al. [14]. These scenarios were developed in expert workshops and described in natural language. The simulation input data were derived from the “if”-part of the scenario. This included, for example, the future development of the price of oil and other quantities considered external factors and thus input variables to the model. The model then simulated the development under the assumptions made in the scenarios. Because the simulation experiments only differed by the input data derived from the scenarios, these data vectors were called “scenarios” in the project.

For each scenario, three sub-scenarios were created which expressed best-case, worst-case, and mean assumptions about model parameters that were specified with a range of uncertainty. The “mean” sub-scenarios simply used the arithmetic mean of the best- and worst-case values of each (input) parameter.

System Dynamics is a specific modeling approach characterized by giving the model builder the possibility of expressing the structure of the system as a network of causal links, or more precisely, stocks that are interlinked by material flow, while the flow rates are controlled by information about the stocks. The models are represented mathematically as ordinary differential equations and solved numerically.

3 Future Scenarios Simulated in 2003

The task of the original study was to make a prediction about the future effect of ICT on environmental sustainability. When building the System Dynamics model, it soon became clear that this prediction would depend on conditions that were external to the model, called “external factors,” in particular: the development of the general economic activity level (usually represented by the Gross Domestic Product, GDP), the labor market, energy prices, the climate for innovation, the general attitude of the population toward ICT and toward environmental issues, spatial dispersion, and the speed of some technological developments.

Given the fundamental difficulty to forecast these factors over 20 years, the project team applied a scenario approach to deal with the uncertainty. In expert and stakeholder workshops, three possible futures were developed in the form of scenarios, each of them representing a development that was internally consistent and plausible according to the participants’ assessment. Brief descriptions of the original scenarios are repeated here [4]:

- Scenario A, called “Technocracy,” was characterized by strong economic growth, leading to an increase in the workforce which is also reflected in an increase in desk workers due to the service-based nature of the economy. Strong growth also leads to a significant increase in the total number of households and buildings due to increased economic activity. Collusion between government and business in determining the framework for business activity is dominated by large companies, which is reflected in a fall in the number of SMEs.
- Scenario B, called “Government first,” was characterized by weak economic growth which is reflected in the lack of growth in the number of households, buildings, and desk workers. The total labor force decreases due to stagnating economic growth and the flight of industry from Europe. The settlement pattern becomes more dispersed due to the development and high take-up of environmental and social applications of technology, for example ITSs, smart homes, and virtual conferencing. This also leads to an increase in the percentage of SMEs.
- Scenario C, called “Stakeholder democracy,” was characterized by steady economic growth, leading to an increase in the number of households and desk

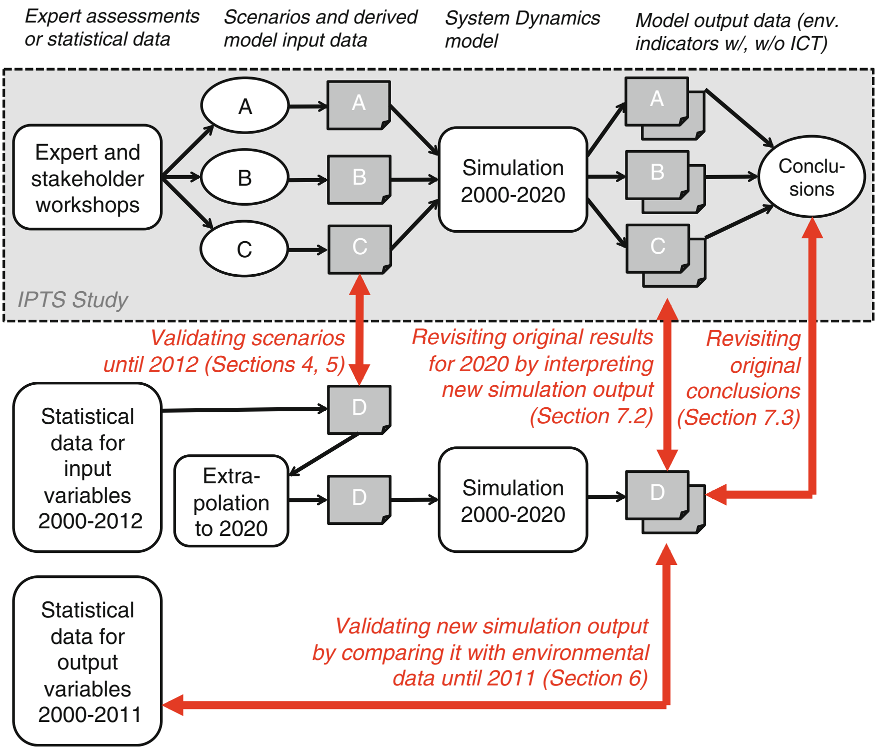

Fig. 1 Data flow in the original study (*grey box*) and in the current study

> workers and the total labor force. A reduction in the levels of inequality between the developed and developing worlds and the expansion of the EU to 35 Member States reduce immigration to Europe and, as a result, the expected rise in population does not materialize. The settlement pattern becomes more dispersed due to business investment in applications that can improve virtual conferencing and smart home technologies.

These scenarios were then operationalized by mapping them to values of 14 external model variables, mostly in the form of parameters that specified the speed of an expected change of the given variable either in terms of an annual growth rate or in terms of a half-life value. The upper part of Fig. 1 shows the role of the scenarios A, B, and C in the original study.

The model was then used to make predictions of the form: "*If* the system under study[1] develops according to Scenario A, *then* ICT will have the following effect on environmental indicators in 2020: …" Most interesting, however, were ICT effects that turned out to be robust with regard to the scenario chosen, i.e., that

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[1] In this case, the system under study was defined as the sum of the national economies of EU15.

could be observed across all scenarios. One example was the result that ICT would (despite telework, teleshopping and virtual meetings, virtual goods and ITSs) not slow down the growth of *overall* passenger transport due to rebound effects (e.g., time-efficient transport stimulates demand), but instead shift the modal split back to more public transport, inhibiting the growth of private car transport. This was explained by the increasing opportunities for mobile work that created a comparative advantage for public transport (time utilization effect). Other output variables depended on the scenario chosen and therefore had to be interpreted with high uncertainty. Examples of output variables on which ICT had a stimulating or inhibiting (if not reducing) effect depending on the scenario chosen include:

- ICT had an inhibiting effect on total freight transport only in Scenario A (under best-case assumptions) and in Scenario C (except for worst-case assumptions). In all other cases, ICT increased freight transport by creating efficiency gains that were compensated for by rebound effects of 100 % or more [4, p. 82].
- ICT had a much more inhibiting effect on total energy consumption in Scenarios A and C than in B [4, p. 57]. This seems surprising because B was the scenario assuming the highest take-up of environmental applications of technologies. However, B is also the one with the weakest economic growth, leading to a stabilization of energy consumption (which increased further in A and C), which in turn left less space for energy-saving ICT applications. In other words, the more energy is used, the higher is the savings potential by efficiency measures, including ICT. Overall, B was the scenario with the most advantageous environmental indicators [4, p. 56].

Today, a decade after the three scenarios were defined, it seems reasonable to conduct an ex-post validation of the simulation study. In the following, we will describe how we not only tested the validity of the original scenarios (the "if" part of the simulation study), but also developed a new one which is exactly calibrated with the empirical data that is now available about roughly the first decade of the time window simulated. This "Scenario D" will then be used to renew the predictions of the model for the second decade of the simulation period in order to restate the "then" part of the simulation result with reduced uncertainty (see also Fig. 1).

4 Comparing Simulation Assumptions with Empirical Data

This section addresses the following research question (RQ), based on a search in currently available data:

> RQ1: Which of the three scenarios comes closest to reality?

To answer this question, we checked parameters such as GDP growth and other assumptions underlying the scenarios against the reality of the past 12 years (2000–2012). None of the three scenarios dominantly represents reality during this period. Scenario A and B come closest to the real-world data in seven cases each, and Scenario C in five cases (as shown in the last column of Table 1).

To answer RQ1, Table 1 lists, in the left-hand columns, all model inputs in the IPTS study (taken from Table 4-3 in the 4th interim report [4]), of which 14 were used to differentiate between the scenarios. These are economic variables (M2, M4, M15, M16, E400, E17), demographic variables (M7, M9), variables regarding the efficiency of electricity supply and use in general (E13, E20), and variables expressing how people use ICT (U400, T400, U201).[2] In addition, W32 describes progress in recycling technology for Municipal Solid Waste (MSW) in general. Each scenario is formally represented as a vector of these 14 variables. The task was to find out which vector is closest to reality, given the observed development in EU15 from 2000 to 2012 (or at least for the years for which data are available). Table 1 presents the real-world statistical data for the model input described in Table 4-3 in [4]. The Compound Annual Growth Rate (CAGR) formula was used to calculate the annual growth rates using empirical data for beginning and ending years (Table 1):

$$CAGR = \left(\frac{Ending\ value}{Beginning\ value}\right)^{\left(\frac{1}{\#\ of\ years}\right)} - 1$$

Detailed calculations associated with Table 1 can be found in a report that provides supplementary information to this chapter [11]. A discussion of the results shown in Table 1.

GDP Annual Growth Rate (M2). For M2, Scenario B was closest to the empirical data. However, assumptions for this parameter were overestimated in all three scenarios. The closest assumption for the expected average annual growth rate of GDP, i.e., 2.12 %/a (in Scenario B) was still about twice as much as the observed GDP annual growth rate, i.e., 1.11 %/a for 2000–2012.

One reason for the overestimation of M2 might be that the IPTS study could not anticipate the 2008 financial crisis and the associated economic slowdown in 2009. The annual growth rate for 2000–2008, i.e., 1.88 %/a, is clearly higher than the rate for 2000–2012 [15], but still lower than Scenario B. Perhaps the general political climate for growth was more positive or optimistic when the IPTS study was conducted.

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[2] We retained the original identifiers for the variables (such as “M2”) for those readers who wish to consult [4] for details.

Table 1 Comparing simulation assumptions (taken from Table 4 in the 4th interim report of the IPTS study [4]) with empirical data. We retained the original identifiers for the variables (such as "M2") for those readers who wish to consult [4] for details

No	External variable	Scenario assumptions used as simulation input 2000–2020			Empirical data for EU15 2000–2012	Scenario closest to reality
		Scenario A	Scenario B	Scenario C		
M2	GDP Annual Growth Rate	2.56 %	2.12 %	2.3 %	1.11 % (14.2 % increase over 2000–2012) [15]	B
M4	Labor Demand Annual Growth Rate	0.42 %	−0.15 %	0.27 %	0.67 % (8.3 % increase over 2000–2012) [16]	A
M7	Population Annual Growth Rate	0.16 %	0.16 %	0 %	0.46 % (5.7 % increase over 2000–2012) [17]	A and B
M9	Number of Households Annual Growth Rate	0.85 %	0.18 %	0.7 %	1.51 % for 2005–2012 (11.1 % increase over 2005–2012) [18]	A
M15	Number of SMEs Annual Growth Rate	0.21 %	0.84 %	0.42 %	0.78 % for 2005–2012 (5.6 % increase over 2005–2012) [19]	B[a]
M16	Office Work Demand Annual Growth Rate	0.42 %	0.0 %	0.27 %	1.28 % for 2008–2011 [18]	A[b]
E400	Fossil Energy Price Annual Change Rate	0.35 %	3 %	0.35 %	2.8 % Automotive gas oil price as proxy	B[c]
U400	Shift to Energy-Efficient ICT Half-life	15 a	15 a	7.5 a	~7.5 a [20–24]	C
T400	ICT-Induced Spatial Settlement Dispersion	0	+25 %	+25 %	20 % increase in average commuting distance over the period 2000–2010 in Finland as proxy [25]	B and C[d]

(continued)

Table 1 (continued)

No	External variable	Scenario assumptions used as simulation input 2000–2020			Empirical data for EU15 2000–2012	Scenario closest to reality
		Scenario A	Scenario B	Scenario C		
E12	D&T Electricity Use Efficiency Potential	+50 %			∼30 a (7.9 % increase in efficiency over 9 years 2000–2009 in EU-27) [26]	A and C
E13	D&T Electricity Use Efficiency Half-life	15 a	7.5 a	15 a		
E17	D&T Electricity Price Annual Growth Rate	−0.45 %	0 %	−0.45 %	3.9 % (35 % increase over 2005–2013) [27]	B
E19	Electricity Supply Efficiency Potential	+25 %			∼20 a (7.1 % increase in efficiency over 10 years 2000–2010) [28]	A and C
E20	Electricity Supply Efficiency Half-life	20 a	10 a	20 a		
U201	Average Useful Life of ICT Annual Change Rate	−8.0 %	0 %	−8.0%	−7.3 % over 8 years 2000–2008 [29, 30]	A and C
W31	MSW Recycling Potential	53 %			∼10 a (28 % recycling rate in 2011) [31]	B
W32	MSW Recycling Half-life	20 a	8 a	20 a		
G50	Industrial Materials Price Elasticity	−0.5 (5 a)			−0.2 [32]	*
E220	Industrial Energy Price Elasticity	−0.5 (5 a) Assumed to be equal to G50			−0.2 Assumed to be equal to G50	*
E15	D&T Electricity Price Elasticity	−0.5 (5 a)			−0.2 [33]	*

(continued)

Table 1 (continued)

No	External variable	Scenario assumptions used as simulation input 2000–2020			Empirical data for EU15 2000–2012	Scenario closest to reality
		Scenario A	Scenario B	Scenario C		
T97	Air Transport Price Elasticity	−1.5 (5 a)			−0.8 [34]	*
T305	Freight Transport Energy Price Elasticity	−1.5 (5 a)			−0.175 [35]	*

Note Short description of the variables: *M2* Expected average annual growth rate of Gross Domestic Product (GDP). *M4* Expected average annual growth rate of labor demand. *M7* Expected average annual growth rate of the population. *M9* Expected average annual growth of the total number of households. *M15* Expected annual growth of the total number of small and medium-sized enterprises. *M16* Expected average annual growth rate of the demand for office work. *E400* Average annual change rate of real energy prices for fossil fuels. *U400* How many years after beginning of simulation will half of the energy-saving potentials for making ICT more energy-efficient (reducing standby and off-mode consumption, power management for servers) be exploited under the assumption of constant real energy prices? *T400* Expected impact of ICT diffusion (e.g., ITSs, virtual conferencing technology, etc.) on settlement dispersion, expressed as the increase in average transport distance of goods and people within a period of 20 years. *E12* Long-term efficiency potential in the utilization of electricity in the domestic and tertiary sector (D&T) in % efficiency increase. *E13* When will half of this (*E12*) potential be realized under the assumption of constant energy prices? *E17* Annual growth rate of electricity prices in the domestic and tertiary sector (*D&T*) in %, taking the price level at the beginning of the simulation as 100 %. *E19* Long-term efficiency potential in the supply of electricity in % efficiency increase. *E20* When will half of this potential be realized under the assumption of constant energy prices? *U201* Average annual change rate of the useful life of an average mass unit of ICT in %. Secondary use is included in the useful life. *W31* Long-term potential for recycling municipal solid waste (MSW), in % of MSW. *W32* When will half of this potential be realized? In years after the beginning of the simulation. *G50* Economic elasticity of industrial materials demand with regard to materials prices for industrial customers. *E220* Economic elasticity of industrial energy demand with regard to energy prices for industrial customers. *E15* Economic elasticity of electricity demand with regard to electricity price in the domestic and tertiary sector. *T97* Economic elasticity of air traffic demand with regard to air fares. *T305* Economic elasticity of freight transport demand with regard to energy prices.

[a] Employment growth rate (M4) for 2005–2012 in EU15 was 0.34 %/a

[b] Employment growth rate (M4) for 2008–2011 in EU15 was 0.69 %/a. The empirical data collected for M16 is a proxy

[c] The empirical data here represents automotive gas oil in the EU. We did not use the world oil price, the CAGR of which was 8.8 % over 2000–2012 [45]

[d] It was unclear whether the increase was ICT-induced or not

* The elasticity parameters G50, E220, E15, T97, and T305 were not used in the comparison since they did not vary among old scenarios A, B, and C. However, these parameters were included in this table because their updated (empirical) values were used in the new scenario D (see Sect. 5)

Labor Demand Annual Growth Rate (M4). For M4, Scenario A was closest to the empirical data. The observed annual growth rate for total employment in EU-15 over 2000–2012, i.e., 0.67 %/a, is higher than the highest value 0.42 %/a (assumed for Scenario A). This assumption was clearly underestimated.

Population Annual Growth Rate (M7). For M7, Scenarios A and B were closest to the empirical data, although the observed growth rate (0.46 %/a) was almost three times higher than the rate assumed for these scenarios. (Scenario C assumed zero growth because of the assumed reduced immigration.) M7 was clearly underestimated in the IPTS study.

Number of Households Annual Growth Rate (M9). For M9, Scenario A was closest to the empirical data. The observed rate is 1.51 %/a for 2005–2012. Here, we should assess the logic behind the assumption made for M9. The IPTS study assumed M9 to be roughly equal to population growth in scenario B, higher in C, and much higher in A (due to GDP growth that allows for smaller households). The observed rate for population growth for 2005–2012 is 0.38 %/a [18]. Note that our observation for this parameter is incomplete, and it does not include data for 2000–2004.

Number of SMEs Annual Growth Rate (M15). For M15, Scenario B was closest to the empirical data. Based on the scenario descriptions, the IPTS study assumed this growth rate to be half, double, or equal to M4, the labor demand annual growth rate. Our observation for M15 (0.78 %/a for 2005–2012) was almost twice as high as the observed data for M4 for the same period (0.34 % for 2005–2012) [19], so Scenario B was chosen as the closest.

Office Work Demand Annual Growth Rate (M16). For M16, Scenario A was closest to the empirical data. Instead of looking at absolute values of assumptions, we assessed the logic behind the assumption. The IPTS study had assumed that in Scenarios A and C, the demand for office work would change in parallel to general labor demand, and that in Scenario B, the demand would be stable (despite negative growth of general labor demand) due to structural change. We collected empirical data on employment growth in knowledge-intensive high-technology services, knowledge-intensive market services, and ICT services, which were used as proxy for office work demand.

Fossil Energy Price Change Rate (E400). For E400, Scenario B was closest to the empirical data. The IPTS study used the world oil price as the proxy for E400. However, since oil prices increased considerably (8.8 %/a) over the past years at the global level, "while natural gas and other energy prices have seen differing developments in each world region" [36], we chose a different proxy for E400: automotive gas oil (diesel fuel) with the CAGR of 2.8 %/a, which was closer to the forecast rate in Scenario B, but much higher than the rates in other scenarios

(0.35 %/a for A and C and 3 %/a for B; the IPTS study assumed that environmental costs are internalized in scenario B, whereas scenarios A and C assumed a strong increase of real energy prices.)

Shift to Energy-Efficient ICT Half-life (U400). For U400, given the data collected on energy efficiency of data centers, microprocessors, servers, and standby mode (presented below), we decided to choose the optimistic estimation, i.e., Scenario C in this case, as the scenario closest to the actual development. To make it simpler, the IPTS study used a half-life parameter (15 years in scenarios A and B and 7.5 years in scenario C) for all of the energy-saving potentials—i.e., 40 % for servers, 12.1 % for client standby consumption, 3 % for client off-mode consumption, and 55 % for the CRT-to-LCD shift. The IPTS study made the claim that all of these potentials were approached at the same speed as a consequence of technology improvement in ICT equipment. To compare (and falsify) this assumption with the real-world data, we chose the energy-saving potential for servers (40 %). How fast has this potential developed since 2000? A study on server and data center energy efficiency [37] identified key components on the server side: microprocessors, servers, storage devices, and site infrastructure systems. The energy efficiency of microprocessors and servers (performance per watt) has increased at an annual growth rate of 50–60 % over 2006–2013 [20, 21]. The efficiency of site infrastructure systems, which is measured in Power Usage Effectiveness (PUE) [22], has also been improved in recent years with an average PUE factor of 2.5 in 2007 to 1.65 in 2013 [23], i.e., about 7.8 % improvement per year. In terms of energy efficiency of Internet data flows, the energy intensity of the Internet has decreased by 30 % per year on average since 2000 [24, 38]. These observations show a faster development of the assumed potential for servers than the half-life of 15 or 7.5 years assumed in the IPTS study. It is obvious that all 3 scenarios greatly underestimated efficiency potentials and speed. Scenario C in the IPTS study had assumed that an LCA/eco-labeling system would be introduced for ICT. Some labels for hardware that have been introduced might have had an influence on the more rapid shift to energy-efficient ICT. (In the other scenarios, no non-fiscal policies promoting a shift toward more rational energy use in the ICT area were mentioned.)

ICT-Induced Spatial Settlement Dispersion (T400). For T400, Scenarios B and C were closest to the empirical data. We collected empirical data on average commuting distance as a proxy for T400. The observed data, 20 % growth over the period 2000–2010 in Finland, comes closest to 25 % within a period of 20 years in Scenarios B and C. These scenarios in the IPTS study had assumed that the settlement pattern would become more dispersed due to the diffusion of ITSs, video-conferencing and intelligent home technology. However, the source of the empirical proxy data used here (Finnish Environment Institute) mentioned three factors as the main reason for the growth in average commuting distance: expansion of commuting areas, increasing levels of commuting between urban regions, and specialization of jobs.

D&T Electricity Use Efficiency Potential (E12) and Half-life (E13). For the combination of E12 and E13, Scenarios A and C were closest to the empirical data. We used proxy data from EU-27, i.e., a roughly 8 % increase in energy efficiency over the period 2000–2009. This directs us to the half-life of 30 years, which is a higher value than the assumptions of Scenarios A and C (15 years) and Scenario B (7.5 years). This means that the assumed D&T electricity use efficiency potential E12 (50 %) has not been exploited as rapidly as assumed in the scenarios. (The high speed in Scenario B had been justified in the IPTS study assuming governmental regulations.)

D&T Electricity Price Annual Growth Rate (E17). For E17, Scenario B was closest to the empirical data. The observed annual growth rate of the domestic electricity price (3.9 %/a, calculated from Eurostat [27]) deviates strongly from the assumed values for Scenarios A and C (−0.45 %) and Scenario B (0 %)—The IPTS study had based its calculations on European Commission data [39].

Electricity Supply Efficiency Potential (E19) and Half-life (E20). For the combination of E19 and E20, Scenarios A and C were closest to the empirical data. The observed data (7 % increase in efficiency over the period 2000–2010) is more consistent with Scenario A and C.

Average Useful Life of ICT Change Rate (U201). For U201, Scenarios A and C were closest to the empirical data. The empirical data (about 7.3 %/a decrease in average useful life of personal computers as a proxy) were closer to the rate of 8 %/a decrease in Scenarios A and C.

MSW Recycling Potential (W31) and Half-life (W32). For the combination of W31 and W32, Scenario B was closest to the empirical data. The observed recycling rate for the year 2011 in EU-15 was 28 % of the MSW. Using this figure, we derived the half-life value of 10 years. This is closer to the speed assumed in Scenario B, where the half-life value of 8 years would result in a recycling rate of 32.6 % in 2011 to realize the potential W31 (53 %)—compared to the half-life of 20 years in Scenarios A and C which would calculate 17 % for recycling rate in 2011. (The IPTS study assumed a rough estimate for the potential W31, and the half-life values W32 were a compromise between the project team's and the workshop participants' estimates. Scenario B was assumed to exploit the potential more quickly because of government regulations.)

Elasticity Parameters. The elasticity parameters G50, E220, E15, T97, and T305 were not used in the original study to differentiate between Scenarios A, B, and C. However, they were now re-calibrated based on empirical data (see references provided in the column "Empirical data for EU15") for the Scenario D simulation.

5 Creating a New Scenario Based on Empirical Data

As seen in Sect. 4, none of three original scenarios A, B, or C emerges as a winner from the ex-post comparison to real-world data over the past 12 years. Therefore it is not a feasible plan to use today's knowledge to select the best among them to reduce the uncertainty of the simulation results. Instead, we will define a new scenario based on the empirical data available today, called "Scenario D", and re-run the model for this scenario.

The new Scenario D is directly based on empirical data: For the years 2000–2012, statistical time series were used (see the background report [11]), and for 2013–2020, the CAGR values drawn from this data (also shown in Table 1) were used for trend extrapolation. Figure 1 shows the role of Scenario D in the current study.

Re-running the model with these data will produce new output data for the entire simulation period 2000–2020. We expect this output to be different from the output the model produced when it was first run in 2003 under the assumption of scenarios A, B, or C. The new simulation output will give us the following opportunities:

1. To validate the model by comparing the simulated trends with statistical data for the period 2000–2012. These trends are output data (such as "total energy consumption") and therefore not included in the scenario assumptions, but predicted by the model. These predictions can potentially be falsified and are therefore useful for model validation.
2. To compare the simulation results for 2020 (based on Scenario D) with the original results that were based on scenarios A, B, or C due to a lack of knowledge. Given that roughly half of the simulation period has passed since the model was first applied, we can expect to reduce the uncertainty when making predictions for the second half. In particular, it will be interesting if the quantitative results and qualitative conclusions of the study are still valid in light of the new and more realistic scenario D.

6 Comparing Simulated Trends with Empirical Data

This Section addresses the following research question, based on a search in currently available data:

> RQ2: Are the main trends (in energy, transport, etc., as shown in Figs. 6-2, 6-3, 6-4, 6-5, 6-6, 6-7, 6-8, and 6-9 in [4]) that the IPTS model predicts for a realistic scenario consistent with the currently available data?

As mentioned earlier, none of the three scenarios dominantly represents the reality over the past years. So we defined a new scenario (Scenario D) based on the empirical data available today. Figures 2, 3 and 4 show selected trends in energy,

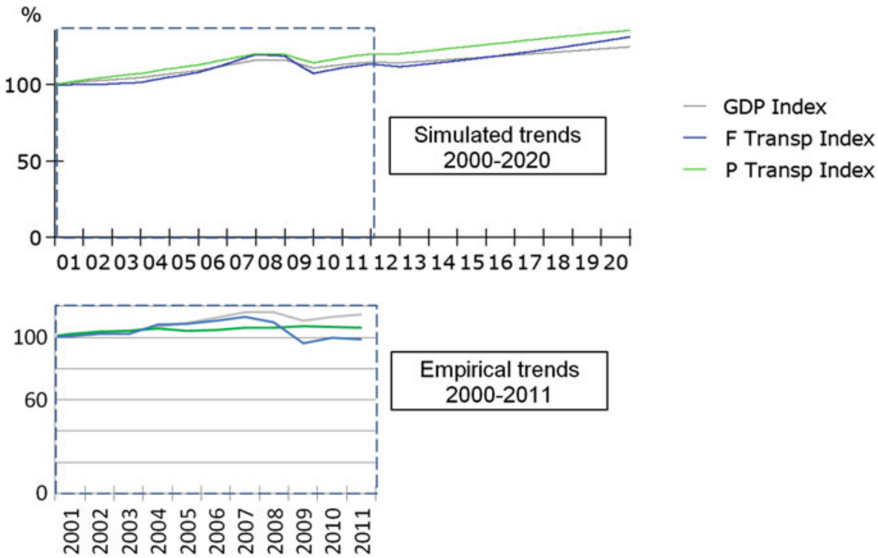

Fig. 2 Comparison of simulated trends (Scenario D, mean sub-scenario) with empirical trends [41] of: freight transport performance ("F Transp Index") and passenger transport performance ("P Transp Index"), compared to GDP index. (2000 = 100 %)

transport, and waste, comparing the simulated development in Scenario D with the real world trends.

As shown in Figs. 2, 3 and 4, the predictions were roughly plausible, but cannot be taken as precise predictions, which is not surprising because the purpose of the model was not to predict the development of transport and energy demand and other environmental indicators in absolute terms, but the relative impact of ICT on these indicators. Further comparisons of the trends are presented in the background report [11].

7 Reducing the Uncertainty of Simulation Results for 2020

This section addresses the following research question, based on a search in currently available data:

> RQ3: Can the main quantitative and qualitative results regarding the impact of ICT provided by the IPTS study be confirmed or disconfirmed and their uncertainty reduced by the currently available data?

The goal of the original model was to quantify the effect of ICT on environmental indicators in 2020. In order to do so, the model was applied according to the following steps:

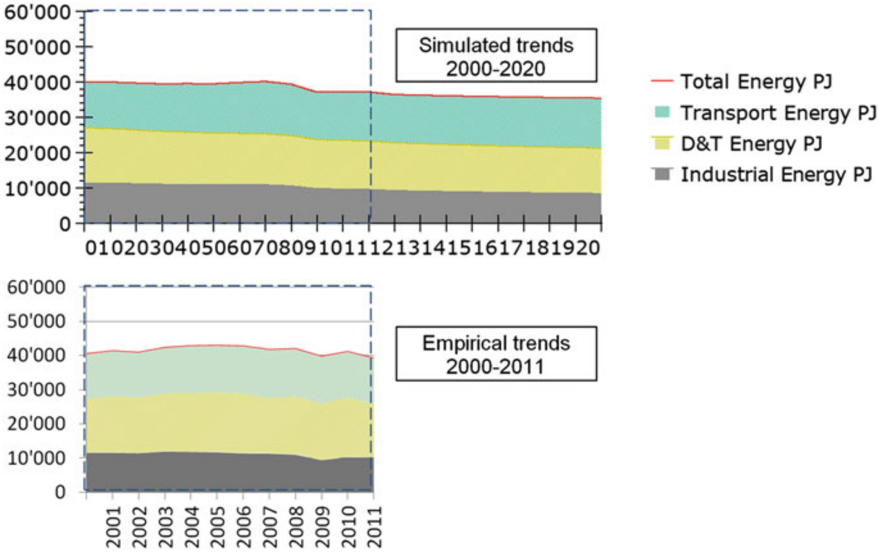

Fig. 3 Comparison of simulated trends (Scenario D) with empirical trends [42] of: energy consumption by the sectors transport, domestic and tertiary, and industry. *Abbreviations PJ* Petajoule, *D&T* Domestic and tertiary sector

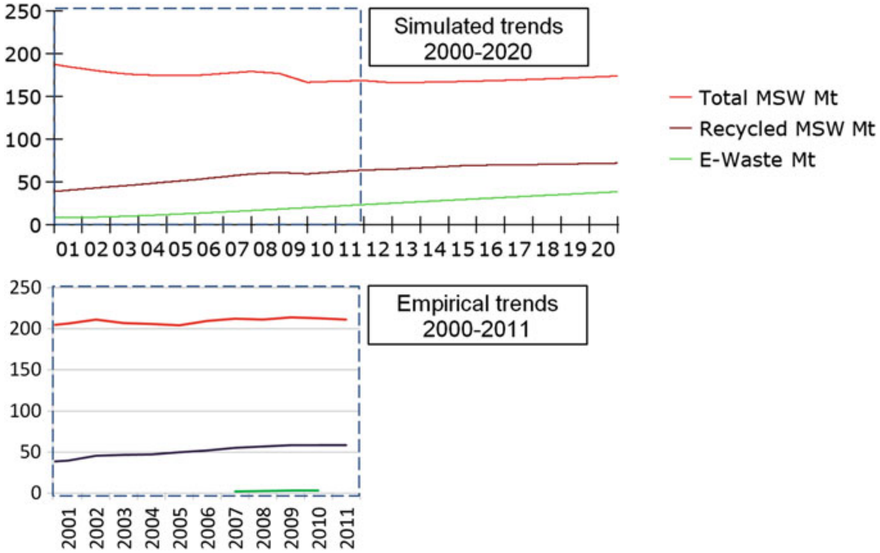

Fig. 4 Comparison of simulated trends (Scenario D) with empirical trends [43, 44] of: municipal solid waste (MSW), the recycling rate, and the e-waste fraction in megatonnes (Mt)

1. Define the data for the external (i.e., independent) variables in the form of a scenario. We described this in Sects. 3–5.
2. Create two versions of the given scenario, one which simulates the development of ICT as it is predicted over the simulation period (called "reference" run) and one which "freezes" ICT diffusion and use at the level of the year 2000 (called "ICT freeze"). An "ICT freeze" switch is built into the model for that purpose.
3. Calculate the difference between the reference and the "ICT freeze" version of the scenario.
4. Conduct sensitivity analyses with regard to all uncertain input that is not determined by the scenario. This yields three values for each result, one calculated under "best case," one under "worst case," and one under "mean" assumptions regarding all uncertain input that is not determined by the scenario. Total energy consumption is used as the lead output indicator that is minimized for the best case and maximized for the worst case.
5. Draw quantitative conclusions (with quantified uncertainties) and qualitative conclusions. For the original three scenarios A, B, and C, these conclusions were described mainly in [6] and [7], with background information in [4].

To answer RQ3, we first reproduce the steps 2 to 4 for Scenario D exactly as they were conducted for A to C in the original study.

7.1 Simulation Results for Scenario D

Table 2 presents the simulation results for the environmental indicators in 2020 in terms of a relative increase or decrease compared to their values in the year 2000. The first row for each indicator shows the results of the simulation for our projected development of ICT (the reference run). The second row (the value in parentheses) shows the result for the "ICT freeze" version of the scenario, e.g., under the assumption that ICT remained as it was in 2000.

7.2 Revisiting the Main Quantitative Results of the IPTS Study

The ability to focus on Scenario D has reduced the span between the maximum and minimum values that were produced in the original study by running the model for all three scenarios as well as for a best-case, a mean, and a worst-case sub-scenario in each case. For example, the values for total freight transport, as shown Table 2, range from 106 % in "D best" to 143 % in "D worst" (i.e., a factor of 1.4), whereas, in the original study, this ranged from 85 % in "B best" to 269 % in "C worst" (a factor of 3.2) [4].

Table 2 Simulated values for environmental indicators in the year 2020, expressed in % of the values of the year 2000

%	Initial 2000	D worst 2020	D mean 2020	D best 2020
Total freight transport	100	143	131	106
		(145)	(138)	(130)
Total passenger transport	100	140	136	130
		(135)	(129)	(124)
Private car transport	100	134	125	118
		(142)	(229)	(121)
Total energy consumption	100	97	89	77
		(103)	(98)	(94)
RES share in electricity	100	286	167	191.0
		(141)	(160)	(179)
Total GHG emissions	100	78	79	64
		(97)	(89)	(81)
Total material demand	100	86	78.9	64
		(101)	(96)	(90)

Under the values of the reference run in each cell, the values in parentheses show the results for the "ICT freeze" simulation runs. The three columns represent the results calculated under worst-, mean, or best-case assumptions for uncertain model parameters. *RES* Renewable Energy Sources, *GHG* GreenHouse Gas

The role of ICT can be assessed by comparing the figures of the reference simulation run in each cell of Table 2 with the values in parentheses ("ICT freeze" run). Dividing the reference value by the corresponding "ICT freeze" value yields an index for the impact of ICT. Table 3 presents this index for all sub-scenarios for both the original scenarios A, B, and C and the new scenario D.

Similar to the pattern seen for the original scenarios, the impact of ICT in the new Scenario D seems to be basically stimulating for passenger transport and basically inhibiting for energy, GHG, and materials. However, for freight transport, the new scenario shows a slightly inhibiting effect of ICT (0.99) even under worst-case assumptions (see below for explanation).

A general observation is that the impact of ICT on the environmental indicators is roughly between −25 and +30 % in the original scenarios and roughly between −30 and +5 % in Scenario D (rounded extreme values from Table 3). Scenario D, which is based on empirical data, seems to have changed the behavior of the model in the following way: the potential damage caused by ICT is reduced, but not the potential positive effect, which even seems to be slightly higher. This can be explained by the fact that energy prices have been increasing faster since 2000 than assumed in all scenarios of the original study. Higher energy prices work against rebound effects.

In any case, the overall conclusion of the original study that "the impact of ICT on the environmental indicators is relevant and should be taken into account by environmental policies" [4] is still valid. It should also be repeated that ICT can

Table 3 ICT impact index (the value for the reference simulation run divided by the value for the corresponding “ICT freeze” run) for the five main output variables of the model used as environmental indicators

ICT impact index	A worst	A mean	A best	B worst	B mean	B best	C worst	C mean	C best	**D worst**	**D mean**	**D best**
Freight Transport	1.04	1.01	0.90	1.32	1.27	1.11	1.03	0.98	0.83	**0.99**	**0.95**	**0.81**
Passenger Transport	1.03	1.02	1.01	1.04	1.04	1.02	1.03	1.02	1.00	**1.03**	**1.05**	**1.04**
Energy	0.98	0.95	0.89	1.03	0.99	0.92	0.97	0.93	0.85	**0.94**	**0.90**	**0.82**
GHG	0.97	0.93	0.87	1.03	0.98	0.90	0.97	0.92	0.83	**0.81**	**0.89**	**0.79**
Materials	0.90	0.88	0.79	1.00	0.97	0.87	0.90	0.86	0.74	**0.85**	**0.83**	**0.71**

The values for Scenarios A–C are copied from [4], the values for Scenario D are newly computed. A value of 1.0 means that ICT has no influence, values >1 mean that ICT causes an increase of the environmental indicator by this factor, i.e., that ICT causes more environmental burden. Values <1 (*emphasized by a gray background*) indicate that ICT reduces environmental burden have positive and negative environmental effects in different areas and that policymakers should strive to systematically support the positive (decreasing) effects and inhibit the negative ones. The effects in the three main areas freight transport, passenger transport, and energy are discussed in more detail below.

Freight Transport. As shown in Table 3, ICT has a reducing influence on total freight transport demand (which is different from the pattern of increasing effects in the original scenarios). With the "ICT freeze," as shown in Table 2, we have roughly the same level of increase in "D worst" that we see with the reference run, i.e., about 45 % increase in both runs. In "D mean" we have about 7 % more increase in freight transport for "ICT freeze," which could still be considered insignificant given the overall uncertainty of the results. In "D best," however, we have the difference of roughly 25 % more freight transport with "ICT freeze." This means that—under the most optimistic assumptions made with regard to all uncertain model parameters—there could be less increase in freight transport by roughly 25 % due to ICT. This effect is then mainly due to the virtualization of goods (which is seen in Table 2 and 3 as the reducing influence of ICT on total material demand), leading to less transport demand, and to a much lesser extent due to the optimization effect of ICT, which makes transport cheaper and therefore leads to a rebound effect. One could conclude that, if the model is correct, a policy intending to reduce freight transport should focus more on the dematerialization of goods than on the optimization of logistics.

Passenger Transport. As shown in Table 3, ICT also has an increasing influence on total passenger transport in Scenario D. As shown in Table 2, the simulated values in Scenario D show an increase in passenger transport in 2020 for both reference and "ICT freeze" runs, even though the increase with the "ICT Freeze" is slower. So there is a larger increase in the reference run, which is explained by the fact that ICT generates demand for passenger transport by making passenger transport more time efficient. This basic effect is still observed in the new scenario; the picture changes if we differentiate between modes of transport (see the background report [11] for detailed results on passenger transport modes). As shown in Table 2, ICT seems to help slow the growth in private car transport. This can be explained by the time utilization effect represented in the model: Mobile ICT makes it possible to use the time spent on public transport more productively. The extent of this effect with regard to the comparative disadvantage it produces for private car transport is even greater in Scenario D than it was in the original scenarios.

Total Energy Demand. In the new results, ICT has decreasing impact on total energy consumption, not only confirming the decreasing pattern in the original results, but also demonstrating a more optimistic perspective (e.g., see the lower "best" and "mean" values in Scenario D compared to the corresponding values in the original scenarios). Intelligent heating is an area where ICT can help reduce energy consumption. Taking the energy consumption in the domestic and tertiary sector (one of the main components of total energy consumption in the model) as a proxy for heating energy consumption, the simulated values in the new scenario D for the year 2020, expressed in percentages (assuming 100 % for the year 2000) are as follows: 87 (92) for "D worst," 82 (94) for "D mean," and 81 (95) for "D best" [11] —the values in parentheses again indicate "ICT freeze" results. Although the efficiency of heating and other energy consumption in buildings is increasing even with ICT "frozen" at the level of 2000, ICT has a boosting effect on this efficiency. Using Scenario D assumptions, ICT is responsible for saving 15 % of the energy consumed in the domestic and tertiary sector, mainly due to intelligent heating (which is not presented here, but is the main effect behind these figures in the model). This result of the original study is therefore confirmed and even reinforced by the simulation output of Scenario D.

7.3 Revisiting the Main Qualitative Results of the IPTS Study

Table 4 presents the main qualitative results (main conclusions) of the original IPTS study [9] and briefly evaluates them in light of the new simulation results based on Scenario D.

Table 4 Revisiting the main conclusions of the IPTS study (cited from [9]) by checking them against the new results produced for this book chapter

Main conclusions of the original IPTS study [9]	The main conclusions revisited
ICT applications supporting a product-to-service shift (virtual goods) "Although there are widely diverging opinions concerning an ICT-supported product-to-service shift and its potential energy saving and dematerialization effects until 2020, it is the high potential for change that makes this issue important. In the model, almost every output turned out to be directly or indirectly linked to the product-to-service shift variables, first of all freight transport, but also waste and the energy used by the industrial sector"	*Confirmed by new results* ICT has a reducing influence on total material demand (dematerialization effect)
ICT applications for heating management (intelligent heating) "ICT has a high potential impact on the rational use of heating energy. Heating accounts for roughly 30 % of total energy consumption and conservation measures using physical materials tend only to be applied to the small annual share of buildings that is	*Confirmed by new results* ICT has reducing effect on energy consumption in the domestic and tertiary sector, which is dominated by heating

(continued)

Table 4 (continued)

Main conclusions of the original IPTS study [9]	The main conclusions revisited
renovated or newly built. 'Soft measures' using ICT (such as intelligent heating systems) have the advantage of being applicable in all buildings, and could therefore have a significant effect"	
ICT applications for passenger transport efficiency "All ICT applications that make passenger transport more time efficient (such as ITSs) will create a rebound effect leading to more traffic and possibly more energy consumption. Induced passenger transport demand has severe environmental consequences in energy use and greenhouse gas emissions, although ICT contributes to lowering the energy and GHG intensity of passenger transport"	*Confirmed by new results* ICT has a stimulating influence on total passenger transport by making it more cost and time efficient (rebound effect)
ICT applications for mobile work "Mobile work enabled or supported by pervasive computing and other new forms of ICT application can have a significant effect on passenger transport, because it increases the share of time spent in traffic that people can use productively. This can create more transport demand, while stimulating public transport more than private car transport. The effects of ICT on personal time management and time utilization are probably the most underestimated indirect impacts of ICT on the environment, with great potential in either direction"	*Confirmed by new results* Time utilization effects of mobile ICT create an advantage for public transport compared to private car transport
ICT applications for freight transport efficiency "All ICT applications that make freight transport more cost efficient (i.e., cheaper) will immediately create more freight transport and more energy consumption. There is no evidence for assuming anything other than a strong price rebound effect here. By making transport more cost efficient, ICT creates freight transport demand, with severe environmental effects, unless measures are taken to limit demand of transport"	*Not confirmed by new results* ICT now slightly inhibits growth of freight transport. This ICT effect is mainly due to its dematerialization effect, which is stronger than in the original study

8 Conclusion and Future Research

Revisiting the IPTS study on future impact of ICT on environmental sustainability in EU-15 for the time horizon of 2020, we answered three questions on the inputs and outputs of the model and the main conclusions of the IPTS study:

Which of the three scenarios in the IPTS study comes closest to reality? (*RQ*1) In response to this question we collected empirical data and found that none of the scenarios can be considered realistic. Based on the data, we defined a new scenario which was then used for further simulation experiments.

Are the main trends the IPTS model predicts for a realistic scenario consistent with the currently available data? (*RQ*2) Simulation runs based on the new scenario were compared with empirical trends for selected categories such as transport and energy. The predictions were roughly plausible, but cannot be taken as precise predictions, which is not surprising because the purpose of the model was not to predict the development of transport and energy demand and other environmental indicators in absolute terms, but the relative impact of ICT on these indicators.

Can the main quantitative and qualitative results regarding the impact of ICT provided by the IPTS study be confirmed or disconfirmed and their uncertainty reduced by the currently available data? (*RQ*3) In response to this question we found the following results.

The results of the IPTS study indicate that ICT will slow the growth of private car transport, but will stimulate the growth of total passenger transport. This and the other main results of the original study were confirmed, with the exception of the impact of ICT on freight transport, which was now more environmentally positive (leading to a bit less growth of freight transport) due to the stronger dematerializing effect of ICT. Overall, it seems that Scenario D has made the simulation results slightly more positive (optimistic) with regard to the effect of ICT on the environmental indicators, compared to the old results. The availability of empirical data which made it possible to define Scenario D reduced the error margins of the input data (difference between the best- and worst-case assumptions for uncertain parameters), which also reduced the uncertainty of some output variables, but not of all of them. The span between the best- and worst-case results for 2020 could be reduced for all environmental indicators (expressed in % of the year 2000 initial value of each indicator): From 180 to below 40 % for total freight transport, from 40 to 10 % for total passenger transport, from 50 to 20 % for energy consumption, from 60 to 15 % for GHG emissions, and from 60 to 20 % for total material demand [11].

The IPTS study used many socioeconomic input and output variables. In this revisiting effort, we collected empirical data from statistical sources such as EuroStat. EuroStat regularly prepares statistics on the information society, tracking the usage of ICT. However, many ICT-relevant parameters used in the study (e.g., average telework hours and average lifetime of ICT devices in the EU) were not covered by EuroStat, and it was difficult to find empirical data on the trends of such parameters. Future work could provide detailed data requirements for systematic and comprehensive tracking of development and usage of ICT.

The feedback-loop mechanisms used in the IPTS model enabled it to take the rebound effects of ICT applications into account. For example, two types of rebound effect in passenger transport, one based on increased cost efficiency (direct economic rebound) and one based on increased speed (time rebound) were modeled to explore the role of ICT in passenger transport demand. A further step would be to equip the model with a microeconomic framework to conduct a quantitative analysis of the magnitude of rebound effects. Such microeconomic frameworks have already been presented in previous studies, e.g., [40], which evaluated energy efficiency rebound, showing that it likely reduced the net savings by roughly 10 to 40 % in two cases of energy efficiency improvements.

The IPTS study employed System Dynamics, a macro-level approach to modeling the causal mechanisms underlying socioeconomic systems. Other modeling approaches such as agent-based modeling with a focus on micro-level aspects and dynamic interactions of individual actors and institutions can be employed to provide a complementary perspective on how ICT affects environmental sustainability and to explore how changes at the micro level aggregate to macro-level effects.

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