ICT-Enabled Intelligent Efficiency:

Shifting from Device-Specific Approaches to System Optima

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About This Working Paper

Both the United States and the global markets waste more than 80 percent of the high-quality resources used to power economic activity. That magnitude of waste generates an array of costs that limits the robustness of the many world economies. Information and communication technologies (ICT), made possible by the use of semiconductors and networked devices, provide a critical resource that can unlock large improvements in resource efficiencies – whether the more efficient use of materials, water, and especially energy.

The good news is that there is growing recognition of the savings potential throughout all levels of society and economic activity. Yet, in the case of networked devices, the focus too often is on minimizing the energy consumption of individual devices rather than optimizing the energy and resource benefits of entire systems. This working assessment, funded by the Digital Energy and Sustainability Solutions Campaign (DESSC), explores new and emerging perspectives on ways to harness significantly greater energy productivity improvements by building on the use of ICT-enabled networks and services. Our hope is that the insights here provide the basis for further collaborations with industry, governments and both consumer and environmental groups as all parties seek immediate solutions with the urgent issues of energy security and climate change.

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Executive Summary

Yes, it takes electrons to move bits of information across the Internet. And also yes, the scale of information technologies is one of exponential growth, reaching more than 100 billion networked devices by 2030. Both of these facts drive understandable and genuine concern about the global footprint of networked devices, about their costs, energy demands, climate change impacts and other environmental effects. But there has been an unfortunate distraction in the analytics, and a limited policy focus that may overstate the worries and undervalue the potential contribution of information technologies to contribute to long-term economic and climate solutions.

On the one-hand, an overly narrow analytic framework that focuses on the sheer growth in the availability of information and communication technologies (ICT) overplays the net energy impact of such tools. For example, recent projections by the Energy Information Administration (EIA) suggest that electricity consumption of these technologies may actually decline compared to current levels of use. Perhaps more interesting, compared to projections looking at the year 2030, first made in 2008, the projections released in 2014 now suggest substantially lower energy use in both 2012 and 2030. At the same time, worries about the electricity requirements of individual devices rather than their potential contribution to larger system efficiencies may preclude the development of policies that facilitate cost-effective functional and organizational designs that can, in fact, reduce total energy needs. In effect, ICT-enabled networks may reduce the energy footprint of the larger economy by many times their energy handprint.

This working paper provides an overview that is a first step toward a meaningful appraisal of the ICT handprint as it might more positively shape and significantly reduce the global energy footprint of the economy. Unfortunately, the data are incomplete so that it is difficult to know what the larger benefits might look like. Furthermore, the optimal intelligent efficiency designs are still emergent. It is difficult to know with any certainty how an ideal ICT-enabled system or network might really function. Therefore, early prescriptive standards which focus prematurely on minimizing energy use may exclude the development of more robust systems that lower costs, improve performance, and reduce greenhouse gas emissions.

All of these ideas and insights would benefit from a more substantial review and a more rigorous assessment of how the current energy (and economic) paradigm might be reshaped through a more positive energy systems perspective. A useful step to encourage an innovation-based systems assessment would be to convene a series of national workshops and/or a progression of international conferences that are specifically designed to explore the fundamental aspects of at least five different policy opportunities. These are to:

- Establish common definitions and metrics;
- Build international cooperation about the larger public purpose of energy productivity, and about smart standards and test procedures;
- Proliferate credible and common (or generally accepted) protocols for measuring specific intelligent efficiency applications;
- Research ways to actively advance energy harvesting techniques and technologies; and
- Raise much greater awareness about the intelligent efficiency handprint.

Notwithstanding the further insights that might emerge from a progression of workshops and conferences, or a further and more rigorous assessment of the full benefits of intelligent efficiency as it stimulates a more robust economy, the evidence underscores one very critical idea—the U.S. and global economies will be better off by ‘Thinking Big’ about energy productivity gains powered by information and communication technologies. More to the point, if policymakers miss the big gains that are likely to follow systems thinking, focusing instead on minimizing the energy demands of individual devices, we run the risk of a continued weakening of the greater economy. On the other hand, the combination of market incentives and policy signals that open up the immense opportunities for intelligent efficiency can increase the productivity of the economy in ways that enable our prosperity to improve and continue.

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I. Introduction

Yes, it takes electrons to move bits of information across the Internet. This point was made in a 1999 report for the now defunct Greening Earth Society which suggested that, by 1998, the explosive growth of the Internet consumed as much as 8 percent of total electricity use in the United States. More critically, that same report indicated that the digital infrastructure's burgeoning demand for power would increase to as much as 50 percent of total electricity consumption by about 2020 (Mills 1999; see also Huber and Mills 1999).[1] At the same time, a thorough review by analysts from the Lawrence Berkeley National Laboratory (LBNL) identified numerous analytical errors in that 1999 assessment. They concluded the analysis overstated electricity consumption by a factor of eight (Koomey et al. 1999).[2] More recent assessments further indicate that, in fact, semiconductors more broadly, and information and communication technologies (ICT) in particular, have contributed to a large net electricity savings for the U.S economy. A 2009 study by the American Council for an Energy-Efficient Economy (ACEEE) concluded, for example, that with the advent of microprocessors, the economy may be saving about 20 percent of total electricity consumption compared to a world without such technologies (Laitner et al. 2009).[3]

Notwithstanding the early misdirection and the substantial evidence on the net benefits of semiconductors, the Internet, and the system of ICT-enabled services, much of the policy focus on these technologies remains a discussion and review of a "device-oriented" minimization of energy usage. The International Energy Agency (IEA), for example, published a generally useful 2014 study, *More Data, Less Energy*, which worried that the number of networked devices would soar from 14 billion to more than 100 billion by 2030. It further noted that by 2025 the corresponding energy demand would climb to 1,140 terawatt-hours per year (TWh/year). While this is more than the current annual electricity consumption of Canada and Germany combined, it is still just 6 percent of global energy consumption (IEA 2014). At the same time the evidence suggests that, but for the energy productivity benefits of these devices, electricity consumption would be much larger. Pointing again to the ACEEE study, an expansion of ICT-enabled services might save a net of 27 percent of U.S. electricity consumption by 2030 (Laitner et al. 2009).[4]

This working paper is an effort to place the growing electricity demands for network devices and ICT-enabled networks into the broader economy and a broader systems context. The intent is to open discussion about net system benefits rather than focus only on the apparent energy burden in talking through ways to minimize energy demands of such devices. The evidence that underpins this initial discussion suggests two things. First, the net electricity savings from such devices are potentially much larger than the growing demand for energy services they might otherwise require. Second, there are other aspects of emerging technologies and markets which militate in favor of a more flexible "systems

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[1] The Greening Earth Society was a public relations organization which promoted the idea that there was considerable scientific doubt about the effects of climate change and increased levels of carbon dioxide. One society staffer was a registered lobbyist for Peabody Energy, a coal company.

[2] See especially the memo by Koomey et al. (1999) which explores the assumptions in Mills report titled The Internet Begins with Coal that relate to current electricity use "associated with the Internet". The team at the Lawrence Berkeley National Laboratory (LBNL) found that Mills significantly overestimated electricity use, in some cases by more than an order of magnitude. We adjust his estimates to reflect measured data and more accurate assumptions, which reduces Mills' overall estimate of total Internet-related electricity use by about a factor of eight.

[3] See also Laitner (2010) for a short journal article base on that longer assessment.

[4] The 2009 analysis estimated a gross electricity savings of 31 percent, but it also noted that the new equipment would require about 4 percent of that electricity savings to actually power the upgraded ICT-enabled networks and systems. Hence the net gain of 27 percent.

approach" to encouraging not only greater electricity savings, but also larger energy savings as such improvements also reduce the need for oil and natural gas consumption as well. To that extent this working paper is organized within four sections to help understand the larger context.

Following this introduction, Part II of the manuscript provides an initial background on several key concepts and definitions to open a more complete understanding of a systems perspective. Among the critical elements in this section is the critical distinction between an enabling "handprint" that can greatly reduce the much larger "footprint." Another concept that is explored is the prospect of energy harvesting techniques which can become a new form of energy efficiency improvements, and which suggest the need for even greater flexibility in the management of networked devices.

Part III then explores the evolution of technology components that are giving rise to a more systemic energy savings. Part IV provides a closer reexamination of ICT-enabled handprints which make possible a much smaller footprint. From there, Part V offers a set of thought experiments to imagine how ICT networks and services might catalyze a larger scale of productivity improvements. This is an important discussion of the many different ways such devices might catalyze and sustain a more robust economy even as they also contribute to a significantly reduced level of greenhouse gas emissions. In effect, while networked devices do require a minimum level of electricity to maintain their operations, they actually end up saving much larger amounts of energy by optimizing uses across the economy.

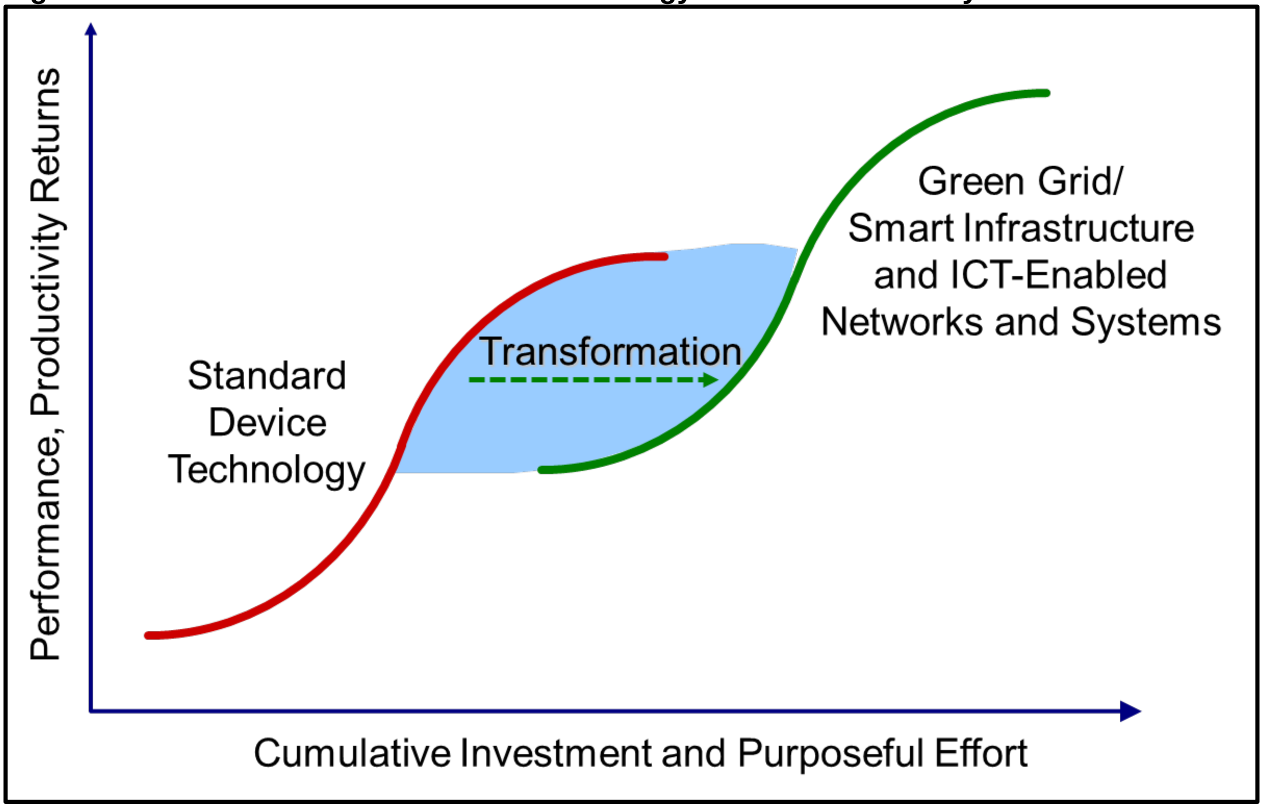
Finally, Part VI provides a summary and preliminary set of evidence-based policy principles and recommendations that might encourage a more collaborative process and review of emerging opportunities.

II. Key Concepts and Definitions to Understand a Systems Perspective

The economy continues to evolve; there is no single element or factor of production that drives social, economic and environmental well-being.[5] At the same time, ICT-enabled networks and systems are an emerging driver that will increase productivity of all factors of production (Laitner et al. 2014a)—precisely because of the many possibilities of networked or system optimizations that will be made possible by what is increasingly referred to as "intelligent efficiency." As suggested in Figure 1 on the following page, the standard tools and apparatus of what Rifkin (2011) refers to as second industrial revolution machines are being transformed into what he refers to as Third Industrial Revolution technologies. In contrast to the transformation brought about by the second industrial revolution, the Third Industrial Revolution is catalyzing a shift away from device-centric approaches to a more appropriate focus on networked energy savings and productivity benefits. To better explore the transition and its associated productivity benefits, this section provides a discussion and working set of definitions of key concepts and definition of terms that will provide a more dynamic context to understand the emerging systems perspective.

[5] In conventional economic parlance, the robustness of the economy depends on what economists call "factors of production. The first is the labor that both benefits and directs activity to provide for social well-being. The second is capital – in effect, the infrastructure and the ongoing investments in the equipment, appliances and devices necessary to process and transform the array of materials into the desired goods and services which provide for our social well-being. The last is energy which animates or activates both capital and labor (Laitner 2014a).

Figure 1. Transformation of Standard Technology into ICT-Enabled Systems and Networks



Source: Laitner (2011)

A. Intelligent Efficiency/Intelligent Networks

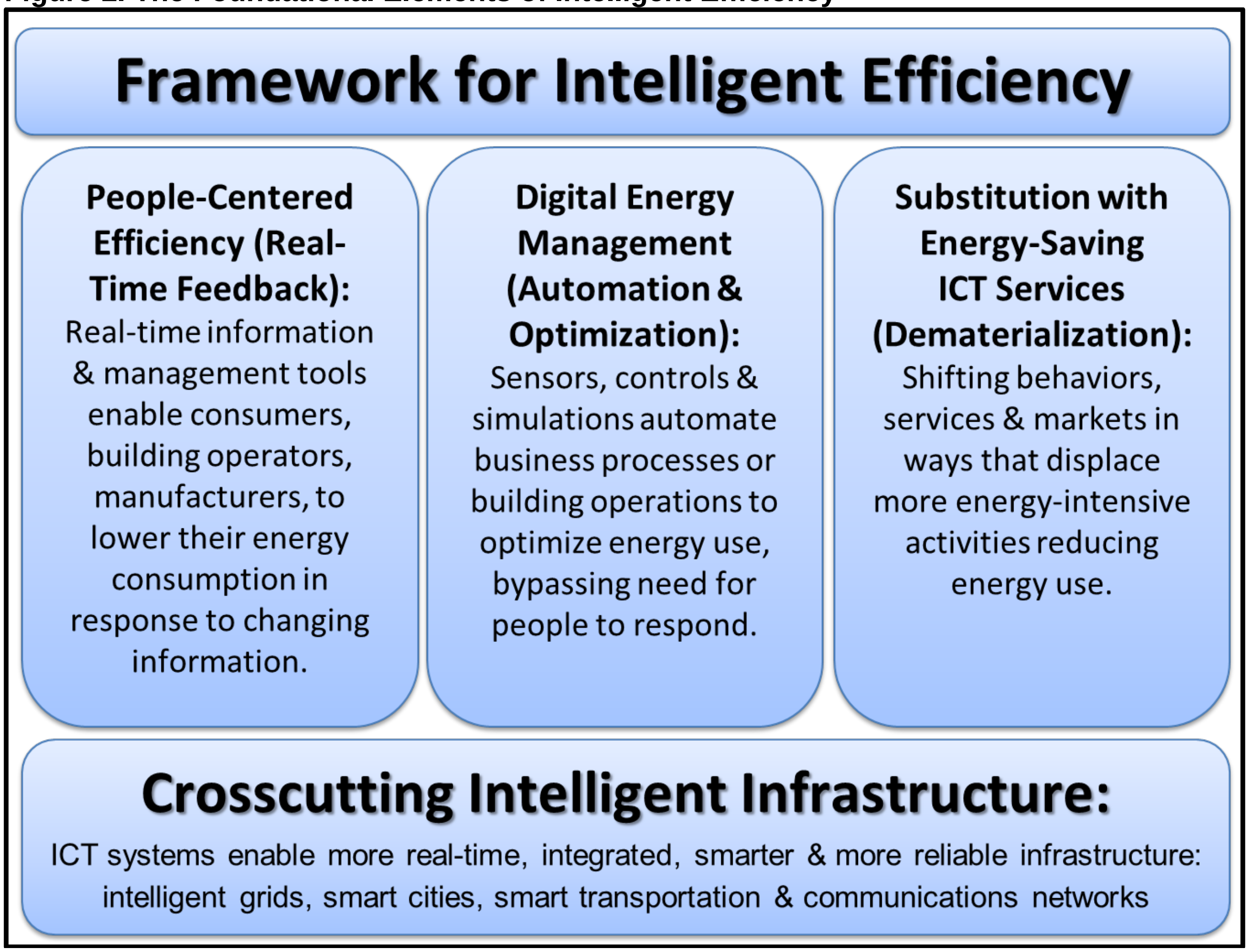
In perhaps the first articulation of *intelligent efficiency*, the American Council for an Energy-Efficient Economy (Elliott et al. 2012) referenced a systems-based approach to improving the overall energy efficiency of a nation's infrastructure as well as productivity improvements in building, transportation, and industrial processes, and energy production activities. Enabled by information and communication technology (ICT) and user access to real-time information, intelligent efficiency differs from "component energy efficiency" in that it is adaptive, anticipatory, and networked.

In an earlier discussion of this idea, Laitner (2011) noted the need for purposeful effort and investment to drive the transformation of discrete technologies and devices into a robust and resilient network or system that could drive needed energy efficiency improvements. Again, Figure 1 captures the key idea of purposeful effort as necessary to drive technology transformation into a more robust system of performance.

As Elliott et al. originally characterized it, intelligent efficiency opportunities exist along a continuum of technology and human behaviors which were classified into three broad categories: (1) people-centered efficiency; (2) technology-centered efficiency; and (3) service-oriented efficiency (Elliott et al. 2012). Yet, the concept has evolved as Figure 2 now indicates. Intelligent efficiency continues to include people-centered efficiency, but it now moves to Digital Energy Management and Materials substitution with an Energy-Saving Crosscutting Intelligent Infrastructure: ICT systems enable more real-time, integrated, smarter & more reliable infrastructure: intelligent grids, smart cities, smart transportation & communications networks.

If the United States were to take advantage of currently available information and communications technologies that enable system efficiencies, Elliott et al (2012) concluded that the United States could reduce energy use by about 12–22% and realize tens or hundreds of billions of dollars in energy savings and productivity gains. In addition, they noted, there are technologies which are just beginning to be implemented and which promise even greater savings. They cited ten case studies of intelligent efficiency in the nation's homes, buildings, industry, and transportation sectors, all of which demonstrated the potential benefits of scaling-up the networked or intelligent efficiency resource. Also in 2012, ACEEE published a more extensive assessment of the "long-term energy efficiency potential" out to the year 2050 (Laitner et al. 2012). Exploring those same sectors, but also including electricity generation, their assessment suggested up to 60% economy-wide savings through large-scale investments and improvements in energy usage patterns. Although not spelled out in specific terms, intelligent efficiency and networked systems was determined to provide a significant, or even a majority of the energy efficiency benefits.

Figure 2. The Foundational Elements of Intelligent Efficiency



Source: Adapted and updated from Laitner (2011) and Elliott et al. (2012)

Tremendous potential exists for greater adoption of intelligent efficiency, but significant barriers exist. Policy can facilitate the deployment of systems built around intelligent efficiency in several key ways, such as leading by example in the public and private sectors, enhancing information infrastructure, and redefining regulatory business models to promote greater system efficiency.

Box 1. One Gigabyte of Data versus One Metric Ton of Paper

Whether we refer to it as the digital economy or the knowledge economy, the benefits of the more intelligent use of resources are both numerous and disparate; and at times, very difficult to quantify. Despite the sometimes intangible nature of networked devices and ICT-enabled services, however, we can provide an illustrative example can help illuminate the importance of a device handprint as it might compare to the larger system's energy footprint.

Indeed, the authors of this report were able to highlight the attendant benefits of an ICT energy handprint. Mr. McDonnell, remaining in Tucson, AZ, transmitted a number of documents that totaled one gigabyte (GB) worth of data by way of his smartphone to Mr. Laitner who was working the week in Washington, DC. According to the Centre for Energy-Efficient Telecommunications (CEET 2013) this simple transfer of 1GB consumed somewhere between 0.4 and 0.8 kWh of electricity (as confirmed by Koomey 2013). But let's examine how much energy would be required by this simple transmission of data without the use of ICT-enabled devices.

According to our working analysis, if printed, 1 GB worth of data is about one metric ton of paper. This assumes, among other things, that a printed page might require about 25 kilobytes of data per page. Depending on the use of tables, graphics, illustrations and other artwork, it might be more or less than this amount. But if it were about 25 kilobytes per page, this would result in about 40,000 pages of copied material if that one gigabyte were printed – or about one metric ton of paper. It takes about 2,500 to 5,000 kWh of electricity equivalent to produce a metric ton of recycled paper. And another 500 kWh to ship that ton of paper the 2,275 miles from Tucson to Washington, DC. The usual caveats apply with these estimates, as the actual amount of energy consumed would vary depending on what type of paper was used (whether a heavy or lighter bond of paper, or whether it was printed on recycled or virgin product), what mode of transportation was employed to ship the document, and whether the document was printed for multiple users or it becomes a shared document.

Despite these and other variables, it is clear that the 0.4 to 0.8 kWh of electricity consumed by the ICT-enabled device allows us to avoid consuming upwards of 5,500 kWh. This amount of energy use is equivalent to 1.4 tons of waste sent to the landfill, 400 gallons of gasoline consumed, or two tons of coal that might be burned. So yes, while ICT-enabled devices may consume as much as 10 percent of the world's total electricity generation, it is important to acknowledge the significant amount of energy that ICT-enabled devices allow us to save in the process.

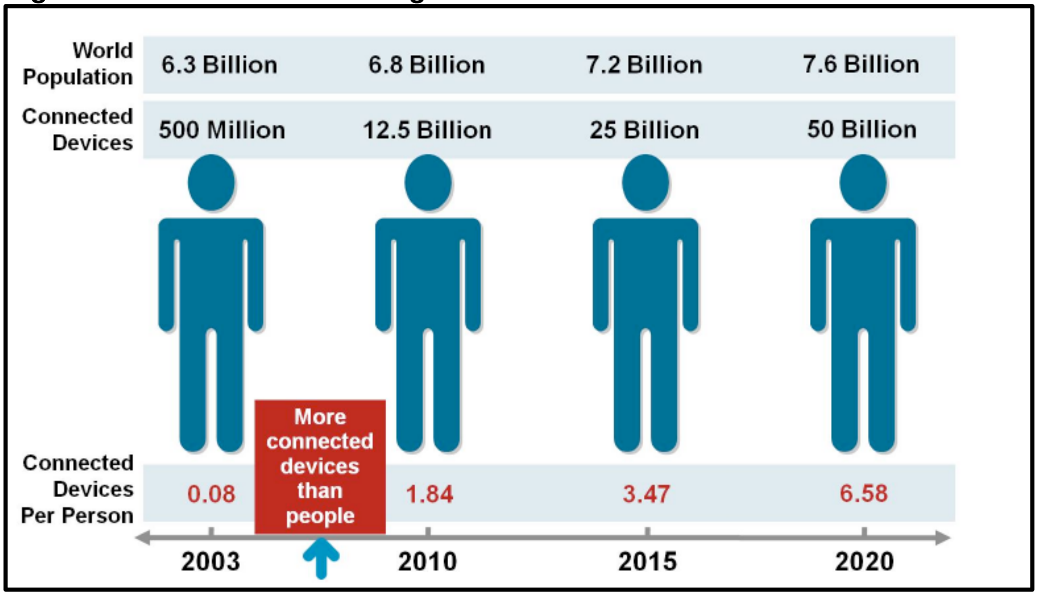
B. Internet of Things

The next step in the progression toward intelligent efficiency is the bridging of the gap between the ever-expanding world of virtual networks and the multitude of physical objects with which we interact every day. The Internet of Things (IoT), as defined by technology analysts and visionaries, is the network of physical objects accessed and managed through the Internet (Evans 2011). It has also been called the Industrial Internet (Annunziata and Evans 2013). In effect, these networked objects contain embedded technology that interacts within both their own internal states and with the external environment in which they operate. In other words, when objects can sense and communicate, it changes how and where decisions are made, and who makes them. In many respects, this emerging phase of the Internet is already well under way. The IoT is connecting new institutions and services—such as manufacturing floors, energy grids, health care facilities, and transportation systems—to the Internet. When an object can represent itself digitally, it can be controlled from anywhere. This connectivity means that more data gathered from more places are likely to increase efficiency and improve safety, security, and productivity (Evans 2011).

The roots of IoT can be traced back to the Massachusetts Institute of Technology (MIT), from work at the Auto-ID Center. Founded in 1999, this group was working in the field of networked radio frequency identification (RFID) and emerging sensor technologies. The labs consisted of seven research universities located across four continents. These institutions were chosen by the Auto-ID Center to design the architecture for IoT. According to the Cisco Internet Business Solutions Group (IBSG), IoT is simply the point in time when more things or objects were connected to the Internet than people (Evans 2011).

In 2003, there were approximately 6.3 billion people living on the planet and 500 million devices connected to the Internet. By dividing the number of connected devices by the world population, we find that there was less than one (0.08) device for every person. Based on IBSG's definition, the IoT did not yet exist in 2003 because the number of connected things was relatively small. While their numbers are now pervasive, devices such as smartphones were just being introduced in 2003. Steve Jobs did not unveil the iPhone until January 9, 2007, at the Macworld conference.

Figure 3. The Internet of Things was born between 2008 and 2009



Source: Cisco (2011)

Explosive growth of smartphones and tablet PCs brought the number of devices connected to the Internet to 12.5 billion in 2010, while the world's human population increased to 6.8 billion, making the number of connected devices per person more than 1 (1.84 to be exact) for the first time in history. By this metric, and as alluded to in Figure 3, the IoT was born at some point between 2008 and 2009. The impact of ICT is being felt across all sectors. Equipment and systems used in buildings, transportation, and manufacturing are becoming adaptive to environmental inputs, anticipatory in performance, and networked to one another both within a facility and across a supply chain. These networked objects can be given added capabilities like context awareness, increased processing power, and independent or site-based energy resources. As the objects are interconnected, especially managed by the use of multicriteria or multi-objective analytics, what we now refer to as the Internet of Things or the Industrial Internet can become an optimized network of networks, perhaps called the Internet of Everything (Laitner et al. 2014).

The deployment of next-generation sensor, control, and communication technologies will encourage a significantly greater number of uses and users, facilitate a more collaborative engagement of consumers and producers, and amplify learning and productivity. ICT-enabled networks exponentially aid our ability to gather, store, manage, interpret, communicate, and act upon disparate and often large volumes of data. More data gathered from more places is likely to increase efficiency and improve productivity, safety, and security (Evans 2011). Innovative uses, greater collaborative involvement, and enhanced productivity will result in higher levels of economic activity.

As we approach the Internet of Everything, we increasingly activate three drivers of productivity (Laitner et al. 2014):

- A higher level of system-wide energy savings (as opposed to energy savings from the enhanced efficiency of individual devices) made possible by the array of interconnected equipment, appliances, systems, and infrastructures
- The set of net positive economic externalities (non-energy benefits) or spillovers that arise from those greater linkages and interactions
- The increased capacity for individuals, systems, and regional economies to learn and act at higher levels of performance as experience and knowledge build up over time

Two key points emerge from the transition from a collection of smart devices, to the Internet of Things, and next to the optimized network of networks that we now refer to as the Internet of Everything. First, the transition to an optimized network of networks is hardly complete—neither in scale, scope nor design; nor can we suggest with any confidence what the next phases might actually look like or how they might actually interact. Yes, we have some pretty good ideas of possible outcomes, but it remains an emergent system which strongly militates in favor of an open architecture so that we do not unnecessarily limit the full set of system improvements. Second, as highlighted above and summarized by the 2012 ACEEE long-term energy efficiency assessment (Laitner et al. 2012), there are very large economic productivity benefits that will emerge from the optimized network of networks (Laitner et al. 2014). And it is the optimized network where the major focus of attention should be turned.

C. Network Standby

In the current policy context of the European Union (EU) and elsewhere, network standby denotes the set of devices that are in a low power mode with network connectivity. In effect, it is a state or mode in which an energy-using device is connected to a power source, but not performing its primary function(s) and has powered down to lower levels of energy consumption. This is sometimes called the "sleep" mode. The device is, however, providing secondary functions. It can then be woken up to an active state of performance by a signal that may either be automated or provided by a user (for example by pressing a button on a remote control). Typically, the secondary functions are user-orientated or provide additional services, and may continue for an indefinite period: they include the ability to transfer to other modes or states by remote switch (including remote control); to respond to internal sensors or timers; or to perform continuous functions such as information or status displays or the playing of music. More complex devices, such as computers, maintain the capacity to provide multiple functions when they have powered down.

D. Edge Devices

A network is a system or interconnection of many individual devices which enables communication and interaction between and among those devices. It consists of the network equipment that maintain the primary function of the network itself (switches, routers, access points, and modems). It also includes edge devices which primarily serve the needs of the end user (whether entertainment, work, or internal home or business operations). The system of devices usually have several or many links which are active at the same time to: (i) enable desired end-user services, and (ii) to manage the flow of information and operate the network. Two main types of edge devices exist:

- **Electronic edge devices** are those for which the primary function is data use or storage. They may undertake any combination of acquiring, processing, storing, transmitting, displaying or acting on information. They include computers, printers, tablets, phones, set-top boxes, televisions as well as other audio and video equipment. The amount of data that is stored transmitted and processed is often large and their interactions complex.
- **Other edge devices** comprise those for which the primary function is not data-related; that is, those appliances and equipment other than electronic devices. These include kitchen and laundry appliances, cooking equipment, heating and cooling equipment, lighting, and all manner of commercial and industrial equipment.

As the transition to an Internet of Everything continues to unfold, individual consumer appliances and industrial equipment may also be able to function as a network device. For example, a set-top box that includes multiple network links can also perform the functions of a small router or switch, and as such, it can be considered a hybrid device or a network-enabled device. As all devices meld with an optimized network, they will become more than a network-enabled edge device. They will contribute to the optimization of the system or network, powering down or providing additional services in response to other signals and interactions within the full system.

E. Energy Harvesting Processes

Energy harvesting is the gathering of ambient energy (i.e., the many forms of energy around us) from our immediate environment, and then converting it into electricity either for immediate use, or stored for later utilization. There are a variety of opportunities to apply energy harvesting techniques as they might power or charge low-voltage devices like watches, switches, sensors, and other solid-state devices such as light-emitting diodes (LEDs). For example, the Otis Elevator Company has escalators that feature special drives to capture energy generated by the escalator on the way down and deliver it back to the building for use by other systems. This reduces energy consumption by up to 60 percent compared to conventional systems (Mandyck 2015). Researchers at Columbia University have developed the first prototype of a fully self-powered camera in which the photodiode of a simple pixel circuit can be used to not only measure the incident light level, but also to convert the incident light into electrical energy (Nayar et al. 2015).

While there is no defined level of the energy benefit from these devices, researchers are pointing to "milliwatts with a mega impact" (Chandler 2010). Yogesh Ramadass, lead design engineer at Texas Instruments, notes that advances in circuit design techniques and architectures have made it possible for electronic systems to be completely self-powered. This requires a holistic optimization of the complete system from the energy sources to the load circuits to build and power a successful IoT system (Ramadass 2014).

The emerging opportunities in energy harvesting has sparked a growing interest and accelerated investment in the many varieties of energy harvesting technologies. Over the next decades those investments are likely to take the technology to greatly expanded levels of both performance and production. In some locations, we are already seeing this happen. The 2012 market for energy harvesting was between $300 and $700 million. That number is expected to increase exponentially to $4.2 to $5 billion by 2022 (Zervos 2014). Should that happen we are likely to see a diversity of applications that may be able to power a very large number of networked devices. Using ambient energy in place of conventional energy or electricity resources – especially as they become more cost-effective – is the functional equivalent of using aggressive energy efficiency measures to optimally lower the energy requirements of a variety of devices and ICT-enabled systems. The Appendix provides a more thorough discussion of energy harvesting and its future prospects.

F. The Footprint

Much of the policy discussion behind reducing energy use in networked devices and ICT-systems is seen through the lens of what is called the "carbon footprint." Although lacking a precise, historical definition, the idea is traditionally understood as "a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product" (Wiedmann and Minx 2008).

The concept of the carbon footprint is a negative one that originates from ecological footprint discussion, developed by Rees and Wackernagel in the 1990s. That opening discussion provided an estimate the number of "earths" that would theoretically be required if everyone on the planet consumed resources at the same level as the person calculating his or her ecological footprint (Rees et al. 1996; and Safire 2008). Given that ecological footprints tend to be a measure of failure, the City of Lynnwood (Washington), as but one example, chose the more easily calculated "carbon footprint" to measure the use of carbon as an indicator of unsustainable energy use (Mitra 2007). Carbon footprints are more specific than ecological footprints since they measure only the emissions of greenhouse gases which contribute to the growing burden of climate change.

Despite the fact that the term "carbon footprint" originated as an indicator of unsustainable energy use, almost two decades later the narrow focus on carbon emissions alone—or more fully, all greenhouse gases (GHG) including carbon dioxide—has led to a distorted view of the full depth and breadth of issues that impact the well-being of both the climate and the economy. Indeed, if we wish to develop meaningful policy prescriptions to reduce our impact on GHG emissions, we must shift the discussion back to the core element that drives both the problems we face—energy (Laitner 2014a).

Given the vital role that the productive use of energy plays in maintaining both a healthy economy as well as a healthy climate, we would be smart to advance our lexicon once again and utilize the term "energy footprint." For purposes of the present discussion, a working definition of "energy footprint" might be: the total quantity of direct and indirect energy (whether measured in joules, British thermal units, or kilowatt-hours) that is required to sustain a given social or economy activity. This idea is explored more fully in Section IV.

In effect, the footprint quantifies the burden (or negative impacts) in the use of energy, its attendant carbon dioxide emissions, and other GHG emissions from industrial processes. The World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) have collaboratively established a GHG Protocol that provides a useful way to categorize the direct footprint of a manufacturing enterprise in terms of different boundaries or "scopes" of operation (GHG Protocol 2015):

- *Scope 1* is the different onsite uses of energy and the associated greenhouse gas emissions that arise from the varied processes of a manufacturer (whether boilers, onsite transportation, and non-energy related emissions such as nitrous oxides or perfluorocarbons).
- *Scope 2* is the electricity and associated emissions that is purchased from off-site suppliers.
- *Scope 3* is the energy and emissions associated with a company's supply chain, its logistical operations, and business air travel.

The footprint differs significantly from the positive "handprint" of ICT-enabled applications that enable both higher levels of energy productivity and reduce levels of GHG emissions throughout the economy. Intel, among many others, has actively put this idea to work (Intel 2014). The concept is discussed next.

G. The Handprint

All tools, machineries and infrastructures, both in their immediate functional form and in their specific social applications, require energy and materials to perform or operate. As previously mentioned, their footprint—the energy consumed and associated emissions that are generated in the manufacture and distribution of goods and services, for example—can be negative in that respect. Yet, their redesign, their different use and/or their new applications—in effect, their handprint—may reduce the total global footprint of the energy consumed. For example, the nation's demand for electricity is provided by a network of power plants, transmission lines and distribution system that is only 33% efficient. Moreover, natural gas boilers needed to provide steam for various industrial operations is approximately 85% efficient.

Both the electricity and the steam technologies, operating individually, may have an aggregate footprint of 165 units of energy, delivering 85 units of work with a combined efficiency of 52%. However, if that same 85 units of electricity and steam load were delivered using a combined heat and power (CHP) plant with a shared system efficiency of 85%, the footprint may be dropped to just 100 units (Laitner 2015). In effect, the energy "handprint"—born of redesign, reconfiguration, and smarter algorithms—dropped the corresponding energy footprint by 65 units of energy. In a similar way, the positive contribution of industry's handprint (that is, information and communications technologies) can provide significant indirect contributions to a more productive economy even as it provides a significant step to mitigate the impact of climate change.

Building energy management systems provide an especially useful parallel as the focus moves closer to the handprint of network systems. In addition to many different sensors, an energy management system can consist of dozens full function devices and twice that many reduced function devices, all focused on the more efficient use of energy in within the building system. Microsoft now uses what it calls "Internet of Things meets Big Data" approach to turn its 500 acre headquarters into a smart campus that achieves energy savings and other efficiency gains. An engineering team now collects 500 million data transactions every 24 hours, and its smart buildings software presents engineers with prioritized lists of misbehaving equipment. Their conventional tune-ups were making the buildings run more efficiently, saving the company around $250,000 annually – but the new data gold rush will help them save six times that much. All of this data management and analysis takes energy to run, but the ICT handprint can enable much larger reductions in the system footprint. Part IV of this paper provides a further discussion on these points (Warnick 2015).

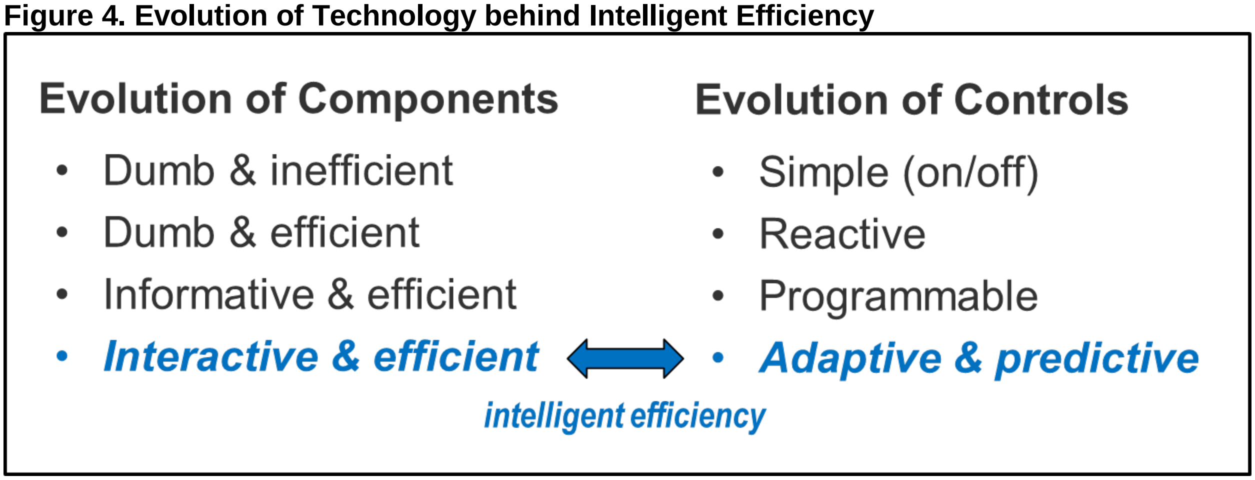
III. The Evolution of a Systemic Energy Savings

Economic historian, scholar, and best-selling author Jeremy Rifkin notes that the great economic revolutions in history occur when new communication technologies converge with new energy systems (Rifkin 2011). The energy revolutions animate both capital and labor to work more productively together. The new communication revolutions enable the smarter deployment of resources and the management of complex commercial activities. In the mid- to late eighteenth century and early nineteenth century, cheap print technology and the introduction of public schools gave rise to a print-literate workforce with the communication skills to manage the increased flow of commercial activity made possible by coal and steam power technology. This ushered in the First Industrial Revolution. In the early twentieth century, centralized electricity-based communication—first the telegraph and telephone, and later, radio and television—became the media to manage a more complex and dispersed oil, auto, and suburban era, and the mass consumer culture of the Second Industrial Revolution.

Today, new materials, new designs, coupled with digital technology, the Internet, and renewable energies, are all beginning to merge to create the possibility of a new and highly energy-efficient infrastructure for a Third Industrial Revolution. If the transition is successful, it can change the way people interact and the way power is distributed in the twenty-first century. In the coming era, hundreds of millions of people will be able to produce their own green energy in their homes, offices, and factories and share it with each other—as Rifkin describes it, within a distributed "Energy Internet," just as we now generate and share information online. The democratization of energy with an information and logistics commons can provide a fundamental reordering of human relationships, impacting the way we conduct business, govern society, educate our children, and engage in civic life.

The economic revolutions are enabled by the evolution of technologies and social enterprises; in this case, the evolution away from the device-centric focus, suggested earlier in Figure 1, to an emphasis on smart infrastructure and ICT-enabled networks and systems. Figure 4 below highlights the shift in the key characteristics of networked components as they become what we now refer to as intelligent efficiency.

Figure 4. Evolution of Technology behind Intelligent Efficiency

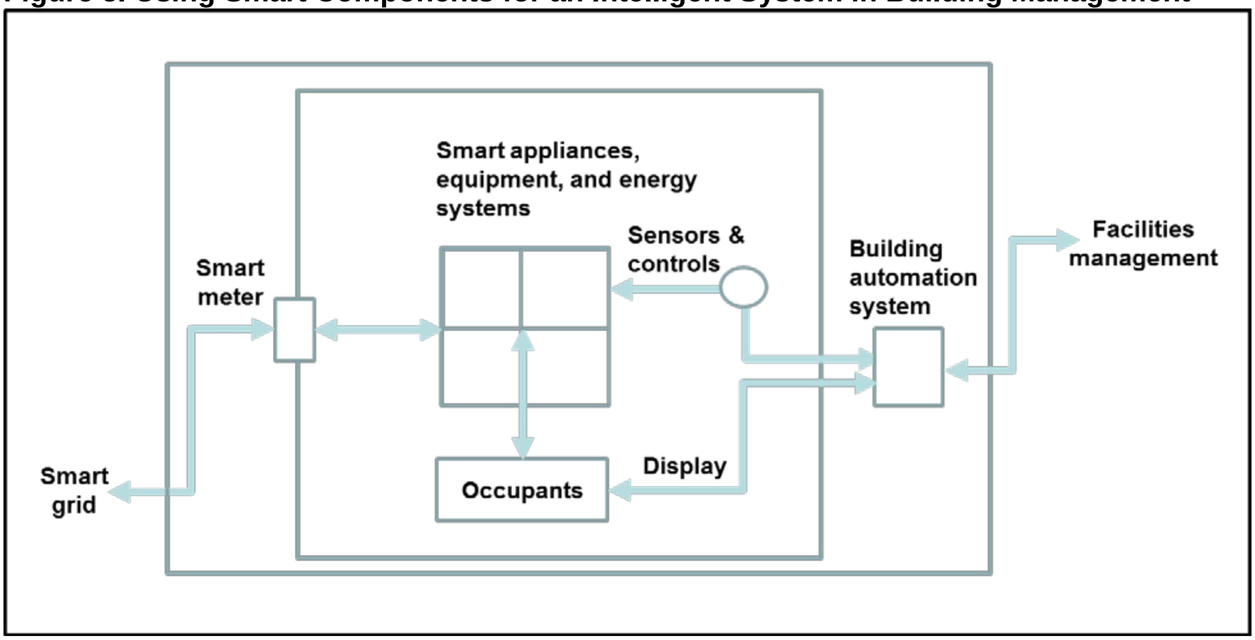


Source: Elliott (2014)

Following Elliott's (2014) evolution of components and controls, early steam engines functioned as stand-alone machines with single digit efficiencies, and could only be turned off and on. They were simple, dumb and inefficient. New materials and new designs kicked up their performance to much higher levels with sensors and controls allowing a reactive response that improved device efficiencies to 40% and higher. They were still dumb, however. By integrating programmable controls into a combined heat and power arrangement, the system efficiencies are now moving into the 70-90% range (Laitner 2015). By giving CHP systems more interactive capabilities, and enabling more adaptive and predictive response with the demand for heat and power, the performance can be pushed beyond the CHP system into the full operation of an industrial plant. A full step might be dropped out of the manufacturing process which saves both resources and money. Greater efficiencies might be developed in both the demand for energy, and in the production of specific energy resources. Material and feedstock requirements might also be reduced, saving even more money. ICT services—as they consistently support and become new forms of intelligent efficiency—are able to boost system performance to much higher levels of operation.

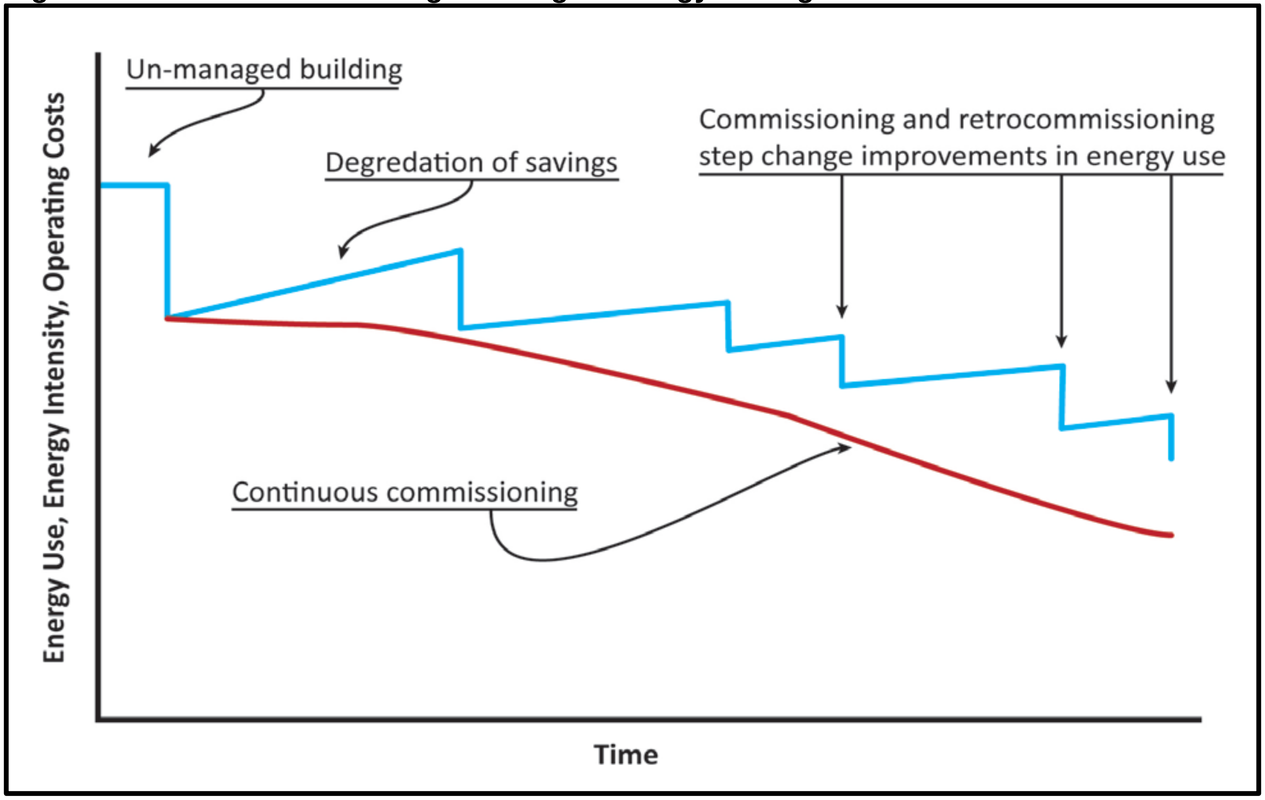
Figure 5 highlights a similar logic for intelligent systems in the management of buildings and facilities. Many interconnected devices—ranging from smart meters, appliances and equipment to displays, sensors, controls and automated systems—enable a more productive facilities management. Figure 6 illustrates the ability of ICT services, through a process of continuous improvement, to manage and increase energy savings over time. The degradation of performance can be preemptively managed even as a continuous commissioning can slowly reduce energy throughout the effective life of a building. In short, an emphasis on system rather than device performance is likely to unlock a greater level of energy savings whereas a preemptive efficiency standard may lockout further system performance.

Figure 5. Using Smart Components for an Intelligent System in Building Management



Source: Elliott (2014)

Figure 6. ICT Services Enabling a Managed Energy Savings over Time



Source: Elliott (2014)

A deeper look at the evidence suggests that these positive trends are already beginning to emerge. The data in Table 1 reveal a compelling backdrop. Here we use the EIA Annual Energy Outlook (AEO) for various years to compare their projections for electricity use for ICT services in 2012 and 2030.

Table 1. Estimated ICT Use of Electricity over Time

	2008		2012		2030	
Projection	**TWh**	**%Total**	**TWh**	**%Total**	**TWh**	**%Total**
AEO 2008 (2005–2030)	243	6.5%	281	7.1%	419	8.6%
AEO 2011 (2008–2035)	n/a	n/a	191	5.1%	246	5.7%
AEO 2014 (2011–2040)	n/a	n/a	134	3.6%	123	2.8%

***Source**:* EIA Annual Energy Outlook (2014 and various other years)

According to the AEO 2008, ICT electricity use in 2008 was estimated at 6.5% of 3,743 Terawatt-hours (TWh or billion kWh) of total electricity consumption, rising to 7.1% of 3,957 total TWh by 2012, and then to 8.6% of 4,880 total TWh by 2030. Three years later the AEO 2011 pointed to a much smaller 5.1% of total electricity needs in 2012 with the 2030 usage also dropping to 5.7% of the total. The most recent AEO (2014) suggests an even further decline in ICT-related electricity use, dropping to 3.6% and 2.8% for 2012 and 2030, respectively.

Two items are particularly notable. First the AEO 2014 projections suggest that the year 2030 electricity demands for all services will be less than what was projected in the earlier AEO 2008. Second, the AEO 2014 shows that ICT-related electricity demands are now projected to be smaller in 2030 compared to 2012 usage. In effect, the ICT-related equipment and services appear to be increasing their own efficiencies in significant ways, even as they appear to be strengthening the efficiency of overall electricity demands.

In short, some combination of the ICT-enabled productivity improvements and other efficiency gains appear to be dampening the demand for electricity consumption. Although it is not shown explicitly in Table 1, it can be inferred that both the use of electricity by ICT devices and overall demands for electricity services are substantially less in the AEO 2014 production for 2030 compared to the AEO 2008 projection, also for 2030. While Table 1 does not lock in the confirmation that ICT services are enabling greater levels of energy efficiency throughout the economy, the pattern appears to support that finding.

IV. Rethinking Handprint and Footprint

An energy footprint is the result of system-scale operations. These range from the size of a building to as large as a national or even the global economy. Moreover, each energy footprint is composed of multiple energy uses. In the context of a building, its total energy use would constitute its footprint—a sum of the many energy handprints of its heating, ventilation and air conditioning (HVAC) system, its lighting, the use of internal equipment and appliances, etc.

In pursuit of the serious goal of reducing our energy footprints (and concomitant carbon footprint), a systems approach is likely to achieve a greater impact than is likely to occur by focusing on individual devices. For example, we might assume that in order to reduce our energy footprint we must correspondingly reduce the energy used by each device by a certain amount in order to effectuate system-level reductions. But in many circumstances, increasing energy handprint of one device may have the effect of reducing pooled energy uses of other connected devices, such that the energy footprint of the system is reduced more than if the energy of a single or group of devices were individually reduced. This concept is illustrated in the table below.

Table 2. Illustration of an Optimized Systems Approach to Energy Usage

Total Energy Usage Scenario	System-wide Energy Use (footprint units)	Energy Management Device (Energy Use handprint)	Percentage of System-wide Energy use	Percentage System Reduction
Reference Case	10	2	20%	--
System Upgrade	7	3	43%	30%

In the illustrative example highlighted in Table 2, the operations of an energy management device clearly expanded the handprint of the energy use (going from 2 units to 3 units). Yet that 50% increased operation resulted in a 30 percent system-wide reduction in the energy footprint (dropping from 10 units to 7 units). The reason for the increased energy use in the management device is the need to handle more data and also the need to manage more system operations. In effect, the increased consumption in this case, and resulting whole building optimization, led to a lower system requirement with an improved overall building performance (e.g., better ambient lighting or more comfortable indoor humidity and temperatures).

Table 3. Illustration of a Device-Based Approach to Energy Usage

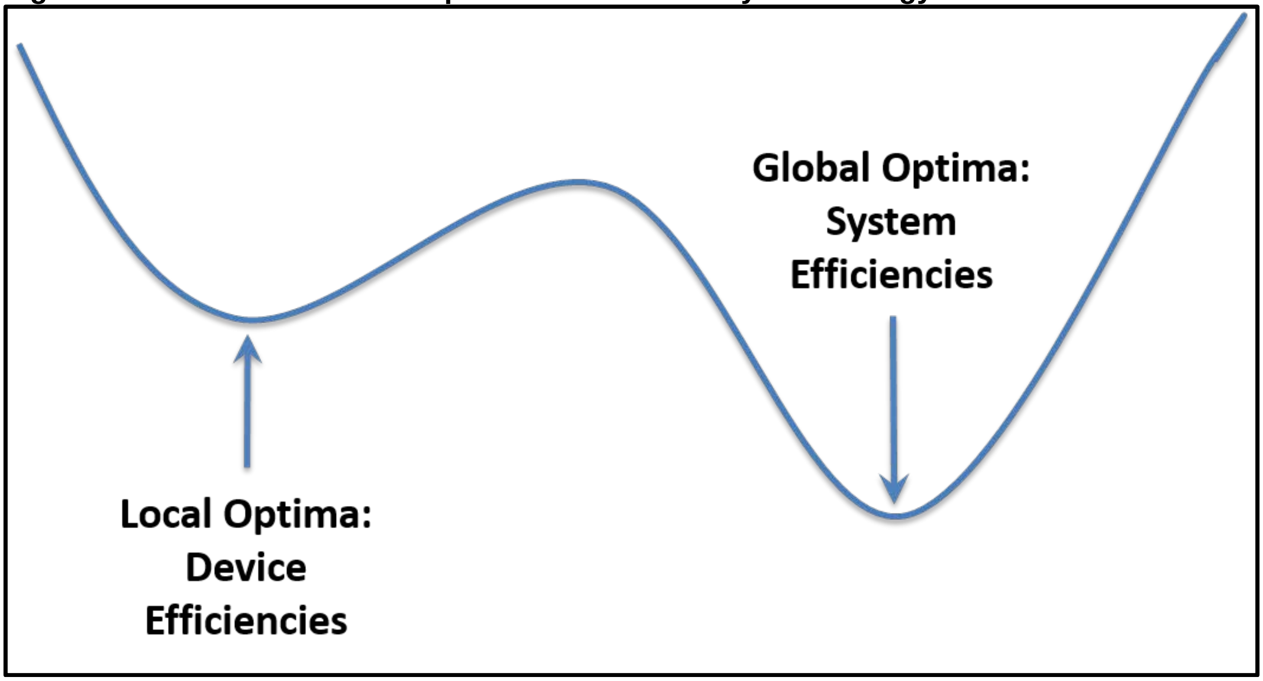
Total Energy Usage Scenario	System-wide Energy Use (footprint units)	Energy Management Device (Energy Use handprint)	Percentage of System-wide Energy use	Percentage System Reduction
Reference Case	10	2	20%	--
System Upgrade	9	1	11%	10%

Conversely, we can see in the Table 3 illustrative situation that a narrow focus on minimizing device energy use might lead to a suboptimal outcome. Indeed, the energy use of the management device in this instance was cut in half, but because we lose the synergies at work in the first example, the energy footprint as a whole is only reduced by 10 percent.

It is through this same lens that we should view energy efficiency improvements in the world of ICT-enabled devices. In many ways, as shown in Figure 7 on the following page, the device-centric approach might be described as the pursuit of a local optima which, yes, does provide a measured degree of improvement—that is, a reduced energy consumption. But that is an improvement with respect to a limited set of device-driven options. This compares to the broader set of system improvements—represented in Figure 7 as a global optima, or a larger system reduction in energy use (Laitner 2015).

Yes, the array of ICT-enabled devices are responsible for perhaps 2% of total worldwide greenhouse gases or GHG emissions (GeSI 2008). This is no small number in magnitude of emissions, but the impact these devices have on reducing energy consumption or providing an increased quality of services should not be underestimated. It may well be the case that ICT-enabled device energy use, amounting to 2% of GHG emissions today, actually reduces our overall GHG emissions by 16% or more (GeSI 2012). They may also provide an even larger catalyst in the full emergence of the Third Industrial Revolution (Rifkin 2011), or the prospective 60% reduction in energy suggested by the 2012 ACEEE long-term energy efficiency potential study (Laitner et al. 2012). Indeed, as we demonstrate in Table 2 above, we may want to increase the energy use of ICT-enabled devices to perhaps 3% (or more) of total global GHG emissions in order to further reduce our system-wide energy footprint.

Figure 7. Local versus Global Optima—A Device or System Energy Use?



Source: Laitner (2015)

V. Imagining a Larger Scale of Opportunity

The long-term vigor of the U.S. and the global economy is weakening (Laitner 2014a and 2014b). Among the reasons for a less robust economic activity is the inefficient use of resources – whether materials, water, and especially energy use. Information and communication technologies (ICT) embedded in intelligent appliances and networks may catalyze a higher level of energy efficiency and economic productivity. Accelerated investments in ICT-enabled networks could lead to productivity benefits including more energy-efficient array of technologies and global infrastructures that save money and reduce environmental impacts.

A. What Might be Possible?[6]

The evidence already points to an accelerated growth in ICT devices (IEA 2014). How might we then imagine an economy that is slowing; and in particular, how might we imagine economy-wide productivity improvements may be weakening even as connectivity is growing? The answer is twofold. First, we currently invest much more in social networks than in intelligent building and industrial energy efficiency systems. Second, the huge scale of the total existing capital stock and fixed assets in the United States is now on the order of $54 trillion dollars as of 2012, and it will require decades to replace at current rates and current patterns of investment. If we are to realize the full economic potential of ICT-enabled networks, we must accelerate targeted investments in these systems, focusing on productivity improvement rather than merely generalized replacements and upgrades of existing capital stock or single devices.

[6] Unless otherwise cited, the information, data, and analysis in the remaining Section V of this working paper is adapted from a more extensive report published by the American Council for an Energy-Efficient Economy (Laitner, McDonnell and Ehrhardt-Martinez 2014).

Our working hypothesis is that redirecting greater investments into ICT-enabled networks will enhance the nation's energy and economic productivity—even as GHG emissions are also significantly reduced. Although ICT services are already enabling greater levels of energy efficiency throughout the economy, we lack definitive evidence of a positive relationship between expanded investment in ICT-enabled networks and a more robust economy. Neither the nation's businesses nor the National Economic Accounts provide meaningful data that will help us learn how big, how necessary, and how productive the contributions from ICT and smart appliances might be. We have case studies and ad hoc estimates, but not a consistent tracking of data that can really inform the business community and congressional and other public-policy decision makers.

The data now generally collected do not track either energy efficiency or productivity improvements driven specifically by the Internet or by smart appliances and ICT-enabled networks. Rather, the available metrics tend to follow the many different usage patterns (e.g., the number of users or downloads) rather than the fiscal and monetary impacts that such technologies might have on the larger economy. We do not know how networks inform, enable, and amplify the capacity of other elements of the economy as they rise to a higher level of performance. As for energy efficiency, data collection and analysis tend to focus more on energy supply and energy price volatility than on the productivity benefits that might be driven by ICT-supported energy efficiency improvements. In short, we need an analytical effort to quantify the system-wide improvements that might be possible through an accelerated investment in ICT-enabled networks.

To provide at least an initial foundation to explore the prospective economy-wide benefits of ICT-enable technologies and networks, we incorporate what we know broadly about costs and savings associated with such systems to lay out a range of working estimates of prospective gross domestic product (GDP) benefits within the United States. To begin with, we know that telecommunication investments rose very sharply from $29.4 billion in 1997 to a high of $83.7 billion by 2000, but then averaged only $69 billion over the years 2000 through 2011. Had we continued the economy-wide pattern of investments since 2007, and had the outlays for new ICT-enabled networks at least followed those historical investment trends, the nation's GDP in 2013 would have been closer to $13.9 trillion, or about $600 billion more than actually recorded when measured in 2005 constant dollars.

Continuing this first-phase assessment, the paper presents a series of thought experiments to indicate the near-term economic impacts that might follow from an accelerated deployment of ICT-enabled networks and services. We highlight five different analytical areas and compare their aggregate impacts to the $600 billion in foregone economic activity otherwise reported in 2013. We approach the thought experiments as a Fermi problem in which we are modeling for insights, not precision.

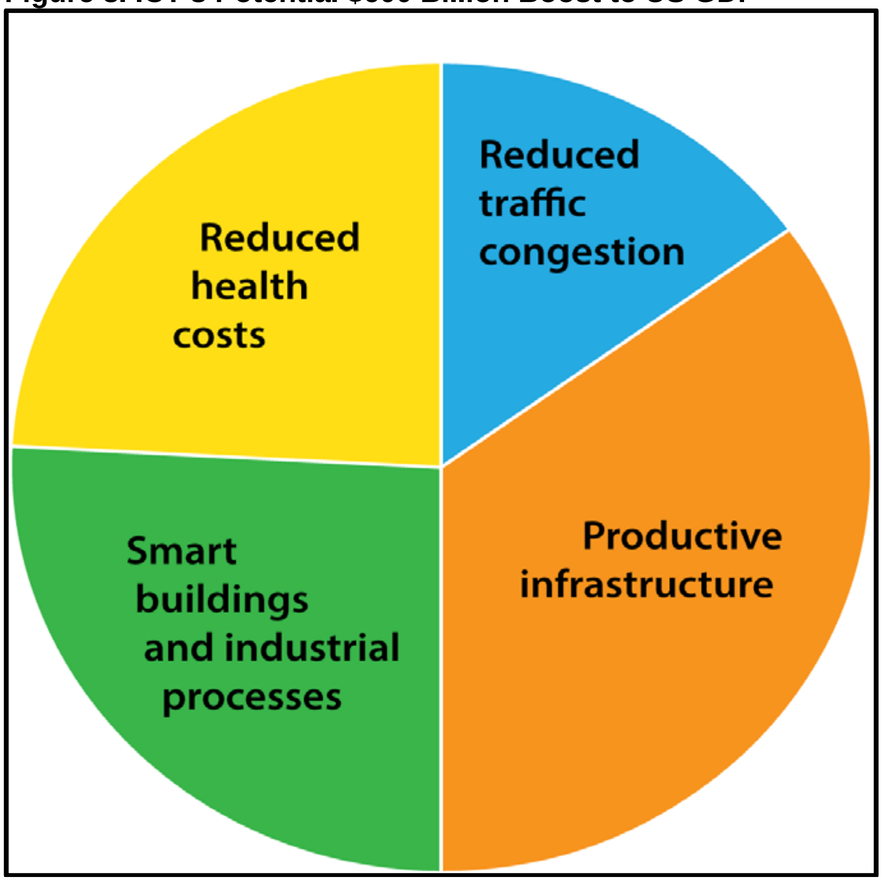
The results, shown in the table below, are as follows. In the buildings sector, we generate a working estimate of net $17 billion (rounded) contribution to the nation's GDP from ICT-related energy efficiency upgrades. By reducing inefficiency and congestion in transportation systems by 50%, ICT-enabled networks might add about $114 billion to GDP. In terms of economy-wide productivity, we estimate that a 50% increase in ICT investment would result in a GDP benefit of $272 billion. Accelerating the development of the Industrial Internet might add another $200 billion to the economy. Finally, lower ozone levels due to ICT-enabled energy efficiency might lead to increased labor productivity with an economic benefit of $185 billion. The total is $788 billion. Assuming 75% of the total to allow for some interaction and double counting, we arrive at $591 billion, which is very close to the foregone $600 billion we originally estimated. Table 4 summarizes these outcomes.

Table 4. Possible economic outcomes from ICT-enabled networks

Thought experiment for the Year 2013	GDP benefit (billion 2005 $)	Source of scenario assumptions	Working notes
Intelligent efficiency in buildings	17	Laitner (2010), GeSI (2012), Rogers et al. (2013)	Energy efficiency with a net 550,000 jobs times 35% ICT share at $86,000 GDP per job
Decreasing traffic congestion by 50%	114	Sweet (2013)	Congestion cut by half w/elasticity of –0.022; total jobs 56% of population
ICT investment up 50%	272	Cardona et al. (2013)	ICT investment has output elasticity of 0.05.
Accelerating Industrial Internet	200	Annunziata-Evans (2012)	Labor productivity was 1.5% higher in 2013.
Reduced ozone pollution	185	Graff Zivin & Neidell (2011)	Labor productivity up 4.2% with 13% lower ozone affecting 1/3 labor force
Total GDP impacts	600	Sum of the five thought experiments net of interactive effects	Assuming a ~75% factor to minimize interactive effects and possible double counting

Source: Laitner, McDonnell and Ehrhardt-Martinez (2014).

Figure 8. ICT's Potential $600 Billion Boost to US GDP



Source: Laitner, McDonnell and Ehrhardt-Martinez (2014).

Given the set of outcomes described above, we can then conclude that ICT-enabled networks and services might enhance overall economic activity by as much as $600 billion per year (in constant 2005 dollars) over the next several decades. At full deployment, this is sufficient activity to boost GDP by about 3% compared to current levels of economic activity.

ICT-enabled networks and services might also reduce the nation's total energy requirements. As it turns out, the energy savings is comparable to an equivalent 1.1 billion barrels of oil annually in the period 2014 through 2030. At average energy prices in 2013, that might imply a $79 billion reduction in the nation's overall energy bill (again in 2005 dollars). These initial findings clearly suggest that smart appliances and ICT-enabled networks can provide a vital lift both to the nation's economy and to energy efficiency gains and related energy bill savings. While there is a strong probability that this relationship can be confirmed, a final assessment will require more information and data than we can provide at present.

B. Extending the Perspective through Improved Analytical Techniques

This current look at the array of net benefits suggests a number of recommendations to explore the larger energy and economic potential of networked devices. The chief element of a needed future analysis is the collecting of big data to confirm the market potential and the positive impacts of smart appliances and ICT-enabled networks. Big data techniques allow analysts, business leaders, and policymakers to draw conclusions from economic development patterns they might discern within the massive data sets they collect and store. In addition, a variety of software programs and algorithms will be needed to process the full array of data to transform it into useful information and knowledge. It is true that computers with machine learning capabilities no longer rely only on fixed algorithms and rules provided by programmers; they can also modify and adjust their own algorithms based on analyses of the data, enabling them to see relationships or links that a human might overlook. However, no project to date has enlisted big data to generate the type of macroeconomic findings envisioned here. Hence there is a need to provide some initial suggestion for the kinds of analytical techniques that might be of use—with an eye toward the substantial modification or actual changing of the approach as the project unfolds and as new insights and learning emerge.

As Laitner et al. (2014) further propose, new analytics might integrate the use of Bayesian statistics and a multicriteria analytical tool such as goal programming. From the big data, we may or may not be able to confirm the net positive economic impacts of ICT-enabled networks, but we may be able to use Bayesian inference and statistics to show the very high degree of probability of positive economy-wide outcomes, and the very real need to accelerate investments in smart appliances and networks. Bayesian statistics is a way of calculating conditional probabilities given other uncertainties; Bayes' rule transforms probabilities that look useful (but often are not), into probabilities that are useful. This analytical perspective would be further supported by the use of multicriteria analytical tools. A critical shortcoming of most standard economic analysis and models is that they tend to focus on a single objective to be achieved, either to minimize cost, or to maximize profit, welfare, or consumer utility. Standard theory tends to restrict the full set of possible choices that would increase consumer welfare across a variety of social, economic, and environmental objectives. Ideally, however, all resources should be managed in a way that promotes the variety of goals or purposes typically found within any society or economy. Such goals may range from expanding the employment base to minimizing environmental impacts.

One multicriteria analytical tool that might provide further insights is known as goal programming (GP). This model solves for the set of choices that best satisfies multiple goals from among a variety of alternatives that are all competing for a pool of limited resources. It is based on the presumption that better decisions can be made if emphasis is given to achieving minimum levels of satisfaction rather than maximizing a single objective. Finally, the integration of more of the social rather than the purely economically-rational perspective in order to understand how smart appliances and ICT-enabled networks might contribute to a more resilient and economic sustainable future. Efforts to engage individuals on energy and climate issues need to be concerned with how people feel about the issues and not just about how they think about them. We must look to new information and data that explore the ways in which social rules, resources, and context shape individual patterns of energy consumption.

VI. Conclusion and Relevant Policy Principles

This working paper provides a first step toward a meaningful appraisal of ICT-enabled intelligent efficiency as it might more positively shape and significantly reduce the global energy footprint of the economy. The evidence seems compelling. The handprint of ICT-enabled networks and systems are already facilitating significant reductions in GHG emissions. Still, there are larger scale improvements that remain possible, but only with: (a) greater magnitudes of investment in more productive technologies, and (b) with policies that support a systems-based approach—ones which emphasize economy-wide productivity improvements rather than those which focus on the more narrow device-centric performance standards. From the evidence developed to this point, a number of compelling policy principles emerge that might guide the thoughtful development of a more productive economy. These are highlighted next and we then follow with what we believe are appropriate next steps to act on those principles.

A. Evidence-Based Policy Principles

Unfortunately, the data remain unsatisfyingly incomplete. Hence, it is difficult to know what the larger benefits might look like. Furthermore, the optimal ICT designs and functional arrangements are still emergent. It is hard to evaluate with any certainty how an optimal ICT-enabled system or network might actually function. Therefore, early prescriptive standards which focus prematurely on minimizing energy use may exclude the development of more robust systems that lower costs, improve performance, and reduce greenhouse gas emissions. But if the U.S. and the global economies are to move ahead in a proactive and sustainable manner, then policies must developed that focus on overall system efficiency gains. This means the greater deployment of intelligent efficiency to maximize benefits rather than device-level efficiency improvements which only minimize energy use. Given that perspective, these five principles emerge.

First, do no harm. If we are looking for a more robust and sustainable economy then we need to look for ways to encourage more systems innovation rather than limit the focus to minimizing the energy required by individual devices.

Second, don't miss the forest (handprint) for the trees (footprint). As we explore the larger opportunities for much higher levels of energy productivity we should examine the benefits as well as the burdens of intelligent efficiency (and all new energy systems more broadly).

Third, yes, reduce the energy and carbon footprint, but not at the expense of an expanding handprint. This follows from the first two principles in that we should expand innovation and investments which maximize the many benefits rather merely reducing the apparent energy burden.

Fourth, focus on building a more robust market and sustainable economy. Again following from previous three principles, the major focus should be looking for smart incentives to stimulate the sizeable market investment that will be needed to ensure the transformation of the built environment and the existing capital stock.

Finally, all policy efforts should harmonize and converge around common and agree-upon testing and measurement standards—especially in light of the larger system benefits that are needed to drive large-scale market transformation.

B. Potential Policy Opportunities

The ideas advanced here challenge the conventional analysis of energy demands within the economy. All of these ideas and insights would benefit from a more substantial review and a more rigorous assessment of how the current energy (and economic) paradigm might be reshaped through a more positive energy systems perspective. A useful step to encourage an innovation-based systems assessment would be to convene a series of national workshops and/or a progression of international conferences that are specifically designed to explore the fundamental aspects of at least five different policy opportunities, to: (1) establish common definitions and metrics, (2) build international cooperation about the larger public purpose of energy productivity and about smart standards and test procedures; (3) proliferate credible and common (or generally accepted) protocols for measuring specific intelligent efficiency applications, (4) research ways to actively advance energy harvesting techniques and technologies, and (5) raise much greater awareness of the intelligent efficiency handprint.

Notwithstanding the further insights that might emerge from a progression of workshops and conferences, or a further and more rigorous assessment of the full benefits of intelligent efficiency as it stimulates a more robust economy, the evidence underscores one very critical idea—the U.S. and global economies will be better off by 'Thinking Big' about energy productivity gains powered by information and communication technologies. More to the point, if policymakers miss the big gains that are likely to follow systems thinking, focusing instead on minimizing the energy demands of individual devices, we run the risk of a continued weakening of the greater economy. On the other hand, the combination of market incentives and policy signals that open up greater opportunities for intelligent efficiency can increase the productivity of the economy in ways that enable our prosperity to improve and continue.

Appendix A: Emerging Trends in Energy Harvesting

A. Energy Harvesting Processes

There are three methods of harvesting energy that are being exhaustively researched today. They are Photovoltaic (energy from sunlight), Piezoelectric (energy from motion), and Thermoelectric (energy from heat) generation. Photovoltaic (PV) technologies are easiest to use of the three. They have been in use since the 1970's in the form of solar or PV panels. Piezoelectric and Thermoelectric are relatively newer concepts with respect to electricity generation, although both have first applications that date back to the late 19th century.

Photovoltaic systems are used all around us in the form of solar panels on rooftops. With respect to energy harvesting, however, PV is a relative newcomer in the market. Researchers are working on ways that they can harness the sun's energy for small-scale use by embedding PV components in a variety of applications, ranging from the clothing we wear to the windows through which we look almost daily. The biggest challenge facing this scaled down version of PV is finding cost-efficient materials and the means to mass-produce them at a scale that can keep up with the increasing number of mobile and small external devices we use today.

Piezoelectric, or kinetic energy harvesting, takes the movements of our everyday lives, like breathing, walking, running or talking, and converts these movements to useable electricity. The process uses what are called piezo crystals. These give off electrons when deformed by vibrations or compressions. A conducting material is then used to convert the energy from the crystals to electricity that can be immediately used to power a low-voltage device or stored in a battery for later use. This method is highly applicable to the emerging boom in wearable devices. Indeed, the market for wearables is expected to increase from $14 billion in 2014 to $70 billion over the next decade (Donovan 2013).

Thermoelectric harvesting requires a temperature differential or thermal gradient that can then be transformed into the desired electricity. The greater the differential, the greater the transfer of electrons via positively and negatively charged metals to generate electricity. When one area of a metal is heated more than the other, the electrons then move over to the colder areas. By connecting the cold ends and capturing the transfer from positive to negative, one can harvest small amounts of electricity. The best application for this technique is in devices and machines that generate excess or waste heat. The ultimate goal is to install devices that capture the excess heat given off by vehicle engines and boilers, and then use the electricity gains to power ancillary equipment thereby reducing the need for primary energy resources such as natural gas or gasoline. This supplemental electricity enables a more efficient machine or device (Johnson 2014).

B. Techniques Now in Use

Photovoltaic

- Portable Solar Chargers – equipped with USB for charging mobile devices
- Calculators – use solar power to charge coin-cell battery
- Watches – can hold charge up to 6/8 months without light
- Street Lights – self-sufficient street lights with attached solar panel
- LEP - thin light emitting polymer coating for full-spectrum LED displays

Piezoelectric:

- PaveGEN tiles – recycled rubber tiles that harness footstep energy to power lights and charging stations. Best suited for high foot traffic areas (PaveGEN 2015).
    - 200 tiles installed in a football pitch in Rio (powers field lights)
    - 51 tiles installed in terminal at London airport (powers hall lights)
    - 14 tiles at train station in France (powers lights and USB chargers)
- VTT Electricity Harvesting Tree – can harvest solar/kinetic energy through light/wind to power phones, humidifiers, LEDs, and thermometers (Luimstra 2015).
- Flashlights – kinetic energy flashlights that charge battery when you shake them
- Philips Hue Tap – Works in conjunction with Philips Hue lights, a kinetic powered light switch with 3 settings. Set up is easy with Hue App
    - 30 meter distance (even through walls)
    - Rated for 50,000 taps or virtually unlimited
    - $60 currently (Campbell 2014)

<u>Thermoelectric:</u>

- KAIST Wearable Thermo Element – glass/fabric device converts heat difference between skin/outside air into electricity. Goes into production 2016 (Borghino 2014).
    - 13 grams
    - Generates 40mW
- GMZ Thermoelectric Generator – can produce 7.2 Watts with 500° C temperature gradient best applied to waste/primary heat sources (Lamonica 2014).
- Logimesh Logimotes – self powered electronic sensors installed on engines and compressors for the oil and gas industry. They operate on the waste heat given off to generate low voltage and monitor the engines
    - Track health and production of engine/compressor
    - Transmits data every 10 seconds
    - 4-volt rechargeable solid state chemistry (Innosphere 2014).
- ABB WiTemp – wireless TEG that is installed on industrial devices/pipes that need temperature monitoring. Runs off the excess heat given off.
    - Can be configured to update from 4 seconds – 60 minutes
    - Only needs a 35° C temperature gradient
    - Greater than 6 year battery life (ABB 2014).

C. Future Energy Harvesting Trends

Future Uses (2-7 Years)

Photovoltaic:

- New Energy Technologies SolarWindow – small organic solar cells 1/10 the size of a grain of rice sprayed onto a window. This see-through PV will have a shorter payback period and produce more power than rooftop PV (Windows 2015). *Estimated Arrival: (3-5 years)*

Piezoelectric:

- Kinetic Clothing – Multiple companies are in the R&D stages of integrating kinetic energy harvesting materials into clothing and outerwear such as wristbands. Prototypes have been released but proven inefficient or too pricey. The growth in this field will be spurred by the sports & fitness as well as military sectors. Challenges include constructing efficient materials that can stretch and retain their shape while still performing at a high level Pitcher 2015). *Estimated Arrival (2-4 years)*

Thermoelectric:

- TEGs for Automobiles – The DOE and VTO (Vehicle Technologies Office) have funded and worked with companies such as BMW, Ford, and GM to come up with waste heat thermoelectric generators (TEGs) for automobiles by 2020. This will cut vehicle emissions, increase fuel efficiency, and reduce engine strain to increase vehicle life (Energy.Gov 2014). Challenges include price, TEG integration, efficient materials as well as minimizing thermal conductivity while maximizing electrical conductivity. Will improve fuel economy 5 percent, with hopes of 7.5 percent (Wostenhagen 2015). *Estimated Arrival (3-5 years)*

Long-Term Market Perspective

IDTechEX estimated the following for the growth of energy harvesting sectors displayed in Millions of Current US Dollars (Das 2014):

Table A-1. Anticipated Growth of Energy Harvesting Market (Millions of Current Dollars)

	2012	2013	2014	2015	2016	2018	2023	2024
Organic Photovoltaics		$0	$0.1	$0.3			$87	
Piezoelectric	$15	$18	$35				$824	
Thermoelectric			$42	$58	$95			$950
Energy Harvesting*			$163			$596		$2,600

***Note:** This market items is for all areas of Energy Harvesting technologies, including but not limited to Photovoltaic, Piezoelectric, and Thermoelectric technologies. **Source:** Das (2014).

There are some incredible new technologies on the horizon that will change the way the human race provides itself with energy. Many of these concepts will be incorporated into traveling, walking, exercising, and many more of the everyday aspects of our lives to make them more efficient and productive. Companies like Intel are researching energy harvesting materials that are weavable, washable, and stretchable enough to be seamlessly integrated into the clothing we wear. IDTechEx, estimates that by 2025, the market for wearable technologies will eclipse $70 billion (Harrop 2015).

Wearable Technology Europe, an event hosted by IDTechEx in Berlin, will showcase multiple prototypes and concepts of materials with embedded electronics. The development and production of sensors will be the driving force in the wearables market, which will see a market of $5.8 billion alone by 2025 (Das 2015). However, while the sensors and storage components of the technology are already being produced and tested, the timeline for distribution of these products appears to still be a decade out, as developers await a market for the intermediate materials needed to bring these ideas to global, cost effective, production. Their estimated arrival as a full market is around the year 2015 (Harrop 2014).

Also on a longer timeline, the aerospace manufacturer Airbus, is researching ways to harness passenger body heat in the seats aboard the aircraft. The concept plane, which will potentially be developed by 2050, will be incorporated with biometric ID scanner, form fitting smart seats, and a transparent exoskeleton. The thermoelectric energy harvested from the seats will support the on-board electronics, making the entire aircraft more energy-efficient (Champ 2011).

D. Implications for Networked Devices

If power is pulled from small-scale ambient energy resources rather than depending on the separate large-scale production of electricity, then energy harvesting effectively amounts to a more energy-efficient use of resources. Despite the enormous potential of such devices to contribute to the system improvements, a policy environment that focuses only on minimizing energy may constrain a more complete systems performance across the global economy.

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