Smart Everything: Will Intelligent Systems Reduce Resource Use?

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Abstract

Until recently, the main environmental concerns associated with information and communication technologies (ICTs) have been their use-phase electricity consumption and the chemicals associated with their manufacture, and the environmental effects of these technologies on other parts of the economy have largely been ignored. With the advent of mobile computing, communication, and sensing devices, these indirect effects have the potential to be much more important than the impacts from the use and manufacturing phases of this equipment. This article summarizes the trends that have propelled modern technological societies into the ultralow-power design space and explores the implications of these trends for the direct and indirect environmental impacts associated with these new technologies. It reviews the literature on environmental effects of information technology (also with an emphasis on low-power systems) and suggests areas for further research.

Contents

INTRODUCTION

Innovation in modern industrial societies has been driven in the past two centuries by a series of what economists call "general-purpose technologies," which have far-ranging effects on the way the economy produces value. The most important of these were the steam engine, the electric power grid, the internal combustion engine, and, in the past few decades, information and communication technologies (ICTs) (1, 2).

Until recently, the wider use of ICTs has mainly been driven by rapid reductions in the cost of such equipment (3). Those cost reductions have resulted in widespread adoption, with important implications for the structure of businesses and the ways consumers access information (4).

The technological factors enabling Moore's law (5), which projected a doubling of component densities every year after 1965 and a doubling every two years after 1975, have been important drivers of these cost reductions since the 1960s. However, the recent push toward "smart" devices (i.e., those with embedded computing and wireless communications) owes more to a parallel set of trends in the efficiency of computing and communications, the development of new sensor and control technologies, and improvements in energy storage and harvesting. These trends have led to a new class of computing devices that are small, cheap, connected, and so low power that they can operate for long periods using batteries or power scavenged from ambient energy flows.

This design challenge is very different from that for earlier computing devices. Some of our most talented engineers have for decades been drawn to building the biggest supercomputer or the fastest personal computer (PC), and the innovations to achieve those goals revolve around maximizing performance. Now our fastest processors have clock speeds in the gigahertz (GHz) range, and large computing systems can have tens or hundreds of thousands of computing cores operating in parallel.

In contrast, creating low-power devices requires attention to minimizing standby as well as active power and an intense investigation of ways to communicate in ever more efficient ways. Because these devices are small and cheap, they can be embedded almost everywhere, which allows us to apply computing power and communications in ways that nobody could have imagined decades ago. In raw performance terms, these devices cannot match a PC, but in many applications, processors with relatively low performance are adequate as long as their average energy use over time is low enough to fit within a tight power envelope.

These ultralow-power devices have the potential to revolutionize our ability to understand and respond to the world around us. Consider the low-power communication technology that Proteus Biomedical (**http://www.proteusbiomed.com**) now embeds in pharmaceuticals (6). This 1-cubic-millimeter device has no battery; it has an anode and a cathode, and it uses the patient's stomach juices as the electrolyte. When ingested, the pill sends a low-power signal to a patch on the patient's skin, and the patch relays the signal to a mobile phone or similar device. This signal records when the patient takes the medicine, which matters greatly for certain patient populations. Later incarnations of this technology will relay sensor data as well, and they open up the possibility of truly personalized medicine.

The amount of computing performed by such a device is tiny, but the value of the information delivered is orders of magnitude higher than the cost of manufacturing the device. Technology delivering such value can be a catalyst for truly disruptive innovation throughout the economy.

The advent of ICTs has seen growth in the direct electricity used by computing equipment as well as changes in the overall efficiency and consumption in the broader economy. This article reviews the literature on the direct and indirect energy and environmental effects of ICTs, with an emphasis on the transition to ultralow-power systems. Although it is impossible to estimate many of these effects quantitatively, it is important to characterize them in

General-purpose technology: a technology that catalyzes and enables broad and deep structural changes throughout the economy, e.g., the internal combustion engine

ICTs: information and communication technologies

Moore's law: an empirical observation from Gordon Moore of Intel in 1965 that the number of components on a chip would double every year (changed to every 2 years in 1975)

PC: personal computer

GHz: gigahertz (billions of cycles per second) a consistent and accurate way, and to identify fruitful areas of further research.

International Data Corporation: a widely referenced collector of data on the information technology industry

FACTORS DRIVING ADOPTION OF MOBILE INFORMATION AND COMMUNICATION TECHNOLOGIES

A confluence of improvements in the costs and efficiency of computing, communications, sensors, energy harvesting, and energy storage technologies has led to a vast increase in the numbers and types of ICT equipment, with consequent improvements in our ability to monitor changes in institutions, technological systems, and the environment in real time. This section reviews data on these trends and summarizes their implications.

The Relationship Between Conventional and Low-Energy Information and Communication Technologies

The history of computing has until recently focused on the rise of general-purpose computing devices,[1] such as PCs and servers (3). As computing becomes more distributed and more mobile, PCs are diminishing in importance. For example, laptops passed desktop PCs in annual unit shipments worldwide for the first time in 2009 according to the International Data Corporation (7). And now, tablet computers (e.g., the iPad) are starting to eat away at the market share of both desktops and laptops, with tablets capturing almost 25% market share worldwide in late 2012 (8).

This trend is reflected also in the shift toward ultralow-power computing and sensors (9). PCs are occasionally used as part of the data collection scheme for these devices, but more often sensors send their data straight into what is colloquially known as the "cloud."[2] This term is commonly used to refer to anything on the other side of the customer's wall, but in practical terms, it means data stored and processed at the large centralized computing facilities known as data centers. These facilities house thousands of servers and provide centralized computing that can be extremely efficient. Once information resides at a data center, it can then be compiled, shared, and analyzed far more easily than it could be otherwise.

Computing is now shifting toward more mobile and distributed devices and more use of centralized servers in data centers. That shift has complicated the research questions around electricity use and information technology. Because computers are now being embedded in objects of all sorts, the boundary between what is computing and what is not has become blurred. It may in fact be impossible in practice to determine how much electricity computing devices use as distinct from that for other energy-using equipment. That is because embedded processors are not tracked or measured as discrete units in many cases.

There is additional complexity brought on because of the broader systemic effects of more widespread use of computing. For example, many clothes washers are equipped with sensors and computer technology that improve the service being delivered and save both motor and hot water energy in amounts many times larger than the electricity used by the computing equipment. Automobile engines are almost all computer controlled nowadays, which gives them higher efficiency and lower emissions than they would otherwise have. Data centers and the information services they deliver enable structural changes that increase efficiency throughout the economy. In each of

[1]The concept of general-purpose computing is different from that of general-purpose technologies described earlier in this article. General-purpose computers can be programmed to assess many different kinds of problems. Special-purpose machines can sometimes be created that can solve particular classes of problems much more efficiently than a general-purpose computer (but are not as efficient in attacking other types of problems).

[2]This colloquial term is distinct from the concept of "cloud computing," which is a way to design data centers that generally results in far more efficient use of the equipment, lower energy use, and smaller environmental impacts per transaction compared with traditional "in-house" data centers.

these cases, a relatively small amount of electricity used for ICT can affect much larger amounts of energy used in bigger systems.

Efficiency of Low-Energy Computing

Low-energy device consumption is governed by the schematic graph in **Figure 1**, which applies to both computing and communications applications.

The goal for low-energy devices is to minimize the area under the power curve, so that a computing application can operate for years using a primary battery or some kind of energy harvesting. Electricity use can be reduced by affecting the four components listed in **Figure 1** (active task time, active power, standby power, and transition time), as well as by reducing the frequency of tasks (i.e., the number of times per hour the task is performed). Active power and standby power can be reduced by improving efficiency, and active task time can be reduced by faster processing (moving from an 8-bit to a 32-bit microcontroller, for example). Transition time can be reduced using faster switching technology. There can also be different levels of standby—usually, the deeper the sleep, the longer the transition time (latency) for shifting to an active mode.

Reducing task frequency is one of the most powerful ways to reduce energy use. For example, the University of Michigan has developed a sensor that occupies about 1 cubic millimeter (10). With standby/sleep power of 11 nanowatts (nW), a deep sleep mode of 185 picowatts, and an active power of 40 microwatts (μW), it can operate for a long time with a tiny battery or with energy harvesting. The developers have suggested that the device, if used as a tumor pressure sensor, need only communicate every 15 min. Clearly, this application does not require gigahertz processors, and the low task frequency, combined with tiny standby losses, makes this and many other such applications feasible.

Active power. The long-term trends in the active power efficiency of general-purpose

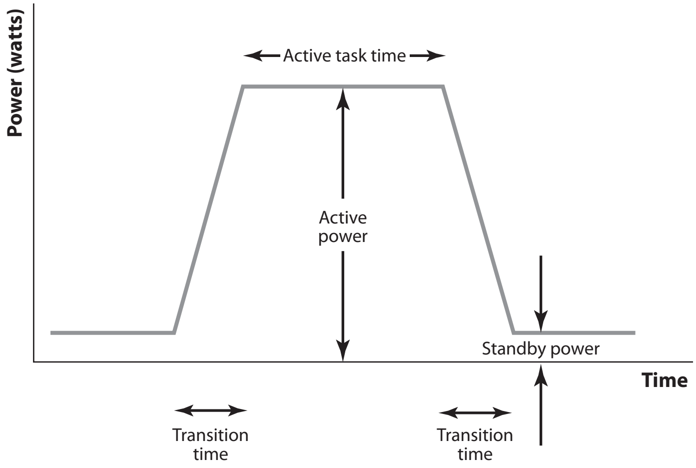

Figure 1

Factors affecting energy use of computing and communication tasks.

computing devices have been well documented. Koomey et al. (7) showed that the energy efficiency of computing (measured in computations per kilowatt-hour) doubled every 1.6 years from the mid-1940s until 2009, a trend that is comparable to that describing efficiency changes in the microprocessor era (see **Figure 2**). This trend is related only to the active power of general-purpose computers running at maximum computational output—it says nothing about standby power, coding efficiency, or other aspects of computer systems that can affect the total energy used by these devices. It is, however, a well-established trend affecting an important aspect of computing technology, and it has been the most important driver that has made it possible for the technology industry to focus more strongly on low-power devices in the past decade or two.

Will this trend continue? Nobody can say for certain, but we are still far from the limits to efficiency. In 1985, the physicist Richard Feynman analyzed the electricity needed for computers that use electrons for switching and estimated that there was a factor of 10^{11} improvement that was possible compared to computer technology at that time (11). Performance per kilowatt-hour for computer systems improved by a factor of 4×10^4 from 1985 until 2009, on the basis of regressions in

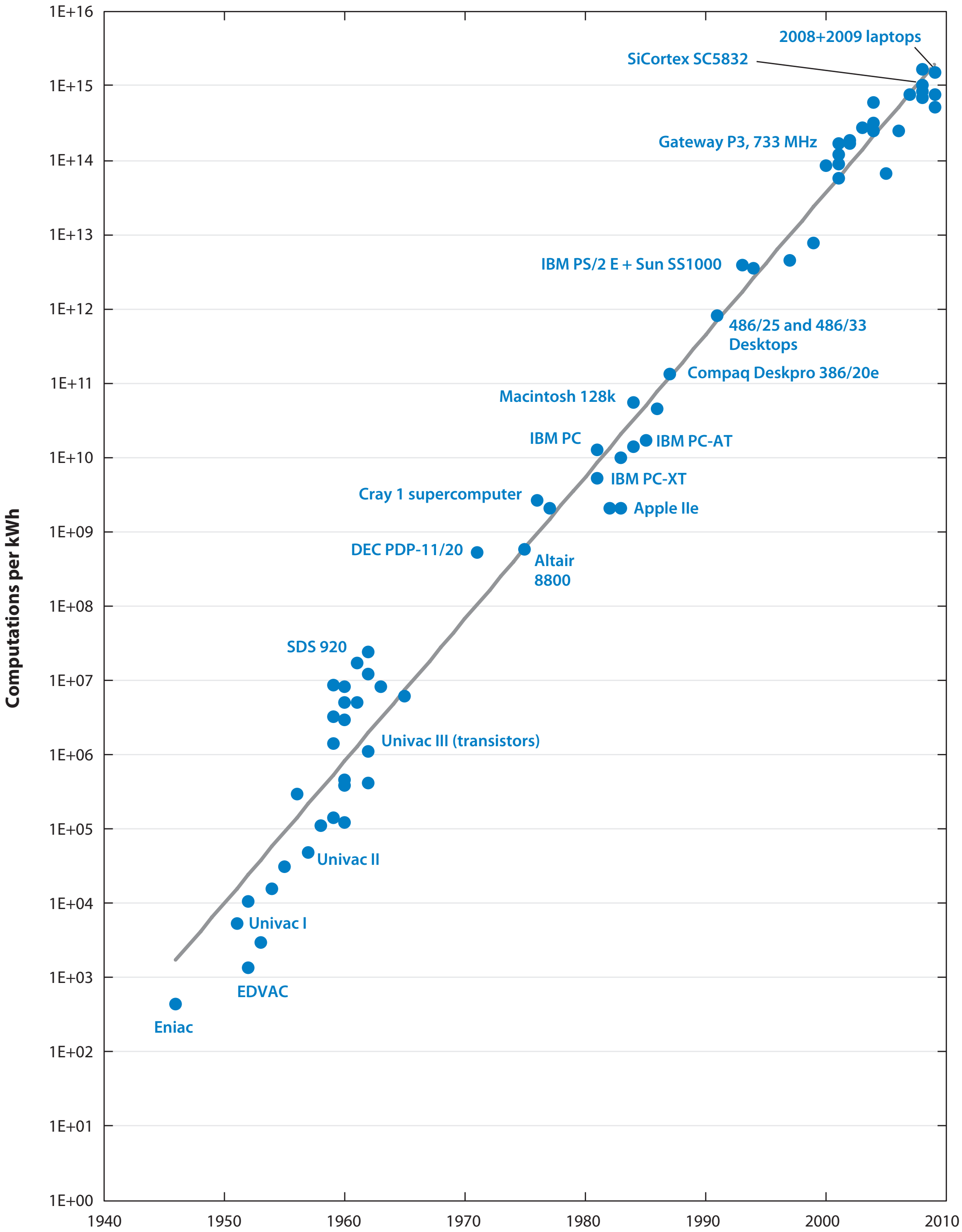

Figure 2

Energy efficiency of general-purpose computers over time (1946–2009). Adapted from Reference 7.

Koomey et al. (7), so there is still a long way to go with current technology before reaching Feynman's limit.

Feynman assumed a three-atom transistor to calculate his limit, but he made it clear that if we could create smaller transistors, then the limits would be pushed out even further. This has recently come to pass—*Nature Nanotechnology* in 2012 published an article by researchers at US, Australian, and Korean universities demonstrating a reliable one-atom transistor (12). Their current version uses electron energy levels for switching. It operates only at liquid helium temperatures, but this innovation may ultimately yield a way of capturing efficiency improvements beyond Feynman's limit. Other analyses have pointed to physical limits well beyond those calculated by Feynman (13).

If the long-term trends in Koomey et al. (7) continue unabated, we will reach Feynman's original limit in 2041, a little less than three decades from now (see **Figure 3**). That result implies that sometime during the near future our computing technology must undergo fundamental changes if we are to continue active power efficiency improvements at historical rates.

The problem is more proximate than that, however. Electrical engineering has been wrestling with key constraints since the early 2000s, and those required a fundamental rethinking of how to improve performance and energy efficiency of semiconductors (14, 15). In a classic paper in 1974, Robert Dennard and his colleagues (16) laid out a path for improving performance and efficiency of semiconductors that held for almost three decades (17). As transistors shrank in size, designers were able to improve efficiency by reducing the chip supply voltage (a process known as "Dennard scaling"). Unfortunately, the limits of Dennard's approach were reached just after the turn of the millennium (18).

As transistors shrank and threshold voltage levels declined, leakage current for semiconductors started to increase rapidly (19), and clock speeds could no longer be increased to improve performance. That led the industry to move to multicore computing, packing more and more cores on a single chip, and forcing software designers to redesign their code to implement multiprocessing.

Multiprocessing also has limits (20), and this realization has forced electrical engineers to consider other possibilities for improving processor architectures. We can still pack more transistors on a chip, which reduces capacitance and thus energy use per transistor, but we no longer can count on the efficiency improvements that come from lower voltages, which were a big part of the historical gains. There are challenges in transistor reliability, communications, and costs of fabrication that all need to be overcome if our current technologies are to continue to improve in efficiency and performance over the next two decades (14).

One promising area of research lies in carbon nanotubes, which have the potential to substantially improve transistor performance compared to current technologies (21–23). IBM recently demonstrated assembly of more than 10,000 nanotube transistors onto a single chip (24), which is an important step toward practical application of this technology in processors. Whether this technology can be applied successfully to the production of microprocessors remains to be seen.

Standby power. There are no studies of which we are aware documenting long-term trends in standby power over time, but the industry has focused on ways to improve this aspect of computing technology since the first laptops were introduced in the 1980s. In the early 1990s, the Energy Star program for PCs first attempted to prod desktop manufacturers to adopt low standby power for PCs and monitors, with significant success (25). That effort has also spread to other kinds of ICT equipment, including fax machines, printers, copiers, multifunction devices, and most consumer electronics (**http://www.energystar.gov/**). Improving standby power involves both hardware and software innovations and is a fundamentally different design challenge than improving efficiency of computers at maximum processing output.

Dennard scaling: a functional relationship between chip voltage and transistor size that allowed power use of transistors to decline for decades

Carbon nanotube: a form of carbon that may allow creation of significantly faster microprocessors than using current semiconductor technology permits

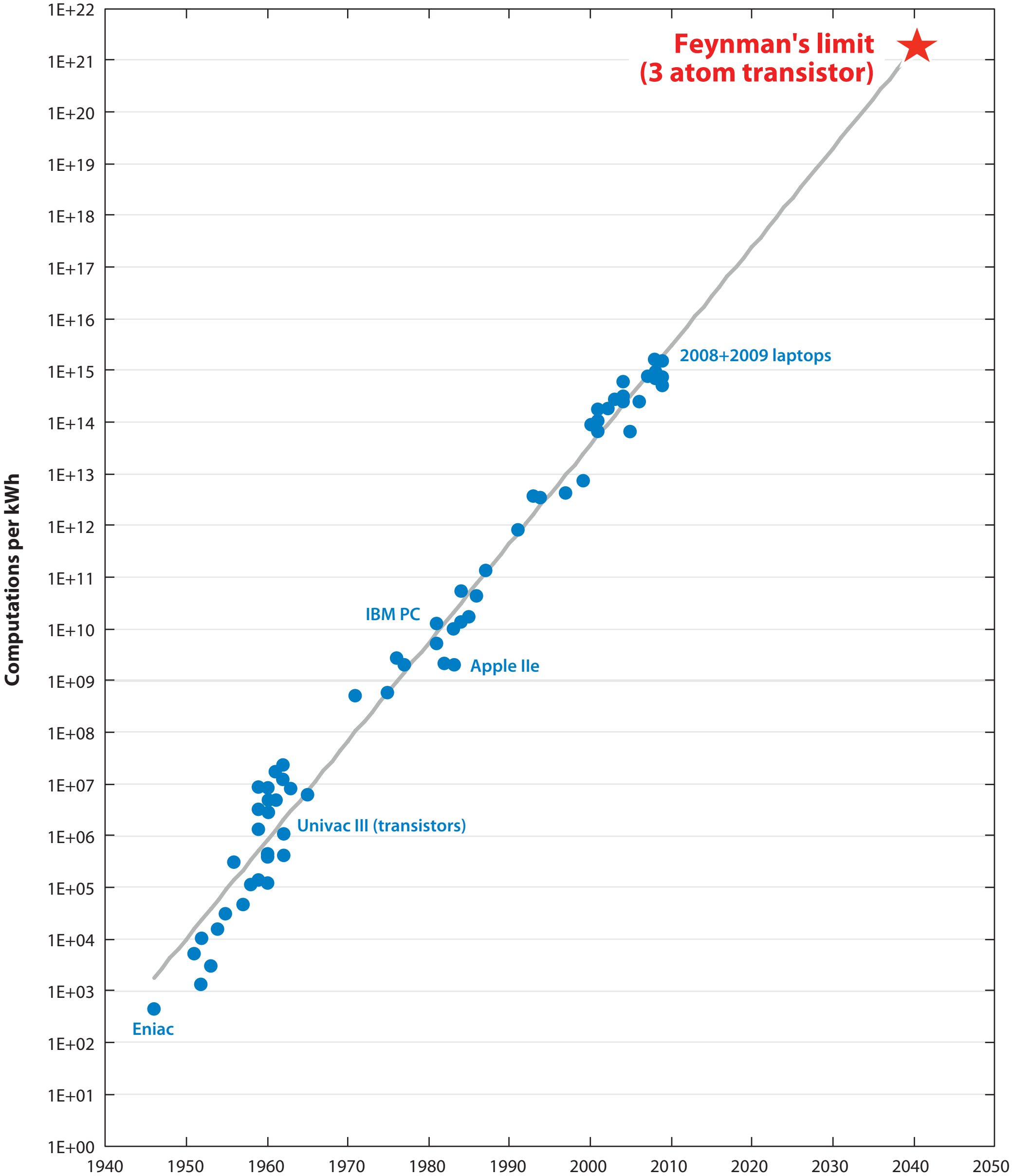

Figure 3

When will the energy efficiency of general-purpose computers hit Feynman's limit (11) if historical trends continue? Historical data taken from **Figure 2**.

Reductions in standby power are limited by leakage current and thus are related to semiconductor architecture, voltage (26), and transistor size. Since the end of Dennard scaling in the early 2000s, various methods have been used to reduce leakage current for the fastest microprocessors (19), but the engineering techniques used for those devices are not necessarily the same as the techniques that would be successful for ultralow-power chips running at less than gigahertz speeds (27). One set of promising techniques revolves around the subthreshold operation of transistors, with the potential for substantial improvements in efficiency (28).

Task time. Task time can be reduced by increasing the clock speed of the computer, increasing the data bus width (a 32-bit bus can transfer information four times as fast as an 8-bit bus for a given clock speed), improving software performance, and optimizing the hardware and software to work together more efficiently in a process known as "codesign" (29). This latter approach is common in embedded systems, and it is used to optimize the microcontrollers so common in manufactured products (30). It has also recently been applied to the design of supercomputers to overcome power-related design constraints (31–34).

Transition time. Transition time depends in part on what kind of standby mode a device has entered. Typically, deeper sleep modes mean longer transition times. One of the most commonly used microcontrollers, the Texas Instruments MSP430, lists a typical wakeup time from standby of 3.5 microseconds (μs) (**http://www.ti.com/msp430**). For many applications, the transition time is small compared to the active task time and can be ignored without sacrificing much accuracy.

Power gating, which shuts off parts of a chip when they are not in use, is one method for reducing standby losses (35). One of the key factors affecting transition time is the way power gating is implemented on the chip, and different designs can affect the time to move from standby to active power (36). Other factors affecting the transition time include the system architecture and the amount of data or communications needed to restore active mode functionality, inherent device physics, computational speed, clever power management techniques, and the access characteristics of memory.

Task frequency. Task frequency is in some sense arbitrary, but it is strongly dependent on the nature of the computing task being performed. Low task frequency combined with very low standby power level allows us to apply ICTs to many new and unexpected applications.

Efficiency of Wireless Communications

The long-term trends in the power efficiency of computing also apply to some degree for communications, but there are additional complexities. The power needed to send a signal by wireless communications is governed by information theory (37, 38) as well as the inverse square law associated with electromagnetic radiation emanating from a source. It is also affected by the design of network protocols and involves a complex interplay between software, hardware, and user behavior (39). In many low-power applications, the transmission power and task frequency are the most important determinants of battery lifetime (9, 40, 41).

Active power. There is not yet a definitive analysis of historical trends in active power for communication, but there are at least two anecdotal data points that are suggestive. First, in August 2012, Kris Pister, who was the founder of one of the pioneering companies in creating mesh networks (Dust Networks), told the first author of this review (Koomey) that there has been about a factor of ten reduction in active transmission power for mesh network nodes over the past decade, which corresponds to a doubling time of about every three years for active power efficiency.

Second, **Appendix A**, in the **Supplemental Material** (follow the **Supplemental Material link** from the Annual Reviews home page at **http://www.annualreviews.org**), contains a schematic calculation comparing the number of minutes of talk time for the first battery-powered cell phone to one of the simplest "feature phones" sold in 2011. This calculation shows a slower rate of improvement than the wireless mesh example (a doubling time of almost eight years), but that is to be expected

Supplemental Material

RF: radiofrequency

because the complex systems in cell phones are harder to optimize than simple nodes, such as those used in mesh networks.

Both of these examples suggest that the efficiency of these devices has improved, although not as rapidly as has efficiency for general-purpose computers. Just how far current wireless devices are from the theoretical limits has not been well studied, which is why we include this topic in the "Open Research Questions" section below. There is also a systems-level aspect to the active power for cell phones, because the design of the network affects the overall efficiency of data transmittal beyond the wireless sensor or handset.

One potential area of efficiency improvements involves integrating antennas onto silicon (42). Carbon nanotubes are also promising for improving the efficiency and performance of radiofrequency (RF) devices. Rutherglen et al. (43), Burke et al. (44), and Hanson (45) explore different aspects of applying nanotubes to small-scale transmitters, and Burke & Rutherglen (46) assess the whole systems design challenge for creating transmitters at nanoscale.

Standby power. Similar uncertainty prevails on trends in standby power, with only some systematic data compiled on this issue for wireless communications. The best existing data are from researchers at the University of California, Berkeley (41).

Task time. Some of the same technological tricks for reducing task time in general-purpose computing can also work for communications, but information theory limits the efficiency with which signals can be sent (9).

Transition time. Just as for general-purpose computers, transition times between standby and active modes are related to the characteristics of the relevant standby mode. Deeper sleep implies a longer transition time. System architecture also makes a difference (40).

Task frequency. For mobile sensor networks, task frequency is application specific. For measuring systems that change rapidly, the task frequency must be rapid, but for many other systems, task frequency measured in hours may be acceptable.

Task frequency for mobile phones relates to what we might call "protocol overhead." Mobile phones use protocols that have deep historical roots, and some of those protocols force mobile phones to unnecessarily use power when they need not (for example, keeping the phone active when it is not really doing anything useful). Modest changes in how phones interact with base stations can have substantial effects on energy use of cellular phones (reducing it by more than 50%) (47).

Trends in Energy Storage

Energy storage comes in many different types, but for low-power electronics applications, the most important ones are primary batteries, secondary batteries (also known as rechargeables), and super/ultracapacitors. Other energy storage devices, not discussed in detail here, include fuel cells, flow batteries, and betavoltaic (nuclear) batteries. For more details, see Reddy (48) and Bogue (49, 50).[3]

Primary batteries. Primary batteries are single-use batteries that come in many shapes and sizes. Leclanché (carbon-zinc), alkaline, and lithium are the most common chemistries, and each of these has many variants. They have improved significantly over time (with the biggest jump attributable first to alkaline and then to lithium-based batteries), but the rate of change is nowhere near as rapid as that for computing technology. **Figure 4**, adapted from Reddy (48), shows that primary batteries have improved in specific energy by a factor of about 12.5 since 1946. Over the same period, the active power efficiency of computing has increased by about 13 orders of magnitude (7).

Many critical applications now use lithium thionyl chloride batteries, which have specific

[3]The characteristics of energy storage devices are often illustrated using a Ragone chart, which plots power density versus energy density on logarithmic scales (see Reference 51 for an example).

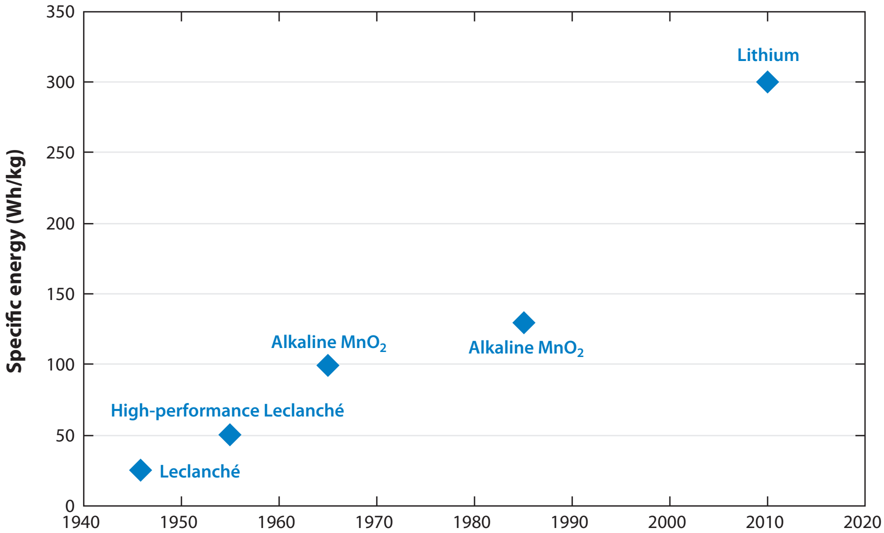

Figure 4

Specific energy in watt-hours per kilogram (Wh/kg) over time for primary batteries, adapted from Reddy (48). Abbreviation: MnO_2, manganese dioxide.

energies about twice that of the most common lithium batteries shown in **Figure 4** (48). Because of safety concerns, these batteries are not generally available to consumers.

Secondary batteries. Rechargeable (secondary) batteries have also improved significantly over time. **Figure 5** shows a factor of ~4.7 for progress in the specific energy of such

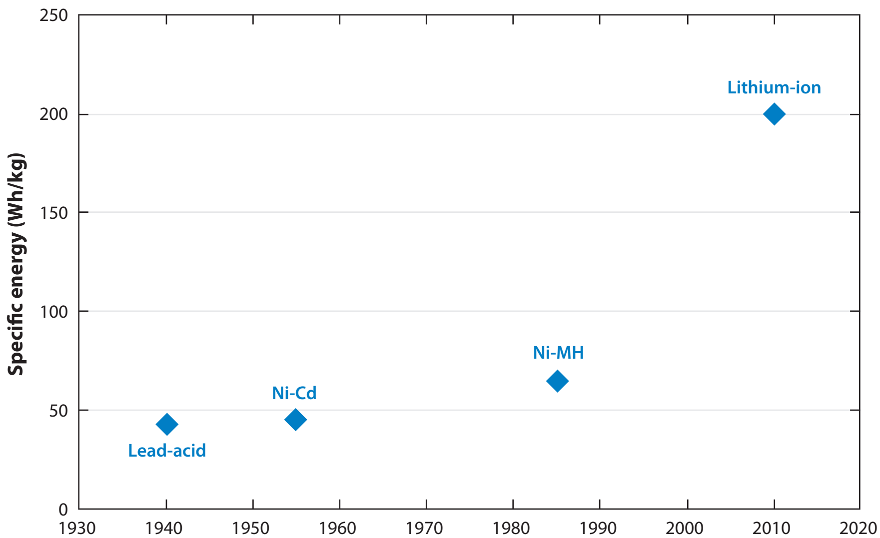

Figure 5

Specific energy in watt-hours per kilogram (Wh/kg) of rechargeable (secondary) batteries over time, adapted from Reddy (48). Abbreviations: Ni-Cd, nickel-cadmium battery; Ni-MH, nickel–metal hydride battery.

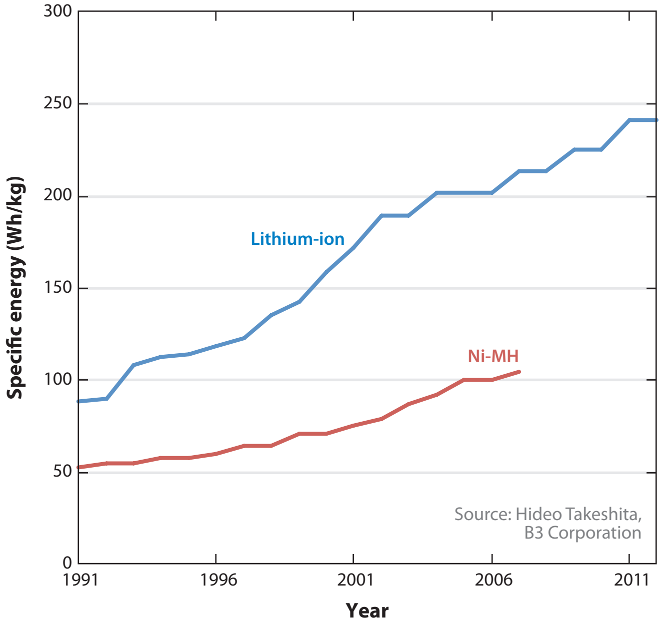

Figure 6

Specific energy of nickel–metal hydride (Ni-MH) and lithium-ion batteries in watt-hours per kilogram (Wh/kg) after 1991.

Supercapacitor: an energy storage device that uses two metal plates separated by an insulating material, with much higher storage capacities than a standard capacitor

batteries between 1940 and 2010 (48). The big jump was to lithium-ion batteries, which are now the rechargeable battery of choice for most electronics applications. Nickel metal hydride is still important for rechargeable AA and AAA cells used by consumers, but cell phones and other high-value electronics have almost all switched to lithium-ion batteries. Boeing's recent experiences with fires sparked by lithium-ion batteries highlight some of the challenges of this technology (52), but the energy density advantages of these batteries are still important in many applications.

Both lithium-ion and nickel–metal hydride (Ni-MH) batteries have improved over the past two decades, as shown in **Figure 6**. Ni-MH batteries improved by a factor of 2 from 1991 to 2007, whereas lithium-ion technology improved by about a factor of 2.5 from 1991 to 2010. Just as for primary batteries, these changes are nowhere near as rapid as for electronics efficiency, but the new lithium-based battery technologies have been particularly important in expanding the potential for applications dependent on energy storage (53).

Supercapacitors/ultracapacitors. Batteries store energy in chemical reactions, whereas capacitors store electricity by maintaining an electrical potential between two conducting plates held a small distance apart. The energy densities of traditional supercapacitors (also known as ultracapacitors) are given by Reddy (48) as between 5 and 12 watt-hours per kilogram (Wh/kg), which is much lower than Ni-MH or lithium-ion batteries. Supercapacitors can be charged and discharged more rapidly than batteries, giving them advantages when bursts of power are needed (as for automobile applications). They also last longer than batteries, but the voltage they deliver falls as they are discharged, which can be a disadvantage in certain applications.

Recent innovations using advanced materials show promise for increasing energy densities of supercapacitors. Liu et al. (54) demonstrated a graphene-based supercapacitor with a specific energy of 85.6 Wh/kg, a level approaching that of current-day Ni-MH batteries.

New Developments in Sensors and Controls

The biggest shift in sensors in the past two decades has been the development of small-scale sensors and actuators fabricated out of silicon, known in the trade as microelectromechanical systems, or MEMS (55). More recently, a class of much smaller sensors (nanoelectromechanical systems) has become more prominent (56, 57). In both cases, smaller-scale sensors allow for applications that were not possible previously (58). One of the more active areas of recent research has focused on monitoring buildings for their structural health over time, using wireless technology (59).

Another important trend in sensors is the shift to wireless communications (9). There are still applications for which wired sensors are required (mainly for high monitoring frequency, typically in high-reliability industrial production plants), but with advances in the power efficiency and capabilities of wireless sensors, the domain of wired sensors has begun to shrink. Wireless sensors are cheaper to install and offer more flexibility but at the expense of lower bandwidth. Wireless sensors can be battery powered, but they can also draw from line power, depending on the application.

Finally, the focus on low-power mobile sensors has highlighted the importance of optimizing all parts of such systems, not just the processors (60). Analog, digital, and RF circuits all must be redesigned to achieve long battery lifetimes; this represents a unique design challenge. Packaging such small devices also remains a challenge (9).

Trends in Energy Collection and Transfer Technologies

Secondary batteries and super/ultracapacitors require some means to recharge them. The two most important areas of research are energy harvesting and intentional wireless energy transfers. The first involves tapping ambient flows of light, heat, motion, or stray RF signals, and the second involves directed energy transfer without a physical connection.

Energy harvesting. One of the most discussed topics related to mobile computing and communications is that of energy harvesting (49, 50, 61–65). There have been many interesting research investigations, but it has been hard in practice to develop small-scale energy harvesting applications that are commercially viable. It is fair to say that energy harvesting is in its infancy.

Table 1 summarizes power densities from different ambient energy flows. Vullers et al. (66) conclude from these data that energy harvesting "can supply approximately 10 μW to 1 mW" (p. 36), which is the sweet spot for wireless sensor nodes. Although this conclusion is true in principle, implementing it in practice at a competitive cost has proved to be a challenge.

One of the few examples of energy harvesting in widespread use is that of tire pressure sensors, which have been mandated for new US automobiles since 2008. These devices often rely on MEMS technology, use wireless to convey information to the car's central computer, and can use the rotational energy of the wheel to power themselves (67–70).

Energy harvesting from ambient light is well developed, especially for outdoor applications,

Table 1 Power levels for energy harvesting[a]

Source	*Source power*[b]	*Harvested power*
Ambient light		
Indoor	0.1 mW/cm^2	10 μW/cm^2
Outdoor	100 mW/cm^2	10 mW/cm^2
Vibration/motion		
Human	0.5 m @1 Hz, 1 m/s^2 @50 Hz	4 μW/cm^2
Industrial	1 m @5 Hz, 10 m/s^2 @1 kHz	100 μW/cm^2
Thermal energy		
Human	20 mW/cm^2	30 μW/cm^2
Industrial	100 mW/cm^2	1–10 mW/cm^2
Radiofrequency		
Cell phone	0.3 μW/cm^2	0.1 μW/cm^2

[a]Reprinted from *Solid-State Electronics*, 53/7, Vullers et al., "Micropower energy harvesting," pages 684–693, copyright 2009, with permission from Elsevier (66).

[b]Abbreviations: kHZ, kilohertz; mW, milliwatt; μW, microwatt.

Nanopiezoelectronics: the study of devices that convert motion (of clothing, for example) into small amounts of usable electricity

but it is harder to apply to sensor applications indoors because of the need for a sufficient collector area in areas of low light (71).

Wang (72) introduced the concept of nanopiezoelectronics, which focuses on the use of piezoelectric materials to generate small amounts of electricity in unusual applications. For example, researchers have demonstrated energy capture from specially designed clothing in the range of 4–16 milliwatts (mW) per square meter of fabric (73). Other researchers have focused on tapping human body heat for power (64).

Another interesting example is that demonstrated by Sample & Smith (74). This application harvests stray RF signals from local radio and TV broadcasts and collects enough power (about 60 μW, on average, from a TV antenna about 4 km distant) to power sensors of different types. It requires an antenna that is 33 cm long by 32 cm at its widest point, but for some applications, that should not be a constraint, and devices capable of being powered with smaller antennae are on the way.

The variability of many ambient energy flows has encouraged some researchers to develop hybrid power generation approaches. Bandyopadhyay & Chandrakasan (75) developed an energy harvesting chip that converts motion, light, and heat into electricity at relatively high efficiency. Such a device can level out the peaks and valleys endemic to ambient energy and lead to more predictable rates of energy harvesting. Tan & Panda (71) demonstrated a different hybrid system focusing on ambient light and heat.

Wireless energy transfer. In this section, we focus on the intentional transfer of energy to specific devices. This category of energy supply is unique because the designer has control of both the transmitter and the receiver of energy. It allows for better optimization and higher-power transfers than are ordinarily possible with standard energy harvesting techniques. The most common application to which this technique now applies is in wireless-power transfers to cell phones using commercially available charging mats, but it has encountered roadblocks in consumer acceptance because of the incompatibility between devices and the difficulty of shifting from one standard for charging to another (76).

Sample & Smith (74) and Sample et al. (77) describe wireless energy transfer (measured in microwatts) to a radio-frequency identification device located no more than 10 m from the energy source. This application uses what is called far-field transmission; if used in a directional mode (as is commonly done with microwave transmissions), the efficiency of such transfer can be high, but it requires line of sight to work well (78). In broadcast mode, far-field techniques suffer from the dissipation of power common to all radiation, governed by the inverse square law.

Another approach is demonstrated by Sample et al. (79), showing coupled resonance transfer of power measured in tens of watts, achieving about 70% efficiency at a distance of 0 to 70 cm. This technique can be useful for biomedical devices implanted inside the body (65); if sufficient energy can be transferred to power such devices, patients can avoid having a power wire penetrating their bodies (such wires are significant pathways for infection).

Relationships Between Power Use, Energy Storage, and Energy Harvesting

A mobile technology becomes most feasible when it can achieve either (*a*) long battery lifetime, measured in years, or (*b*) tapping of ambient energy flows so that it can operate indefinitely without changing its power source. Achieving either goal requires attention to both the efficiency of the electronics and the characteristics of the chosen power source, and it is a complex optimization problem. This section describes how these factors are related.

The lifetime (L in years) of a device with average power P_a^{Device} (in watts) using a primary battery (i.e., one that is not rechargeable) can be expressed as the function of the actual capacity of the battery (C, in watt-hours, corrected for

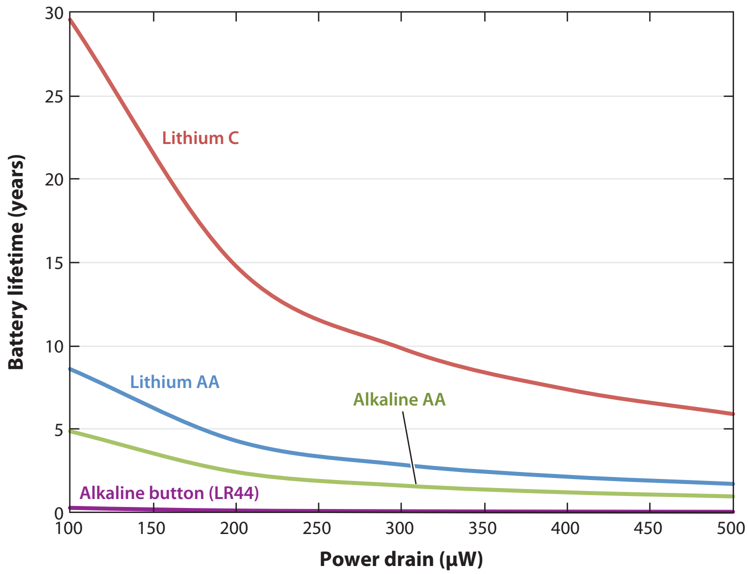

Figure 7

Battery lifetime (years) as a function of power drain for some common batteries. Abbreviation: μW, microwatt.

the limitations of real batteries in use):

$$L = \frac{C}{P_a^{\text{Device}}} \cdot \frac{1\ \text{year}}{8,766\ \text{hours}}, \qquad 1.$$

where 8,766 hours is the number of hours in one year, adjusted for leap years. It is only when L reaches multiple years that mobile applications become interesting, although there is no hard-and-fast rule.

Figure 7 shows the relationship between average power and battery lifetime for several common battery types (**Appendix B**, in the **Supplemental Material**, contains the data and calculation details). For power drains in the hundreds of microwatts, lithium batteries in the AA or C configuration are required to achieve lifetimes of a few years or more. Once the power drain dips below 10 μW, then even the tiny LR44 button cell battery (commonly used in watches) can achieve such lifetimes (see **Figure 8**). Lithium thionyl chloride batteries have roughly doubled energy densities compared to standard lithium primary batteries, which is why they are used in many ultralow-power applications in spite of some of their limitations (48).

As an illustration, consider the sensor (discussed above) developed by the University of Michigan, which has standby power of 11 nW and active power of 40 μW. Let us assume the task time is 2 s, the transition time is 3.5 μs (like the TI MSP430 microcontroller), and the task frequency is 4 times per hour. Those assumptions combined with the formulas in **Appendix B** yield an average power for the device of about 0.1 μW (100 nW), which would allow the device to operate for more than a decade using the primary lithium version of an LR44 button cell according to **Figure 5** (the alkaline version might not last that long for reasons unrelated to the power drain). Cycle times of 0.5 times per hour (i.e., once every two hours) would result in an average power of 22 nW.

Supplemental Material

Let us assume that the LR44 lithium cell could be scaled down to 1 cubic millimeter and that the smaller cell has the same energy density per liter. How long could our 22-nW load be powered using such a battery, which holds 0.5 mWh of electricity? The answer is ∼2.6 years, which is not bad for such a tiny device. To achieve longer lifetimes would require

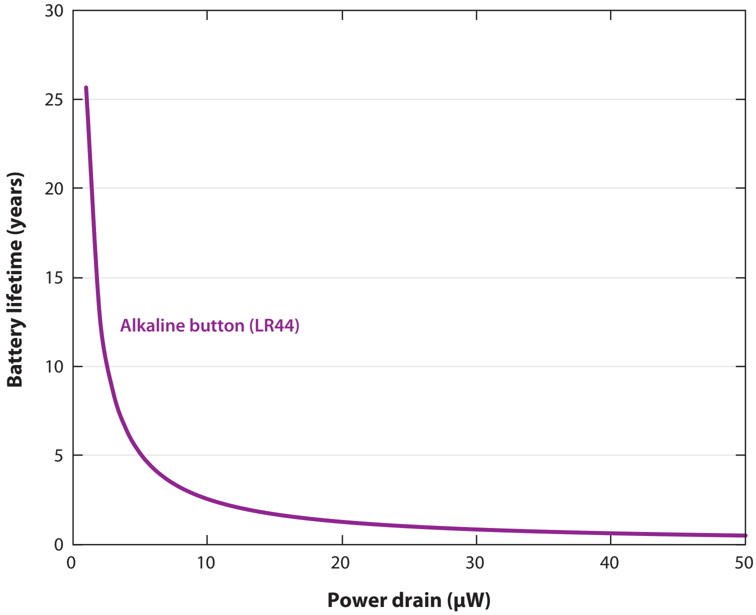

Figure 8

Battery lifetime (years) as a function of power drain for an LR44 watch battery. Abbreviation: μW, microwatt.

lower standby power and/or energy harvesting to supplement the battery.

Communication Protocols

The smart everything domain needs a communications infrastructure, including methods of connecting devices together and the ability to report and take action. Such infrastructure generally is built upon low-level protocols that package and send information between devices. This article does not seek to list all of the technology options but instead presents the range of the most widely used technologies. **Table 2** summarizes those discussed in **Appendix C**, which is in the **Supplemental Material**.

Supplemental Material

Wired communications. There are various wired technologies, ranging from open global networking standards to closed, proprietary systems developed by specific vendors (because there are so many, we will not mention them). Historically, most wired communications protocols in the smart domain in the residential setting have used home power lines as a backbone, and in commercial or industrial applications, proprietary technologies have been used. The residential protocols have been for "home automation," and in the business sector, they have been for "controls."

Wireless communications. Even though wired solutions have been around for 40 years, beginning in the late 1990s the use of wireless technologies in this domain has exploded. What were originally test-bed networks for universities and Fortune 500 businesses are now deployed globally in 25% of the households with Internet access (80) and in businesses and public places around the world. For wireless networking, use of WiFi (IEEE 802.11 series) and Bluetooth protocols is very common. Their use in smart device and energy management domains is less common but growing. A primary cause of the recent upsurge in popularity of such applications are the smartphone platforms, e.g., iOS and Android, which have lowered the barrier to entry for such features

Table 2 Overview of wired and wireless technologies for smart devices

Protocol[a]	Standard (if applicable)	When created	Link
X10	X10	Mid-1970s	Wired (PLC)
UPB	X10 like	Late 1990s	Wired (PLC)
INSTEON®	—	Mid-2000s	Wired (PLC), RF
HomePlug®	IEEE 1901	Early 2000s	Wired (PLC)
Ethernet	IEEE 802.3	Early 1980s	Wired
Bluetooth®	IEEE 802.15.1	Mid-1990s	Wireless, 2400–2480 MHz
WiFi	IEEE 802.11 family	Mid-1990s	Wireless, 2.4 or 5 GHz
WirelessHART®	IEEE 802.15.4, IEC 62591	Mid-2000s	Wireless, 2.4 GHz
Z-Wave	—	Mid-2000s	Wireless, 900 MHz
ZigBee®	IEEE 802.15.4	Mid-2000s	Wireless, ~900 MHz or 2.4 GHz

[a]Abbreviations: GHz, gigahertz; IEC, International Electrotechnical Commission; IEEE, Institute of Electrical and Electronics Engineers; MHz, megahertz; PLC, programmable logic controller®; RF, radiofrequency; UPB, universal powerline bus.

and have (again) leveraged existing infrastructure (in this case, existing WiFi networks) so as to avoid the need for users to invest in or learn significant new technology to use these systems.

Like the wired technologies mentioned above, there are open and closed protocols. WiFi is of course open because of its IEEE standard roots. In the smart device domain, several are prevalent and also are generally device focused as opposed to being core networking technologies, like WiFi.

Mesh networks. Mesh networks have untraditional configurations (81, 82). The nodes of these networks not only manage their own communications but also act as relays for other nodes in the network. Mesh networks are envisioned for application areas where an otherwise pervasive communications network is not available, such as in a remote area where there may be a single node with a communications link but all others need to "hop" their data back and forth to each other outside of the range of the main link. One limitation of such networks is that they need to be built out all at once, not piecemeal; otherwise the node density will not be enough to support mesh communications (this factor can prevent mesh networks from being used in certain applications).

This type of architecture has proven popular for distributed wireless networks, in part, because of its power efficiency. The power needed to transmit a signal increases as the square of the distance, so if you can send the signal over multiple short hops you can reduce transmission power (as long as your nodes are sufficiently low power and efficient). For transmission distances greater than 10 m, transmission energy becomes the dominant term (83) in total energy consumption.

Communication protocols for power management. Nordman et al. (84) have coined the word "nanogrid" to describe a set of energy producing and consuming nodes inside a computer, a sensor node, or a house. Issues of interoperability of energy harvesting and energy using devices in the face of time-varying prices and other constraints will become more prominent in a world of smart everything, but researchers are only beginning to explore the implications of this reality. For example, each part of a system needs to communicate with the other parts, and it needs a language to do so. For sending data streams, we have the various protocols discussed above, but similar protocols need to be created for managing power in real time for such systems to allow interoperability of different technologies.

THE EFFECTS OF INFORMATION TECHNOLOGY ON RESOURCE USE

This section discusses the four major effects of ICTs on economic activity: direct electricity use, manufacturing energy and emissions, efficiency gains from use of ICT, and increases in consumption associated with lower costs and increased wealth. As the technology shifts toward ultralow-power mobile devices, the direct electricity use of these devices will likely decline in importance, whereas the emissions associated with manufacturing will claim a larger share of the direct emissions associated with ICT (85). The indirect effects of ICT will also loom larger and will likely overshadow the direct environmental impacts of ICT.

Use-Phase Electricity Consumption of Information and Communication Technology Equipment

The traditional categories of ICT equipment are data centers, networking equipment, telephone network equipment, on-premise computing/office equipment, and embedded systems, but there are always difficult boundary issues to address in estimating use-phase electricity use. For example, data centers, commercial buildings, and industrial plants all contain networking equipment, so studies that attempt to estimate networking equipment electricity use need to differentiate between equipment in data centers and those in other places. Telecommunications networks were formerly distinct from Internet networks, but as old-style telecom equipment has been replaced by newer voice-over-IP (Internet protocol) equipment, that distinction has faded. And the electricity used by embedded sensors and computing controls in appliances and industrial applications is almost impossible in practice to estimate because the needed data are closely held proprietary secrets of many different companies.

With the exception of data centers and networking equipment, there has been little credible, transparent, reproducible, peer-reviewed work conducted on total ICT power use since the early 2000s. Around that time there was controversy over how much ICT contributed to US power demand, with many analysts uncritically accepting erroneous but widely circulated claims that ICT used 13% of US electricity and would grow to 50% over the next decade (86–88). Out of that controversy grew peer-reviewed reports and articles on US ICT electricity use (89–91) that showed definitively that the US total was about 3%, not 13%. It also led to the first peer-reviewed measurements of electricity used in a data center (92) as well as to follow-on research (93).

The most comprehensive attempt to compile ICT electricity use since 2002 was conducted by Malmodin et al. (94). It assessed ICT electricity use and carbon emissions, including both the manufacturing of equipment as well as the use phase, focusing on 2007. Such analyses always contain assumptions and simplifications, but this study attempted to be as comprehensive as possible. It arrived at a global total of electricity used for ICT in 2007 of 930 terawatt-hours (TWh), or about 5.4% of global electricity consumption in that year (17,110 TWh, according to Reference 95, assuming 7% average line losses). This total includes telephone networks, mobile phone networks, the Internet core network, data centers, and some end-user equipment (PCs, fax machines, cell phones, etc.). It is not entirely clear whether all types of office equipment (copiers and business printers) are included in this total. In addition, many things have changed since 2007, so it is not known whether the percentage of all electricity consumption has increased or decreased since then.

More recent work is sparse. Lanzisera et al. (96) analyzed global and US networking electricity use for 2007 and 2008 and projected it to 2012. They found total electricity used for global networking was about 58 TWh, representing about 0.3% of the total electricity consumption in 2010 (18,118 TWh). If cooling and other auxiliary energy uses are included, the total would be a little over 100 TWh, or 0.6% of 2010 consumption. The numbers are higher in percentage terms for the United States, with US networking totaling about 0.5% in 2010 (0.9% with infrastructure energy use).

Lambert et al. (97) built on the work of Lanzisera et al. and did the most comprehensive available review of various studies on networking electricity use. Lambert et al. also dealt with some (but not all) of the boundary issues associated with estimating total electricity used by communications equipment (including telecommunication networks).

For all data centers, Koomey (98), building upon his earlier work (99), estimated total global electricity use for 2010 of between 203 and 272 TWh (which includes cooling and other infrastructure energy use), or between 1.1% and 1.5% of the total. For the United States in 2010, data center consumption was between 1.7% and 2.2% of total US electricity consumption.

There is overlap between the Koomey and the Lanzisera data sets, with some networking equipment housed in data centers. No one has yet attempted to reconcile the two sources completely, but there is clearly some double counting—the percentages cannot just be added together.

The shift toward mobile devices has profound implications for the total direct electricity used by ICT equipment. Because these devices are battery powered, they use orders of magnitude less power than devices that draw electricity from power lines. They also exist in numbers much greater than conventional computers, but it is not yet clear whether greater numbers will offset higher efficiencies and cause the total electricity use associated with ICT to increase. Assessing this issue will require careful analysis for the world akin to that conducted in the early 2000s for the United States, with a special focus on distributed computing applications and careful attention to boundary issues.

LCA: life-cycle assessment

EIO: economic input-output

Manufacturing Energy and Emissions Associated with Information and Communication Technology Equipment

As computing shifts from general-purpose computers to low-power devices, there are two effects on direct greenhouse gas emissions. First, the use-phase energy consumption per device goes down significantly compared to ICTs that draw electricity from power lines; the most extreme example is that of data centers, where the use-phase still dominates (100). Second, the mass of these devices goes down compared to general-purpose computers, which reduces manufacturing energy. In general, the use-phase energy falls faster than the mass, yielding an increase in the contribution of manufacturing and product delivery to total greenhouse gas emissions. To understand these changes, we rely on life-cycle assessments (LCAs).

How is life-cycle assessment done? The life-cycle inventory part of LCA uses process, economic input-output (EIO), and hybrid methods. We use the term process to denote the most common form of life-cycle inventory, delineated by the International Standards Organization (101). This method is based on a bottom-up model of a supply chain, with each constituent process described in terms of material inputs and environmentally significant releases or outputs. The method to compile the inventory ranges from the simple constituent summing of a supply chain to a matrix formulation that holistically accounts for circularity effects (102–104). EIO-LCA, by contrast, utilizes top-down macroeconomic models that describe a national economy via monetary transactions between sectors (105–107). Combined with sector-level environmental data, these models can be used to estimate the total supply-chain impacts of production, though at a more aggregated level than process models. Hybrid LCA is an umbrella term for approaches to combine both process and EIO methods in ways that address their respective weaknesses (108–110).

Life-cycle assessment and electronics. The application of LCA to electronics started in the 1990s (111) and has since evolved to become a critical part of the debate on environmental interventions. LCA studies of electronics have demonstrated the importance of high-purity processing in the supply chain (112, 113), shown that manufacturing of PCs can consume more energy than their operation (114, 115), and revealed that lead-free solder alternatives are far from impact free (116). When the manufacturing energy exceeds that of operation, extension of the product's life span can be an effective option for mitigating energy use and other impacts. This idea led to the inclusion of reuse criteria in the environmental certification of computers (see, e.g., the EPEAT® rating system, **http://www.epeat.net**).

Electronics are particularly challenging for LCAs for a number of reasons. One challenge is a complex supply chain involving high-tech processes for which material flow data are difficult to collect. A second challenge is the rapid evolution of processes (117) and product functionality (118), as well as how products are used by consumers (119). A third challenge is the far-flung international supply chain for manufacturing and recycling electronics.

These challenges and a lack of consensus in the LCA community have led to divergent LCA results. For example, a process LCA analysis of laptop computers, contracted by the European Community to inform the Energy Using Products Directive, reported 27% and 73% energy shares for production and operation, respectively, whereas a hybrid LCA analysis obtained roughly the opposite: a 62–70% share for production and 30–38% for operation (115). Some argue for the importance of EIO or hybrid techniques to ensure complete coverage of the supply chain (114, 120–122). Other analysts prefer the process-sum approach (123), some arguing that EIO-LCA estimations of component contributions are inaccurate (124). The pivotal philosophical issue in the choice of method is: When facility-level information for a process is unavailable, is it preferable to use an uncertain estimate (EIO-LCA) or to eliminate that process from the supply chain (process sum)? A consensus in the LCA community on this question is still being developed.

Trends in scale and production versus operation share. Although LCA is still evolving, it is still worth looking for general trends pertinent to the hardware evolution considered in this article. We focus on the magnitude of energy use and the breakdown between manufacturing and operation for different types of devices. The production versus operation share is important for two reasons. First, a larger share for production implies additional complexity and uncertainty in the assessment owing to the need to model material flows in supply chains. Second, the manufacturing versus operation share may suggest priorities for interventions.

There are a number of drivers affecting life-cycle energy use. One is technological progress. On one hand, technological progress reduces impacts per functionality (e.g., energy per transistor) for both manufacturing (118) and operation (7), though not necessarily at the same rate. On the other hand, increasing functionality embedded in succeeding generations of devices tends to increase impacts (118). Another factor is the type of functionality delivered by the device. Higher computational load (e.g., servers) and graphic output (e.g., monitor size/resolution) tend to increase operational energy use. Smaller device size reduces energy use in producing constitutive materials.

Figure 9 shows the carbon dioxide (CO_2) emissions for production and operation of a server, laptop, smartphone, and flash memory chip (125, 126). The progression of products, from server, laptop, and smartphone to flash memory chip illustrates trends toward the decreasing intensity of computation and

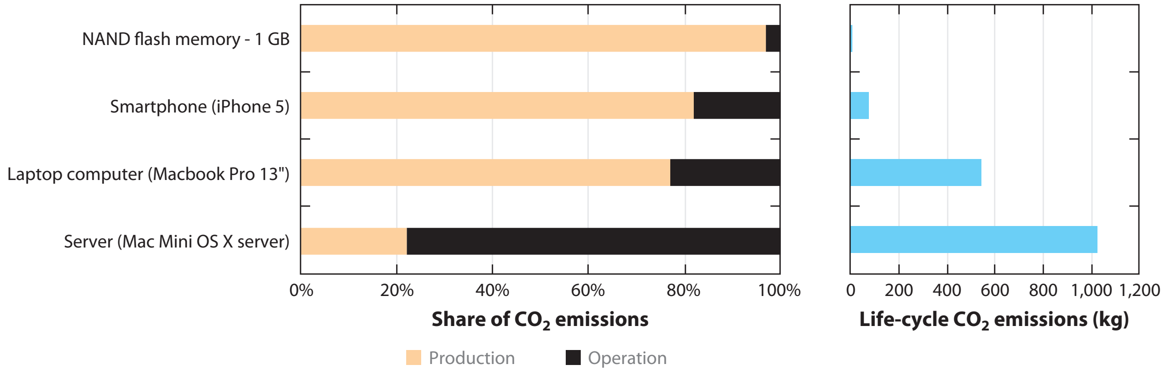

Figure 9

Life-cycle CO_2 emissions for server, laptop, smartphone, and flash memory chip. Sources: Reference 125 for server, laptop, and smartphone, and Reference 126 for the memory chip.

decreasing physical size. The results indicate decreasing life-cycle CO_2 emissions as a function of these two trends and a shift from the operation phase being dominant to manufacturing becoming more important as a source of emissions.

Given the uncertainty in LCA mentioned above, how robust is this trend? Although a full analysis is beyond the scope of this review, other studies provide supporting evidence. A process-sum analysis of a rack server yielded a production/operation split of 5% production and 95% operation (127). The hybrid laptop analysis, mentioned above, was 60% CO_2 emissions for production and 40% for operation (115), and an analysis of smartphones reported a 76% production and 24% operation split (128).

What do these results indicate for the direct environmental impacts of the cloud of small sensors and other devices discussed in this article? First, the manufacturing phase is likely to be a critical factor, implying that an LCA is required to properly assess the magnitude of impacts. Second, the magnitude per device will probably be small, suggesting that the number of devices will drive impacts.

Information and Communication Technology and Economic Efficiency

When economists talk about efficiency, they often refer to a concept known as the "production possibility frontier," which expresses the level of output possible for the economy given current technology and as a function of how output is distributed between two representative goods (129). If an economy is operating on the frontier, it has achieved maximal economic efficiency. As Sanstad et al. (130) put it,

> along this frontier there is a resource constraint, so that increasing one output requires reducing some other output. This resource constraint that prevails at the frontier is the source of opportunity cost, the loss in output of one type when another type of output is produced instead. When goods are appropriately priced, an optimal or efficient allocation exists. (p. 1300)

Real economies often diverge from the simplified models in economic textbooks, and so they operate at less than optimal efficiency (131). Sometimes new technologies (like ICT) can help firms and consumers move closer to the production frontier because they make markets work more like the idealized economic models. Technologies, such as ICT, can reduce information costs, thus moving consumers and firms closer to having perfect information (a necessary condition for optimal efficiency). For example, Jensen (132) showed significant economic efficiency improvements from the introduction of mobile phones for local fisheries in south India. Another effect of technology may be to expand the frontier, so that the resource constraints that were binding in the first case become less so as ICT reveals or creates opportunities that were not there before.

Capabilities Enabled by Information and Communication Technology

ICT speeds up our ability to collect data, manage complexity, and more rapidly learn and adapt, with the potential to alter the way the economy operates. A list of new capabilities enabled by these technologies is contained in References 87 and 133 and repeated below.

1. Near-zero marginal cost of reproduction and distribution
2. Quicker publishing
3. Easier sharing of data
4. Quicker review of technical material
5. Easier ordering and distribution
6. Direct feedback from suppliers to consumers (and vice versa)
7. Indirect feedback from consumers to suppliers (through data collection)
8. Collaboration among users
9. Access to information 24 hours per day
10. Universal searching
11. Easier and more widespread public access to technical information
12. Dematerialization of products and services
13. Improving measurement and verification of processes
14. Improving the speed and accuracy of analysis
15. Enabling more rapid institutional change

The first 11 points of this list (87) relate to dissemination of existing information, represent improvements in the way the economy functions, and are likely to have measurable but incremental effects on economic activity. In contrast, the last four ideas apply ICT to innovations (what economists refer to as invention) for both technologies and institutions; these factors will probably result in large structural changes in the economy and thus have particular importance to our narrative. This distinction between the two parts of this list parallels the discussion of economic efficiency above, where the information dissemination technologies move the economy closer to the production frontier, and technologies generating new innovation expand that frontier so that new opportunities become manifest.

Because of the importance of invention to transforming economic activity, we explore the components of the second group of capabilities in more detail below.

Dematerialization of products and services. It is not always true that using bits instead of atoms reduces emissions, but it is often true. Hilty et al. (134), building on concepts taken from UNEP (135), define dematerialization as "resource decoupling," which separates economic growth from growth in the use of materials and resources. It is usually possible to make products simpler in design using software and controls in the device itself, but we can also save energy and materials by avoiding the need to move physical objects and people from place to place. The three archetypal examples of this effect are telecommuting (136), replacement of physical compact discs with downloadable music (137), and video conferencing (138).

Improving measurement and verification of processes. Because of the rapid decline in the costs of monitoring technology (driven by improvements in computing and communications), our ability to understand the effects of our actions in real time is increasing at a furious pace. This means better control of processes, less waste, and better matching of energy services demanded with those supplied. The most sophisticated data center operators, for example, have sensors that measure temperature, humidity, power flows, and other key information tens or hundreds of times per second, so their control systems will not miss anything. In general, the more accurate the measurements, the easier it is for economic actors to respond to reality appropriately and the better markets will function (139).

Improving the speed and accuracy of analysis. Fortunately, the inrush of data from monitoring technologies has been accompanied by improvements in our ability to analyze and understand those data. Without new tools we would have a hard time keeping up with the information, which is why new data centers and industrial operations are increasingly demanding more powerful tracking software.

These developments are important because the information that is starting to become available on energy use will be at increasingly fine levels of geographic and temporal disaggregation. With the proliferation of "smart meters" that allow real-time metering of electricity use, our ability to understand electricity use in buildings will rapidly improve (140). For example, in the early days of energy efficiency analysis (in the 1970s), we conducted market assessments using simple averages of costs and savings for a single refrigerator model for the United States as a whole (141). Soon we will be able to monitor the response of millions of households to electricity price in real time and to disaggregate household electricity into its component parts with unparalleled accuracy. That will allow much more precise assessments of efficiency potentials and will give businesses the opportunity to target the biggest electricity users with energy-saving innovations.

Enabling more rapid institutional change. When companies first started buying computers on a large scale, economists were puzzled by the apparent lack of effect on productivity (this puzzle eventually became known as "the productivity paradox," as described in Reference 142). This delay actually had historical precedent. With electric motors, for example, the real benefits of that technology did not arrive until production processes were modified to take full advantage of the new technology's benefits, and the same was true for computers (143). Once companies reorganized themselves to capture those benefits, productivity improvements started on a rapid upward march that continues today (2).

But it is not just that ICT requires that companies reorganize themselves to take full advantage of its benefits, it also makes such reorganization easier because it improves communication, coordination, and process controls, and it creates the conditions under which complementary cost-reducing innovations can more rapidly be brought to market (143). It is in this deep sense that ICT is a transformational technology.

Information and Communication Technology and Energy Consumption in the Whole Economy

With the advent of "the Internet of things," ICTs offer the prospect of unprecedented visibility to the flows of energy, emissions, materials, and dollars throughout the economy, which promotes increased efficiency (better tracking and management of these flows will allow consumers and businesses to optimize them in ways they never could before). They also make it easier and faster to restructure institutions, thus allowing efficiency improvements to spread more rapidly throughout the economy. Because total use-phase electricity consumption by ICT is relatively small compared to that of the broader economy (probably representing less than 10% of the total), and because ICT can have systemic effects on the optimization of non-ICT energy use in the economy, it is in our opinion likely that the net effect of ICT has been and will continue to be to increase overall energy efficiency, but this proposition is difficult to prove conclusively.

Estimating use-phase ICT electricity consumption is the easiest part of the problem, but it is still not trivial. Much of the data for assessing use-phase consumption are proprietary, so accurate calculations are difficult, particularly for data centers and telecommunication systems. For low-power embedded systems, the proprietary problem is overlaid on top of poor tracking of components because these systems are usually a tiny part of a much larger system or device. The technical knowledge to do a careful job on this task is also rarely found, as it requires integrating many different technical sources in a way that illuminates rather than obscures the uncertainties in the data and calculations.

An even more complex issue is that the effects of ICT are often systemic and cannot be easily attributed to individual energy-using devices. This makes assigning causality problematic. For example, the advent of electronic systems for dynamically setting airplane ticket prices and related systems for consumers to discover them has presumably led to increases in air travel, but these changes have also had other systemic effects on airline operations that are difficult to disentangle.

ICT has probably led to increasing load factors on planes that would have flown anyway (which increases energy use somewhat), but to the extent that more planes are flying than would have otherwise, that increase in energy use in principle should also be counted. Such energy penalties must also be weighed against energy savings (and other cost savings) that might accrue from better data collection, improved measurements, and superior optimization of airline systems. Airlines now organize themselves differently than they used to, in large part because of the advantages of ICT, so those effects are also germane. The complexity of such assessments is daunting, even for employees of airline companies. There is simply no prospect for accurate calculations of these energy-related effects for the economy more generally. That is why carefully crafted case studies are so important.

Information and Communication Technology and Broader Measures of Consumption

Because ICT increases efficiency and reduces costs, it can lead to greater wealth and thus promote greater consumption in certain instances. There is little credible quantitative research on this issue, and it is notoriously difficult to separate the various interrelated effects.

One of the key complexities in assessing the effect of ICT on consumption is that the structural innovations enabled by this technology make it almost impossible to model the relevant effects. ICT allows us to modify institutional arrangements, so economic models estimated from historical data can tell us little about what these structural changes might imply (133).

This effect of technology on wealth and consumption is well known in economics, but it is often confused by naive observers with "the rebound effect" [see, for example, Owen (144)]. If people become richer over time and want bigger houses and cars, that is not the rebound effect. The causes of increased wealth are many and varied, and efficiency is only one of many factors contributing to this trend. It is only the change in behavior that can be assigned directly to improved efficiency that can properly be called the rebound effect, and in general, those effects are modest. The only case related to ICT where it might be significant is in data centers, but we have been able to identify only one data center where peer-reviewed empirical data indicated the existence of a sizable rebound effect (92, 93).

OPEN RESEARCH QUESTIONS

The new capabilities enabled by information technology will create new challenges. This section summarizes some research questions that emerge from the review above, to help set the agenda for further study.

Direct Electricity Used by Information and Communication Technologies

The best current knowledge indicates that electricity used by ICT is probably less than 10% of total electricity consumption, but there is significant uncertainty around that number. The latest attempt at such an analysis focused on worldwide ICT consumption in 2007 (94), and no one to our knowledge has compared those results in a consistent way to the earlier analyses (86, 89, 90) or to related analyses focusing on specific ICT segments for more recent years (96–99).

The effort to tally direct electricity use requires a significant effort by a single research group (the complexity of the task and the need for consistency across different ICT segments make such integration imperative). It is likely that the shift to ultralow-power devices will make the total direct electricity use a less critical issue in the future, but there is also a shift toward centralized computing (in data centers), and so those facilities will still need to be tracked with care.

Effect of Information and Communication Technology on the Broader Economy

The difficulties in analyzing the effects of ICTs on the broader economy argue for the creation of carefully designed case studies rather than high-level modeling. Except in rare circumstances, economic models are unable to assess situations where the underlying structural relationships in the economy are changing rapidly, but this kind of change is exactly what ICT enables. Instead, the focus should be on developing before-and-after case studies to document the effects of ICT on production processes in firms or on behavior within a well-defined customer segment.

Quantifying Network Electricity and Emissions Associated with Data Transfers

As more opportunities arise for dematerialization, the field will need more accurate estimates of the electricity intensity of network data flows. For example, in their comparison of downloading music to buying physical CDs, Weber et al. (137) used an upper bound estimate of the electricity intensity of data flows (145) and showed significant emissions savings for downloads even in that case. Other applications will require use of "best estimate" numbers for data flow electricity intensity, and this will require accounting for the rapid changes in network data flows and equipment over time, for average intensities versus marginal intensities, and for the serious boundary issues that affect most such comparisons. None of these issues have been well characterized so far, although there is movement toward more comprehensive treatment of the electricity intensity of data flows (146, 147).

Possible Rebound Effects in Data Centers

The one area of ICT where rebound effects could be important is data centers. Many of these facilities are power or cooling constrained, which means that improving the efficiency of computing equipment will free up infrastructure to power more servers. For businesses constrained in this way, ICT efficiency might lead to the installation of more ICT equipment, with the total facility energy use staying about the same. The only data center for which this effect has been documented in the peer-reviewed literature is in California (92, 93), and the efficiency improvements in the facility allowed it to expand the ICT equipment footprint. It is not known what fraction of data centers face such power constraints.

Comparison of Current Wireless Data Transmission Efficiencies to Physical Limits

Anecdotal data show that there have been significant improvements in the efficiency of wireless data transmission over the past few decades, but no one has yet published comprehensive work in that area. Once such data exist, it will be imperative to compare current and historical data transfer efficiencies to the physical limits, in the same way as the text above compared actual active power computing efficiency to Feynman's limit. Such a comparison will reveal just how much more potential there is for improving transmission efficiencies. Cook et al. (9) summarize important foundational work related to such a comparison, but more work is clearly needed in this area.

Achieving Even Lower-Power Levels for Information and Communication Technologies

Some of the biggest technical challenges for ICTs will be in reducing power use, especially in standby mode. We have made great strides in this area in recent years, but achieving another one to two orders of magnitude improvement in "best-in-class" standby power (reaching picowatt levels) would have a dramatic effect on the range of mobile applications that become feasible. Improving data transfer efficiencies by an order of magnitude would not hurt either, and both of these goals are within reach in the next decade or so.

Identifying New Applications for Low-Power Information and Communication Technologies

Successfully integrating ultralow-power ICTs into new products will require research into where small amounts of real-time information can have the highest value. Such research will occur at universities, but there will also be significant experimentation in entrepreneurial start-up companies because the potential for disruptive innovations is so high in this design space.

Creating New Analytical Tools to Cope with the Inrush of New Data

One of the biggest buzzwords in technology industry today is "big data," but as mobile sensors become ubiquitous, our sense of what represents big data will change rapidly. We will need to develop new analytical tools and techniques to face this inrush of data, and we will grow to rely more on sophisticated software and machine-learning techniques to help people make sense of it all. We will also become more selective about which data we collect and will use context to determine which to keep and which to ignore.

CONCLUSIONS

Small amounts of information can have immense value, particularly for systems for which we have little real-time data (which is true of most systems in modern economies). The advent of ultralow-power ICTs portends big changes in the way we understand and respond to the world around us because they allow real-time visibility into flows of energy, materials, and dollars. That visibility allows us to identify opportunities for cost reductions more effectively than we ever could before.

Dramatic improvements in power requirements, costs, and wireless data transfers have propelled us into a new design space for ICT. The primary factor enabling this development is the long-term trend toward high energy efficiency for computing, which resulted in 13 orders of magnitude improvement in the active power efficiency of computing since 1946. Improvements in computer standby power, communications, energy storage, energy harvesting, directed wireless energy transfers, and sensors have also contributed to making these new devices possible, but it is the change in active power efficiency, because of its magnitude, that is most responsible for the recent technological focus on low-power information systems.

The direct effects of manufacturing and using ICTs have been of primary environmental concern in the past, and those effects will continue to be tracked, but the shift to ultralow-power devices will focus more attention on the potential effects of these technologies on the rest of the economy. Computing and communications can be embedded in virtually any object, which means we will be able to optimize most systems and reduce costs significantly. The implication of these developments for the future is profound. These new technologies can result in a more flexible and efficient world than has ever existed, if we use them wisely. Here's hoping that we do.

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Errata

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