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Sustainability and ICT – An overview of the field

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Abstract: Sustainable development requires the decoupling of economic growth from environmental impacts and from the use of natural resources. This article gives an overview of existing approaches to using Information and Communication Technology (ICT) in the service of sustainability: Environmental Informatics, Green ICT, and Sustainable Human-Computer Interaction (HCI). These approaches are then discussed in the context of the Jevons paradox, an economic argument implying that technological efficiency alone will not produce sustainability. This consideration leads to the conclusion that a combination of efficiency and sufficiency strategies is the most effective way to stimulate innovations which will unleash ICT's potential to support sustainability.

Keywords: Sustainable development, Environmental informatics, Green information technology, Sustainable human-computer interaction, Resource decoupling.

1. Introduction

The most cited definition of Sustainable Development is the "Brundtland definition" named after the former Norwegian Prime Minister Gro-Harlem Brundtland, who chaired the United Nations World Commission on Environment and Development in the 1980s. This commission produced the report *Our Common Future* in 1987, which contained the following definition: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

During the last decades, sustainability research has emerged as an interdisciplinary research field and knowledge about how to achieve sustainable development has grown, while political action towards that goal is still in its infancy.

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Quite recently, almost a quarter of a century after the Brundtland report, the International Resource Panel of the United Nations Environmental Programme (UNEP) published the Report *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth* (UNEP, 2011). This report is today the most comprehensive document explaining on scientific grounds what needs to be done to make sustainable development possible.

The report focuses on the issue of decoupling, namely resource decoupling and impact decoupling (see Figure 1).

- *Resource decoupling* is defined as “reducing the rate of use of (primary) resources per unit of economic activity”. Resource decoupling leads to a gradual dematerialization of the economy, because it becomes possible to use “less material, energy, water and land resources for the same economic output” (UNEP, 2011: 4).
- *Impact decoupling*, by contrast, means reducing negative environmental impacts per unit of economic activity. “Such impacts arise from the extraction of required resources (such as groundwater pollution due to mining or agriculture), production (such as land degradation, wastes and emissions), the use phase of commodities (for example, transport resulting in CO_2 emissions), and in the post-consumption phase (again wastes and emissions)” (UNEP, 2011: 4f.).

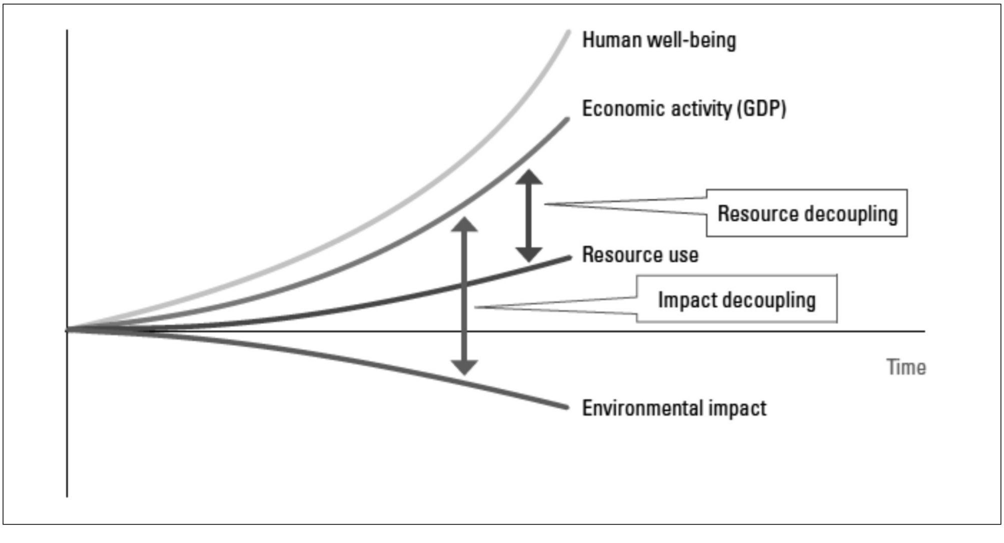


Figure 1. An illustration of resource decoupling and impact decoupling. The trajectories of human well-being, economic activity, use of natural resources, and environmental impact are normalized to an initial value (100%); the vertical axis is therefore dimensionless. Resource decoupling makes it possible to have more economic growth than the growth in the use of natural resources. Impact decoupling does the same for environmental impact (UNEP, 2011: 5).

Impact decoupling has been a political focus during the last decades. After attempts to reduce local and regional pollution have been quite successful in some countries, the so-called Stern Review on the Economics of Climate Change (Stern, 2006) finally triggered political awareness of the problem of global warming as an impact of greenhouse gas emissions, which mainly consist of CO_2. Because the main source of CO_2 emissions is the combustion of fossil fuels, impact decoupling is roughly congruent with resource decoupling in this case.

Climate policy, as important as it is, does however not address other issues of resource decoupling which are equally important for sustainable development. The UNEP report on decoupling can therefore be considered a milestone in bringing sustainability issues beyond climate change onto the political agenda.

Figure 2 shows how the extraction of several groups of natural resources is ever increasing at the global level, despite the limited decoupling that is indeed taking place. This means that the activity level of the global economic system is still rising faster than the level of resource decoupling, thus counteracting the benefits of decoupling (We will discuss reasons for this development in Section 5.).

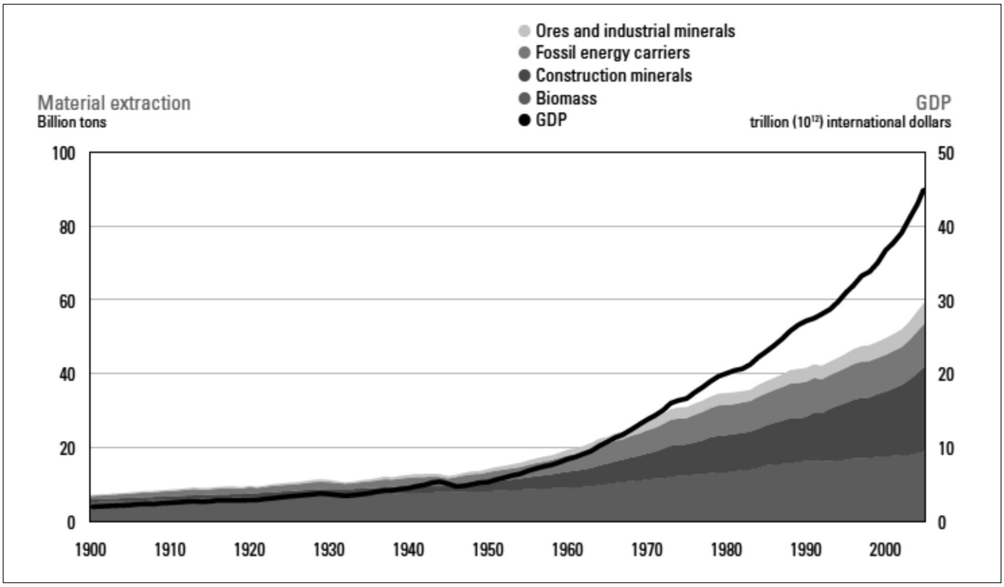


Figure 2: The rapid increase in the annual extraction of ores and industrial minerals, fossil energy carriers, construction minerals and biomass is not sustainable. History shows that there has been at least some resource decoupling since the 1970s, when GDP started to grow faster than total resource extraction (Krausmann *et al.*, 2009, cited in UNEP, 2011: 18).

The idea of resource decoupling is based on the difference between material and immaterial[1] resources. One strategy of decoupling (also called dematerialization) is to shift the focus of economic activity from material to immaterial resources. Immaterial resources can be multiplied infinitely. “Using immaterial resources does not change the qualities that make them useful, or reduce the range of available applications. The same song of the bird may be used by still another composer or give highly-valued pleasure to a birdwatcher, and the same starlight can provide information for hundreds of captains and later provide information to astronomers about the creation of the universe" (UNEP, 2011: 1f).

For the material resources we use, there must be a second strategy of decoupling, aiming to slow down their decline. "Material resources do not disappear through transformation (basic physics does not allow for the disappearance of energy/matter), but their potential usefulness for the same purpose is no longer available. How much of a resource declines as it is used (or converted from one state to another) depends largely on how much the resource is modified through use" (UNEP, 2011: 2).

Given that decoupling is a basic condition for sustainable development, an analysis of the relationship between Information and Communication Technology (ICT) and sustainable development should then focus on the potential contribution of ICT to implement decoupling strategies. Although there is not much political attention being paid to the "ICT for sustainability" issue yet, there are scientific voices pointing out the crucial role that ICT could play for sustainable development in the future. The basic idea is that the hardware/software distinction in ICT, which is essentially the difference between material and immaterial resources, and the way in which value is created with software could become a paradigm for the decoupled economy of the future. "The long-term availability of ICT services may enable and foster a transition to a less material-intensive economy" (Hilty, 2008: 153ff.).

Several approaches to using ICT in the service of sustainability have emerged during the last two decades in the academic and industrial worlds:

- Environmental Informatics;
- Green Information Technology (IT)/ICT;
- Sustainable Human-Computer Interaction (HCI).

Each of the approaches will be discussed briefly in the following Sections 2-4. In Section 5, we will discuss critically the efficiency paradigm, which is underlying many of the approaches in this field, from a historical perspective, and formulate a possible alternative.

2. Environmental Informatics

Processing environmental information has been supported by ICT applications for decades in the form of monitoring systems, databases and information systems, analytical and simulation models, spatial information processing and other kinds of ICT applications for environmental protection, research, planning, and disaster mitigation. This field is called "Environmental Informatics" (Avouris and Page, 1995; Page and Hilty, 1995; Hilty, Page *et al.*, 2006) or sometimes "E-Environment" (WSIS, 2003; ITU, 2008); its contribution to sustainable development is that a consensus on environmental strategies and policies may emerge in the long term, based on shared data and understanding.

Computer-based systems for processing environmental information have been in use since the 1970s. A broad range of applications is covered by these systems, including monitoring and control, information management, data analysis, as well as planning and decision support. The umbrella term for this type of system is "Environmental Information System (EIS)" (Günther, 1998; Rautenstrauch and Patig 2001; Hilty *et al.*, 2005).

Progress in computer science and informatics has made an invaluable contribution to our ability to analyze the biological, chemical and physical processes in the environment. Inversely, the complex nature of problems occurring in environmental contexts is a great challenge to informatics. Environmental Informatics combines computer science topics such as database systems, geographic information systems, modeling and simulation, knowledge based systems and neural networks, with respect to their application to environmental problems. Examples can be found in the proceedings of the three conferences series:

- EnviroInfo (since 1986): International Symposium on Informatics for Environmental Protection (e.g. Wohlgemuth *et al.*, 2009; Greve *et al.*, 2010; Pillmann *et al.*, 2011);
- ISESS (since 1995): International Symposium on Environmental Software Systems (e.g. Swayne *et al.*, 1997; Schimak *et al.*, 2003; Hrebícek *et al.* 2011);
- iEMSs (since 2000): Bi-annual summit of the International Environmental Modeling and Software Society (e.g. Voinov et al., 2006; Sànchez-Marrè *et al.*, 2008; Swayne *et al.*, 2010).

3. Green IT/ICT

The notion of Green IT has become hype after the publication of Gartner's report *Green IT: a new industry shock wave* (Mingay, 2007). Many projects have been conducted and seminal studies published by industry associations (e.g. GeSI, 2008), non-governmental organizations (e.g. WWF, 2008) and international organizations (e.g. OECD, 2010). Most of the existing studies focus on the impacts of ICT on CO_2 emissions, either related to the power consumption of ICT or to the role of ICT as an enabling technology for conserving energy in various fields (Coroama and Hilty, 2009).

Green in IT/ICT

As far as the resource consumption and sustainability impact of the ICT sector itself is concerned ("Green in IT/ICT"), an energy and CO_2 perspective seems too narrow, because many scarce resources are used in electronics products (see also the contribution by Patrick Wäger in this issue). The most comprehensive methodology to be used here is Life Cycle Assessment (LCA).

The variety of materials contained in ICT hardware makes recycling difficult and less efficient. Digital ICT is the first technology claiming the use of more than half of the periodic table of the elements. For example, 57-60 chemical elements are used to build a microprocessor today; in the 1980s, a microprocessor contained only 12 elements

(National Research Council, 2007; Behrendt *et al.*, 2007). Memory components, peripheral devices and external storage media are also increasing in material complexity.

Miniaturization and integration work against efforts to close material loops by recycling electronic waste. Some metals are contained in very small concentrations (such as indium in flat screens) and could therefore only be recovered in centralized industrial processes – as far as recovery is profitable at all, both in economic and energy terms. If not recovered, these resources are dissipated and therefore irreversibly lost. The combination of highly toxic and highly valuable materials in digital electronics adds to the challenges of recycling, which are not only of a technical nature, but also involve trade-offs among environmental, occupational health and economic objectives.

By focusing on the reduction of CO_2 emissions caused by power generation from fossil fuels, the Green ICT debate tends to underestimate the supply risks and resulting geopolitical and ecological problems following on from ever increasing hardware churn rates combined with miniaturization and integration.

The demand for rare metals is growing fast: For the elements gallium, indium, iridium, palladium, rhenium, rhodium and ruthenium, over 80 percent of the quantities extracted since 1900 were mined in the past 30 years (Wäger *et al.*, 2010). There will be no really Green ICT until society learns to reverse the trends towards higher material complexity and shorter service lives of ICT hardware.

Not all ICT products are the same in terms of production, use and end-of-life treatment. For some ICT products (such as servers or set-top boxes) it is essential to reduce the power consumption during use, because the use phase comprises the largest share in their total life cycle impact; for others it is more important to optimize their design for recyclability or to avoid negative effects during end-of-life treatment. For example, Radio-Frequency Identification (RFID) chips and small embedded ICT products entering the waste stream can affect established recycling processes, such as paper, metals, glass or plastics recycling (Kräuchi *et al.*, 2005; Wäger *et al.*, 2005) or textile recycling (Köhler *et al.*, 2011).

Green by IT/ICT

If ICT is viewed as an enabling technology to improve or be substituted for processes in other sectors ("Green by IT/ICT" or "Green through IT/ICT"), the effects in the target sector – called second-order effects – must also be evaluated from a life cycle perspective. This leads to the "linked life cycles approach" (Hilty, 2008; OECD, 2010) to assess the net environmental impacts of an ICT application (see Figure 3).

According to the linked life cycle approach, ICT can modify the life cycle of other products in the following ways (the following numbers correspond to the numbers in Figure 3):

1. optimizing the design of other products;
2. optimizing the production of other products;
3. optimizing the use of other products;
4. optimizing the end-of-life treatment of other products;
5. modifying the demand for another product, either by

a. substitution (decreasing demand) or by
b. induction (increasing demand).

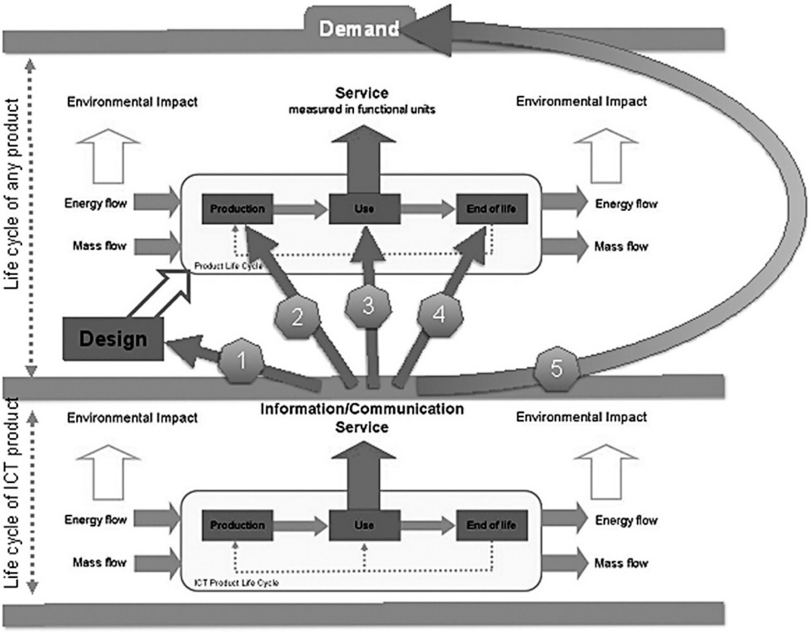


Figure 3. The linked life cycle framework. Both ICT products and non-ICT products that are influenced by the availability of ICT services are assessed by applying Life Cycle Assessment (LCA) methodology, yielding the first-order effects of each product. By estimating the second-order effects (1-5) and accounting for them, the net environmental impact of the system can be assessed (*source*: own elaboration based on Hilty, 2008, and OECD, 2010).

The distinction between optimization, substitution and induction effects was originally introduced to classify the impacts of telecommunications on physical transport and can be explained best using this special case as an example:

- *Optimization*: Telecommunications helps to optimize transport systems;
- *Substitution*: Telecommunications is substituted for physical transport;
- *Induction*: Telecommunications induces transport demand (e.g. by enabling distributed forms of production).

This scheme can be generalized to cover all kinds of ICT and their respective impacts on all kinds of physical processes. This can be demonstrated taking paper consumption as an example: ICT has in fact the potential to reduce paper consumption. There is an optimization effect, since for instance many errors can be corrected before a text or picture is printed for the first time. Paper production, transport or recycling may also benefit from ICT-based process optimization. Plenty of textual and graphical information can be transported through data networks and received directly from the screen, which is therefore substituted for paper in many cases. There is, at the same time, an induction effect: The increased availability of information induces the demand for paper on which to print out at least some of it. Only by accounting for all effects linking the two life cycles is it possible to assess the net environmental effect of ICT with regard to paper consumption.

4. Sustainable Human-Computer Interaction (HCI)

A more recent development in sustainability and ICT is the emergence of Sustainable Human-Computer Interaction (HCI) as a field of research and design. Sustainable HCI focuses on the relationship between humans and technology in the context of sustainability, and comprises several approaches. In 2007, Blevis first presented the concept of Sustainable Interaction Design (SID), which argued that sustainability should be considered a first-class criterion for the design of technology, as important in the design process as more conventional design criteria such as usability or robustness (Blevis, 2007). 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. Much of the technology design in Sustainable HCI is grounded in foundational research that focuses on understanding how humans perceive, acquire, use, and dispose of technology (Chetty *et al.*, 2009; Huang and Truong, 2008). The findings of these studies form the basis for the design of technologies or systems that fit with existing human practices and needs while promoting environmentally sustainable use. Such studies provide important groundwork for the design of sustainable interactive technologies because such systems, regardless of their potential for environmental benefit, will only be adopted (and therefore be environmentally beneficial) if they fit appropriately into the lives of their intended users.

Regarding technology, Mankoff *et al.* (2007) proposed a characterization of sustainability in interactive technologies with two major categories: "Sustainability through design" considers how the design of technology and interactive systems can support sustainable lifestyles or promote sustainable behavior, while "sustainability in design" considers how technology itself can be designed such that its use is sustainable. The majority of technology research in the area of Sustainable HCI has thus far focused on the former category, largely in the design of interactive technologies that are intended to promote awareness of the user's individual actions or practices (Gustafsson and Gyllenswärd, 2005), encourage the adoption of more sustainable practices (i.e. "persuasive technologies") (Fogg, 2002; Grevet *et al.*, 2010; Froehlich *et al.*, 2009), or create a more general awareness of environmental issues (Kuznetsov, 2011). An especially comprehensive treatment of sustainable HCI and the various approaches and perspectives represented in the field can be found in DiSalvo and colleagues' survey of the sustainable HCI research landscape (DiSalvo *et al.*, 2010).

5. Why technological efficiency alone will not produce sustainability

In1865 William S. Jevons published his book *The Coal Question*, in which he argued that technical progress in using coal efficiently would not lead to decreasing demand for coal, but to the very opposite. He was proven right, although no shortage of coal ever occurred, because coal as a source of energy was later replaced by oil. The hypothesis of the counter-intuitive effect of efficiency progress was later generalized to what is now called the Jevons paradox or the rebound effect, and has been underpinned with much empirical evidence (Polimeni *et al*., 2009).

Saving resources such as energy by improving the efficiency with which a resource is used is therefore not an approach that is as straightforward as it might appear from a technical perspective. From an economic and behavioral perspective, the situation is more complex, because the dynamics of markets has to be taken into account to predict the outcome. This implies that decoupling – as defined in Section 1 – is not a sufficient condition for saving resources. (It may, however, be a necessary condition.) In particular, resource decoupling may result in a growth rate higher than the decoupling rate, therefore counteracting the resource-saving effects of decoupling. This applies not only to steam machines, but to ICT or many “smart” technologies as well. To illustrate this point, we shall use the example of the smart soft drink vendor machine originally provided by Joseph A. Tainter (2009).

The smart vending machine

Roughly a decade ago, an entrepreneur proposed a new business model, namely to place and service soft drink vending machines in small offices where only a few people work. The potential investors wondered how this business model could ever be profitable, and if so, why no one else had already placed vending machines in all these small offices. The answer was found in the innovation that was occurring at the time of the proposal: A new type of vending machine cut the energy cost of operating the machine roughly by half due to the following innovative features:

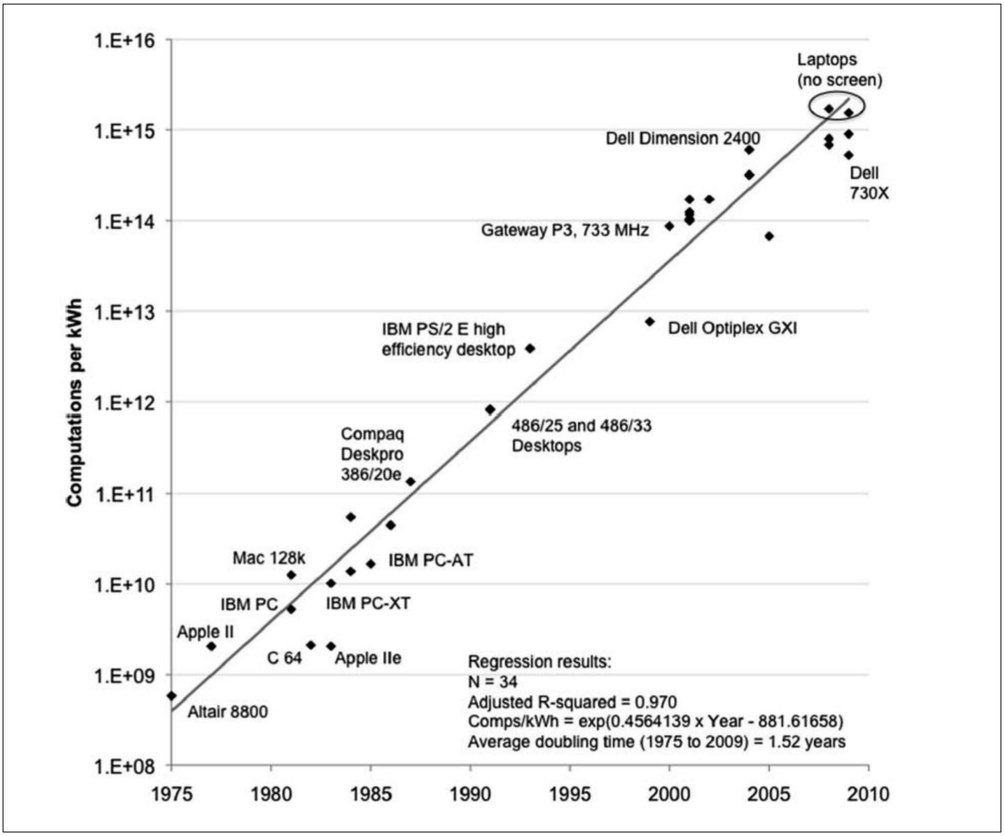
- Improved monitoring of and forecasting the ambient temperature;
- Motion detectors to switch on lighting only when a potential customer approached;
- Some of the machines even had the ability to learn customers’ habits.

These machines were not only “smarter” than the old ones; they also seemed to deserve the attribute of “green”. Consequently, the “Energy Star” label was conferred on such vending machines, because they proved that more than 1500 kWh of electric energy per machine and year could be saved. Given the fact that energy cost is the main component of the operating cost of a soft drink vending machine, the doubling of energy efficiency made it possible to operate these machines at a profit even in places where only a handful of people per day might purchase a soft drink. Since the number of small offices is much higher than the number of big offices, this innovation must be assumed to have more than doubled the number of soft drink vending machines operating around the world. The total power consumption of smart vending machines, hence, exceeded the consumption of the fleet of "dull" vending machines that had been in use before. Although it could be argued that the smart vending machine has contributed to some decoupling of the "making soft drinks available" service from energy consumption, there is obviously no contribution to sustainability (in fact, quite the contrary). Tainter concludes: "In short, as technological improvements increase the efficiency with which a resource is used, total consumption of that resource may increase rather than decrease" (Tainter, 2009).

"Koomey's Law" and its consequences

The strongest rebound effects can be observed in the ICT sector itself. Koomey *et al.* recently showed that the energy efficiency in computing, expressed in computations per energy input, has doubled every 1.57 years between 1947 and 2009, as shown in Figure 4 (Koomey *et al.*, 2011; Koomey *et al.*, 2011b).

Figure 4. Computations per kilowatt-hour over time. These data include a range of computers, from personal computers to mainframe computers and measure computing efficiency at peak performance. Efficiency doubled every 1.57 years from 1946 to 2009 (Koomey *et al.*, 2011).



However, between 1975 and 2009 the computing performance per personal computer doubled every 1.5 years, so that these early improvements have since then been cancelled out. On top of that, the number of installed computers doubled on average every three years between 1980 and 2008. Bottom line: we observe a rapid increase in the use of electricity for computing.

The usual response of software engineers (and users as well) to an increase in the processing power and storage capacity available at a given price is to capture more of the same. One example is the development of computer games using a combination of fast action and graphics: Each new gain in performance is greedily translated into an increased reality of the scenes. New patches delivered to increase the resolution of textures and to improve graphics may even slow down the speed of the game (Ernst and Steinlechner, 2011).

Where Green ICT is missing the point

One main criticism of "Green IT/ICT" and the related "Smart X" rhetoric is that the trends ignore such rebound effects, both in the "Green by IT/ICT" case (the smart vending machine example) and in the "Green in IT/ICT" case (the computer games example).

A recent comparison of the ten most influential studies assessing the effects of ICT on climate change revealed that only a few of them even tried to take rebound effects into account. The five studies published in 2007 or later (i.e. after the beginning of the Green IT hype) almost completely ignored systemic effects, whereas the older studies showed more ambition to account for these effects (Erdmann and Hilty, 2010). This shows that the recent idea of Green ICT is almost always based on an efficiency approach. The expectation behind the Green ICT wave is that, by increasing the energy efficiency in the ICT sector itself and in other sectors with the aid of ICT, continued growth and steps towards a low-carbon economy can be stimulated at the same time. However, we have obviously had considerable efficiency gains in and by ICT during the last decades, and the result in terms of total energy consumption provides no evidence that efficiency strategies alone have led to a more sustainable situation.

The same criticism holds for approaches pursued under the label of Environmental Informatics or Sustainable HCI, as far as they rely on introducing efficiency without presupposing a context of resource limitation.

Efficiency + Sufficiency = Innovation for Sustainability

Sustainable development cannot be achieved by decoupling strategies alone because of macro-level rebound effects (alias the Jevons paradox). Instead, policies leading to a *deeper structural change* are needed, a change which prevents or minimizes the rebound effects that diminish the positive impact of the decoupling.

The total energy consumption by ICT has grown rapidly from a negligible quantity in the 1970s to 2% of all energy consumption today, corresponding roughly to the percentage of energy consumption attributable to air traffic. Imagine for a moment that the energy supply to ICT were frozen at the current level by some global regime. It would then still be possible to double the computing power provided to society every 1.57 years, provided that "Koomey's Law" still remained valid. This doubling time corresponds to an annual growth rate of 55.5 %.

In such a scenario, it would even be plausible for the ICT industry to outperform "Koomey's Law" because there would be much stronger incentives for innovation towards energy efficiency. All opportunities to save energy would be taken: In addition to the hardware becoming ever more energy efficient, the system and application software, and the communication protocols and data formats would also be optimized to run while utilizing a smaller amount of hardware resources.

Such incentives are already in place in mobile computing, because the capacity of batteries in terms of energy density (energy/mass) is limited. This limitation has created a lot of innovations in this segment of the ICT sector. If, however, mobile devices could be provided with infinite energy, we would probably be running overly complex operating systems (such as Windows Vista) on today's tablet computers and smartphones.

On the other hand, if no resource constraints are in place, developers tend to rapidly increase what E. W. Dijkstra called unmastered complexity: "Because we are dealing with artefacts, all unmastered complexity is of our own making; there is no one else to blame and so we had better learn how not to introduce the complexity in the first place" (Dijkstra, 1996: 1 f). Unmastered complexity always creates resource demand, as can also be seen in growing bureaucracies. This is in fact a rebound effect of time-efficient ICT (Hilty, Köhler *et al.*, 2006).

The same argument applies – with much more impact – for the use of ICT as an enabler of decoupling in non-ICT sectors such as transport or housing ("Green by IT/ICT"). ICT-based optimization or substitution will be most innovative if resource constraints are in place. If, for example, the fossil fuels used for transport were limited by some effective climate policy, intelligent technologies used for traffic optimization and substitution would develop much faster and with greater success – just because this would be the only way to meet the increasing demand for transport. Without effective limitations, the enabling ICT innovations develop more slowly and serve mainly to stimulate additional activities (e.g. an increase in speed makes transport more attractive) instead of replacing existing activities.

6. Conclusions

We have discussed several approaches to using ICT in the service of sustainability which have emerged during the last two decades in the academic and industrial spheres: Environmental Informatics, Green IT/ICT, and Sustainable HCI. Based on an economic and historical perspective, we have argued that to the degree that these approaches depend on *eff*iciency strategies, they will remain unsuccessful, unless they are combined with *suff*iciency strategies.

Under the usual framework conditions, any progress in efficiency usually causes the growth in outputs to accelerate so that, at the end of the day, input resources are not protected at all. On the contrary, improvements in efficiency may even cause the absolute consumption of resources to rise (the explanations for this are provided by the Jevons Paradox and by the concept of the rebound effect).

When, however, the potential of technical efficiency coincides with the factual limitation of input resources (*sufficiency* – as is the case, for example, with the limitation of energy in mobile devices), this causes innovations to accelerate and real progress to be made in the direction of sustainable resource utilization.

Harnessing ICT in the service of sustainability therefore only succeeds when the enormous efficiency potential of these technologies is not used under conditions of seemingly unlimited resource availability, but rather under exogenously imposed framework conditions thus turning natural limits into man-made policies. Under these conditions ICT becomes a key technology for sustainability because more intelligent, information-intensive, immaterial solutions will be the most important source of growth (as opposed to increasing material resource input). Growth will then only be possible to the degree that we succeed in decoupling economic growth from environmental impact and resource use. And because there are powerful incentives for technical innovations – especially in the area of ICT – that will still be an acceptable and sustainable level of growth.

Notes

[1] Here, the term “immaterial“ implies intangible.

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