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

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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

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 (section 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 au-

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thor), 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 Section 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] 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. 1200 TWh/y [7].

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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.

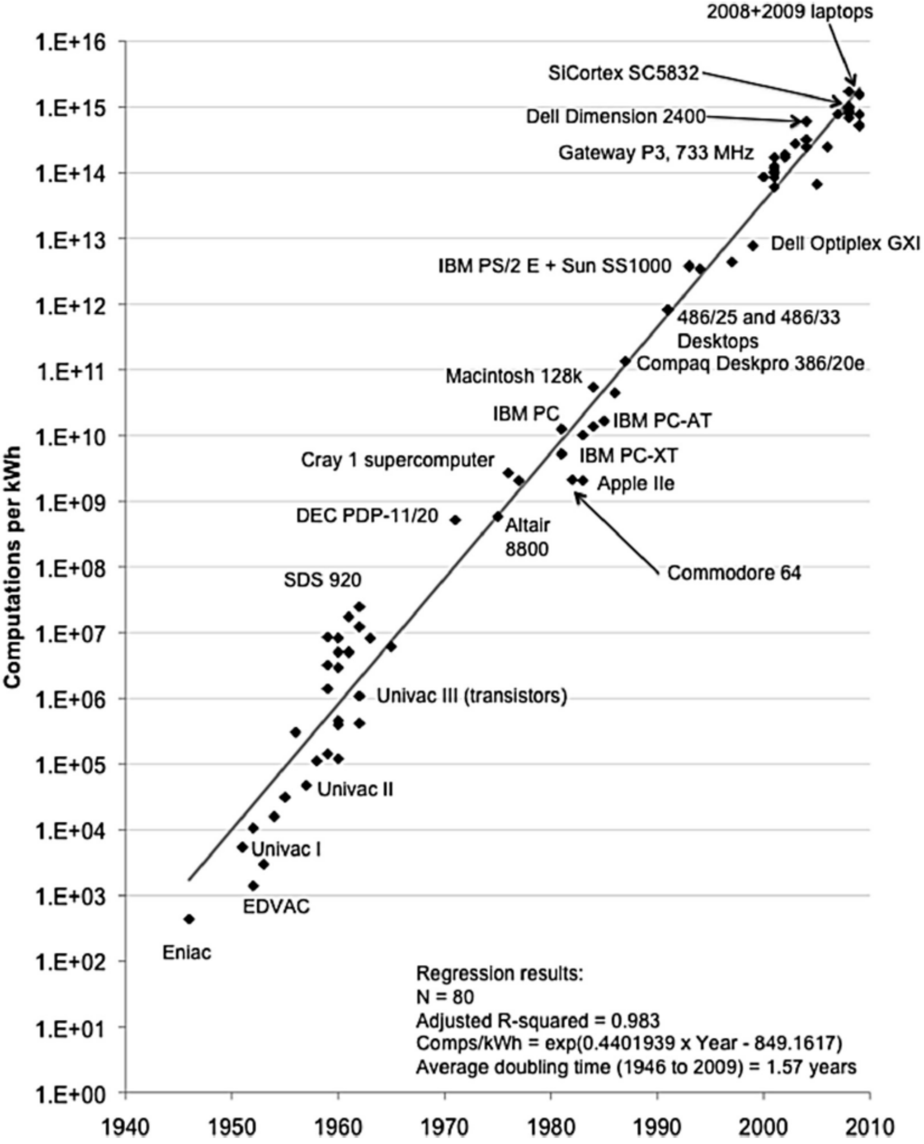

Fig. 1. Computing energy efficiency (in computations per kWh) from 1945 to 2010 (Source: [1], reprinted with permission of IEEE Computer Society)

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 two 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].

  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 (Figure 2).

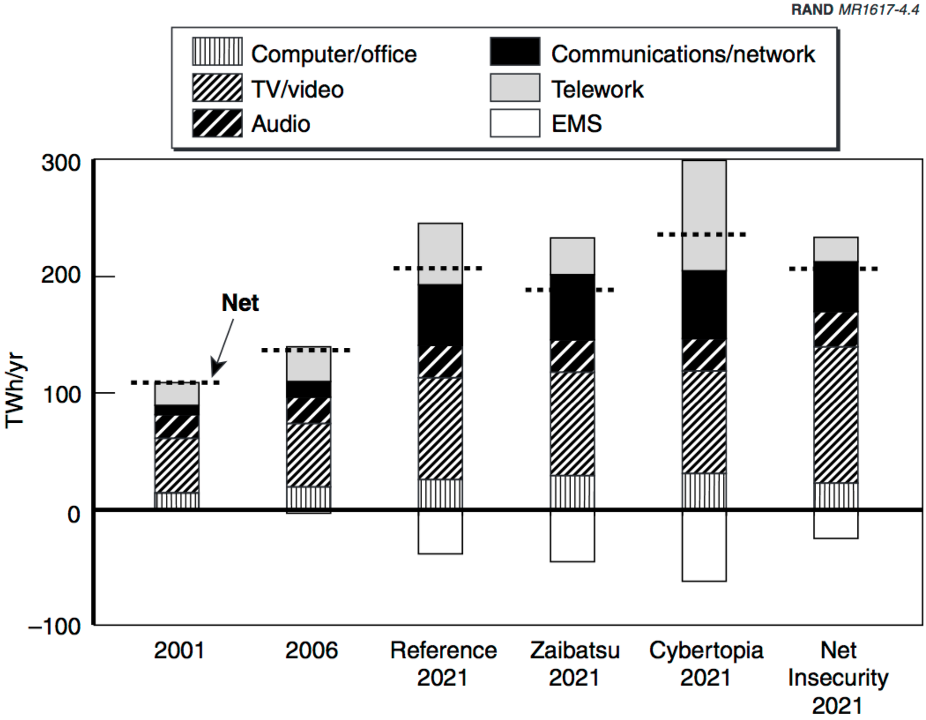

Fig. 2. ICT-driven electricity use in the residential, commercial, and industrial sectors, 2001-2021. Electricity savings (e.g., from EMSs) are shown as negative values. The "net" lines show the sum of the negative and positive components. (Source: [15, Figure 4.9, p. 73], reprinted with permission of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

- 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.

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 manufactur-

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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].

> ing 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 (seven 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].
- 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). 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

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

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.

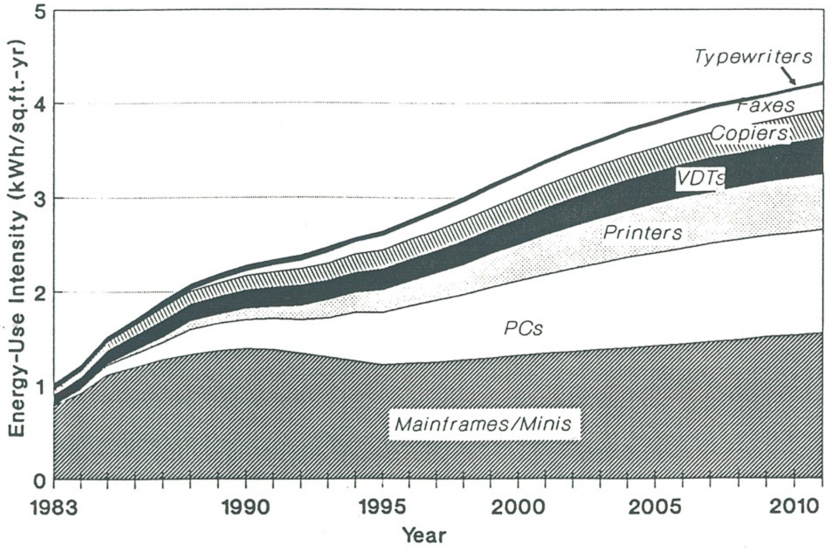

Fig. 3. Energy-use intensity (in kWh/ft^2×year) of office equipment in US office buildings 1983-2010. (Source: [35, Figure 7, p. 44], reprinted with permission of Lawrence Berkley National Laboratory)

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].

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% to 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 & 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 Section 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 Section 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 Figure 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

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

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 Section 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 Janacek 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.

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?

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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.

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 three 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 [77,39,78,79] 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 (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 Figures 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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[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.

[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].

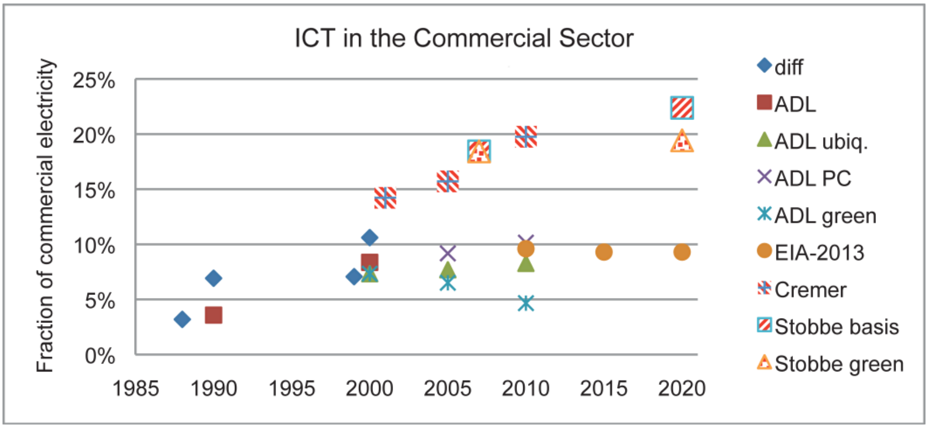

Fig. 4. Fraction of ICT electricity in the commercial sectors in the US and Germany. Data from different sources: **Data for the US:** "diff" = [33,82-84], all cited from [77, Fig. 2-5]; "ADL" = [85]; "ADL ubiq", "ADL PC", and "ADL green" = [77, Figure 2-3]; "EIA_2013" = [79]. **Data for Germany**: "Cremer"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

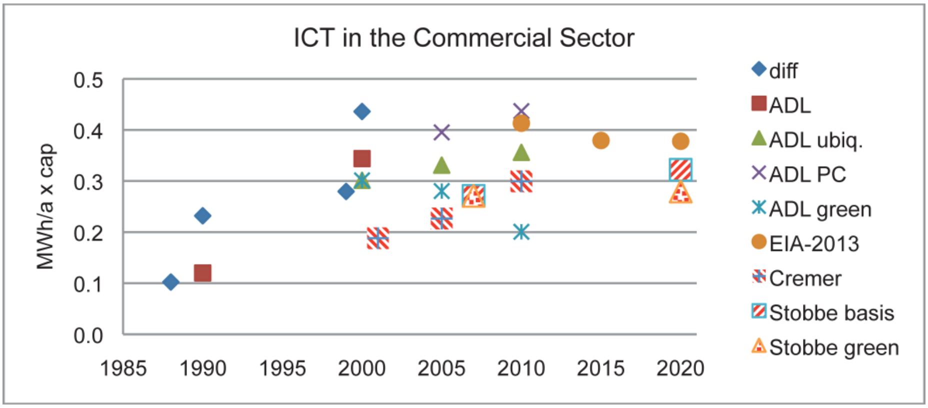

Fig. 5. ICT electricity per capita in the commercial sectors in the US and Germany. Data from different sources (see Fig. 4).

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.

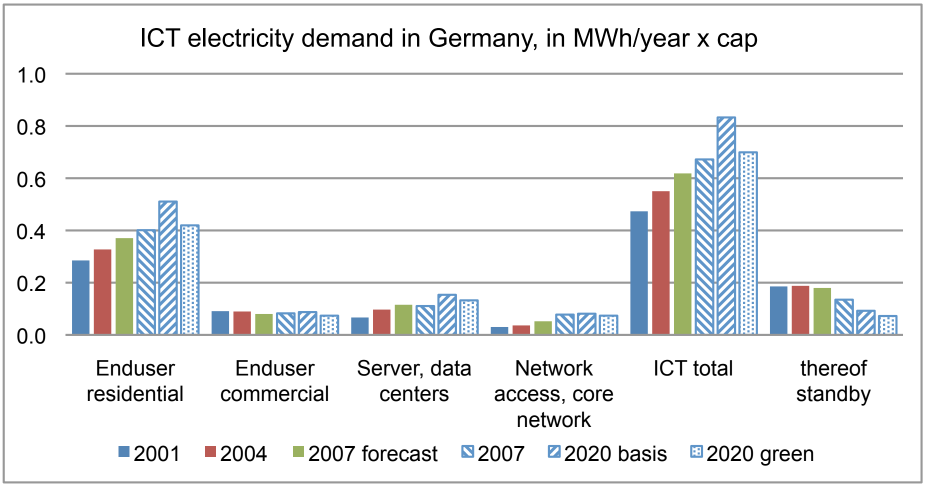

Fig. 6. ICT electricity demand per capita in Germany 2001-2020, estimated in 2009. (Source: authors' chart based on data from [81])

An estimate of electricity consumption by ICT on the global level was provided by Malmodin et al. in 2010 [86] for 2007: 1286 TWh/y or 0.19 MWh/y×cap. 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).

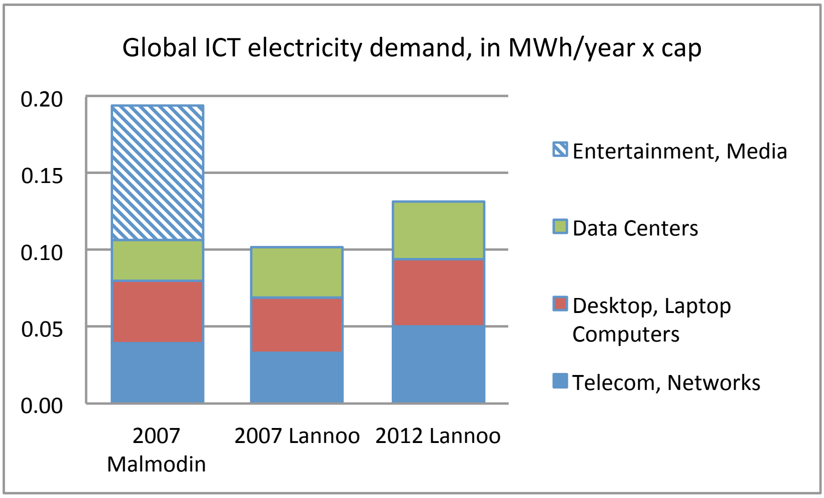

Fig. 7. Worldwide ICT electricity consumption per capita, in MWh/cap×year. (Source: authors' chart based on data from Malmodin [86] and Lannoo [87])

Looking in detail at the electricity consumption of end-user equipment (Figure 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).

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.

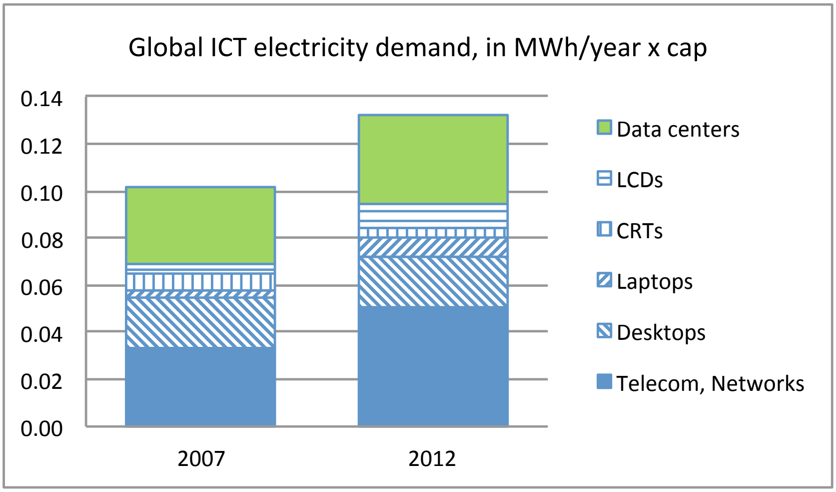

Fig. 8. Worldwide ICT electricity consumption per capita in still greater detail, in MWh/cap×year. (Source: authors' chart based on data from [87])

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 (2778-3333 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 four-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:

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

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 Section 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 IKT production system, which includes the life cycles of application software, system software, and hardware. In the use phase these three product types combine in an IKT system, which provides the desired performance. This depiction is highly simplified, since these days IKT 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.

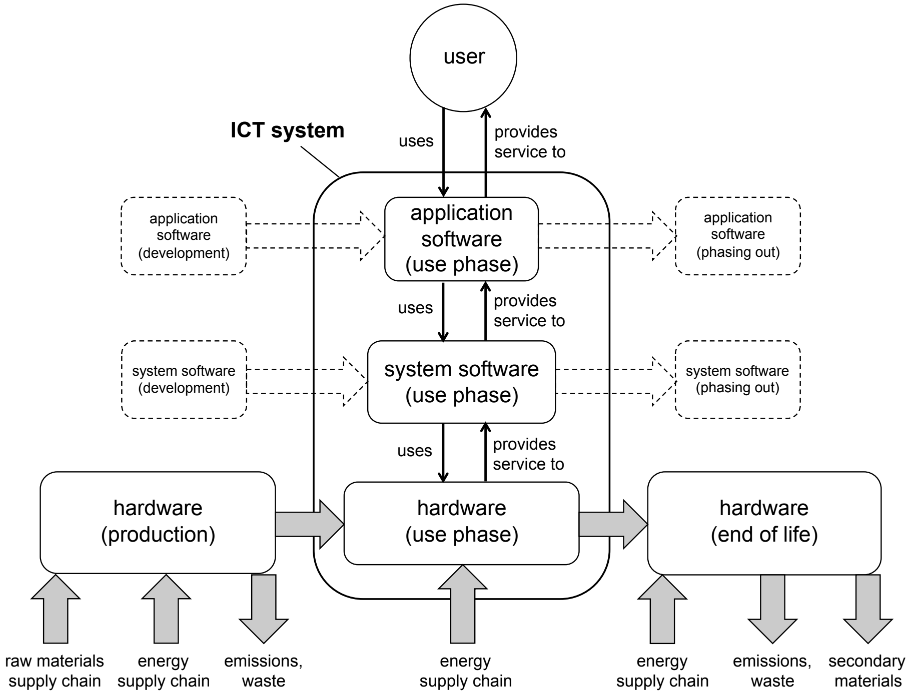

Fig. 9. Simplified representation of the IKT product system. Grey block arrows stand for the most important material and energy flows. (Source: Translated from [114])

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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