

The Energy Efficiency and Productivity Benefits of Smart Appliances and ICT-Enabled Networks: An Initial Assessment

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Executive Summary

The U.S. economy is slowing down. Among the reasons for a less robust economy is the inefficient use of resources, and especially the inefficient use of energy. 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 technologies and infrastructures that save money and reduce environmental impacts.

A precipitous decline in the cost of computing power and data storage, and dramatic improvements in programming science, have made it possible for every device to become a connected, “smart” device. Such devices can collect and process enormous amounts of data, making possible many kinds of analysis and higher levels of performance that were unachievable just a decade ago. One result is increased energy efficiency. To take one of many examples, smart home appliances can have a material impact on residential demand response and load shifting away from peak hours.

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.

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 are 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:

- 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 (nonenergy 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

Why, then, is the economy slowing (and in particular, economy-wide productivity improvements 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 our nation's total existing capital stock and fixed assets—now on the order of \$54 trillion dollars as of 2012—will require decades to replace at current rates and current patterns of investment (BEA 2014). 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.

Our working hypothesis is that redirecting greater investments into ICT-enabled networks will enhance the nation's energy and economic productivity. We can see that ICT services are already enabling greater levels of energy efficiency throughout the economy. To date, however, 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.

In the first phase of this analytical effort, the current paper uses what we know broadly about costs and savings associated with ICT networks and appliances to lay out a range of working estimates of prospective gross domestic product (GDP) benefits. 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 analysis, 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 examine specific costs and benefits in five areas and compare these 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 ES1 summarizes these outcomes.

Table ES1. Possible economic outcomes from ICT-enabled networks

Thought experiment for 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: Author estimates starting with Woods and Poole data for 2014, following assumptions and referenced bibliographic resources in the body of this report.

Figure ES1 illustrates these outcomes.

ICT's potential \$600 billion boost to GDP

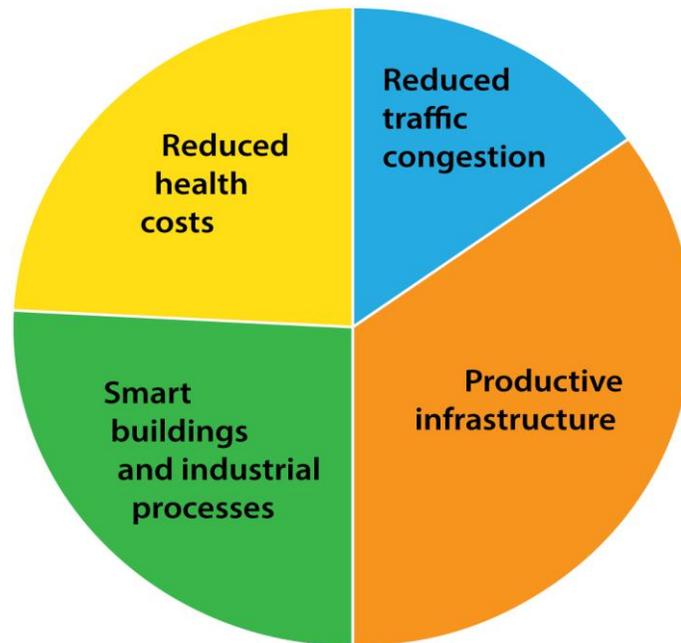


Figure ES1. ICT's potential boost to GDP

Phase 1 of the assessment concludes, then, 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. 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. Although we have available data on the use, growth, and performance of smart technologies, we are constrained by the lack of adequate time series data to characterize their potential contribution to greater levels of energy efficiency and economic productivity. A second phase of the assessment would aim to capture and analyze an array of data to confirm (i) the likelihood of a positive economic impact, and (ii) the necessity of upgrading the core of our economy with a strengthened ICT-related investment portfolio.

The current paper concludes with a set of recommendations for this second phase. 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. This study will use a variety of data-mining techniques to pull information from a combination of available time-series data, ad hoc case-study data, journal and news articles, and relevant databases.

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.

For the Phase 2 study, then, we propose 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.

We also propose the use of a multicriteria analytical tool. 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 (Laitner and Hogan 2000; Greening and Bernow 2004). 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 (Simon 1957).

Finally, we recommend integrating 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. Thus we recommend that the second phase of the study include data and insights from the social sciences as well as from the economic and physical elements of the market.

Acknowledgments

In many ways this report draws on the emergence of ideas in the realm of particle physics, especially the 2012 confirmation of the Higgs boson. The idea of the Higgs, a new particle that is critical to the Standard Model of Particle Physics, was first developed in 1964. Ideas involving thousands of physicists, scientists, and engineers led to the development and building of the Large Hadron Collider (LHC), the most complex machine ever built by human beings. It was initially conceived in the 1980s and began operation in 2009. By July 4, 2012, the LHC had smashed a sufficient number of protons together and tracked the data that appeared from those collisions so that we could believe, with confidence, that a new particle had been discovered. It was the collaborative effort and imagination of both theoretical and experimental physicists that enabled the development of the LHC and confirmation of the existence of the Higgs boson (Carroll 2013).

In a surprisingly parallel way there is a need first, for more theoretical work to understand the critical role of the efficient use of high-quality energy to maintain a more vigorous and sustainable economy (Ayres and Warr 2009; Laitner 2013), and second, for the development of better data to confirm the vital link between energy productivity and a more robust economic process. And there is also a need to build a deeper understanding of how information and communication technologies (ICT) might provide the basis for lifting the economy to a higher level of performance. Yet, just as there were insufficient data to confirm the existence of the Higgs boson until 2012, so there now are insufficient data to confirm the role of ICT-enabled systems and networks to support more productive levels of economic activity without the huge waste of energy that leads to higher costs and unnecessary levels of greenhouse gas emissions and other pollutants. In the same spirit that led to the development of the LHC, this report draws on initial evidence to provide a set of thought experiments suggesting a vital link between ICT-enabled networks and services and a more energy-efficient and productive economy.

More practically, this report began almost three years ago with a series of discussions among the lead author, Dominic Vergine with the UK-based microchip design firm ARM, and Steven Nadel, executive director of ACEEE. ARM then provided the funding to launch the resulting analysis. Collaborators and reviewers of this assessment included Drs. Catherine Dibble of Dell Research, Jim McMahon formerly with Lawrence Berkeley Laboratory, Kurt Roth with the Fraunhofer Institute, Eric Williams with the Rochester Institute of Technology, and Oleg Lugovoy with the Russian Presidential Academy of National Economy and Public Administration. Several conversations with each of these colleagues, as well as their written comments, provided useful guidance and support that allowed us to complete this manuscript. Many of the excellent insights that emerged from these conversations will positively shape the next phase of the assessment as described in the main text of the report. At the same time we must acknowledge the skillful editing provided by Fred Grossberg, which helped bring clarity to the ideas explored in this manuscript. Kate Hayes and Roxanna Usher also contributed to the editing, Eric Schwass worked on the graphics, and Patrick Kiker and Glee Murray assisted in bringing the report to the public. Our heartfelt thanks to all.

Introduction

If it had been possible for historians to observe the transition of the global economy over the course of the industrial age, they might have been able to discern not one but at least three successive revolutions. As Jeremy Rifkin describes it, 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, digital technology, the Internet, and renewable energies are 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 democratization of energy will depend on information and communication technologies (ICT) linked together in a “smart web.” This report explores the potential benefits associated with what we might call an ICT-enabled network effect. But it does so with a different approach than the usual straightforward review of the costs and benefits arising from engagement or participation in network activities. Typical assessments review statistics that highlight the explosive growth of the Internet, the scale of data that might flow over servers and routers on an annual basis, or the number of desktop, mobile phone, or iPad users. Here we explore, instead, the potential impact that ICT-enabled networks and smart appliances – consistent with the full emergence of the Third Industrial Revolution – might have in stimulating both greater levels of energy efficiency benefits and a more productive economy.

There are significant difficulties in completing the desired assessment, however. They arise from three key elements. The first is that the data now generally collected do not track either energy efficiency or productivity improvements driven by either the Internet or smart appliances and ICT-enabled networks. Rather, the available metrics tend to follow the many

different usage patterns rather than the fiscal and monetary impacts within the larger economy. Second, neither energy efficiency nor productivity benefits themselves are tracked in ways that maximize useful insights for either the business community or for congressional and other public policy decision makers. Finally, only about one-half of the initial budget developed for this research assessment has been secured. Hence there is a need to approach this particular assessment in two steps.

The initial effort that we document in this paper provides an overview using currently available data so that we might lay out various testable hypotheses to explore the link between ICT-enabled networks, anchored by smart appliances, as they catalyze a variety of productivity benefits – whether more energy-efficient technologies and infrastructures that save money and reduce environmental impacts, or a greater production of goods and services even as the need for energy and other natural resources is diminished. The balance of this paper walks through five initial steps in this analysis. It then offers suggestions on how the final assessment might actually be undertaken and completed.

In the second section, we lay out the reasons that intelligent energy efficiency improvements matter from the perspective of a more robust and sustainable economy. The third section discusses the rise of the network society (economy) from a variety of surprising perspectives, and the fourth section then reviews the history and the trends that drove the development of smart appliances and networks. From there, the fifth section explores how the accelerated development of these technologies might drive productivity enhancement that might bolster the lagging American (and global) economy. The sixth section offers near-term next steps that might provide a more complete productivity assessment of ICT-enabled networks. The last section draws preliminary conclusions.

Why It Matters

For understandable reasons, business leaders and policymakers have been focused on the lagging performance of the economy since the recession of 2008 and 2009.¹ While the size of the nation's economy, measured as real or inflation-adjusted gross domestic product (GDP) within a given year, was about 6% above the prerecession 2007 peak (reflecting a very weak growth rate of about 1% annually), the number of jobs in 2013 was still 1.7 million fewer than recorded in 2007 – even as there were 16.5 million more people within the United States. Still, the focus on the most recent downturn may be distracting attention from the longer-term, perhaps more troubling economic trends as shown in figure 1 on the following page.

Figure 1 examines the long-term historical trend in the nation's average annual growth in real GDP over the period 1970 through 2012. It then reviews Woods and Poole's (2014) future projections from 2012 through 2040.² The actual year-to-year change in GDP is shown by the solid blue line, while the trend over time is highlighted by the dashed red line.

¹ Note that the National Bureau of Economic Research dates this last recession from December 2007 to June 2009.

² While the historical data from Woods and Poole (2014) are taken from the Bureau of Economic Analysis, the forecast is provided by Woods and Poole's own future projections of how the economy is likely to perform

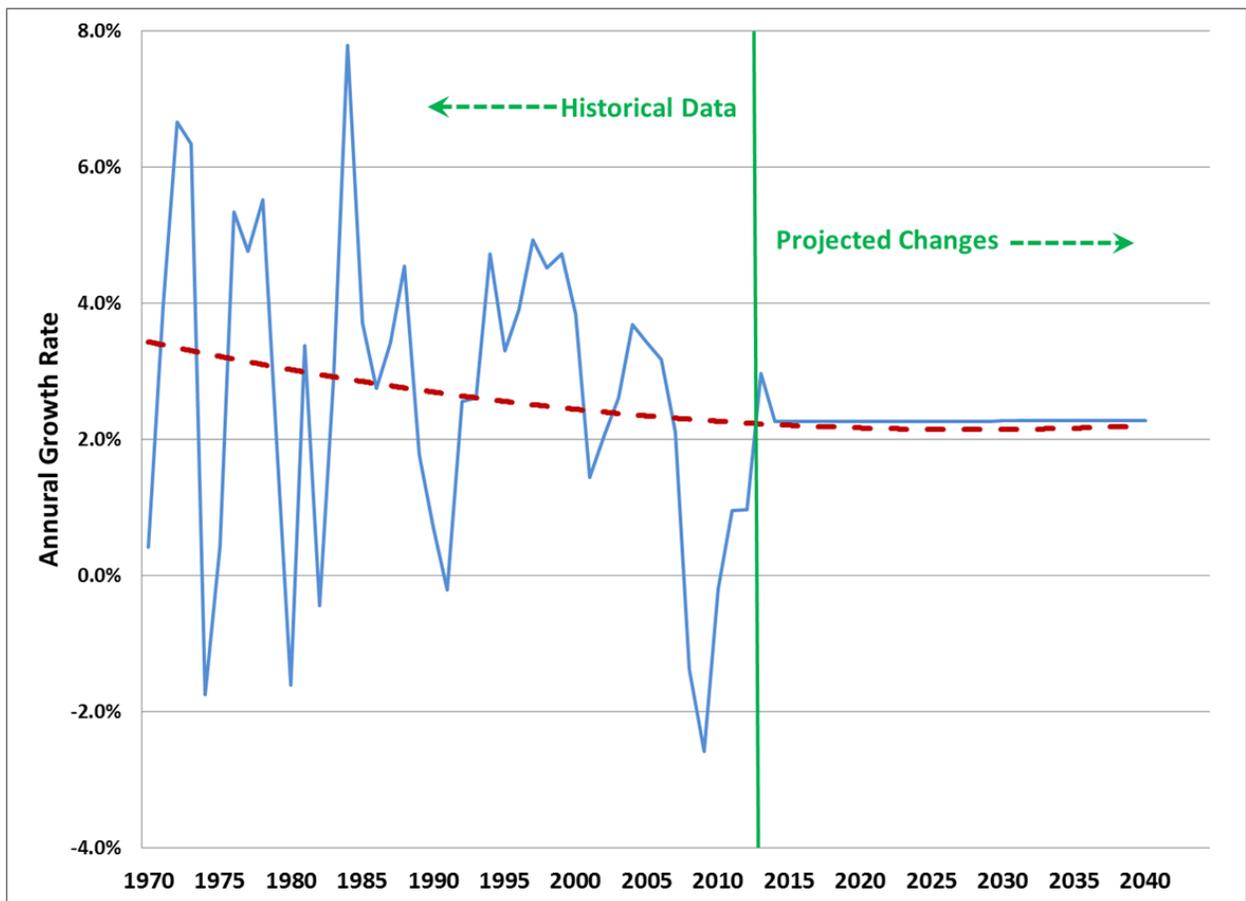


Figure 1. U.S. historical and projected economic growth rates, 1970–2040. *Source:* Economic and Human Dimensions Research Associates calculations based on Woods and Poole (2014).

Of immediate interest is the volatility in annual growth rates that are shown during the historical period of the chart. Perhaps the more prominent feature of figure 1, however, is the slow but markedly downward trajectory in the growth of the U.S. economy over time. Compared to an average annual growth of 3% or more in the nation's GDP through the 1970s, and an average 2.5% over the years 1980 to 2012, projections suggest an anemic GDP growth of just 2.3% annually over the period 2012 through 2040. That level of economic activity may be insufficient to provide the new jobs and incomes to meet expectations of a growing population.

As we explore the economic record, the evidence suggests that accelerated investments in smart appliances and ICT-enabled networks will be among the tools that can reduce the volatility of the U.S. economy (i.e., the significant year-to-year, up-and-down changes over time), restore a greater vitality in overall economic activity, and reduce overall environmental burdens.

through the year 2040. Although providing somewhat different estimates of future economic activity, OECD (2013) and IHS Global Insight (EIA 2014a) show similar projected trends.

Summarizing the trends in figure 1 above, table 1 highlights the average annual growth rates over the historical period (1970 to 2013) and the projected period (2013 to 2040). It also adds an extra element of detail by decomposing the economy's overall growth rate into two components: the annual change in the nation's population and the per capita GDP, which we refer to here as the economy-wide productivity growth rate.

Table 1. Key economy-wide annual growth rates in the United States 1970-2040

	Population	Productivity	GDP
1970-2013	1.04%	1.63%	2.68%
2013-2040	0.92%	1.34%	2.27%

Note that here, productivity gains refer to changes in per capita GDP.
Source: Woods and Poole (2014).

While total population and the productivity (per capita GDP) of that population are important determinants in the size of a national (or regional) economy, the economy-wide productivity is a major driver of social well-being. All other things being equal, a higher level of productivity tends to support a larger personal income for individuals and households, while a smaller rate of productivity generally leads to weaker income levels. Hence the worrisome feature in table 1 is a weakened rate of productivity improvement. Why worrisome? The 0.29% smaller rate of future productivity improvements (found by subtracting 1.34% from 1.63% shown above) could mean an average of 6 million fewer U.S. jobs over the next three decades. This compares to maintaining economic activity as if it were based on the slightly higher rate of productivity improvement that we saw from 1970 through 2013.

More critically, a less robust economy also means fewer investment resources that will be available for upgrading the nation's infrastructure, and fewer financial resources to fund education, health care, energy, and other research and development (R&D) activities, as well as climate change programs. As we have estimated here, even a 0.29% difference in productivity may diminish economic activity by an annual average of \$530 billion (in 2005 dollars) from now through 2040. Assuming that the combination of government spending and our nation's annual rate of investment are about 35% of GDP, the implication is that the U.S. economy will have an estimated 185 billion fewer dollars available to solve both social and economic problems.³

Why the weakening of economic activity? And how might smart appliances and ICT-enabled networks help correct this trend? Among the reasons for a less robust economy is the inefficient use of energy. Ayres and Warr (2009) document that a lagging rate of converting high quality energy into useful work also diminishes the level of economic output. Building on this idea, Laitner (2013) further documents that in 2010 the U.S. economy was only 14% efficient in converting high quality energy into work, and the rate of

³ The national economic accounts (BEA 2014) show that over the period 1970 through 2012, gross private investment was about 15.2% of GDP, while government spending was about 23.5%. Together they were 38.7% of GDP. In 2012 that figure, largely the result of a lower rate of government spending, dropped to about 35% of GDP, which is the value we use here.

improving this conversion efficiency has been lagging in recent decades. This finding is consistent with Rifkin's (2011) assessment that Second Industrial Revolution technologies and infrastructures are showing diminishing returns.

As we suggest later in this report, ICT-enabled networks—in effect, networks of smart, interconnected devices, appliances, and equipment—facilitate a more collaborative engagement of consumers and producers. And because it is easier to move electrons around rather than to physically ship or transport information, people, and goods, intelligent appliances and networks can be among the major catalysts that help restore a higher level of energy efficiency and economic productivity.

The Rise of the Network Society

Networks have always played a vital role in both social and economic activity. Supported by a changing array of devices and technologies over time, networks enable the coordination and decisions affecting the deployment of goods and services. They also provide links that connect people, organizations, and businesses through space and time.

In the latter quarter of the twentieth century, a new economy emerged that sociologist Manuel Castells identifies as not only networked, but also informational and global:

It is *informational* because the productivity and competitiveness of units or agents in this economy (be it firms, regions, or nations) fundamentally depend on their capacity to generate, process, and efficiently apply knowledge-based information. It is *global* because the core activities of production, consumption and circulation, as well as their components (capital, labor, raw materials, management, information, technology, markets) are organized on a global scale, either directly or through a network of linkages between economic agents. It is *networked* because, under the new historical conditions, productivity is generated through and competition is played out in a global network of interaction between businesses. This new economy has emerged in the last quarter of the twentieth century because the information technology revolution provided the indispensable, material basis for its creation. (Castells 2010, p. 77)

While there is clearly evidence of the growing importance of the network society, there is also a conundrum. Even as people, businesses, and organizations are more connected than ever—the direct result of new innovations as well as dramatically lower costs associated with the use and storage of information—there also appears to be a gradual weakening of the larger productivity improvements across the economy.⁴ Yes, there are hotspots of productivity gains in a number of key sectors, and there are dramatic reductions in the costs of providing and using big data. At the same time, however, those information leaps have not materialized as an economy-wide benefit.

The reason is twofold. First, social networks like Twitter and Facebook, more than intelligent building and industrial energy efficiency systems, predominate among the

⁴ As one reviewer commented, countervailing trends such as information overload and the abundance of junk may limit the effectiveness of the increased volume of information.

various economic enterprises. Second, the huge scale of our nation's total existing capital stock and fixed assets – on the order of \$54 trillion dollars as of 2012 (BEA 2014) – will require decades to replace at current rates and current patterns of investment. Thus, there is a need to emphasize both productivity improvement investments (rather than merely generalized replacements and upgrades of existing capital stock), and to accelerate the scale of targeted investments in both smart appliances and ICT-enabled networks. Such investments would be consistent with historical actions such as the Rural Electrification Act of 1935, which enabled rural America to more quickly benefit from access to reliable and affordable electricity resources.⁵

In the sections that follow, we continue to explore the importance of productivity gains from ICT-enabled approaches. We first examine the key ideas behind the economics of networks and then provide an overview of the factors associated with the rise of the Internet as well as the emergence of what we might call intelligent networks. The section concludes with a review of the economic history that gave rise to ICT-enabled networks.

REVIEW OF THE NETWORK EFFECT

The expression "network effect" is applied most commonly to a network externality. It can be thought of as the impact that one user of a good or service has on the value of that product for other people also engaged in the network. For all intents and purposes, the network effect as conventionally discussed is the value of a product or service given the total number of users. It also depends on the way that others are using it. Loosely speaking, network effects are generated by increasing the adoption rate (popularity) of a good or a service (Oz 2010).⁶

The telephone is the classic example of a communication network. The more people who own and actively use the networked device called the telephone, the more valuable the telephone becomes to each owner. This creates a positive externality because a user may purchase a telephone without intending to create value for other users, but the purchase and use of that technology generates a value in any case. Although linked in many different ways, online social networks such as Twitter, Facebook, and Google+ all work much like the telephone – they become more useful as more and more users join and as their participation increases. In these cases the network effect is generally described as a positive network externality. Negative network externalities can also occur, where more users make a product less valuable. Perhaps the most common example is the congestion that occurs when too many users bog down the system and cause delays and lost time.

Our interest here is to identify potential net positive economic effects that are likely to result from an ICT-enabled network. As suggested by the impact of other similar networks, we

⁵ The REA was created by the Roosevelt Administration in 1935 to expedite the availability of electricity to rural areas within the United States. While 90% of urban dwellers had electricity by the 1930s, only 10% of rural dwellers did. But by 1939, the success of the REA had helped an estimated 9 out of 10 farms to become electrified.

⁶ The number of connections (or links) among "n" total participants within a specific network is given by $\text{Links}(n) = n(n - 1)/2$. If the number of participants increases, for example, from 10 to 15 persons, the number of possible connections increases by $\text{Links}(15 \cdot 14/2) - \text{Links}(10 \cdot 9/2) = 105 - 45 = 60$. Hence, the extra 5 participants makes 60 additional connections possible.

expect that an ICT-enabled network would encourage a significantly greater number of uses and users and amplify learning and productivity as the result of a greater collaborative involvement (presumably through a more proactive feedback loop). Innovative uses, greater collaborative involvement, and enhanced productivity are likely to result in higher levels of economic activity. Figure 2 illustrates a working hypothesis of the potential impact of such a network.

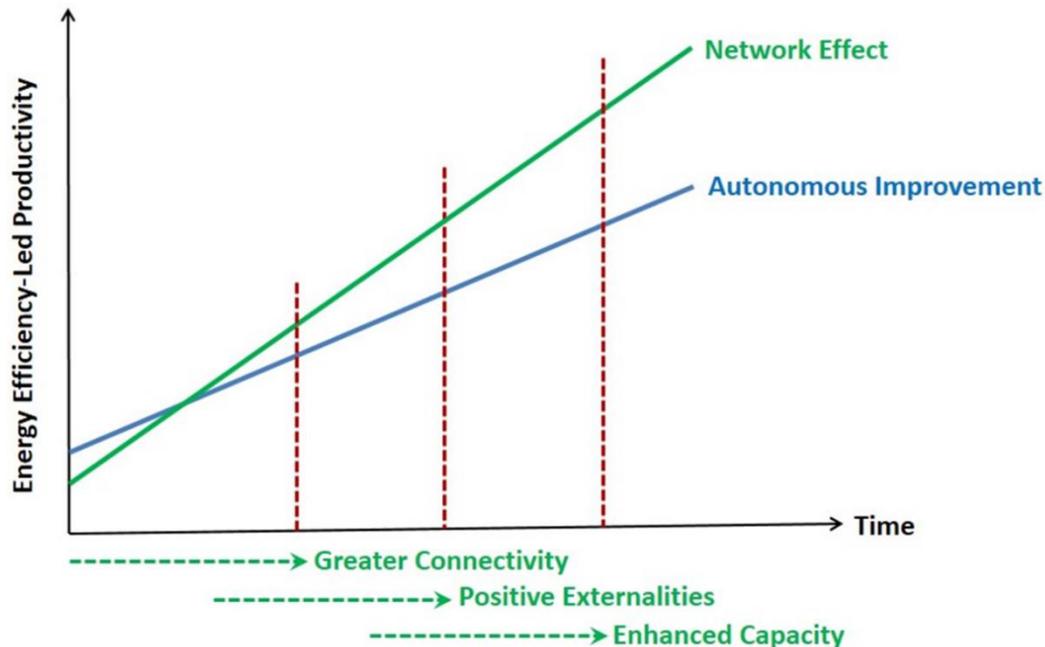


Figure 2. Working hypothesis of the economy-wide impact of an ICT-enabled network. *Source:* John A. “Skip” Laitner (October 2013).

Most of the current public discussion surrounding the smart web or the digital economy focuses either on the impact of social media or the energy consumption of server farms. Alternatively, research funded by the Global e-Sustainability Initiative (GeSI) suggests a one-to-one linkage between ICT and energy savings, with concomitant reductions in greenhouse gas emissions. For example, in the 2012 GeSI study, *Smarter 2020: The Role of ICT in Driving a Sustainable Future*, the Boston Consulting Group found that an array of ICT-enabled solutions offer the potential to reduce worldwide greenhouse gas emissions by 16.5% in that year. At the same time, the investment worldwide would create 29.5 million jobs and yield \$1.9 trillion in lower energy costs by 2020 (GeSI 2012; GeSI 2008; Laitner, Partridge, and Vittore 2012).

Several ACEEE reports have focused on ICT-led gains in energy productivity and the emergence of intelligent efficiency – the ways in which smart, real-time interaction can improve the functioning of building, industrial, or transportation systems (Rogers et al. 2013; Elliott et al. 2012; Laitner et al. 2009; Laitner and Ehrhardt-Martinez 2008). While these studies provide useful initial estimates of improved energy efficiency performance, they are ad hoc assessments that answer a limited set of questions about a narrow range of energy efficiency benefits; and they are non-generalizable to the larger economic productivity gains that might be possible for the nation as a whole. In addition, all of the studies mentioned

above fail to consider the potentially expansive and productive role of the network effect as suggested in figure 2 above. There is clearly a need for more analytical efforts to quantify the system-wide improvements that might be possible through an accelerated investment in ICT-enabled networks.

In figure 2 we see two trend lines as they move through time. The first is the autonomous rate of improvement in the nation's energy-efficiency-led productivity improvements. By autonomous we mean normal improvements that are independent of changes in energy prices or equipment costs, or significant changes in energy and economic policies that shape market activity. This autonomous rate, for example, might follow the prospective 1.34% annual rate of improvement in the economy-wide productivity gains shown in table 1 for the years 2012 through 2040. As we previously noted, this autonomous rate would suggest a slowly weakening level of economic activity compared to the historical period 1970–2012 (and even earlier).

On the other hand, the second trend line represents a step up in the rate of improvement as the result of an accelerated investment and buildup in ICT systems and ICT-enabled networks. The presumption is that such investments, encouraging both a greater level of intelligence but also better coordinated information, will lead to a higher level of economic productivity over time. All of this is supported by three related but separate drivers of productivity: (i) 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; (ii) the set of net positive economic externalities (nonenergy benefits) or spillovers that arise from those greater linkages and interactions; and (iii) 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. As a result of diverting money from more conventional investments and redirecting part of those investments into both ICT and ICT-enabled networks, we hypothesize that the nation's productivity would be enhanced. While the size of the initial benefit would be limited, the net productivity benefit would become stronger over time as a result of the positive feedbacks associated with the ICT-enabled network effects. The assumption is that although smarter hackers, industrial sabotage, and even new forms of terrorism would likely bring negative impacts, nevertheless greater collaboration and coordinated information would lead to a greater net benefit.

We know the economy is forecast to perform at weaker levels, even as investment in ICT systems and networks will increase. The reason appears to be the likely underinvestment in various energy efficiency and intelligent ICT-enabled networks compared to the investments that will be needed to sustain new jobs and incomes. In other words, the evidence suggests that a more expansive and higher level of ICT investments is warranted if we are to encourage a higher level of performance from smart appliances and networks. This insight is not sufficiently or immediately apparent because the national economic accounts do not collect the right energy and economic data, nor do ICT-related investments move sufficiently past social networking activities into the interconnected networks that facilitate the production of goods and services in ways that bolster a more robust economy (Laitner 2013).

BRIEF HISTORY OF THE INTERNET AND EMERGENCE OF INTELLIGENT NETWORKS

The Internet is a global system of interconnected computer networks that use the standard Internet protocol suite (TCP/IP) to serve 2.3 billion users worldwide. It is a network of networks that now consists of an estimated 11.7 billion devices. These include servers, routers, computers, tablets, and, increasingly, mobile phones among private, public, academic, business, and government users. The networks are both local and global in scope as they are linked by a broad array of electronic, wireless, and optical networking technologies (Cisco 2014). The Internet carries an extensive range of information resources and services including websites, the infrastructure to support email, and peer-to-peer networks.

Most traditional communications media, including telephone, music, film, and television are being reshaped or redefined by the Internet, which has given birth to services such as VoIP and Internet Protocol Television (IPTV). Newspapers, books, and other forms of print publishing are adapting to website technology, or are being reshaped into blogs and web feeds. The Internet has enabled and accelerated new forms of human interactions through instant messaging, Internet forums, and social networking. Online shopping has boomed both for major retail outlets and small artisans and traders. Business-to-business and financial services on the Internet affect supply chains across entire industries.

What we have now come to know as the Internet has evolved from rather humble beginnings. An embryonic four-node network, known as ARPANET, was established in 1969 and soon grew to 213 hosts by 1981. The following year, the Internet protocol suite (TCP/IP) was standardized, and consequently, the concept of a worldwide network of interconnected TCP/IP networks, called the Internet, was introduced. Commercial Internet service providers (ISPs) began to emerge in the late 1980s and early 1990s. The ARPANET was decommissioned in 1990, and the Internet was commercialized in 1995 when the last restrictions on its carrying of commercial traffic were removed.

Since the mid-1990s, the Internet has had a revolutionary impact on culture and commerce, including the rise of near-instant communication by email, instant messaging, VoIP “phone calls,” two-way interactive video calls, and the World Wide Web with its discussion forums, blogs, and online commerce. The Internet’s dominance of the global communication landscape occurred almost instantaneously in historical terms. It communicated only 1% of the information flowing through two-way telecommunications networks in the year 1993, had grown to 51% by 2000, and exploded to more than 97% of telecommunicated information by 2007.

Today the Internet continues to grow and, driven in large part by social networking, has displaced point-to-point communication with dynamic, real-time, multidimensional communication. This shift has been profound and disruptive. Networks have emerged as competitors to markets, and open-source commons are challenging proprietary business operations. Many industries have failed to adapt when confronted with the power of peer-to-peer networks, bringing them to their knees. And, yet despite the disruptive, ongoing transformation of culture, business, art, and politics, we have just begun to scratch the surface when it comes to the power of networks like the Internet. Indeed, as we previously

suggested, the use of smart appliances and ICT-enabled networks has yet to become dominant within the economic production of our nation's goods and services.

The next step in the progression will bridge 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, IoT did not yet exist in 2003 because the number of connected things was relatively small, given that ubiquitous devices such as smartphones were just being introduced. Steve Jobs did not unveil the iPhone until January 9, 2007, at the Macworld conference.

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 suggested in figure 3, the Internet of Things was born at some point between 2008 and 2009.

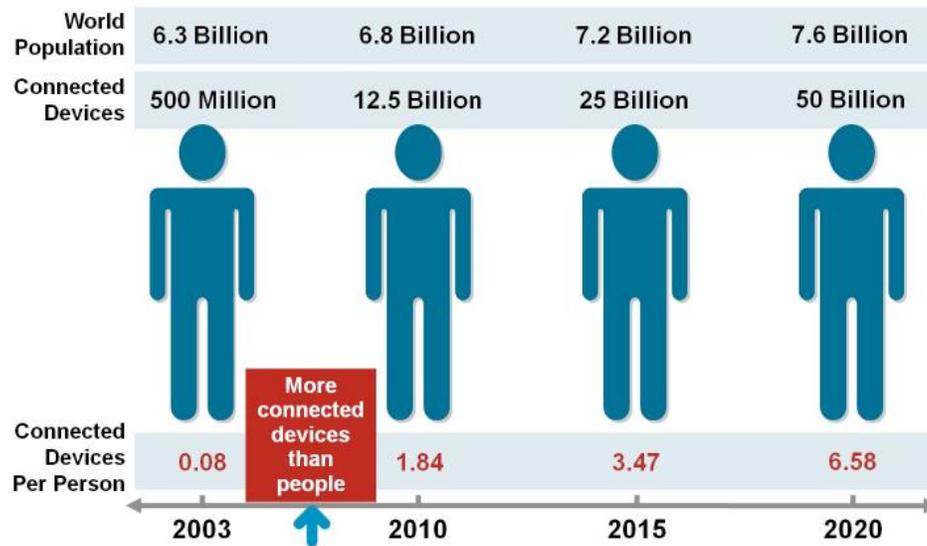


Figure 3. The Internet of Things was born between 2008 and 2009. *Source:* Cisco 2011.

It is fair to say that even with all of the emergent connectivity, IoT remains primarily a loose, noninteractive collection of disparate, purpose-built networks. Today's cars, for example, have multiple networks to control engine function, safety features, communications systems, and so on. Commercial and residential buildings also have various control systems for heating, venting, and air conditioning (HVAC), telephone service, security, and lighting. As IoT is further enabled by smart devices and appliances, the networked objects can be given added capabilities like context awareness, increased processing power, and independent or site-based energy resources. As they are interconnected, and especially as they are managed by the use of multicriteria or multi-objective analytics, what we now refer to as the Internet of Things can become an optimized network of networks, perhaps called the Internet of Everything (IoE). Figure 4 illustrates the IoE.

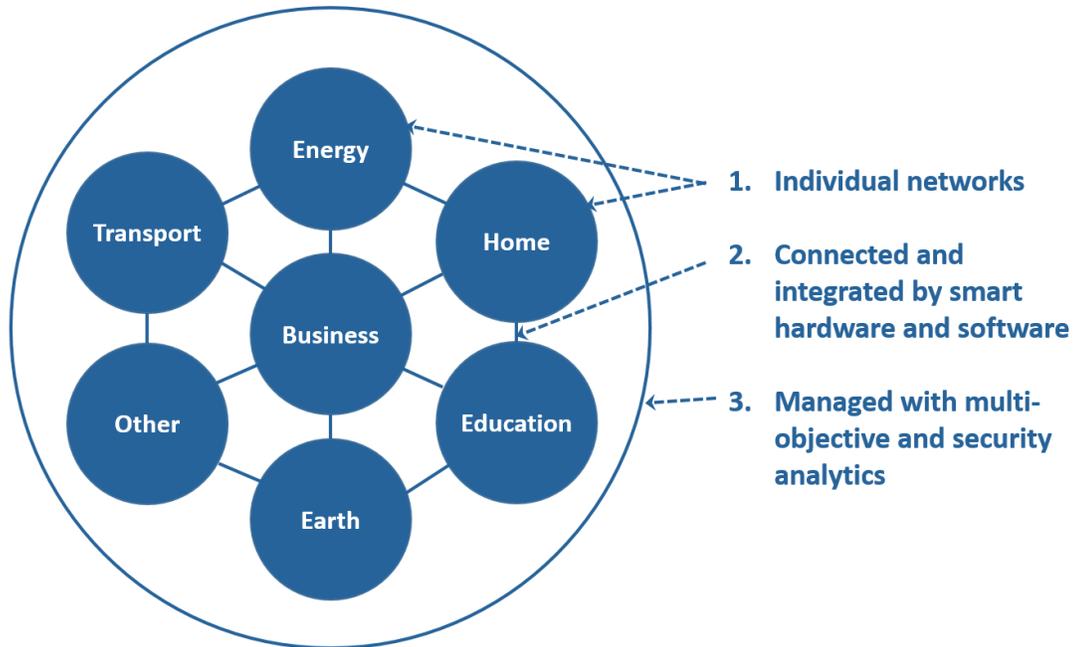


Figure 4. Internet of Everything as an optimized network of networks. *Source:* Laitner as adapted from Cisco Internet Business Solutions Group (2011)

In IoE, both people and smart devices will be able to connect to the Internet in innumerable ways. Today most people connect to the Internet through the use of computing devices such as PCs, tablets, and smartphones, and social networks, such as Facebook, Twitter, LinkedIn, and Pinterest. As the Internet continues to evolve toward IoE, we can move beyond social networks to create highly interactive economic systems that provide new sources of information and learning, and enhance the productivity of our nation's goods and services. We are a long way from IoE, however, with a capital stock of more than \$54 trillion dollars that must be revamped and upgraded (BEA 2014) – even as the value of the economy expands, and even as energy, pollution, and greenhouse gases are substantially reduced. That will require learning, purposeful effort, and large-scale investment dedicated to achieve that optimized result.

THE INTERNET AND SMART APPLIANCES AS A CATALYST FOR LEARNING

Information and communication technologies (ICT), moving away from large centralized sources of information to fast, cheap, and distributed sources, are transforming the way we interface with goods and services as well as how we interact with each other. The precipitous decline in the cost of computing power and the dramatic improvements of programming science have resulted in the potential for every device to become a connected, smart device. Such devices can collect and process enormous amounts of data – making possible many different kinds of analysis and higher levels of performance that were unachievable just a decade ago. The impact of ICT is being felt across industrial 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. The deployment of these next-generation sensor, control, and communication technologies will exponentially aid our

ability to gather, store, manage, interpret, communicate, and act upon disparate and often large volumes of data to achieve greater levels of efficiency and increased economic activity. They will also catalyze new levels of economic interaction that would have been unthinkable before the realization of the network effect.

One key element of this ICT-enabled network transformation is that of smart appliances. This catch-all term can be used to describe varying degrees of connected domestic devices. In the interest of a more sharply defined perspective, however, we can break down this broad, sometimes vague term into three categories, with each level representing an increase in ICT complexity: (1) connected appliances, (2) smart appliances, and (3) ambient intelligent appliances. Figure 5 represents these categories.

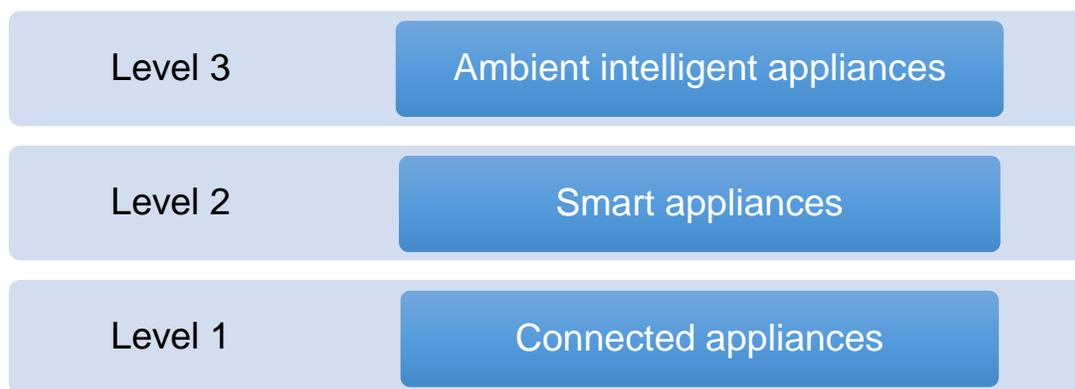


Figure 5. Categories of smart appliances

Technically speaking, the “smart” in “smart appliance” typically refers to the smart grid and the appliance’s ability to respond to fluctuations in the electrical power grid by adjusting its own energy usage when appropriate. Connected appliances, on the other hand, have the ability to communicate, but in more limited ways, and although connected appliances may form a home area network (HAN) among themselves, they lack smart grid integration and the ability to engage in robust network-to-network communication. All smart appliances are necessarily connected appliances, but not all connected appliances are smart. Ambient intelligent appliances, discussed later in this section, represent the highest order of ICT complexity. While the description that follows is limited to the residential market for purposes of this assessment, the idea of intelligent devices can easily extend into the commercial building and manufacturing sectors as well as the various transportation systems.

Connected Appliances

A number of appliance manufacturers are merging ICT capabilities with their residential appliance product lines. However U.S. smart meter penetration as of 2013 was only 23% (Lacey 2013). Because of our limited smart grid infrastructure, the great majority of these ICT-enabled devices are more accurately characterized as connected appliances. Although they have the ability to form a home area network among themselves, connected appliances are, in essence, “dumb” devices with an added feature, that is, a one-dimensional ability to send notifications and receive instructions remotely via a user’s smartphone.

In 2011, Samsung unveiled one of the earlier iterations of connected appliances, a refrigerator with an eight-inch LCD screen and Wi-Fi connectivity. The fridge had the ability to run a total of eight apps: Memos, Photos, Epicurious (a recipe app), Calendar, WeatherBug (weather), Associated Press (news), Pandora (music), and Twitter. But this early, connected appliance could not be controlled remotely, nor could it communicate with other connected devices in the home (Crook 2011).

As manufacturers continue to add ICT-integration to their product lines, connected appliances are moving beyond one-off feature sets and are maturing as a technology, evolving into nodes on a dynamic home network. Users can remotely control these appliances through web-enabled devices and receive real-time feedback. Through LG's Line messaging app and a new service called HomeChat, owners of LG smart appliances will be able to give natural language commands to their devices. If a user tells the system, "I'm going on vacation," for instance, the network will put the refrigerator into power-saving mode and program the robotic vacuum cleaner accordingly. The app will also update the user as to what is in the fridge, show a history of the robotic vacuum's cleaning trips, and recommend recipes via the smart oven. The LG system also provides for smart diagnoses of its upcoming smart appliance lineup, allowing users to help avoid unnecessary repair visits, download new washing machine cycles, and more (Dent 2013).

Although connected appliances may improve energy efficiency, the devices barely scratch the surface when it comes to the levels of efficiency achievable through the network effect. We begin to see a glimpse of the network effect as we explore the improved energy efficiency performance experienced when connected appliances transition from level 1 to level 2 in our three-tiered hierarchy and become smart appliances.

Smart Appliances

In contrast to connected appliances, smart appliances employ multidimensional abilities in the form of network-to-network (n2n) communication. With smart appliances, the home area network interfaces with the energy network, or smart grid. This communication, in turn, allows smart appliances to engage in load shifting and enable demand response, thereby lessening the burden on the electricity grid, permitting a higher penetration of distributed, intermittent generation sources (such as wind and solar) as well as potentially reducing the need for additional supply because of an enhanced ability to manage peak electricity demand.

To get a better sense of how ICT-enabled smart appliances may deliver efficiency gains beyond those achieved by connected appliances, we look to a recent case study. In 2012 the Glasgow Electric Plant Board, located in Glasgow, Kentucky, partnered with the Tennessee Valley Authority and General Electric (GE) to implement a smart appliance demonstration project. The project targeted 20 residential households and provided each with a demand-response-enabled appliance bundle, which included the GE Nucleus™ home energy management system. This smart appliance project was conducted in four phases: (1) measuring the baseline energy of residential appliances, (2) measuring the impact on energy and demand profiles of selected appliances resulting from replacing the appliances with the GE Energy Star bundle, (3) determining the ability and the willingness of residential homeowners to modify load based on information provided by the utility, and, (4)

examining consumer sentiment regarding perceived benefits of modifying their behavior (Pluckett et al. 2013).

In Phase 3 of the project, each participating resident was sent a high-price-period signal by the utility. The Nucleus home energy management system reacted to this energy network signal by directing all of the smart appliances to shift into a low-energy mode. The low-energy mode for each appliance in the bundle is outlined in table 2.

Table 2. Appliance low-energy modes

Appliance	Low-energy mode
Dishwasher	Dry-cycle disabled
Clothes washer	Cold water only
Dryer	Cycle runs in reduced heat mode; one of two heating elements deactivated
Heat pump water heater	Set point lowered to 110° F, heat-pump-only mode activated, upper resistance element deactivated
Refrigerator	Freezer set point raised, features disabled include TurboCool, quick chill, quick defrost, quick freeze, quick ice
Range	Lower oven prevented from starting, outer broil elements disabled on upper oven, preheating slowed, burners reduced to ~80% power, self-clean mode disabled

Source: Newton 2013

The project results demonstrate that smart appliances can have a material impact on residential demand response and load shifting away from peak hours. Project participants allowed third-party control of their smart appliances 97% of the time over a 30-week period; the impact in the energy footprint is evident, as seen in figure 6.

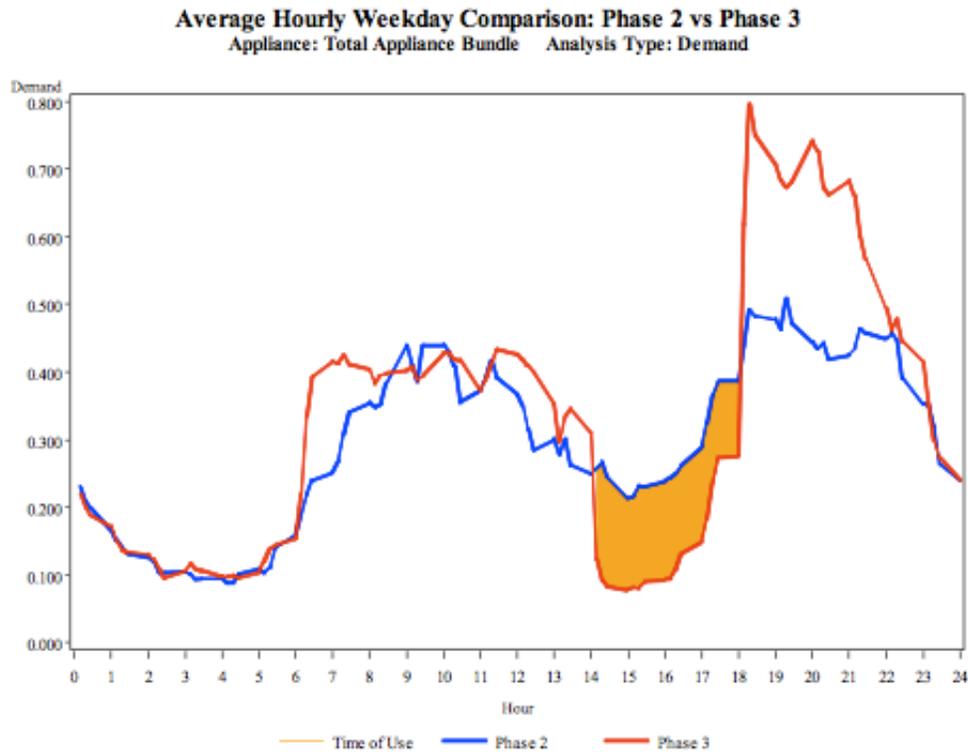


Figure 6. Shape of smart appliance electricity demand. *Source:* Newton 2013.

Indeed, the ability of smart appliances to either shift their time of operation or curtail their operation temporarily upon request can lead to power grid benefits manifested as savings in wholesale power production costs.⁷ A 2010 report by the U.S. Department of Energy (DOE) Pacific Northwest National Laboratory (PNNL) conducted a cost-benefit study of residential smart appliances from a utility-grid perspective. On the benefits side of the calculus, NPPL considered peak-load shifting for some percentage of appliance loads and ancillary services provided by responsive appliance loads. The savings derived from the smart grid capabilities of an appliance were then compared to the slightly higher cost of the smart appliances (Sastry et al. 2010). Tables 3 and 4 summarize smart appliance benefit-to-cost ratios based on optimistic and pessimistic scenarios respectively.⁸

⁷ It is worth noting that the particular case study highlighted in figure 6 focused on shifting peak demand from a more expensive time range, 2:00 pm–6:00 pm, to a less expensive time range, 6:00 pm–10:00 pm. Net energy savings would presumably emerge as the utility also focused more broadly on greater levels of annual energy efficiency benefits.

⁸ NPPL's optimistic scenario generally assumes that all customers can receive grid signals and communicate these to the appliance, that all customers are willing to shift 100% of their on-peak loads, and that customers will make available 100% of their load all the time for 10-minute temporary curtailment needed for spinning reserves. The pessimistic scenario generally assumes that 50% of customers can receive grid signals and communicate these to the appliance, that 70% of customers are willing to shift on-peak loads (90% in the case of the 10-minute curtailment needed for spinning reserves), and that on average these customers will shift about 50% of their on-peak load.

Table 3. Smart appliance benefit-to-cost ratios (optimistic assumptions)

	Dishwasher	Clothes washer	Air conditioner	Freezer	Refrigerator	Dryer
PJM 2006	528%	563%	733%	539%	536%	680%
ERCOT 2008	817%	871%	1060%	881%	877%	1,054%
NYISO 2008	367%	403%	585%	357%	355%	462%
NYISO 2006	353%	389%	712%	346%	344%	442%
CAISO 2008	319%	356%	554%	313%	312%	396%

Source: Sastry et al. 2010

Table 4. Smart appliance benefit-to-cost ratios (pessimistic assumptions)

	Dishwasher	Clothes washer	Air conditioner	Freezer	Refrigerator	Dryer
PJM 2006	136%	134%	131%	150%	150%	207%
ERCOT 2008	203%	200%	295%	230%	228%	337%
NYISO 2008	107%	106%	139%	112%	111%	147%
NYISO 2006	112%	112%	160%	119%	118%	160%
CAISO 2008	99%	100%	135%	102%	101%	134%

Source: Sastry et al. 2010

Breaking down the results presented in the optimistic scenario, spinning reserves accounted for an average of 46% of the total benefits shown above, 32% of the total benefits were derived from peak-load shifting, and 22% came from the feedback effect. The report concluded that the annual benefits realized from having smart grid capabilities in an appliance are significantly greater than the higher costs. Although the gains in energy efficiency achieved through smart appliance capabilities can dwarf those achieved through merely connected appliances, both categories pale in comparison to the levels of energy efficiency possible through robust application of the network effect.

We next turn our attention to level 3, or ambient intelligent appliances.

Ambient Intelligent Appliances

Ambient intelligent (AmbI) appliances, as illustrated in figure 7, represent the highest order of complexity within our intellectual framework. “AmbI” refers to the ambient intelligence paradigm, a model of ubiquitous computing built on an IoE foundation.

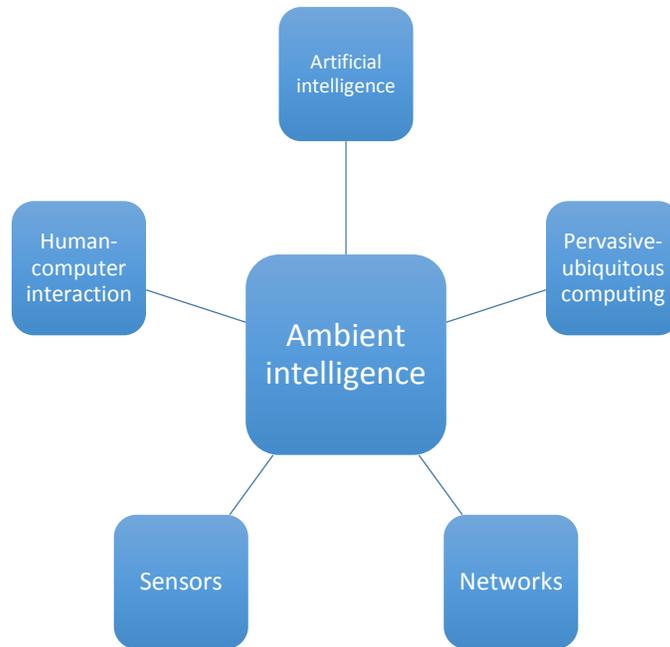


Figure 7. The ambient intelligence paradigm. *Source:* McDonnell adapted from Aarts and Marzano 2003.

In an ambient intelligent world, devices, including appliances, work in concert to support people carrying out their everyday life activities in an easy, natural way using information and intelligence that is hidden in the network connecting these devices (Zelkha et al. 2001). Accordingly, an AmbI appliance is fluent in network-to-network communication, simultaneously interfacing with other AmbI appliances on a HAN, dynamic nodes on the energy network, or smart grid, along with the abundance of other networks inherent in the IoE. The ambient intelligence paradigm builds upon pervasive computing, ubiquitous computing, profiling, context awareness, and human-centric computer interaction design and is characterized by systems and technologies that are:

- Embedded: many networked devices are integrated into the environment
- Context aware: these devices can recognize you and your situational context
- Personalized: they can be tailored to your needs
- Adaptive: they can change in response to you
- Anticipatory: they can anticipate your desires without conscious meditation (Aarts and Marzano 2003)

Ambient intelligence, part and parcel of IoE, embodies a vision of small, inexpensive, robust networked processing devices, distributed at all scales throughout everyday life and generally turned to distinctly commonplace ends. The vision of AmbI is that technologies disappear into the built environment, weaving themselves into the fabric of everyday life until they are indistinguishable from it. In this IoE environment, people are surrounded by intelligent objects that can sense context and respond accordingly, all without conscious mediation on the part of the user (Aarts and Marzano 2003). Appliances operating within an

AmbI environment can leverage the full power of the network effect to achieve exponential gains in energy efficiency.

Until the IoE becomes more pervasive, there will not be a sufficient number of operational devices that can be correctly characterized as AmbI appliances. That said, it is instructive to explore the forms such devices will take as well as the scale of network effect that is possible through their use. In the residential context, for example, an ambient intelligent environment might interconnect lighting and environmental controls with personal biometric monitors woven into clothing so that illumination and heating conditions in a room might be modulated, continuously and imperceptibly. Another example of AmbI appliances might involve refrigerators “aware” of their suitably tagged contents, able to both plan a variety of menus from the food actually on hand and warn users of stale or spoiled food.

The network effects created by the interfacing of these new ICT-enabled technologies catalyze learning and reshape the economic landscape. Value is reexamined, and interactions that previously would have not been considered are brought into the economic landscape. As learning and innovations accelerate, such network effects will foster higher levels of thinking and generate exponential gains in energy efficiency as well as new methods of economic engagement.

Drivers of Smart Appliances and Network Development

As with most things, market penetration of new innovations is the result of lower costs and improved performance levels over time. Table 5 provides a glimpse of how computing power has changed over the last 68 years by comparing the size, cost, and power of the first electronic general-purpose computer, the Electronic Numerical Integrator and Computer (ENIAC), with the typical laptop of today.

Table 5. Computer characteristics, 1946 and present

	Electronic Numerical Integrator and Computer (ENIAC)	Typical laptop
Year	1946	2014
Performance	5,000 addition problems/sec.	2.1 billion operations/sec.
Power use	150,000 watts	65 watts
Weight	30 tons	5.6 pounds
Size	8' x 3' x 100'	15.2" x 10.2" x 1"
What is inside	17,840 vacuum tubes	1.2 billion transistors
Cost	\$487,000	\$430

Source: Author estimates based on a variety of sources.

We can generate a more concrete metric that highlights the dramatic increase in the performance of computers by converting ENIAC’s 1946 cost into 2012 dollars and compare its 5,000 operations per second with the 2.1 billion operations per second that can be carried out by today’s laptop. Based on this comparison, the 1946 cost of roughly \$1,168 per

operation (in 2014 dollars) declined by an average rate of about 28% per year over the last 68 years (authors' calculations). The cost of cell phones has fallen dramatically as well. In 1982 a Motorola DynaTAC 8000X sold for \$3,995. It weighed two pounds, stored 30 phone numbers, and allowed an hour of phone calls on a single battery charge.

Today a smart phone might cost under \$200 with many times the power and capabilities of the Motorola DynaTAC. With this perspective, we can now better appreciate the implications of Moore's law and its impact on computer and other ICT prices.⁹ Table 6 shows the more recent trends in the growth of commodity prices over the period 1987 to 2011. The commodities include energy-related products, construction and manufacturing activities, and ICT-producing industries and services.

Table 6. Growth in real commodity prices, 1987–2011

Sector	CAGR*	Index 1987 = 1.000
All industries	2.44%	1.784
Oil and gas extraction	6.12%	4.161
Petroleum and coal products	6.97%	5.040
Utilities	2.54%	1.828
Construction	3.42%	2.242
Manufacturing	1.88%	1.563
ICT-producing industries	-2.74%	0.514
ICT services	0.79%	1.209

Compound annual growth rate. *Source:* BEA price index by industry, 1987 to 2011 (January 2014).

The average industry commodity saw a compound annual growth rate (CAGR) of 2.44% over the period 1987 to 2011 so that average industrial prices were 1.784 times greater in 2011 than in 1987. The price of utility services was 1.828 times larger, while oil and gas extraction costs were 4.161 times greater. Manufacturing and construction costs rose to a more moderate level of 1.563 and 2.242 times, respectively. The prices of ICT products, however, actually declined 2.74% per year, with an index of only 0.514. While ICT services increased, their 2011 index of 1.209 was significantly less than the average industry commodity prices, so that their relative prices were still substantially less than other goods and services.

Table 7 shows how both the change in performance and relative prices impacted the gross output of key industry, energy, and ICT sectors of the economy. ICT producers and services showed a compound annual growth rate of 8.01 and 6.91%, respectively, while the industry

⁹ Former Intel CEO Gordon Moore suggested in a 1965 paper that the number of transistors on an affordable CPU would double every two years. See <http://www.moorelaw.org/>. The semiconductor industry uses this assumption to set research and development targets.

average increased by only 2.4% annually. Utility services increased by only 0.39% per year, while oil and gas extraction activities declined by 0.37% annually.

Table 7. Quantity index of gross sector output (index 2005 = 100)

	1987	1990	1995	2000	2005	2011	CAGR
Oil/gas extraction	132.12	128.08	125.36	111.54	100.00	120.84	-0.37%
Utility services	78.67	87.56	95.80	130.56	100.00	86.28	0.39%
ICT producers	19.72	24.06	40.70	92.14	100.00	125.41	8.01%
ICT services	29.15	38.11	48.71	82.95	100.00	145.04	6.91%
All industries	57.12	62.41	71.49	90.79	100.00	101.00	2.40%

Source: BEA quantity index by industry 1987 to 2011 (January 2014)

One critical aspect of the ICT story is that the innovations in the ICT-producing sectors, together with the falling prices for IT products and services, converged to drive the first appearance of what we now call the World Wide Web in 1995 (Jorgenson, 2005). This, in turn, drove a large shift in telecommunications investments beginning in the mid-1990s—in effect, a breakthrough we now call the Internet, as suggested by figures 8 and 9.

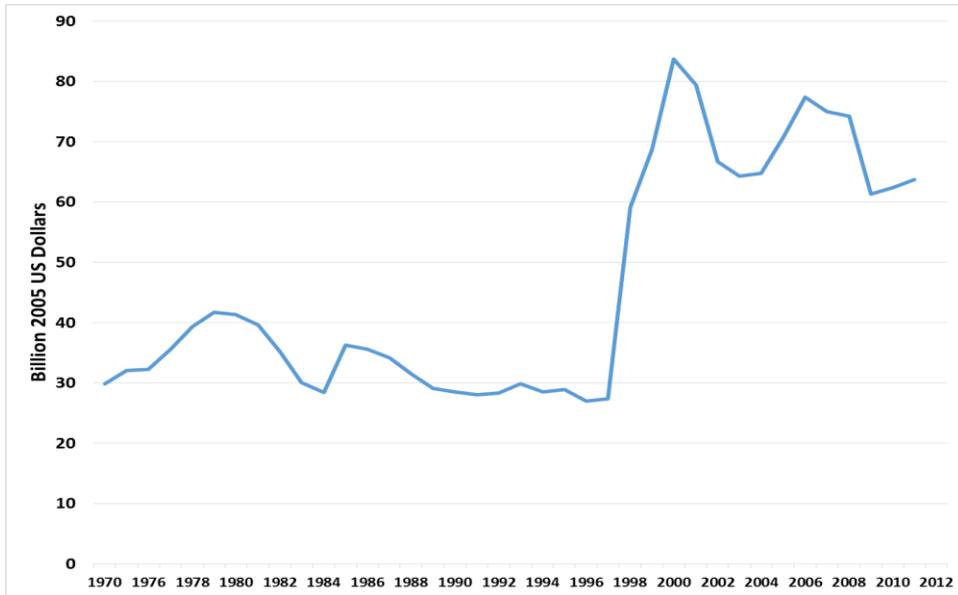


Figure 8. U.S. annual telecommunications investments, from 1970 to 2012. *Source:* United States Dataset, International Telecommunications Union (2013)

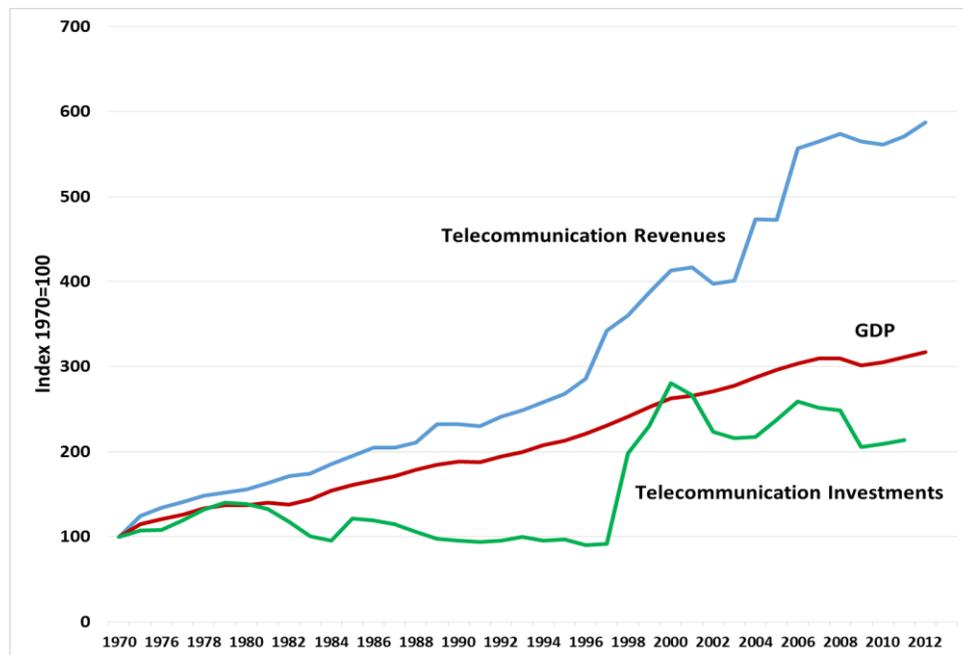


Figure 9. Telecommunications investments, revenues and GDP 1970 to 2012. *Source:* United States Dataset, International Telecommunications Union (2013)

Measured in 2005 dollars, telecommunications investments followed a slow downward trend over the period 1970 through about 1997, hovering close to about \$30 billion annually. Figure 8 shows the dramatic rise in annual investments to \$59 billion in 1998 and peaking at \$84 billion in the year 2000. Although the annual outlays have tapered somewhat in the following decade, they continue at twice the pre-1997 values. Figure 9 shows another perspective indexing both annual telecommunications investments and revenues as they compared to growth in GDP (where 1970 = 100 based on 2005 dollars). While the investment index provides the same pattern as shown in figure 8, telecommunications revenues grow more steadily, with a sharp 1997 inflection that, unlike investments, continues to grow and reaches a 2012 value just short of 600, compared to a value of 200 for investment. In fact, telecommunications revenues have risen from 1.9% of GDP in 1970 to 3.5% by 2012 (ITU 2013). GDP itself rose to an index value just over 300.

Perhaps the key element not immediately apparent from figure 9 is that, despite the very strong growth in ICT investments and revenues, GDP growth (shown especially clearly in figure 1) has continued to weaken over the period 1970 to 2012. More serious, compared to the historical growth of 2.7% highlighted in table 1, the annual growth will weaken to an anemic 2.3% through 2040. As we have already mentioned, there may be two factors in this regard. First, social Internet activity is dominant over economic and industrial Internet activity. This generates business revenue streams but without necessarily increasing the larger productivity of the U.S. economy compared to the production of durable goods and professional services. Second, and closely related, despite the growth of social media, the ICT-enabled activities have not been sufficiently robust to accelerate a greater rate of energy efficiency improvement. As discussed later in this report, a flattening rate of energy efficiency and productivity improvements tends to weaken overall economic activity.

Table 8 highlights the real annual growth rates of ICT, electric power, and total private assets as they compare to growth in GDP. Even as early as the period 1929 to 1970, telecommunications assets expanded at a greater rate than most other sectors in the economy. Indeed, a preliminary review suggests that communication equipment may be slowly substituting for electricity services.

Table 8. Annual growth in ICT, electric power, total private assets, and GDP

	Compound annual growth rate		
	1929–1970	1970–1995	1995–2012
Communication/information equipment	4.0%	6.1%	5.8%
Electric/other power structures, equipment	2.6%	1.9%	1.7%
Total private assets	2.3%	2.9%	2.2%
Gross domestic product	3.7%	3.1%	2.5%

Source: BEA Table 2.1. Current-cost net stock of private fixed assets, 1929–2102, Jan 29 2014.xls.

Table 9 provides similar information about ICT, electric power, and total private assets as they all compare to GDP, but from the perspective of billions of 2009 dollars. ICT assets, starting at a much smaller value in 1929 (about 10% of the electric power assets), and driven by the significant investment leap beginning in 1998, have expanded to very nearly the same scale by 2012.

Table 9. ICT, electric power, and total private assets compared to GDP (billion 2009 dollars)

	1929	1950	1970	1990	1995	2000	2005	2010	2012
Communication and information processing equipment	34	59	169	588	737	1,113	1,445	1,820	1,919
Electric and other power structures and equipment	332	454	942	1,430	1,502	1,600	1,727	1,937	2,013
Total private assets	4,624	5,725	11,677	21,525	23,852	28,066	31,733	33,969	34,448
GDP	1,056	2,182	4,718	8,945	10,164	12,565	14,236	14,779	15,471

Source: BEA Table 2.1. Current-cost net stock of private fixed assets by type, 1925-2102, Jan 29 2014.xls.

The data in table 10 reveal an equally 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 10. Estimated ICT electricity use over time

	2012		2030	
	TWh	% total	TWh	% total
AEO 2008 (2005–2030)	281	7.1%	419	8.6%
AEO 2011 (2008–2035)	191	5.1%	246	5.7%
AEO 2014 (2011–2040)	134	3.6%	123	2.8%

Source: EIA Annual Energy Outlook (various 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 total electricity demands 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 of the ICT-enabled productivity improvements appear to be dampening the demand for electricity consumption. Although it is not shown explicitly in table 7, 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 10 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. While the cost and performance of ICT processing power is greatly improving over time, the cost of data storage has been falling dramatically, as shown in figure 10 below.

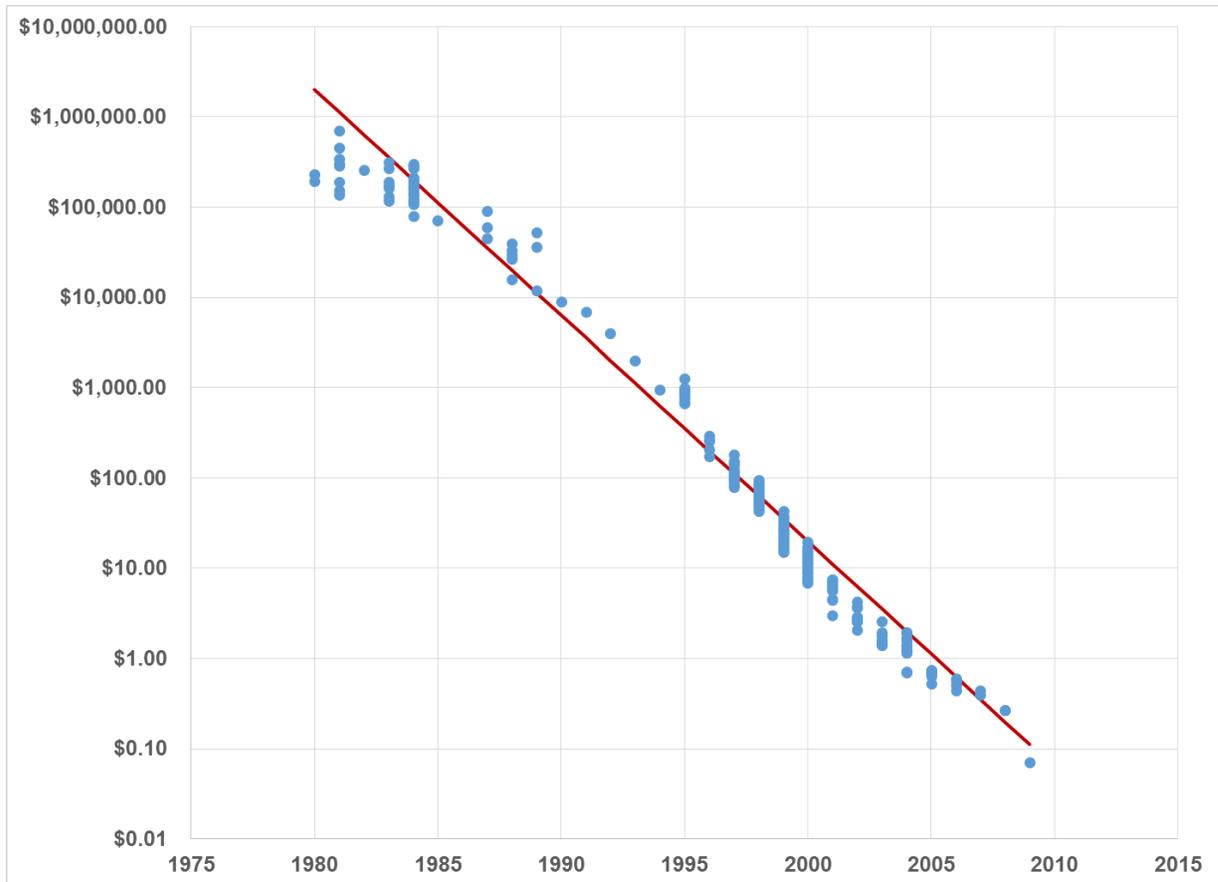


Figure 10. Hard drive cost per gigabyte 1980–2009 (in current dollars). *Source:* Komorowski (2014).

In a review of more than 270 hard drive storage systems, Matthew Komorowski (2014) shows that over the last 30 years, space per unit cost has doubled roughly every 14 months, in effect, increasing by an order of magnitude every 48 months. From a typical cost of more than \$200,000 per gigabyte in 1980, several terabyte-plus drives have recently broken past \$0.06 per gigabyte (with all values in current dollars). This translates into an annual 36% decline in the cost of data storage over that time frame. As we note later in this report, the rapid drop in the cost of storage, as well as the dramatic improvements in processor speeds and programming techniques, have opened up new possibilities in the use and management of real-time data that can enhance energy efficiency gains, systems performance, and productivity.

Table 11 shows yet a further indication that, just as ICT-related electricity demands are lessening even as a greater number of goods and services are being provided, the economy is undergoing a potentially significant dematerialization. Effectively, smart appliances and ICT networks enable increased economic activity while continuing to reduce total energy needs. Here we are looking at the compound annual growth rate of the nation's real GDP as it compares to both changes in energy intensity and the total production of various industrial products over the period 1995 through 2012.

Table 11. Indicators of dematerialization of the economy

Economic indicator	CAGR 1995–2013
Real gross domestic product	2.44%
Total industrial production	2.22%
Manufacturing production	2.10%
Food and kindred products	0.99%
Basic chemical manufacturing	0.97%
Petroleum and coal products	0.95%
Primary metals production	0.27%
Agricultural chemicals	-0.29%
Total raw steel production	-0.35%
Resins and synthetic rubber	-0.40%
Nonmetallic mineral products	-0.47%
Paper and allied products	-1.29%
Energy intensity	-2.00%

Source: EIA short-term energy outlook (September 2014)

In short, while growth in GDP averaged 2.44% over the 18-year time horizon ending in 2013, various manufacturing products including food, chemicals, petroleum products, and primary metals production grew at a smaller rate; at the same time, agricultural chemicals, total steel production, resins and synthetic rubber, nonmetallic mineral products, and paper and allied products showed a significant decrease in output. The nation's energy intensity also decreased at a significantly higher rate of 2% from 1995 to 2013, compared to a rate of 1.2% from 1950 to 1995.

ICT-Enabled Networks as Productivity Tools

The evidence indicates a strong likelihood that accelerated investments in smart appliances and ICT-enabled networks can provide the basis for greater energy and economic productivity benefits. Costs continue to decline for ICT products and services relative to other goods and services, and their overall performance has benefited from steady improvements. To date, however, we lack definitive evidence of a positive relationship between increased investment in ICT-enabled networks and a more robust economy. Given such difficulties, we use a set of thought exercises in this section to infer the ways in which ICT networks are likely to enhance both energy efficiency and overall economic productivity.

First, while it is difficult to measure the effects of ICT networks on productivity and energy efficiency, we know how many subscribers are on Facebook, as well as how many Google users or Amazon deliveries there might be. We also know what the growth rate of ICT-related sectors is likely to be as they compare to other sectors of the economy. But 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. We have case studies and ad hoc

estimates, but not a consistent tracking of data that inform consumers, business leaders, and policymakers about the synergies, learning, collaborations, and innovations that are likely made possible by the more dynamic networks.

Second, the available data focus on the supply-side perspective – on providing sufficient and timely energy and materials to the production process – rather than on helping business leaders and policymakers understand the benefits of ICT appliances and networks. The critical example in this regard is the standard assumption that we need more energy supply, when instead we should be thinking about how to generate greater conversion efficiencies – that is, how to use energy more productively to transform matter into desired goods and services – in order to ensure increased economic productivity. In effect, we treat and track energy as a commodity to be sold rather than as the capacity for economic work.

Finally, some engineers and economists make oblique references to people-centered communication, as if providing real-time information is sufficient to motivate appropriate action. Yet we fail to understand or sufficiently integrate cultural and social factors of the economy. In effect we make the assumption that if costs and benefits are shown in intriguing ways, then producers and consumers will automatically make smart decisions. But a variety of studies by social psychologists and behavioral economists reveal that people often act in ways that may be better described as “socially rational” and “predictably irrational” (Ehrhardt-Martinez and Laitner 2009). As Brendan Greeley (2013) wrote in *Bloomberg Businessweek*, economists have assumed that people were “economically rational” so there has been “no need for data on how people act.” And conveniently relying on a single person, the so-called representative agent, “made the math behind the modeling easier.” The article notes that the standard mathematical assumptions about consumer behavior have been wrong in regards to the recent financial crisis and its aftermath – and with other economic challenges. Hence, there is a need to explore the ways in which individual behavior is shaped by the social context within which people operate, and to present an alternative framework for modeling and encouraging more conservation and more energy-efficient behavior.

A more robust, people-centered model recognizes that while individuals may not always behave in economically rational ways, their behaviors may be entirely rational from other social vantage points. In fact, individuals often determine what is and is not an appropriate behavior by gleaning information from their own observations, from their peers, and from interactions within their sphere of social influence. Therefore 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. This alternative approach has important implications for program design and policy recommendations.

While this analysis has yet to provide a systematic integration of social science insights or assemble the necessary energy and economy-wide productivity data to document net positive benefits of smart appliances and ICT-enabled networks, it does provide a range of working estimates of prospective GDP benefits. These preliminary calculations are based on the development of likely pathways and outcomes that help us establish a set of working hypotheses that can be explored with additional research. We begin by highlighting what we know broadly about costs and savings associated with ICT networks and appliances and

then provide a set of thought experiments to suggest the magnitude of benefits that might accrue from greater levels of appropriate investments.

REVIEW OF COSTS AND SAVINGS

Today's world relies to an astonishing degree on systems, tools, and services that belong to a vast and still growing ICT-enabled network. This network underpins our national prosperity, health, and security. In recent decades, it has also boosted U.S. labor productivity for key sectors of the economy more than any other set of forces (PCAST 2010). Here we provide a variety of metrics and ad hoc studies that: (a) support the working hypothesis discussed above, that redirecting investments into both ICT and ICT-enabled networks will enhance the nation's energy and economic productivity; and (b) provide a foundation for several thought experiments aimed at exploring the magnitude of potential benefits. Our review includes intelligent energy efficiency in the residential and commercial building sectors, transportation systems, electricity production and distribution, health impacts, and larger economy-wide productivity benefits – all potentially driven or supported by ICT-enabled networks. These observations and studies provide a backdrop for the thought experiments that follow by highlighting specific opportunities for ICT investments that can enhance economic productivity and energy efficiency.

ICT and Energy Efficiency in the Building Sectors

A strong historical record suggests that energy efficiency can provide perhaps the largest single wedge of new energy services to power the economy (see, for example, Lovins et al. 2011; Harvey 2010; Committee on America's Energy Future 2009; Laitner et al. 2010; National Academy of Sciences et al. 2009; McKinsey 2009; Gold et al. 2009; American Physical Society 2008; Ehrhardt-Martinez and Laitner 2008; and McKinsey 2008). More recently the American Council for an Energy-Efficient Economy documented an array of untapped, cost-effective energy efficiency resources roughly equivalent to 250 billion barrels of oil (Laitner et al. 2012). That is a sufficient scale to enable the United States to cut total energy needs in half compared to business-as-usual projections for the year 2050. Building improvements are a very big slice of the energy efficiency resource.¹⁰

The continuum of smart appliances and other intelligent technologies – ranging from building management systems to advanced lighting and space conditioning components – provide an array of opportunities to optimize energy use within buildings. Rogers et al. (2013) suggest a range of savings from 5 to 50% depending on the specific end use and the mix of smart technologies employed. Moreover, they estimate that energy bill savings from intelligent energy efficiency measures in commercial and manufacturing buildings could exceed \$50 billion for electricity alone by 2030. The National Renewable Energy Laboratory (NREL) published a database as part of a tool to prioritize more than 400 possible energy efficiency investments in residential and commercial buildings (Farese et al. 2012). As

¹⁰ As a preview of the multiple benefits associated with energy efficiency upgrades, Laitner et al. (2012) also note that capturing this energy efficiency resource could generate from 1.3 million to 1.9 million jobs while saving all residential and business consumers a net \$400 billion per year, or the equivalent of about \$2,600 per household annually (in 2010 U.S. dollars).

highlighted in figure 11, an optimal mix of productive energy efficiency investments could drive a total economic savings of 55% of total energy consumption in those buildings.

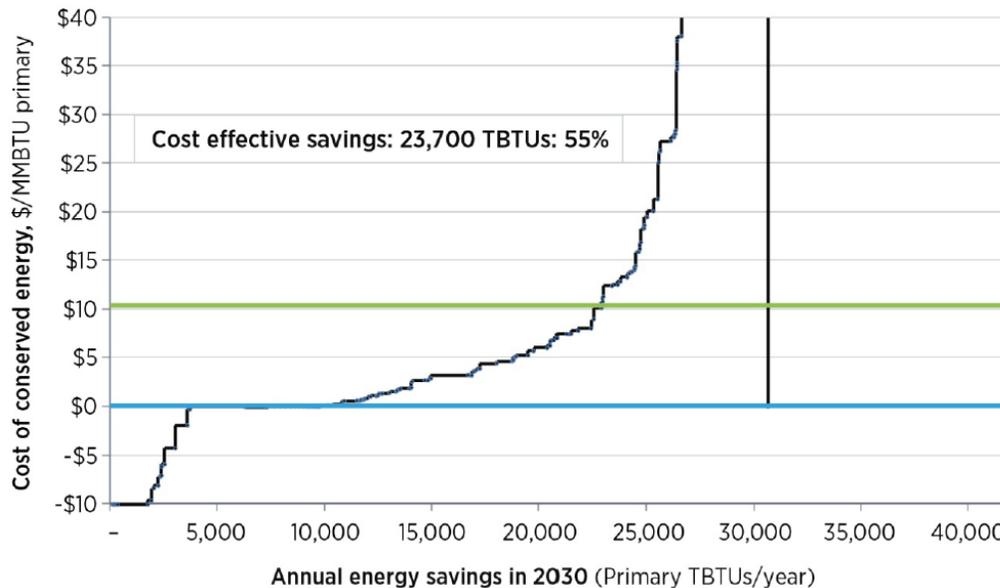


Figure 11. Energy efficiency supply curve and 2030 economic savings. *Source:* Farese et al. 2012.

The straight green line in figure 11 is the reported 2010 cost of primary energy consumption, expressed as 2008 dollars per million Btus (MMBTU). The blue-black curve is the amortized cost of conserved energy (CCE), also in 2008 dollars per MMBTU. By definition, that part of the blue curve with a CCE less than the actual cost of energy reflects the NREL suggestion of economic energy efficiency gains. The *Smarter 2020* study by the Global e-Sustainability Initiative (GeSI) found that ICT-enabled solutions, primarily through improvements in energy usage patterns, could reduce global greenhouse gas emissions in 2020 by 16.5%. For the United States the assessment found that ICT solutions could reduce buildings-sector emissions by 13% and by 15% in the power-supply sector (GeSI 2012). If we apply the GeSI 13% buildings savings to the NREL 55% economic savings, then we suggest that 7.2% might be driven by ICT-enabled technologies. As we explore below, the actual contribution appears to be much larger.

Using a top-down assessment, Laitner (2010) reported that the deployment of semiconductor-enabled technologies since 1976 generated a sufficient energy productivity benefit across the entire U.S. economy to reduce total electricity consumption by 20% compared to an economy without the benefit of those technologies. In other words, the family of semiconductor technologies now at work within the economy – including both ICT-enabled networks and smart appliances – appears to have amplified the productivity of buildings and equipment, labor, and energy resources well beyond normally expected returns.

A further analysis indicated that a policy-driven semiconductor-enabled efficiency scenario (SEES) might stimulate an average annual investment of \$22.5 billion over the period from

2010 through 2030. The study suggested a net 27% electricity savings by 2030.¹¹ More interesting, the findings also suggested an average electricity bill savings on the order of \$61 billion during that same period of analysis (in 2006 dollars). Even if the assessment includes program and administration costs necessary to drive that result, the net savings were still more than twice the total cost of the scenario. Perhaps an even more compelling outcome is the impact on employment. The working analysis suggested that, because energy-related expenditures are so much less labor intensive than almost all other consumer expenditures within the economy, the energy bill savings would support a net increase of about 550,000 jobs over that same 20-year period. This suggests an important additional benefit from the deployment of ICT-related technologies.

Energy efficiency produces multiple benefits well beyond energy cost savings alone (Ryan and Campbell 2012). A 2003 journal article documented over 70 industrial case studies and found that including a full set of co-benefits with standard energy efficiency assessments would double the cost-effective potential for such improvements compared to an analysis excluding those benefits (Worrell et al. 2003). Lung et al. (2005) reviewed 81 industrial case studies and found comparable nonenergy benefits within the industrial sector as well. More recently, ACEEE engineer and associate director of research R. Neal Elliott is quoted as saying, “We typically see nonenergy savings benefits being three to five times the value of energy savings” (Economist and Enerdata 2011, p. 9). At the same time, Amann (2006) suggests that nonenergy benefits of energy efficiency upgrades might range from 50 to 300% of household energy bill savings. These added benefits range from financial savings to energy bill relief, comfort, aesthetics, noise reduction, health and safety, and convenience.

Reduced Congestion in Transportation Systems

Congested roadways cost the nation in both lost time and fuel. In 2008 Samuel Palmisano, then IBM CEO, noted that such congestion costs consumers and businesses about \$70 billion annually (Palmisano 2008). While peak-hour travel is a perennial headache for many Americans (peak-hour travel times average 200 hours a year in large metropolitan areas), some cities have managed to achieve shorter travel times and actually reduce peak-hour travel times. The key is that some metropolitan areas have land-use patterns and transportation systems that enable their residents to take shorter trips and minimize the burden of peak-hour travel (Cortright 2010). These more productive patterns of travel can be enabled by ICT systems. Integrating the use of sensors and improved timing in the nation’s 311,000 traffic signal systems can reduce traffic delay by 5-10%. Fuel savings might approach 3-5% of the nation’s on-road consumption of gasoline and diesel fuel (NTOC 2012). Encouraging telecommuting among the nation’s workforce – in effect, encouraging more people to work from their homes rather than commute to work – might save 3 to 8% of the nation’s fuel consumption (Laitner, Partridge, and Vittore 2012). Other ICT systems might reduce total hours of peak travel and shorten the distances people need to travel (Cortright 2010). If every one of the top 50 metro areas achieved the same level of peak-hour travel distances as the best performing cities, their residents would drive about 40 billion

¹¹ The assessment suggested an initial electricity savings of 31%, but the ICT-enabled systems also require a 4% increase in electricity consumption to maintain their operation. Hence, the net gain of a 27% electricity savings.

fewer miles per year and use 2 billion fewer gallons of fuel, at a savings of \$31 billion annually.

Expanding highways and roads increases congestion by creating more demand – and building public transportation does not necessarily help the problem (Duranton and Turner 2009). A study by Sweet (2013) indicates that higher levels of congestion appear to be associated with slower productivity growth per worker (annualized elasticities ranging from -0.022 and -0.033). In contrast, higher levels of congestion-induced commuting delay (travel delay models) appear to be associated with decreasing job-growth rates, but there is no evidence of a drag on regional productivity growth per worker. Thus, while congestion may degrade mobility services and induce delay and longer travel times, the highest economic costs of congestion appear to be associated with high average daily traffic count (ADT) per freeway lane by spreading road use across the entire day (perhaps indicating travel at less desirable and less beneficial time periods). These results suggest that, alone, congestion alleviation policies that improve peak-period commuting services (such as road pricing) are unlikely to moderate congestion's drag in isolation and, moreover, the focus of congestion alleviation programs on travel time savings may be misplaced (Sweet 2013).

There is also significant opportunity to ICT-related improvements in the movement of freight throughout the United States. In a recent paper, Canadian professor of enterprise networks, logistics, and transportation, Benoit Montreuil, suggests the way physical objects are now transported, handled, stored, and supplied is not sustainable economically, environmentally, and socially. He notes that trucks, wagons, and containers are often half-empty at departure; a large portion of the other half is filled by packaging rather than product. Moreover, he cites official U.S. statistics indicating that trucks are approximately 60% full when traveling loaded. Overall, he suggests, the global transport efficacy has recently been estimated to be lower than 10%. He proposes to exploit the Internet as an underlying metaphor for steering innovation in the physical sphere. This will require a lot of multidisciplinary collaboration among and between academia, industry, and government across localities, countries, and continents.

As a first step, Montreuil proposes a new class of what he calls π -containers (or pi-containers) to distinguish them from current shipping containers. This new set of smart, green cases are modularized and standardized worldwide in terms of dimensions, functions, and fixtures. Moreover, they are designed to exploit smart networks and smart objects that are carried within. As illustrated in figure 12, they are designed to fit in almost any configuration to ensure that a truck, train, plane, or shipping vessel can more easily carry a full load and that any individual container can be easily scanned to be tracked and then pulled and replaced to minimize unused space. In all of this he proposes a universal interconnectivity in developing high-performance logistics that cuts costs and energy consumption throughout the entire system (Montreuil 2011).

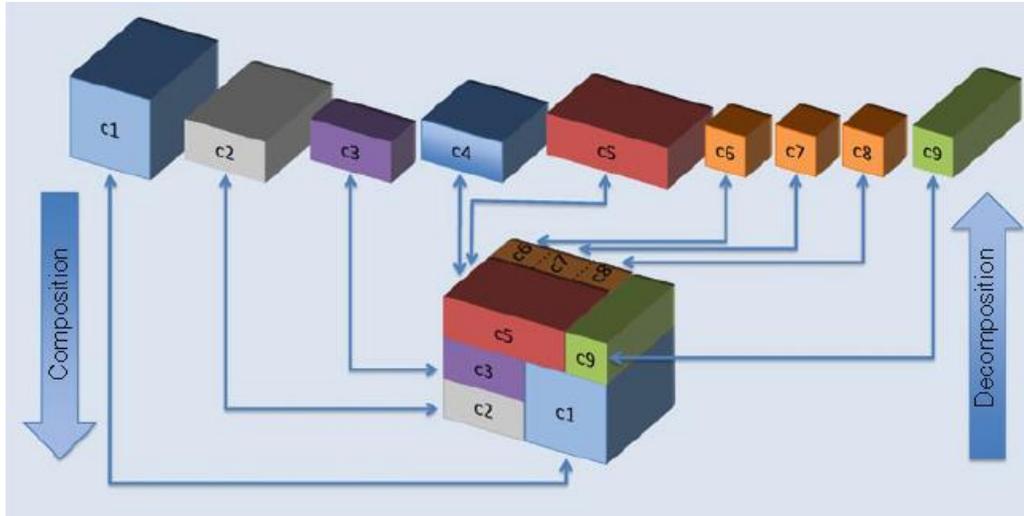


Figure 12. The modularity of unitary and composite containers. *Source:* Montreuil (2011).

Electricity Generation and Distribution

The U.S. electricity generation and transmission grid is a highly inefficient distribution system that wastes an estimated two-thirds of the total energy used to meet the nation's demand for electricity. In fact, what the U.S. wastes in the production and distribution of electricity is more than what either Japan or Hong Kong needs to power its entire economy. Moreover, economic losses from unreliability and inefficiencies within the electricity grid are now on the order of \$250 billion per year, with a further productivity penalty of \$500 billion added to that annual total. The annual cost to upgrade system performance through a fully intelligent grid system, enabled by ICT technologies and systems, will cost an estimated \$25 billion per year (Yeager 2012).

At the same time, how we use electricity also embodies significant waste. Rogers et al. (2013) indicate that intelligent efficiency can generate a net commercial and industrial savings of \$55 billion per year. In an earlier study by Laitner et al. (2009), ICT-enabled productivity might generate more than \$125 billion in economy-wide electricity savings by 2030. The benefit-cost ratio (assuming a 5% discount rate) was a net positive 2.1 as the investments and the energy bill savings catalyzed an average of 500,000 net new jobs.

Health Care Costs

Although we derive many benefits from paying our monthly electricity bills, the current electricity generation infrastructure annually produces 4.03 million tons of sulfur dioxide (SO₂) and 2.1 million tons of nitrogen oxide (NO_x) air pollution. These and other pollutants are expected to add \$125 billion or more to this year's health care costs, leading to 18,000 premature deaths, 27,000 cases of acute bronchitis, and 240,000 episodes of respiratory distress. The noxious effects of these pollutants also include 2.3 million lost work days due to illness and as many as 13.5 million minor restricted activity days in which both children and adults must alter their normal activities because of respiratory health problems (Laitner and McDonnell 2014).

At the same time the U.S. Environmental Protection Agency finds that total combustion emissions in the U.S. account for about 200,000 premature deaths per year as the result of

changes in particulate-matter concentrations, and about 10,000 deaths because of changes in ozone concentrations. The largest contributors for both pollutant-related mortalities are road transportation, causing a total of approximately 58,000 early deaths per year, and power generation, causing approximately 54,000 premature mortalities per year. Industrial emissions contribute to a total of 43,000 early deaths. “The results are indicative of the extent to which policy measures could be undertaken in order to mitigate the impact of specific emissions from different sectors – in particular, black carbon emissions from road transportation and sulfur dioxide emissions from power generation” (EPA 2011a).

In a second EPA study, the agency found the following:

Based on the scenarios analyzed in this study, the costs of public and private efforts to meet 1990 Clean Air Act Amendment requirements rise throughout the 1990 to 2020 period of the study, and are expected to reach an annual value of about \$65 billion by 2020. Though costly, these efforts are projected to yield substantial air quality improvements which lead to significant reductions in air pollution-related premature death and illness, improved economic welfare of Americans, and better environmental conditions. The economic value of these improvements is estimated to reach almost \$2 trillion for the year 2020, a value which vastly exceeds the cost of efforts to comply with the requirements of the 1990 Clean Air Act Amendments. (EPA 2011b)

In a different take, Graff Zivin and Neidell (2011) assess the less visible but likely more pervasive impacts on worker productivity. In particular, they explore a panel dataset of daily farm worker output as recorded under piece-rate contracts merged with data on environmental conditions to relate the plausibly exogenous daily variations in ozone with worker productivity. Their findings provide evidence that ozone levels well below federal air quality standards have a significant impact on productivity. Current standards are about 75 parts per billion (ppb) and a 10% decrease in ozone concentrations increases worker productivity by 4.2%. In other words, if the 10% decrease affects one-third of the workforce, that implies as many as 60 million people might be 4% more productive.¹² As we shall see below, that might have a significant impact on the scale of economic activity.

Economy-Wide Productivity

To this point we have focused on how energy production consumption patterns might impact specific costs and benefits. We can extend the discussion to examine potential impacts on the larger elements of the economy. Although Jorgenson (2005) found that the productivity growth rates were by far the highest in ICT production sectors, he concludes that the overall contribution was limited because of the low shares of this sector in the overall economy. Nevertheless, he suggests that ICT accounted for 60% of increased labor productivity in growth accounting.

A McKinsey team, Manyika et al. (2013), reviewed potential impacts in the public sector and found that many citizen services (including information requests, license applications, and tax payments) could become online services through mobile apps. Based on McKinsey’s

¹² According to Woods and Poole (2014), there were approximately 179 million employees in 2013.

experience, they noted it is possible to raise productivity by 60 to 70% by moving functions such as tax refund services and vehicle registration renewals to online channels. They further noted that moving to an increased share of electronic transactions could have a productivity benefit equivalent to 0.35% of GDP. The total potential economic impact of moving transactions to an electronic format is estimated to be \$200 billion to \$300 billion per year by 2025.

Manyika et al. (2013) also cite a University of Chicago study that found that once medical residents were equipped with iPads, they took less time to schedule procedures and were better able to explain complicated diagnoses to patients using visual aids. For transaction workers such as sales reps, mobile devices are already showing potential to increase productivity by making pricing, options, configurations, financing terms, and other information instantly available. In business-to-business sales, this has increased close rates by 35 to 65% in some cases. Finally, they note that one of the biggest opportunities for operational improvements involves using mobile Internet technology to increase the productivity of knowledge workers, including so-called interaction workers, a category that includes professionals, administrative support staff, and others whose jobs require person-to-person interaction and independent judgment. Such workers stand to benefit most from the use of social technologies that enable communications and collaboration, which could raise interaction-worker productivity by 20 to 25%, particularly by reducing the time it takes to handle email, search for information, and collaborate with colleagues.

More broadly, Cardona, Kretschmer, and Strobel (2013) reviewed about 30 studies in both Europe and the United States that showed that ICT investments can have a significant impact on economic activity. The data show a clear cluster of investment elasticities around the value of 0.05–0.06, but also some negative and high positive outliers.¹³ Ordering the studies by their average year of the data used for the estimation, they found a positive time trend.

While country- and industry-level-growth accounting exercises show diverging ICT effects for the United States and Europe and a stronger impact of ICT on productivity growth in the United States, econometric firm-level studies show no significant country differences. Moreover, the latter provide solid evidence that over the last two decades an increase of ICT investment by 10% translated into higher growth of economic output of 0.5–0.6%. Still, the empirical evidence is mixed and needs further investigation.

A new GE report by Annunziata and Evans (2013) finds that what they call the Industrial Internet can save industries up to \$20 billion per year. They further suggest that, together with new jobs and skills, the Industrial Internet has the potential to save on more than 300 million labor hours in servicing complex machines. In effect, new digital tools and predictive analytics can create a more productive industrial workforce and greater machine-human collaboration will reduce unplanned downtime.

¹³ With a doubling of ICT investment, an elasticity of 0.05 means economic output would expand by 2^{0.05}, or 1.035 times.

THOUGHT EXPERIMENTS TO SUGGEST MAGNITUDES OF ECONOMY-WIDE BENEFITS

Earlier in this report we noted a slumping level of activity for the U.S. economy. The national accounts recorded a preliminary GDP of \$13.3 trillion (in real 2005 dollars) for 2013 – about the same level as 2007. At the same time, per capita GDP in 2013 was held to about \$41,800 – still below the peak of \$43,900 reported in 2007. Hence, any increase in economic activity was almost entirely the result of population growth. Total U.S. private investments were also down more generally. This undoubtedly weakened the growth in per capita GDP, which is our proxy for economy-wide productivity. Indeed, a major driver of productivity is new investment. From a peak of \$2.7 trillion in 2006, total annual investment dropped to \$1.9 trillion in 2009, rebounding to only \$2.4 trillion in 2012.

Figure 8 shows telecommunications investments following a slightly different pattern, rising very sharply from \$29.4 billion in 1997 to a high of \$83.7 by 2000, but then averaging 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, our nation’s GDP in 2013 would have been closer to \$13.9 trillion, or about \$600 billion more than actually recorded (again, when measured in 2005 constant dollars). We can carry out a series of five thought experiments to see how they might compare to the \$600 billion in foregone economic activity otherwise reported in 2013.

We approach the thought experiments more as a Fermi problem than as a means to provide a precise estimate of net economic benefits (Von Baeyer 1993). In effect, we provide working estimates of GDP benefits of five activities that might be positively impacted by ICT-related investments, but ones for which we lack sufficient data to allow us a precise estimate. A Fermi calculation involving the multiplication of several estimated factors will probably be more reasonably accurate than might be first supposed (assuming there is no consistent bias in the estimated factors). This is because there will probably be some factors that are estimated too high and other factors that are estimated too low. Such errors will partially, if not more completely, cancel each other out. Hence, we are essentially modeling “for insights, not numbers” (Huntington et al. 1982).¹⁴

In no particular order we begin by linking the GeSI (2012), ACEEE (Rogers et al. 2013), and Laitner (2010) studies to explore the magnitude of energy efficiency improvements in building operations as they may be supported by ICT-enabled technologies. This range of technologies includes smart appliances, interactive user interfaces, and smart lighting, space conditioning, and appliance components. The 13% GeSI (2012) savings in buildings is a starting point. But if we are to approach the values suggested by Rogers et al. (2013), and as we apply our own internal estimate of ICT-supported contributions, the actual value might

¹⁴ How do you solve a problem for which there is no meaningfully complete set of data, and for which there is very little available in the way of observations to help readers fully understand the array of answers? One of the first and perhaps classic answers was shown by physicist Enrico Fermi. His curiosity prompted him to estimate the strength of the atomic bomb that was detonated in 1945 at the Trinity test site. He based his estimates on the distance traveled by pieces of paper dropped from his hand during the blast. Fermi’s resulting estimate of 10 kilotons of TNT was remarkably close to the now-accepted value of around 20 kilotons. See http://www.lanl.gov/history/story.php?story_id=13 for more information.

be closer to 35% of efficiency gains. Both the GeSI and the ACEEE studies are expressed as investments and dollar savings.

To generate a GDP-level impact, Laitner (2010) first suggests that a net 27% electricity savings might support an average of 550,000 net jobs per year over the period 2010 through 2030. If we conservatively apply 35% for upgrades in buildings, then we might suggest 35% times 550,000 jobs; and drawing from the Woods and Poole data for the United States as whole, which suggests a value-added \$86,000 per job (as measured in constant 2005 dollars) in the United States (Woods and Poole 2014), we generate a working estimate of a net \$17 billion (rounded) contribution to GDP from ICT-related energy efficiency upgrades in buildings. This seems small compared to the estimates that follow, but that may be the result of an underappreciation of the energy efficiency contribution to the nation's larger economic well-being (Laitner 2013). This result is summarized in row 1 of table 12.

Next we highlight a journal article by Matthias Sweet (2013) that indicates that higher levels of congestion appear to be associated with slower productivity growth per worker (annualized elasticities ranging from -0.022 and -0.033). In other words, if ICT systems cut traffic congestion by half, that would increase labor productivity (assuming the lower end) by $0.5^{-0.022}$, which equals 1.0154. Per capita GDP is then assumed increased by that factor. This is then adjusted by 56%, which is the percentage of population that is working at any given time. When multiplied by population and then subtracted from the recorded GDP, the impact is suggested to add about \$114 billion to the nation's GDP (about 0.8% of today's market value when, again, measured in constant 2005 dollars). This result is summarized in row 2 of table 12.

Cardona et al. (2013) indicate that increases in ICT investment have an output elasticity of 0.05 to 0.06 (across both U.S. and European economies). If we assume a 50% increase in ICT investments, then GDP might be increased by $1.5^{0.05}$, or by about 2%. Taking the difference of the recorded GDP from the new value suggests a net gain of \$272 billion, as reported in row 3 of table 12.

Annunziata and Evans (2012) suggest that the Industrial Internet might save manufacturers \$20 billion a year and save on more than 300 million man hours in servicing complex machines. New digital tools and predictive analytics will create a more productive industrial workforce such that productivity, we estimate, might be 1.5% higher in 2013. In this case, the findings suggest the Industrial Internet might add another \$200 billion to the economy, as summarized in row 4 of table 12.

Finally, Graff Zivin and Neidell (2011) indicate that lower ozone levels can increase labor productivity by up to 4.2% by knocking ozone levels down 10 ppb, which is about 13% lower than present regulations enforced by the EPA. The ozone levels are presumably down as the result of greater energy efficiency improvements throughout the economy. Assuming these levels positively impact one-third of the labor force, we find an economic benefit of \$185 billion, as shown in row 5 of table 12.

Table 12. Possible economic outcomes from ICT-enabled networks

Thought experiment for 2013	GDP benefit (billion dollars for 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 with 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 and Evans (2012)	Labor productivity was 1.5% higher in 2013.
Reduced ozone pollution	185	Graff Zivin and 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: Author estimates starting with Woods and Poole data for 2014, following relevant assumptions and referenced bibliographic resources.

The total of all four impacts is \$788 billion. If we allow for some interaction and double-counting, assuming 75% of the total, the amount is reduced to \$591 billion, which is very close to the foregone \$600 billion previously referenced. There are any number of caveats that both positively and negatively impact the net result, and this again brings to mind the nature of Fermi thought experiments in which we are modeling for insights, not precision. Figure 13 shows the potential areas of impact.

ICT's potential \$600 billion boost to GDP

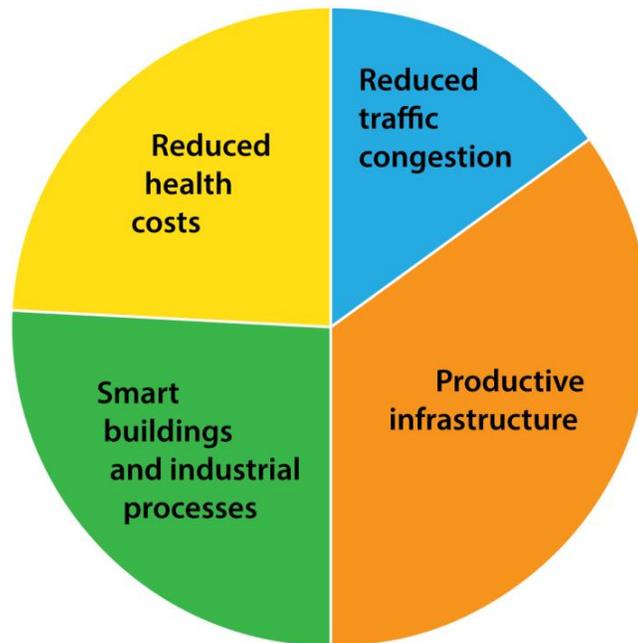


Figure 13. ICT's potential boost to GDP

At the same time, ICT-enabled networks and services might also reduce the nation's total energy requirements even as they boost economic performance. Drawing on Laitner (2010), total electricity savings might average about 741 billion kWh per year over the period 2010 through 2030. After backing out the increased electricity demands made necessary with the greater use of ICT-related equipment, however, the net electricity savings fall to about 645 billion kWh per year. Assuming an average heat rate of 9,965 Btus per kilowatt-hour (EIA 2014a), total primary energy savings would then be about 6.4 quads of total energy, which is about 7% of total energy consumption that was otherwise required in 2013. 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).

The intent of this exercise is twofold. First, it intends to lend a sense of magnitude to the possible impacts that smart appliances and ICT-enabled networks might have on the economy – apart from the added benefits of increased energy efficiency and productivity. Second, it is a reminder of the lack of reliable data needed to provide a more reasonable estimate of economy-wide benefit; except that we know the declining prices of ICT goods and services relative to prices of other goods and services, and with the leveraging of extended knowledge and further collaboration, the impact is likely to be highly positive. The next section outlines a set of recommendations and next steps for developing a clearer picture of the effects of ICT on energy efficiency and economic productivity.

Next Steps in the Assessment

The initial findings clearly suggest a more robust and more environmentally friendly scale of economic activity could be achieved with smart appliances and ICT-enabled networks. At the same time, statisticians and economists have relied on time-series data for over a century to confirm or disprove a working or null hypothesis. For example, an analysis from an energy perspective might integrate various elements of GDP (e.g., personal consumption, annual investment, government spending, and net exports) as they compare to patterns of energy production and consumption, and as those patterns are impacted by changing prices and policies. Or analysts could develop a set of panel data that contains observations of multiple phenomena obtained over multiple time periods. In this case, although we have available data on the use, growth, and performance of smart technologies, we are greatly constrained by the lack of adequate time series data to properly characterize their potential contribution to greater levels of energy efficiency and economic productivity.

Given the emerging diversity, complexity, and indeterminate patterns and shapes of social and economic networks, there is a real need to shed our preference for highly curated and pristine data and to accept messiness. As analyst Thomas Davenport (2013) notes, there are “an increasing number of situations [in which] a bit of inaccuracy can be tolerated because the benefits of using vastly more data of variable quality outweigh the costs of using smaller amounts of very exact data.” In the discussion that follows, we will review three characteristics of a needed future analysis: the use of big data, the development of smart analytics and multicriteria assessments, and the integration of a more social rather than purely economically rational perspective to understand how smart appliances and ICT-enabled networks might contribute to a more resilient and economically sustainable future.

THE USE OF BIG DATA

Today there is enough information in the world to give every person alive 320 times as much of the information as historians believe was stored in the Library of Alexandria in the third century BC (Cukier and Mayer-Schoenberger 2013). But what to do with it as astonishing levels of new information are being collected every hour of every day?

Humans evolve because they communicate. Once fire was discovered and shared, for example, it did not need to be rediscovered, only communicated. A more recent example is the discovery of the helix structure of DNA, molecules that carry genetic information from one generation to another. After James Watson and Francis Crick published their article in a scientific journal in April 1953, the disciplines of medicine and genetics were able to build on this information to take giant leaps forward (Evans 2011).

Brynjolfsson and McAfee (2011) comment that computers (including the hardware, software, and networks) are only going to get more powerful and more capable in the very near future. The good news is that it appears that software progresses at least as fast as hardware does, at least in some domains. For example, computer scientist Martin Grötschel analyzed the speed with which a standard optimization problem could be solved by computers over the period 1988-2003. He documented a 43-million-fold improvement that could be explained by two factors: faster processors and better algorithms embedded in software. His findings suggested that processor speeds improved by a factor of 1,000, even

as these gains were dwarfed by algorithms becoming 43,000 times better over that same period (PCAST 2010).

Manyika et al. (2013) report that computing power continues to grow exponentially (approximately doubling every two years on a price/performance basis). And today a \$400 iPhone 4 offers roughly equal performance (in millions of floating point operations per second, or MFLOPS) to the CDC 7600 supercomputer, which was the fastest supercomputer in 1975 and cost \$5 million at the time. These new capacities enable us to absorb, process, and learn from a diversity of information resources, using what is now being called big data (Cukier and Mayer-Schoenberger 2013).

Learning from Big Data

Big data is distinct from the Internet, although the Web makes it easier to collect, maintain, and share. It is about more than just communication: the idea is that we can learn things from a large body of information that we could not comprehend when we used smaller amounts. The explosion of data is relatively new. As recently as the year 2000, only one-quarter of all the world's stored information was digital. Today, less than 2% of all stored information is non-digital (Cukier and Mayer-Schoenberger 2013).

Given this massive scale, it is tempting to understand big data solely in terms of scale. But that would be misleading. Big data is also characterized by the ability to render into data many aspects of the world that have never been quantified before; call it "datafication," made increasingly possible by low costs of storage.

Instead of trying to teach a computer how to do things like drive a car or translate languages (which artificial-intelligence experts have unsuccessfully tried to do for decades), the new approach is to feed enough data into a computer so that it can infer the probability that, say, a traffic light is green and not red, or that in a certain context, the French noun *lumière* is a more appropriate substitute for the word "light" than the adjective *léger*, which means "not heavy" (Cukier and Mayer-Schoenberger 2013).

Google technologists, for example, used staggering amounts of data about the roads their driverless cars were traveling. Their vehicles also collected huge volumes of real-time data using video, radar, and light detection and ranging (LIDAR) gear mounted on the car. These data were fed into software that took into account the rules of the road, the presence, trajectory, and likely identity of all objects in the vicinity, driving conditions, and so on (Brynjolfsson and McAfee 2011). With more than 500,000 miles behind them, the software known as Google Chauffeur controls the car and probably provides better awareness, vigilance, and reaction times than any human driver (Fisher 2013). The Google vehicles' only accident occurred when the driverless car was rear-ended by a car driven by a human driver as it stopped at a traffic light (Simonite 2013).

Cukier and Mayer-Schoenberger (2013) suggest that using great volumes of information requires three profound changes in how we approach data. First, collect and use a lot of data rather than settle for small amounts or samples, as statisticians have done for over a century. This is what may be necessary to generate an authoritative assessment of smart appliances and ICT-enabled networks and their contribution to greater levels of energy efficiency and a more robust economy.

Second, according to Cukier and Mayer-Schoenberger, shed our preference for highly curated and pristine data and accept messiness. In an increasing number of situations, a bit of inaccuracy can be tolerated because the benefits of using more data of variable quality outweigh the costs of using smaller amounts of exact data. One can easily imagine hundreds, thousands, or tens of thousands of data points and information being collected to confirm the working hypothesis about the economy-wide contribution of smart appliances and ICT-enabled networks.

Third, we may need to give up our question to discover the cause of things in return for accepting correlations. With big data, instead of trying to understand precisely why an engine breaks down or why a drug's side effect disappears, researchers can instead collect and analyze massive quantities of information about such events and everything that is associated with them, looking for patterns that might help predict future occurrences. Big data helps anchor what, not why, and that is often good enough (Cukier and Mayer-Schoenberger 2013). We are likely to discover that many aspects of life are probabilistic rather than certain. Yes, we still need statistics; we just no longer need to rely on small samples. The obsession with accuracy and precision is, in some ways, an artifact of an information-constrained environment. And with big data we can quantify the uncertainty.

Cukier and Mayer-Schoenberger cite the delivery company UPS as an example. The company places sensors on vehicle parts to identify certain heat or vibrational patterns that in the past have been associated with failure. The data do not reveal the exact relationship between the vibrational patterns and the part's failure, but they reveal enough to predict a breakdown before it happens, allowing drivers to replace the part when convenient, instead of on the side of the road. Cukier and Mayer-Schoenberger also note another Google project that in February 2009 created a stir in health-care circles. Researchers published a paper in *Nature* that showed how it was possible to track outbreaks of the seasonal flu using nothing more than the archived records of Google searches (Ginsberg et al. 2009). In the case of collecting big data to confirm the market potential and the positive impacts of smart appliances and ICT-enabled networks, we may or may not be able to confirm the net-positive economic impacts of ICT-enabled networks. However, we may be able to use Bayesian inference and statistics to show the high degree of probability of positive economy-wide outcomes and the real need to accelerate investments in smart appliances and networks to restore a measure of robustness to the economy.

Big Data Used in Smaller Ways

At the same time we can also use big data in smaller ways, in this case in the smarter management of commercial buildings. After successfully squeezing 10% energy savings out of 13 buildings at its headquarters, Microsoft is teaming up with Accenture to bring similar reductions to 2 million square feet of commercial property at other businesses in Seattle. The new initiative is part of a plan by the Seattle Office of Economic Development to encourage and develop a citywide approach to energy efficiency. Money from a U.S. Department of Energy grant will go toward helping fund the investments. The partnership teams Microsoft with the local utility Seattle City Light and Seattle 2030 District, a public-private organization of downtown property owners and managers striving for a 50% reduction in energy consumption across their buildings by 2030. The initial set of buildings encompass 2 million square feet and represents a variety of use cases, including the Seattle Municipal

Tower (the second tallest building in the city, serving 5,000 occupants), the Sheraton Hotel, Boeing's Seattle site, and the University of Washington School of Medicine's research facility.

The anticipated initial savings across these buildings is 15 to 25%, according to Bill Mitchell, senior director of Microsoft's Worldwide Public Sector division. "This is an IT-based solution and doesn't require anything from the building owner except access to the data in their systems," he said (Mitchell 2013). The approach includes Microsoft software and cloud services used both to analyze the collected information and to control the sensors, controls, meters, and building management systems that already exist in the structures. Specifically, the Windows Azure cloud is acting as storage for the terabytes of big data that are being generated, while Microsoft SQL Server 2012 is the database doing the processing. Microsoft SharePoint Server 2013 was used to create the portal and dashboards where managers can monitor their energy efficiency metrics. One of the most intriguing elements of the Seattle program is that businesses are eager to participate, despite the relatively low cost of energy in the region. "We got our payback in less than 18 months, even though we have some of the cheapest electricity in the world," Microsoft chief environmental strategist Rob Bernard said. "Then it should definitely work in places where energy is much more expensive."

Microsoft is already evaluating how to extend Seattle's big data program, which joins its two other publicly disclosed smart energy management projects: its own campus initiatives and the so-called IssyGrid district, a smart-grid test involving 12 buildings in the French city of Issy-les-Moulineaux. Microsoft expects additional projects to be disclosed in the near future. The places to look first are the cities involved in Microsoft's new global CityNext initiative, meant to encourage cities around the world to automate processes for functions including energy and water management, transportation, and public safety. The showcase communities include Auckland, Barcelona, Buenos Aires, Hamburg, Manchester, Moscow, Philadelphia, and Hainan Province and Zhengzhou, China (Clancy 2013).

Turning Data into Knowledge and Policy Insights

Figure 14 shows the logic of turning data into wisdom, or in this case turning mounds of disparate forms of data into wisdom or useful investment and policy insights that can be put to use by business leaders and policymakers.

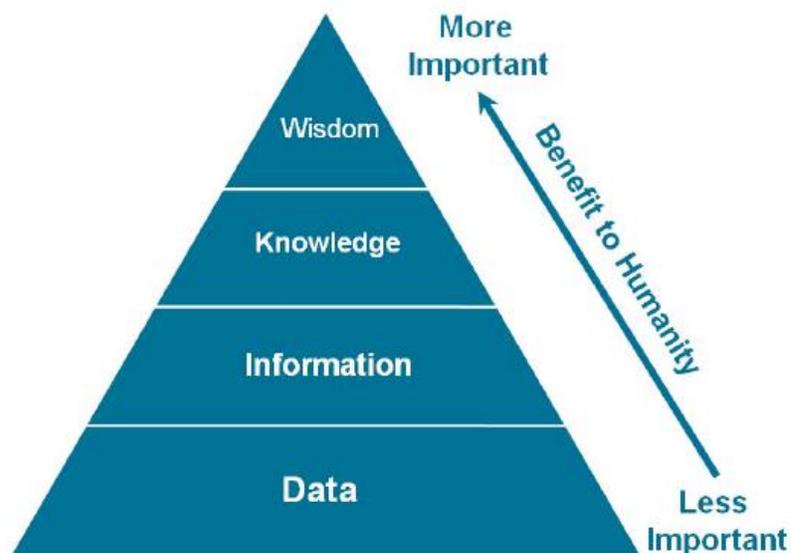


Figure 14. The flow of turning data into wisdom. *Source:* Cisco Internet Business Solutions Group (2011).

Useful data will come from many different project case studies with different information, from discrete analyses, and from the melding of many different databases such as the World Telecommunication/ICT Indicators database (ITU 2013), the National Economic Accounts (BEA 2014), the Annual Energy Outlook (EIA 2014a), *Short-Term Energy Outlook* (EIA 2014a), and the Annual Energy Review (EIA 2014c). Then 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.

Presumably data would be translated into knowledge with the supervision of interdisciplinary experts with the goal of developing policy and investment insights necessary to guide smart decisions about the next steps forward. The use of smart algorithms would include both Bayesian statistics and inferences as well as multicriteria analytics to develop the goal programming technique we discuss below.

USING SMART ALGORITHMS AND MULTICRITERIA ANALYTICS

Big data techniques give analysts, business leaders, and policymakers the ability to draw conclusions from key economic development patterns they might discern within the massive data sets they might collect and store (anything from all legal cases of the past 20 years to data concerning the ways in which molecular compounds react with one another). 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. Moreover, these machines can learn more and get smarter as they go along; the more they process big data, the more refined their algorithms become (Manyika et al. 2013). However, there has not yet been a project that 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 actual project unfolds and as new insights and learning emerge. Two immediate recommendations

materialize: the use of Bayesian statistics and a multicriteria analytical tool such as goal programming.

Bayesian Statistics, Probabilities, and Inferences

Bayesian statistics is a way of calculating conditional probabilities given other uncertainties. Bayes' rule provides a rigorous method for interpreting events or data in the context of previous experience or knowledge. It constitutes a mathematical foundation for reasoning and assessment.¹⁵ After two centuries of controversy in which its methods "have been both praised and pilloried" (in the words of James Stone), Bayes' rule has recently emerged as a powerful tool with a wide range of applications. As we have only recently learned, famed mathematician and computer scientist Alan Turing applied Bayesian methods in translating the German Enigma code in World War II. Other applications include genetics, linguistics, image processing, machine learning, and ecology – among many others (Stone 2013).¹⁶ Bayes' rule transforms probabilities that look useful (but often are not) into probabilities that are useful. In many ways this is entirely consistent with what has been termed Analytics 3.0—a resolve to apply powerful data-gathering and analysis for the benefit of customers and markets rather than simply individuals or firms, and to embed analytics and optimization into every decision that is made at the front lines of operations (Davenport 2013). Or, in this case, to guide policy and investment decisions that enable multiple outcomes to emerge.

Multicriteria Analytical Tools

A critical shortcoming of most standard economic analyses and models is that they tend to focus on a single objective – either to minimize cost, or to maximize profit, welfare, or consumer utility (Laitner and Hogan 2000; Greening and Bernow 2004). But the evidence suggests that both individual consumers and businesses tend to juggle a variety of objectives or concerns as they choose their next investment or make their next purchase (Simon, 1997; DeCanio et al. 2000; Laitner, DeCanio, and Peters 2000). Hence, 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.

Unfortunately, the current generation of policy tools does not have a meaningful capacity to solve for multiple objectives. Yet the need for multicriteria decision models grows as policymakers continue to wrestle with an increasingly complex set of issues in the evaluation of energy and climate policies.

¹⁵ Conditional probabilities are those whose value depends on the value of other probabilities. As one can easily imagine, such probabilities are ubiquitous. For example, we may wish to estimate the probability that smart appliances and ICT-enabled networks are likely to enhance the robustness of the economy. Yet we have no consistent time series or other data to test such a hypothesis. But given an array of diverse information, we can assign weights to beliefs and then explore conditional probabilities that help confirm our given belief.

¹⁶ In both a serious and a fun way, the use of Bayes' rule or Bayesian statistics is not unlike a comment by Sherlock Holmes in Arthur Conan Doyle's *The Hound of the Baskervilles*: "we balance probabilities and choose the most likely. It is the scientific use of the imagination."

The Goal Programming Concept

One analytical tool that might provide further insights, given the existence of multiple rather than single objectives, is known as goal programming. This is an optimization technique adapted from the family of mathematical programming models (Lee, 1976).

The use of energy or other resources is not a goal in itself. Ideally, all resources should be managed in a way that promotes the wide 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. In pursuing these multiple objectives, however, there may be limitations on what strategies can be pursued. It is in this context that the goal programming technique is useful. There are multiple concerns, a variety of choices to be made or not made, and a set of constraints on the financial, human, and energy resources available to implement the eventual choices.

Goal programming (GP) 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 different from linear programming in two ways. First, where linear programming tries to achieve a single goal – usually minimizing cost or maximizing returns – goal programming tries to achieve multiple goals. Second, the GP model is based upon the “satisficing” principle first outlined by Herbert Simon in the 1950s (Simon 1957). Simon and others suggested that better decisions could be made if emphasis were given to achieving minimum levels of satisfaction rather than maximizing a single objective. Again, this differs from both linear programming and conventional economic choice models that seek to maximize (or minimize) a single objective. The appendix of this report provides useful technical detail behind this analytical approach.

Integrating Big Data into an Analytical Framework

The assessment up to this point has highlighted a variety of disparate data, all of which suggest that smart appliances and ICT-enabled networks can provide a vital lift to both energy efficiency gains (and related energy bill savings) and a more robust economy. While this is a strong probability that this relationship can be confirmed, a final assessment requires significantly more information and data than the analysis can provide at present. As we move to a second phase of the assessment, the key element is to capture and integrate an array of data that feed into a Bayesian or other analytical framework to confirm: (i) the likelihood of a positive economic impact, and (ii) the necessity of upgrading the core of our economy with a strengthened ICT-related investment portfolio. Using a variety of data-mining techniques, the information will pull form a combination of available time series data, ad hoc case study data, journal articles and news articles, and relevant databases. As each unique set of information is available, the analytical framework will test and likely confirm the suggested hypothesis. Perhaps even better, the Phase 2 mapping of this information can give us some initial suggestions of a functional relationship among the key elements of a smart appliance and ICT-enabled network. Table 14 highlights the key layers of an ICT-smart economy.

Table 14. Key elements of smart appliances and ICT-enabled networks

Network elements	Execution
Sensors and smart technologies	Pulling in big data
Bayesian algorithms and solutions	Multicriteria decision models
Controllers/actuators	Action and implementation
Feedback/interaction	Management, evaluation, and adjustments

As the right mix of investments is made, a variety of sensors and smart technologies will continuously pull in all kinds of big data. At that point, an array of Bayesian algorithms and multicriteria tools will offer prospective solutions to an optimal use of energy, water, and other resources in our homes and businesses. Then a variety of controllers and actuators – in step with desired economic, social, and environmental objectives – will create conditions, or act on information to bring about the desired outcomes. Finally, an assortment of feedback mechanisms and interactions will both manage and evaluate the information and decisions so that any needed real-time adjustments can be made to ensure either the specified or desired outcome. The intent is to use big data as it might be processed with the aid of Bayesian statistics, and to optimize the results across several different economic, social, and environmental objectives. In short, what we might imagine for Phase 2 of this assessment might also provide new insights into the critical role and structure of emerging ICT-enabled networks, which then become the Internet of Everything.

INTEGRATING SOCIAL RATIONALITY RATHER THAN A PURELY ECONOMIC PERSPECTIVE

While the information and insights drawn from the use of big data and multicriteria assessment might motivate some level of accelerated investments in smart appliances and ICT-enabled networks, will these new insights translate into long-term behavioral changes and more energy-efficient behavior? Research suggests that it will take more than high prices to achieve maximum energy savings. People may like to think of themselves as rational economic actors, but a variety of studies by social psychologists and behavioral economists reveal that people often act in ways that may be better described as socially rational and predictably irrational.

Despite these findings, many residential energy programs and most policy models continue to model potential energy savings as a function of the capacity of existing technologies and the cost of energy resources (Ehrhardt-Martinez and Laitner 2009). Similarly, a report by Lutzenhiser et al. (2009) states, “A key set of assumptions can be found in a physical-technical-economic model (PTEM) that has oriented energy efficiency program design for several decades. The model is focused on technical devices and assumes economic motivations and rational choice by energy users.” The literature suggests that efforts to engage people on energy and climate issues need to be concerned about how people feel about the issues and not just about how people think about them. The end result is that a particular focus of the second phase of this assessment should also include deep insights and big data from the social sciences as well as from the economic and physical elements of the market.

Conclusions

In 2012, ACEEE published a major study, *The Long-Term Energy Efficiency Potential: What the Evidence Suggests*, which found that the United States had the wherewithal to reduce the nation's total energy use by 40 to 60% through highly cost-effective efficiency investments. Moreover, the study indicated that the array of investments could generate up to 2 million jobs while saving all residential and business consumers a net \$400 billion per year, or the equivalent of about \$2,600 per household annually (Laitner et al. 2012). The analysis concluded that the United States would be better off thinking big about energy productivity and energy services rather than relying on the usual set of costly and conventional energy resources. Other studies have shown similar opportunities for large-scale efficiency gains (APS 2008; AEF 2009; Lovins et al. 2011; Rifkin et al. 2013).

With this report we have reasonably established the need for and viability of smart appliances and ICT-enabled networks as they contribute to further gains in energy efficiency and the nation's larger economic productivity. At the same time, neither the nation's businesses nor the National Economic Accounts provide meaningful data that will help us learn or understand how big, how necessary, and how productive the contributions from smart appliances and ICT-enabled networks might be to ensure large-scale returns from big efficiency.

We envision a three-step process to overcome the limitations of the formal data that are available and provide useful insights for the business community and policy leaders. The first step in this assessment would rely on big data rather than only formal but more limited economic accounts. This array of data would include available and appropriate time series data, but also ad hoc case study data, journal articles and news articles, and relevant databases. Second, we suggest a mix of Bayesian statistics and multicriteria optimization algorithms to process the data and demonstrate the optimal contribution of smart appliances and ICT-enabled networks to energy efficiency, economic productivity, and other social, environmental, and economic objectives. Finally, we suggest direct contributions from the social sciences to motivate consumers and producers and encourage a more proactive response to changes in the nation's energy policies.

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Appendix A: Generic Formulation of Goal Programming Problems

In most conventional engineering or economic formulations, optimization routines usually depend on a linear programming (LP) algorithm that tries to achieve a single goal, most often to minimize cost or maximize returns subject to constraints. Goal programming (GP) techniques, on the other hand, try to achieve or satisfy multiple goals or objectives. The GP model is based upon the “satisficing” principle first outlined by Herbert Simon in the 1950s (Simon 1957, 1997). Simon and others suggested that better decisions could be made if emphasis were given to achieving minimum levels of satisfaction rather than maximizing a single objective. Hence goal programming differs from both linear programming and conventional economic choice models that seek to maximize (or minimize) a single objective.

Greening and Bernow (2004) provide a broader context for multicriteria decision making models (MCDM) within coordinated environmental and energy policies. For further discussion on the use of goal programming in energy-based contexts, see Laitner and Hogan (2000) and Laitner, Greening, and Hobbs (2001). This technique allows for the integration of several objective functions into one, with the solution of the problem reflecting a minimization of the deviation from the specific numeric goal set for each objective function. As the technique might apply to some combination of sensors and actuators to maintain system performance, the generalized mathematical formulation might look like this:

$$\min z = \sum_{i=1}^Q \frac{100}{b_i} (u_i n_i + v_i p_i)$$

$$s. t. f_i(x) + n_i - p_i = b_i, i = 1, \dots, Q, x \in C_s$$

where $f_i(x)$ = linear function (objective) of x , which is

a vector of decision variables or technologies, C_s

is the set of all decision variables (inclusive),

and b_i = target value for $f_i(x)$.

n_i and p_i represent negative and positive deviations from b_i .

u_i and v_i are preference weightings.

In this case, the different objectives, b_i , might include maintaining an optimal temperature or process using the least amount of energy and/or other resources, subject to different investment, operating and maintenance, and energy costs, even as we want to maximize employment and income while minimizing greenhouse gas emissions, other pollutants, and water consumption.