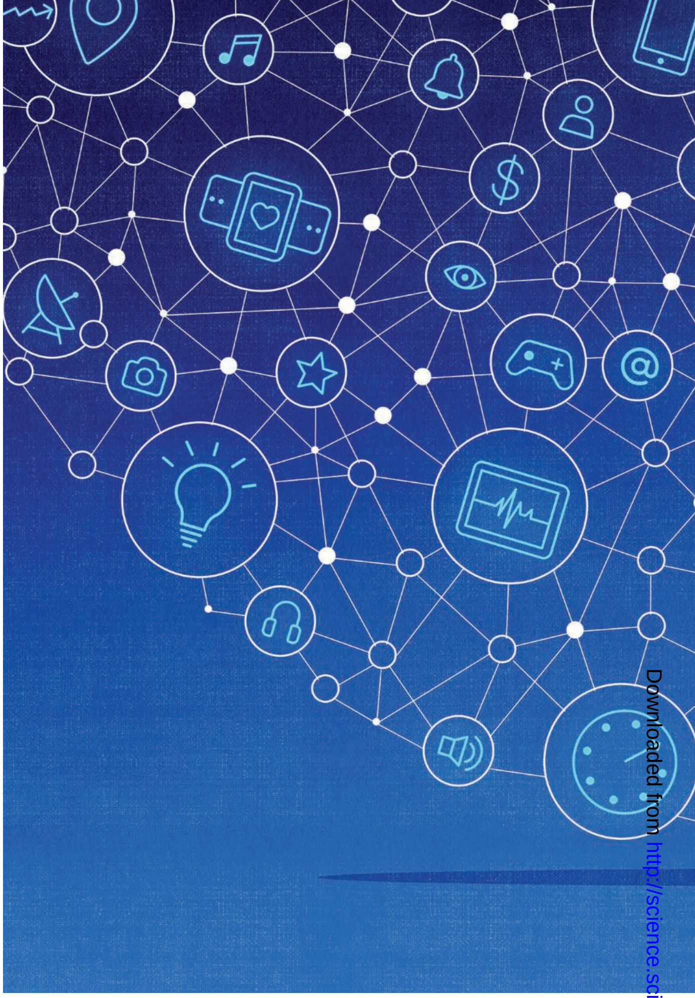
INSIGHTS

PERSPECTIVES

ENERGY

Internet of Things: Energy boon or bane?

Networked digital devices may cause rising energy use, although devices save energy locally



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Since the dawn of the internet, a digital revolution has transformed life for millions of people. Digital files have replaced paper, email has replaced letters, and cell phones provide access to many services that facilitate daily life. This digital revolution is not over, and there is now a growing deployment of technologies grouped under the term "Internet of Things" (IoT)—a worldwide network of interconnected objects that are uniquely addressable via standard communication protocols (*1*). By 2020, there may be as many as 30 billion objects connected to the internet (*2*), all of which require energy. These devices may yield direct energy savings (*3*, *4*), but it is much less clear what their net effect on the broader energy system will be. Scientists and regulators will need to work together to ensure that the IoT's benefits do not come at the expense of rising energy use.

The IoT is a network of physical devices, including things such as personal health monitors, smart appliances, and autonomous transportation systems, which are embedded with digital technologies that enable the devices to interact with each other by collecting and communicating data (*5*). It has the potential to further transform human lives with applications including smart electricity grids, smart homes, smart cities, health monitoring, transportation system control, and environmental management (*1*). The IoT will also affect energy production and use, which will in turn affect the environmental impacts of the energy system.

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IoT technologies can have complex effects on energy use. For example, adding smart functionality to an existing appliance, such as a thermostat, normally causes a small increase in energy used by the temperature control system because of the addition of new sensors, electronics, or displays. That smart functionality may allow the appliance to operate in a way that saves much greater amounts of energy, such as turning off air conditioning when occupants leave the home. However, the local energy use of an IoT device may be a small portion of its overall energy footprint. Because use of these devices could involve a large amount of data transfer and remote processing, a proper analysis must account for both the local and remote energy use.

To better frame the discussion about the energy impacts of the IoT, it is helpful to consider four mechanisms through which these impacts may occur, listed in order of increasing complexity and uncertainty: (i) direct (local) impacts of IoT components on energy systems, (ii) remote energy use for the supporting infrastructure, (iii) energy use associated with device production, and (iv) indirect energy impacts of IoT systems through behavioral changes, such as increased use of devices or services.

DIRECT IMPACTS ON ENERGY SYSTEMS

Estimates of total energy use from IoT devices are unavailable, but previous experience with energy use of household electronics provides an indication of likely patterns of local energy use. Ryen *et al.* (*6*) produced estimates of the number and type of consumer electronics in U.S. households, as well as the energy associated with their use. According to the study, active power use of specific consumer electronics products rose about 30% between 1992 and 2007 while standby power consumption fell about 60%. However, although active power use may have increased, these devices gained a lot of functionality over this time, with greater processing power, larger screens, and related improvements.

Assuming that the energy intensity trend for IoT devices follows that observed for consumer electronics, IoT technology also has the potential to reduce the energy use of the systems into which it is embedded. A growing body of literature on the energy impacts of the IoT suggests benefits to the energy system through smarter use of resources. For example, Shrouf and Miragliotta (*3*) suggest that the IoT would enable energy data harvesting that could be used to optimize energy use in industrial production processes. Similarly, in the transportation sector, the IoT has enabled more advanced adaptive traffic control systems, which can reduce congestion and thus improve fuel efficiency (*4*). Smart homes and smart offices could also rely on

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ILLUSTRATIONS: (LEFT TO RIGHT) ADAM SIMPSON/HEART AGENCY; BENEDETTO CRISTOFANI/SALZMANART

IoT devices to optimize thermal management and even lighting, and the IoT could support more efficient operation of electricity systems, improving demand management and the integration of renewable resources (*7*).

There are no firm estimates of these benefits or how they compare to the increased energy used to power IoT objects. However, the IoT is likely to result in a net reduction in energy used to provide a fixed level of services.

REMOTE ENERGY USE

Although the IoT may lead to local energy efficiency improvements, all of these applications require remote data communication and processing, which contribute to the growing demand for information and communication technology (ICT) infrastructure. Cloud computing, data centers, and cell phone infrastructure are energy-intensive components of the ICT system. Early projections of ICT energy use in the 1980s and 1990s suggested that ICT accounted or would soon account for 10% of all electricity use, a figure that could rise to as much as 50% by 2020 (*8*). A more recent review of these estimates suggests that the overall energy footprint of ICT technologies is smaller than was projected and that this energy demand is growing at a slower rate. This slower rate results from a balance between the massively increased demand for data transfer and processing and the impressive gains in efficiency of those activities; for example, in terms of number of computations per kWh, the performance of a computer produced in 2010 exceeds that of a computer from 1990 by three orders of magnitude (*8*).

Malmodin *et al.* (*9*) have performed an extensive assessment of the production and operational footprint of the global ICT and media industries. They estimate that ICT technologies in 2007 used 3.9% of global electricity and accounted for 1.3% of global greenhouse gas (GHG) emissions, whereas entertainment and media used 3.2% of global electricity (1.7% of global GHG emissions). Van Heddeghem *et al.* (*10*) performed a similarly detailed analysis that investigated trends over a 5-year period; they concluded that ICT technology accounted for 3.9% of global electricity consumption in 2007 but that this increased to 4.6% in 2012. Andrae and Edler (*11*) estimated the electricity use of all communications equipment and came up with a higher figure, concluding that ICT currently uses 10% of global electricity and could consume as much as 21% by 2030. Although these estimates are uncertain, they suggest that energy use for ICT infrastructure could continue to increase. However, there are no estimates of what portion of the overall energy demand for ICT systems is attributable to IoT services now and in the future.

DEVICE PRODUCTION

IoT devices have additional processing, communication, and display requirements relative to their traditional, “non-smart” counterparts, and producing these components requires additional materials and energy. Dematerialization can mitigate this effect. Dematerialization is the observable trend of declining materials inputs for a given product (such as a laptop) or service (such as music distribution and playback) over time. For example, Ryen *et al.* (*6*) estimated that a laptop computer in 1992 had an annualized manufacturing energy footprint of 1930 MJ; by 2007 this value had fallen to 350 MJ, even though the computational power of computers increased substantially during that period.

Although dematerialization and efficiency improvements of electronics mean that an individual product may have a smaller manufacturing footprint, the rapid increase in the number of IoT devices being deployed may lead to an overall increase in energy use for material extraction, material processing, and component manufacturing. Using values from Ryen *et al.* (*6*) for the number of appliances in a typical household and their typical energy use, we estimate that the energy required to produce the average U.S. household's electronics was 2150 MJ per year in 1992; this increased to 2600 MJ per year in 2007. The increased number of electronic objects in the household outpaced the lower production footprint of a given device, clearly illustrating the importance of consumer behavior and purchasing decisions in projections of IoT energy use.

USER BEHAVIOR

Efficient and effective IoT services could also change user behaviors in ways that would indirectly affect energy use. The rebound effect—whereby efficiency improvements lower the costs of a good or service and drive increased consumption—offers an example of behavioral responses that lead to unexpected consequences. In the case of energy efficiency, the rebound effect has been found to reduce (but not eliminate) the expected benefits of efficiency interventions (*12*). For example, research on autonomous vehicles, which are part of the IoT, suggest that these vehicles could lead to greater fuel use through increased total miles of travel as well as increased travel by currently underserved communities (*13*, *14*). For an average U.S. household, direct energy use of consumer electronics tripled between 1992 and 2007, from 4800 to 15,300 MJ per year per household (*6*). This net increase was driven by higher usage and greater numbers of devices in homes, rather than by increases in a specific product's power consumption.

These behavioral responses, which may lead to a rebound effect for IoT adoption, are poorly understood. Paetz *et al.* (*15*) suggest that "national policy does not sufficiently take into account the behavioral aspects that go beyond information needs and it neglects many of the motives and barriers affecting the individual decision-making process, even though they are decisive for the diffusion of smart technologies." It makes good economic sense to use more of a service or device if it becomes cheaper or more useful. However, these changes in behavior potentially make the IoT another venue where economic expansion is at odds with energy and environmental concerns.

OUTLOOK

It is hard to predict the long-term effects of the IoT and related technologies such as artificial intelligence and blockchain. Because the IoT is just emerging, research into its broader effect on energy use faces two important uncertainties: What IoT applications will be broadly adopted, and how will human behaviors change in response? For example, progress in artificial intelligence and personal monitoring might result in highly functional but computationally intensive personalized assistants, whereas a new generation of telepresence technology could reduce global air travel. These scenarios are speculative but could have a substantial effect on global energy use.

The invention of the steam engine and the launch of the Industrial Revolution, the rise of automobiles and the emergence of suburbs, and the profound effect that the internet has had on both business and everyday life all show that the most profound changes in energy use patterns come from technologies that restructure society in complex and unpredictable ways. IoT technologies promise to deliver energy savings by helping us to use our resources more efficiently, but it is unclear whether these savings outweigh indirect increases in ICT use, the production footprint of IoT devices, and rebound effects. Research about the effects of specific devices or interventions is available, but existing data on behavior and likely adoption scenarios are insufficient to understand the large-scale energy implications of the IoT. This knowledge is needed to identify strategies that could mitigate unintended consequences—for example, by establishing new forms of energy efficiency standards for IoT devices. In the end, our goal should be to capture the benefits of the IoT while avoiding problematic energy implications. ■

"It is hard to predict the long-term effects of the IoT and related technologies..."

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PHYSIOLOGY

Fat cell progenitors get singled out

Distinct adipocyte progenitor cells may reveal therapeutic strategies for obesity

By **You-Ying Chau** and **William P. Cawthorn**

Fat tissue is essential for the safe storage of excess calories and thereby plays a key role in metabolic health. By storing lipid droplets, fat cells (adipocytes) protect organs from the damaging effects of ectopic lipid accumulation (*1*). Understanding how to promote healthy fat expansion may therefore reveal treatments for obesity and related diseases. Such expansion depends on the formation of new adipocytes from progenitor cells within fat tissue (*2*). Distinct populations of adipocyte progenitor cells (APCs) have been identified, but their interrelationships and relevance to physiological and pathological fat expansion have remained poorly understood (*3*). On page *353* of this issue, Merrick *et al.* (*4*) identify three new classes of APCs that are regulated with obesity, one of which resides in a potential new stem cell niche for tissue regeneration and repair.

Deciphering APC biology is complicated by the heterogeneous nature of fat tissue. To isolate APCs from the fat of mice, Merrick *et al.* used a method called fluorescence-activated cell sorting (FACS), which separates fat cells based on the presence of specific cell-surface proteins. This cellular pool was further resolved using single-cell RNA sequencing (scRNAseq), allowing cells to be grouped on the basis of similarities in their gene expression. Most cells fell into one of three groups that had not been defined previously: interstitial progenitor cells (IPCs), defined by expression of a protein called dipeptidyl peptidase–4 (DPP4); preadipocytes, marked by expression of intercellular adhesion molecule–1 (ICAM1); and group 3 cells, which expressed the protein CD142 (see the figure). Each group formed adipocytes in cell culture, thus supporting their identification as APCs.

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