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Environmental effects of information and communications technologies

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The digital revolution affects the environment on several levels. Most directly, information and communications technology (ICT) has environmental impacts through the manufacturing, operation and disposal of devices and network equipment, but it also provides ways to mitigate energy use, for example through smart buildings and teleworking. At a broader system level, ICTs influence economic growth and bring about technological and societal change. Managing the direct impacts of ICTs is more complex than just producing efficient devices, owing to the energetically expensive manufacturing process, and the increasing proliferation of devices needs to be taken into account.

One of the most striking aspects of information and communications technology (ICT) is the speed of its progress and adoption. Thirty years ago, information flows were mediated by postal deliveries, landline telephones and broadcast television, whereas now we access a globally interconnected world through a variety of devices from smart phones to large flat-screen displays. Technological progress in ICT is reflected in Moore's law, the observation that the number of transistors that can be packed into an integrated circuit doubles every 18 months[1]. Moore's law has become a self-fulfilling prophecy: the semiconductor industry actively aims to maintain Moore's rate of progress[2]. Although ICT currently relies on silicon-based integrated circuits, new technologies are on the horizon, including materials such as germanium and carbon, new architectures such as fin field-effect transistors (FinFETs), and new conceptual models such as quantum computing.

Few would dispute that ICTs are transforming societies and economies around the world. ICT is an example of a 'general-purpose technology', meaning that it interacts with and enhances other technologies[3]. Although the economic and social implications of ICTs are much discussed and analysed, the environmental implications receive much less attention. Yet ICTs interact fundamentally with environmental issues. To justify this assertion, first consider how previous technological revolutions, such as steam engines, the combustion engine and electricity, have fundamentally restructured human interactions with the environment. On the positive side, engines and electricity have greatly increased the efficiency of delivering energy services. At the same time, technology is a key element in an economic growth engine[4] that drives the increasing use of technology.

Consider, for example, the replacement of horses by automobiles in the twentieth century. Cars are much more efficient than horses in terms of environmental impact per distance travelled[5]. But their greater convenience and functionality, as well as their lower cost, mean that cars are used orders of magnitude more than horses ever were. Despite substantial improvements in efficiency and reductions in emissions during the twentieth century, the environmental challenges associated with automobiles remain unsolved. The key lesson here is that increasing the efficiency of a technology does not necessarily reduce its environmental impact.

ICTs interact with environmental issues at different system levels. Figure 1 depicts four types of interaction. The most direct and easily understood interaction is the physical layer, shown in the smallest circle in Fig. 1. At this level, ICT is physically embodied in an infrastructure and a set of devices whose manufacturing, operation and disposal have environmental impacts. At the next level, ICTs can be used to reduce environmental impacts with applications such as smart buildings, teleworking and optimized manufacturing[6–8]. Expanding the system boundary, ICTs contribute to economic growth[9] and shift consumption patterns[10,11]. At the broadest system level, ICTs are a key part of the info–nano–robotics–bio technological convergence that some believe will transform industry and society[12,13]. The capacity to comprehend and manage the different system levels decreases as the system boundary increases, as the higher levels are complex systems.

Here I discuss the various ways in which ICTs affect the environment. Society puts most emphasis on the direct impacts of ICT equipment, so these make up much of the article. I also discuss the implications of higher system levels, as in my opinion these are vastly more important than the direct impacts, despite receiving relatively little attention.

Assessing the environmental implications

Sustainability can be considered to be a societal reaction to human activities having global implications. The attempt to grapple with larger systems led to the development of methods to understand the systemic relationships between technology, environment and society. As discussed in the introduction, different levels of interaction involve different levels of complexity. New approaches are being developed to characterize different aspects of the problem. Not surprisingly, the degree of quantification and certainty decrease with increasing system levels.

Traditional methods of energy and environmental analysis can be used to characterize the first level of direct impacts. In addition, fresh insight can be obtained from newer approaches, such as material flow analysis (MFA) and life-cycle assessment (LCA). The first of these, MFA, is a general approach to measuring resource flows and emissions in industrial and natural systems[14], whereas LCA is a specialization and extension of MFA designed to quantify flows for the life cycle of a product or service[15,16]. LCA also includes impact assessment, which aims to characterize and assign trade-offs between different environmental impacts. Both approaches can be combined with forecasting approaches to estimate trends in macroscopic impacts[17], and both face the challenge of analysing complex and rapidly changing production chains and products.

The most popular form of LCA, the 'process-sum' method, builds a bottom-up model of materials flows facility by facility[15]. The complexity and proprietary information in ICT supply chains results in facility-level

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data being unavailable for many processes, such as the purification of chemicals used to make semiconductors[18,19]. These data gaps mean that the process-sum method underestimates environmental impacts. Alternative LCA methods can address these data gaps, however. Economic input–output LCA (EIOLCA)[16,20], for example, is a holistic description of an economy based on a matrix of economic transactions between sectors[21]. It has the virtue of not excluding processes in the supply chain but has the disadvantage of aggregating multiple, sometimes diverse, processes into single sectors, which results in coarse-graining error[22]. Hybrid LCA aims to use both the process-sum and EIOLCA approaches together to minimize their weaknesses[18,19,23,24] but has yet to be widely adopted.

The environmental benefits of specific ICT applications such as teleworking, smart buildings and intelligent transport systems can be characterized by combining models of energy and materials use, technology and user behaviour. The main challenge is dealing with 'rebound effects', which occur when adopting a technology (such as a fuel-efficient vehicle) or practice (teleworking, say) indirectly induces additional impacts[25]. An economic rebound effect occurs when a technology change results in monetary savings that are then spent using that product more[26] or purchasing other environmentally intensive goods or services[25]. A second rebound effect occurs when saving time results in a behavioural change that induces further impacts, such as increased non-work driving by teleworkers[27].

The third and fourth system levels are more complex. Different disciplinary approaches can be applied to examine pieces of the system. The contributions of ICTs to economic growth are both direct, in terms of the economic output of ICT-related sectors, and indirect, by promoting growth in other sectors. Economists have explored the effects of ICT on economic growth by using neoclassical growth models (ref. 9). Further examples of disciplinary approaches are examining the effects of ICT on urban form through the lens of urban planning[28] and studying societal change through environmental sociology[29]. The different methodological approaches that could be applied are too numerous to recount here, but I make two high-level comments on the challenge of understanding the systemic implications of ICTs. First, an attempt to fuse disciplinary perspectives could bear fruit both in terms of methodological development and providing insight to manage the future. Second, given the complexity of the system, many important questions will be beyond the scope of quantitative or predictive modelling. Moving out through the system levels in Fig. 1, there is a transition from smaller subsystems that can be modelled with relative certainty to complex systems that are highly uncertain.

Most efforts to assess and manage the environmental implications of ICTs focus on direct impacts of ICT hardware. The primary issues of concern currently identified by society are the potential for exposure to hazardous materials and the use of energy, so I explore these in greater detail.

Exposure to hazardous materials

To review the relationship between ICT and exposure to hazards, first note that the impressive functionality of modern ICT is achieved by using a variety of exotic and highly refined materials both in products and as auxiliary materials in manufacturing. Given the wide range of materials used, it is not surprising that some are potentially hazardous.

It is important to distinguish between risk and hazard. Risk characterizes macroscopic health impacts, whereas hazard focuses on the potential for harm. Scientists and engineers generally gravitate towards a risk perspective, but the public sector, in particular non-governmental organizations, often take a hazard-based view that divides the world into acceptable and unacceptable materials (see, for example, ref. 30). Public policies to address hazardous materials in ICTs, including bans on landfill or materials such as lead-based solder, are based on a hazard perspective, as risk is little studied and poorly understood[31].

The primary concern for manufacturing is exposure to ancillary chemicals used in high-tech processing, in particular making semiconductors (see ref. 32 for recent results on cancer effects and ref. 33 for a review of earlier studies). In the operation of ICT devices, the main issue is exposure to brominated flame retardants (BFRs), which are added to casings and circuit boards in electronics, ostensibly to improve fire safety (see refs 34 and 35 for reviews of environmental issues for BFRs).

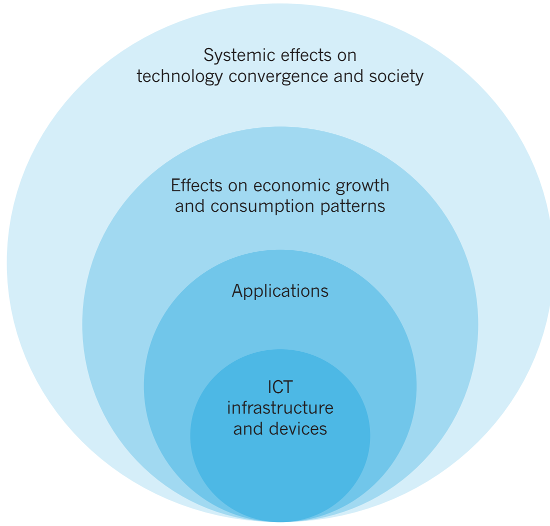

Figure 1 | Levels of system interactions between ICT and the environment. The inner circle shows direct impacts of ICT equipment and infrastructure. The second circle represents environmental applications of ICTs, such as teleworking. The third circle refers to effects on consumption caused by economic growth and changes in products. The outer circle represents larger societal and technological changes influenced by ICTs.

Potential exposure following the disposal of ICT devices has gained the most attention and is centred on three materials: metals, BFRs and compounds generated or used during recycling. An inventory of valuable and hazardous metals in a desktop computer system appears in Table 1. In addition to valuable metals such as copper, gold and silver, there are hazardous metals such as lead and cadmium. Hazardous materials are liberated or generated after disposal in three ways: leaching from landfills, incineration and recycling. Circuit boards and cathode-ray-tube monitors fail environmental regulatory tests for potential leaching from landfills, although there is scant evidence that leaching from sanitary landfills with leachate treatment systems poses a noticeable degree of risk[31]. Sometimes ICT devices are incinerated when inadvertently mixed into municipal waste streams, however, mobilizing hazardous metals and transforming BFRs into hazardous compounds such as brominated dioxins and furans. The degree to which combustion results in harmful emissions depends on the pollution controls at the incinerator.

Recycling is the third reason for post-disposal emissions. When recycling occurs in properly regulated facilities, efforts are made to ensure the safety of workers and the public alike. A great deal of ICT equipment is not recycled in proper facilities, however, but is processed by an informal (or backyard) industry in the developing world. With low labour cost and no environmental controls, recycling valuable metals from ICT devices in this way generates a profit, rather than incurring a net cost when faced with expensive labour and strict environmental controls. This economic situation drives the growth of an informal electronics industry in many parts of the developing world, such as China, India and Africa[36–38]. Copper is often recovered from wires by open burning of the insulation, which is usually made from polyvinyl chloride, so combustion releases dioxins, furans and other toxic chemicals. Gold in printed circuit boards is recovered by hydrometallurgical treatment using cyanide and acid without environmental controls. There is mounting evidence that informal recycling in the developing world is causing serious environmental pollution (see ref. 39 for a review).

Society's response to these hazardous concerns mainly takes the form of restricting the use of materials and establishing take-back

Table 1 | Quantities of valuable and hazardous metals in a desktop tower computer and cathode-ray-tube monitor[31]

Metal	Amount (g)
Aluminium	680–960
Antimony*	2.4–18.0
Arsenic*	0.06
Bismuth	0.23
Cadmium*	3.3
Chromium	0.05
Copper	1,370–2,640
Ferrite	480
Gold	0.39–0.67
Indium	0.04
Lead*	620–1,370
Nickel	4.5–30.0
Platinum	0.92
Steel	7,300–8,880
Silver	0.86–2.60
Tin	67
Zinc	21

*Most hazardous metals.

and recycling systems for electronics. The most prominent materials legislation is the European Restriction of Hazardous Substances Directive, which restricts the use of six substances — lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBBs) and polybrominated diphenyl ether (PBDE) — in many electronics applications. Such restrictions and mandatory recycling presumably mitigate hazard, but they do not solve the most serious pollution issue, that of informal recycling in developing countries. One reason is that hazardous materials such as volatile organics and cyanide result from the recycling processes, rather than the toxic content of the products[31]. Second, difficulties in enforcement mean that exports of end-of-life electronics continue even when legislation is in place[40–42]. Third, global MFA forecasts indicate that by 2016–18 developing countries will generate more electronic waste than the developed world, and most of it will probably be recycled informally[17]. The heuristic goals that emerged from social processes (less toxic content and more recycling) need to be examined from a more systematic perspective.

Energy use

The effects of ICT hardware on energy and climate have come under increasing scrutiny. The life-cycle approach discussed above is crucial when examining the energy use of ICT because the production phase can be much more important for ICT than for other technologies, such as vehicles and buildings. For products with a plug or a fuel tank, the energy used during operation is far greater than that used during manufacturing. For example, 91% of the energy consumed by a typical home in Michigan is used while it is occupied, with just 9% used in materials and construction[43]; similarly, 88% of the energy that goes into a typical automobile relates to the fuel used to drive it[44]. The dominance of the use phase supports the traditional emphasis on improving operational energy efficiency.

For ICT devices, the energy used during manufacturing is a much bigger proportion. At the component level, LCA shows that at least 1.2 kg of fossil fuel is needed to manufacture a 2-g dynamic random access memory (DRAM) chip, a ratio of 600:1 compared with a 1:1 or 2:1 ratio for other manufactured goods[45]. The high energy use is due to the stringent purity standards required for semiconductor processing materials and environments. For a DRAM chip, at least 73% of the lifetime energy use goes into manufacturing, with just 27% used during operation. For computational logic chips, the roles are reversed, and operational energy (82%) far exceeds the energy used during manufacturing (18%)[46,47]. Note that both examples underestimate the contribution of the purification of chemicals and gases for semiconductor manufacturing, for which data are largely unavailable. Analysis of selected materials used in semiconductor manufacturing indicates that the energy used increases rapidly with higher purity[48].

For a typical laptop computer, hybrid LCA shows that 64% of the lifetime energy is used during manufacturing, with just 36% in operation[19]. This is partly because manufacturing computers is energy intensive, and partly because rapid obsolescence leads to computers being purchased more often than many other products with a plug. Figure 2 shows the ratio of manufacturing energy to operational life-cycle energy for ICT devices and other products.

The speed of technological progress in ICTs implies that environmental assessment must consider temporal change. One approach to assessing the effects of technological progress poses this question: how does the environmental impact per unit functionality change over time? The general answer is that it declines over time. For example, the electricity use per MHz in fabricating a desktop microprocessor has fallen from 0.028 kWh MHz^{-1} in 1995 to 0.001 kWh MHz^{-1} in 2006[49] as a result of improvements in manufacturing processes. The total energy use per functionality, including the supply chain for materials used in fabrication, has also decreased dramatically[47]. These results do not, however, include the increasingly stringent purity requirements for materials used in semiconductor manufacturing; higher purity could increase energy use[48].

It is not enough to consider environmental impact per functionality, however. As discussed in the introduction, the efficiency of automobiles, for example, has vastly improved over time but has coincided with rapidly increasing use of automobiles, which has brought new and as yet unsolved environmental challenges. One alternative to the functionality measure is to examine trends in environmental impact per typical product. As newer generations of products have additional functionality, it is instructive to compare the impact of succeeding generations. Here the 'typical product' measure parses out only the 'per product' piece of technological progress; the net impact from additional adoption is a separate factor. To complement the functionality measure (electricity per MHz) mentioned above, we can also track the electricity required to manufacture successive generations of typical desktop microprocessors. Measured in this way, the electricity used

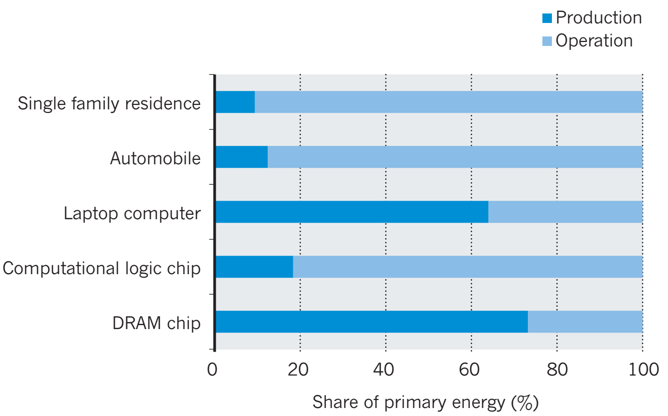

Figure 2 | Proportions of energy used in production and operation of various products. Figures for the DRAM chip, computational logic chip and laptop computer assume a three-year lifespan and home-use pattern of three hours per day, seven days per week. The energy used to run the logic chip, the automobile and the family home exceed the energy used in production, whereas the production energy is dominant for the DRAM chip and laptop computer.

per typical processor has not changed from 1995 to 2006[49]. Increased functionality — a faster processor — has cancelled out the efficiency gains per MHz. This example shows that progress in efficiency per functionality does not necessarily inform progress towards managing net environmental impacts.

The use of LCA often focuses on the product level. Although a product study provides information about the relative environmental impacts from different life-cycle stages, it does not address the question of macro-level impacts. To address net impacts, there is a stream of literature that estimates the total electricity use of ICT in different aggregations. For example, Kawamoto and collaborators[50] combined an inventory of computers, printers, copiers, faxes and networking devices in US offices with 'per device' data on electricity use. They found that in 2000, electricity use in computing and networking equipment in US offices was 74 TWh, or 2% of national electricity use[50]. A similar type of analysis covering 15 types of device, including televisions, computers, telephones and audio equipment, found that in 2002 consumer electronics in US homes consumed 147 TWh of electricity, or 4% of national electricity use[51]. Ignoring the different years of the studies, the two results combine to suggest that ICT devices in homes and offices constitute around 6% of US electricity use. The energy used to manufacture these devices has yet to be estimated, and there are no figures for temporal trends in energy overheads driven by changes in ownership and use.

Society's response to the energy used by ICTs has focused mainly on improving the efficiency of the operational phase of devices (the Energy Star standards set by the US Environmental Protection Agency for computers and displays, for example[52]). Manufacturers of components and devices have responded by making significant progress in improving operational energy efficiency. But it is not yet clear how well they are managing the net energy use over the devices' life cycle. In addition, there has been a continued proliferation of new ICT devices on the market, with the recent rise of smart phones, tablet computers and flat-screen televisions. The portfolio of ICT devices in use continues to increase, so reduced impacts for individual products may not lead to a reduced impact for the entire portfolio.

Managing future direct impacts

Nanoscale manipulation, which was pioneered in semiconductor manufacturing, has spun off into a nanotechnology industry. Given its potential use in everyday products such as textiles, paints and infrastructure, the scale of nanoparticle production could be orders of magnitude larger than for semiconductors alone. Semiconductor technology is also the basis for the manufacturing of photovoltaic modules, an area whose growth far outpaces the ICT industry. New materials and manufacturing processes are being developed for all of these applications. What are the strategic issues for assessing and managing the direct environmental impacts of these new technologies?

The pursuit of increased functionality is driving the use of more exotic materials, so concerns over potentially hazardous exposure will presumably continue. New issues are emerging, such as the effects of nanoparticles on health and ecosystems[53]. The public perception of hazard tends to dominate society's response, but this trend needs to be balanced with more science-based work that has a risk perspective.

Quiescent since the 1970s, concerns over the scarcity of resources have recently re-emerged. For electronics, the focus is on 'critical metals' such as tantalum, indium and ruthenium. Critical metals have supply constraints resulting from limited reserves, geopolitical problems or difficulty in recycling[54].

Societal response to managing the environmental impacts of ICTs has focused on heuristics such as removing toxic materials, increasing recycling and improving energy efficiency. As discussed earlier, following these heuristics has led to progress but has not solved the environmental challenges. In the future, managing the environmental problems facing ICTs will require a broader focus that considers life cycles, growth and technological progress.

Indirect effects

The direct environmental effects of ICT devices and infrastructure are important, but they should not distract us from the profound systemic environmental implications of ICTs. Environmentally beneficial applications need to be developed and promoted. Progress has been made in areas such as optimized control of manufacturing processes, but most of this progress has been achieved through market mechanisms rather than deliberate environmental intent. Public investments made to understand and use ICTs for environmental objectives pale in comparison with those made in industrial-age technologies such as engines, buildings, energy and road infrastructures.

Going beyond applications, the interaction of ICTs with economic growth, technological progress and society must not be ignored. The history of the automobile teaches an enduring lesson: improving a technology does not necessarily result in reduced environmental impacts. In fact, in an economy based on continuous growth rooted in technological progress, the opposite can be true. Understanding the interaction of ICTs with economic and social systems presents significant and interdisciplinary methodological challenges. Grappling with such complexity is at the heart of modern society's emerging concern over sustainability. ■

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