Information and Communication Technologies: The Power of Productivity

How ICT Sectors Are Transforming the Economy While Driving Gains in Energy Productivity

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Foreword

By the end of this year, the United States will have expanded its economic output by nearly 65 percent since 1990. Likewise, per capita incomes will have grown by 35 percent. Notably, however, the demand for energy and power resources will have grown by only 23 percent during the same period. This decoupling of economic growth and energy consumption is a function of increased energy productivity; in effect, we have increased our ability to generate more energy services from each unit of energy consumed.

While the emergence and widespread adoption of advanced information and communication technologies (ICT) have been identified as principal drivers of the growth in economic productivity, their effect on energy productivity has received much less attention. This lack of recognition is likely due to what might be called "the ICT energy paradox" whereby analysts tend to pay more attention to the energy-consuming characteristics of ICT than to their broader, economy-wide, energy-saving capacity.

While it is easy to imagine that the proliferation of ICT technologies would lead to an increase in power demand across sectors, calculating their net effect on energy usage requires a more comprehensive understanding of the ways in which new technologies have continued to displace and improve upon older processes and systems.

As Laitner and Ehrhardt-Martinez present in this report, historical measures of energy efficiency clearly indicate that the pace of energy efficiency gains has increased significantly since 1995. For example, U.S. energy intensity declined an average 1.2 percent annually between 1950 and 1995. That pace accelerated to 2.2 percent between 1995 and 2006.

More importantly, however, this path-breaking analysis argues that a significant proportion of these energy productivity gains—especially in recent years—appear to be the result of the explosive growth in ICT and the related shift in the predominant technological paradigm. The authors build their case for ICT on the pioneering work of Dale Jorgenson and his colleagues (2005) as well as the dynamic model of technological revolutions as described by Carlota Perez (2002).

Despite the lack of precise data, Laitner and Ehrhardt-Martinez provide a new and innovative assessment of the ICT energy paradox and make a compelling case that much of the current efficiency gains have resulted from the proliferation of ICT investments and products. Nevertheless, the authors argue that continued progress is dependent on our institutional and cultural capacity to direct these technologies toward addressing our most pressing energy and climate problems.

Overall, this study provides readers with ground-breaking research on the relationship between ICT and energy productivity, and although preliminary in nature, provides robust, working estimates of the net energy impact of ICT. This report will undoubtedly prove to be a valuable resource and starting point for future research on this topic.

Steven Nadel, Director
American Council for an Energy-Efficient Economy

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All of the views expressed in this report are those of the authors and do not necessarily reflect the views or have the endorsement of those individuals or organizations who shared their thoughts and insights with us. One important caveat seems especially relevant. The conclusions in this study are based on our best professional judgment and are based in part on materials and information provided to us by a wide variety of sources. As with any research effort of this type, any person relying on this report should exercise due diligence and confirm their own judgment about the significance of these report findings.

Finally, we thoroughly appreciated the taskforce commitment to develop insights that, in turn, might help forge a productive technology perspective as a step toward crafting a vitally needed Energy Efficiency Action Plan for the United States, and to do so without advancing their own brand name technologies, or to give the appearance of picking possible winners that might otherwise benefit from this policy assessment. At the same time, we would be remiss if we did not mention specific company support for this study—which we happily do in ascending alphabetical order. Toward that end, we express our deep appreciation to Applied Materials, Dell, EMC, HP, IBM, Intel, Micron, Motorola, NCR & Unisys. Many thanks!

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Executive Summary

Information and communication technologies (ICT) have transformed our economy and our lives, but they also have revolutionized the relationship between economic production and energy consumption.

Since the early 1990s, ICT applications and systems have become a critical means of achieving both energy and economic productivity.

Huge cost reductions and important new ICT innovations have worked together to drive the expansion and diffusion of new applications that have subsequently enabled the development of additional high-tech products and services, new investments, and new ways of doing things. In other words, the positive economic feedback generated by most ICT innovations have stimulated higher levels of economic productivity and driven net gains in cost-effective energy savings throughout the U.S. economy.

How big of an impact? The available data and statistics now collected by various governmental agencies do not yet allow a precise estimate. Nonetheless, the evidence is compelling:

- For every extra kilowatt-hour of electricity that has been demanded by ICT, the U.S. economy increased its overall energy savings by a factor of about 10. These productivity gains have resulted in significant net savings in both energy and economic costs. The extraordinary implication of this finding is that ICT provide a net savings of energy across our economy.

- The realization of ICT-driven energy savings has been, and will continue to be, dependent upon our institutional and cultural capacity to direct these technologies toward addressing our most pressing energy and climate problems as much as it is about our technological capacity alone.

- Since 1970, the United States has dramatically reduced the amount of energy required to support economic activity. Today, it takes less than half the energy to produce a dollar of economic output as it did in 1970. U.S. energy consumption per dollar of economic output will have declined from 18,000 Btus in 1970 to less than 9,000 Btus by the end of 2008. That gain in energy productivity enabled the economy to provide approximately 75 percent of the new demand for energy services through energy efficiency improvements.

- Information and communications technologies have played a critical role in reducing energy waste and increasing energy efficiency throughout the economy. From sensors and microprocessors to smart grid and virtualization technologies, a strong correlation is found among efficiency, productivity, and energy savings. And while discrete technologies have successfully enabled significant energy savings, system-wide energy savings have also emerged from the growing ubiquity of ICT systems and technologies.

- The evidence suggests that we have yet to optimize the full range of opportunities for additional gains in energy and economic productivity. For example, the Climate Savers Computing Initiative estimates that today's standard desktop computers waste nearly half the power delivered to them. For that reason, the industry has committed to a 50 percent reduction in power consumption in computers by 2010. These types of initiatives will improve the energy efficiency of critical appliances and equipment. In addition, the continued expansion of ICT equipment in everyday household and business functions, as well as the substitution of ICT for travel, will provide the means through which additional

> efficiency gains will emerge. These accomplishments will require a set of smart policies to further catalyze the optimal development of ICT so as to maximize energy and economic productivity.

ICT systems have revolutionized the relationship between economic production and energy consumption, becoming a critical energy and economic productivity tool for consumers and industry alike. Despite the significant energy-saving potential of ICT, they have generated a notable lack of recognition due to what might be called "the ICT energy paradox." The paradox is one in which more attention tends to be paid to the energy-consuming characteristics of ICT than to the broader, economy-wide, energy-saving capacity that emerges through their widespread and systematic application. Given the economic and energy challenges that await us, as a nation we should commit to the realization of the energy-saving opportunities that new ICT opportunities provide.

Economic Productivity and Information and Communications Technologies

There is broad agreement that greater levels of productivity can lead to greater economic returns. Economist William Baumol and his colleagues (Baumol et al. 1992) write, for example: "For real economic miracles one must look to productivity growth." By this they mean that if we can amplify the use of our capital, labor, and energy resources beyond the routine deployment of those inputs, we are more likely to ensure a robust economic benefit. During the current historical period, gains in productivity are most likely to result from the continued development and application of new information and communications technologies (ICT). And recent evidence confirms the growing importance of the emerging generation of ICT and the myriad opportunities that they provide us to strengthen our economic productivity.

By way of highlighting the importance of productivity to our nation's economy, we note, for example, that annual growth in U.S. labor productivity between 1950 and 2006 (shown in Table 1) averaged 2.4 percent. During the same period, the nation's Gross Domestic Product (GDP)—the sum of all value-added contributions to the economy in a given year—increased by an average of 3.4 percent.[1] Interestingly, the annual variation of labor productivity within that 56-year period was significant and greatly affected the expansion of the economy. Following a decline in labor productivity in what we might call the Oil Embargo Period of roughly 1973 to 1995, more recent productivity trends indicate a strong resurgence. In other words, workers have recently become more productive. The evidence points to the development and application of a wide variety of ICT as the cause.

The trend over the period 1995 through 2006 mirrors the high growth rates encountered in the period immediately following World War II (here shown as the years 1950 through 1973). During the post-war years, the expansion of the economy was driven by a convergence of factors, including the reentry of military soldiers and sailors into the workforce in large numbers and the growth in productive investments made possible through the diversion of investments from munitions to industrial applications. In addition, the accelerated level of education and worker training associated with the post-War period also contributed to the above-average level of productivity gains. Altogether, the combination of these factors resulted in a compound annual growth rate in labor productivity of 3.1 percent for the 23-year period between 1950 and 1973. During the same period, GDP grew at rate of 4 percent annually.

Table 1. Average Annual Growth in U.S. Labor Productivity and GDP

Time Horizon	Labor Productivity	GDP
1950 to 2006	2.4%	3.4%
1950 to 1973	3.1%	4.0%
1973 to 1995	1.5%	2.8%
1995 to 2006	2.8%	3.2%
Note: Labor productivity refers to output per hour in all business sectors of the economy. The data is adapted from the Bureau of Labor Statistics.		

During the period following the oil crises (1973 to 1995), however, growth in labor productivity fell to about one-half of the preceding period, or about 1.5 percent. As we've already alluded, the growth rate this past decade rebounded to 2.8 percent annually as investments in ICT have expanded. This expansion

[1] As a rule of thumb we can say that the nation's GDP will expand at roughly the growth in the level of effort times the productivity of that effort. In this case, if labor productivity grows on average at 2.4 percent per year, and the labor force grows about one percent annually, then we might expect the economy to expand by about 3.4 percent per year, as suggested in Table 1 above. Because labor productivity in this instance reflects activity for the business sector only, the relationship to GDP in this specific example is only approximate but it illustrates the point.

likely resulted in significant part from the unexpected drop in prices associated with microprocessors and related equipment. This, in turn, stimulated large-scale investments in ICT beginning in 1995. Although there were some year-to-year changes in this past decade, the growth in overall labor productivity was robust. Moreover, the productivity growth was also coupled with other technological and structural changes as consumers, businesses, and the market found new ways to exploit the new technologies and information and as they transformed the World Wide Web from a means of communication to a platform for service delivery. Analysts have dubbed this as "the new economy."

This very pronounced relationship between productivity and ICT investments was documented in a variety of studies on the topic. In a succession of pioneering reports, Dale Jorgenson and his colleagues specifically cite the importance of ICT as they have driven productivity gains in the U.S. (Jorgenson et al 2005).[2] Faster, better, and cheaper microprocessors, computers, and telecommunications equipment—and the improved software capabilities that drive their performance—have accelerated both the adoption of these technologies and their growing networked use. This, in turn, has ignited changes in the way we manufacture products, conduct business, and maintain social activities. As Jorgenson notes, these "changes are improving productivity and raising the long-term growth trajectory of the U.S. economy" (Jorgenson and Wessner 2007).[3] The trends are so pronounced that *Time* magazine named Internet users as its person of the year in 2006 (Grossman 2006).

Table 2 (adapted from Jorgenson and Stiroh 2000) highlights the growing influence of ICT as they sustain overall economic activity or output of the economy. The level of investments and productivity associated with ICT contributed about 0.68 percentage points to an average economic growth of 3.38 percent over the years 1980 to 1989. In effect, ICT were responsible for about 20 percent of the growth in that period. In a somewhat weaker economy, that share grew to 30 percent in 1989 to 1995. Between 1995 and 2001, and with a much stronger economic performance, the ICT share grew to 39 percent.

Table 2. Average Annual Rates of Growth (Percent)

	Labor	**ICT**	**Non-ICT**	**Output**
1980 to 1989	1.33	0.68	1.37	3.38
1989 to 1995	0.98	0.72	0.73	2.43
1995 to 2001	1.12	1.47	1.17	3.76
Source: Jorgenson et al. (2005).				

Highlighting the link in a different way as shown in Table 3 (below), Jorgenson and his colleagues again show that U.S. productivity growth accelerated in recent years, despite a series of negative economic shocks (Jorgenson et al. 2005). An analysis of the sources of this growth over the period 1995 to 2003 suggests that the production and use of information technology account for a large share of the gains.

[2] The evidence indicates that the "digital" ICT constitute a fast-growing proportion of GDP elsewhere. In the OECD countries, as one example, the relevant ICT sectors have grown from 4 percent of GDP in 1990 to about 7 percent in 2002. One paper suggested that it is likely to grow to 10 percent by 2012. See Knast and Johnston (2005).

[3] As they also comment in a footnote, the rate of growth since 1995 appears to be robust, "having survived the dot-com crash, the short recession of 2001, and the tragedy of 9/11." Most of the data cited in the various Jorgenson studies were through the year 2002. Especially since 2006, the sub-prime mortgage problem in the U.S. has begun to show serious effects in the financial markets that, together with the huge uncertainties associated with energy and world oil prices, has begun to erode the market gains. The good news in all this is that the fundamentals associated with ICT investments and performance provide a basis for continuing productivity gains.

Table 3. Sources of U.S. Output and Productivity Growth 1959-2003

Economic Indicator	1959-2003	1959-1973	1973-1995	1995-2003
Private output	3.58	4.21	3.06	3.90
Hours worked	1.37	1.36	1.57	0.85
Average labor productivity	2.21	2.85	1.49	3.06
Contribution of capital deepening	1.21	1.41	0.89	1.75
Information technology	0.44	0.21	0.40	0.92
Non-information technology	0.78	1.19	0.49	0.83

Notes: The table was adapted from Jorgenson et al. (2005). Data are for the U.S. private economy. All figures are average annual growth rates. The contribution of an input reflects the cost-weighted growth rate. Capital is broadly defined to include business capital and consumer durables. Information technology includes computer hardware, software, and communications equipment.

From an energy perspective the relationship between ICT and productivity gains may not be quite so straightforward. Notably, past productivity gains have tended to be "energy using." This makes sense when we think of large machinery that substitutes for skilled and semi-skilled labor. In the case of ICT, we might at first think of these productivity technologies as also energy using—especially with recent news articles that discuss the apparently large electricity requirements associated with so-called "server farms" or "data hotels" that form the backbone of the Internet economy. But it does appear that ICT investments may actually be "energy saving" more broadly speaking. That is, the same digital age investments that are driving a more robust economic productivity are also increasing the efficiency in how we use energy more generally.[4]

Initial evidence of the link among ICT production, economic sectors, and overall energy productivity is shown in Table 4. With the economy aggregated to the four sectors shown[5] (representing all industrial, commercial, and government sectors totaling about 89 percent of the larger economy and omitting households and nonprofit organizations), energy production has remained approximately flat over the period 1998 through 2005. On the other hand, producers of ICT equipment and appliances expanded 11 percent while ICT-related services grew at 8.3 percent. All remaining sectors of the economy grew at about 2.4 percent annually while the combined industrial and government sectors grew 2.8 percent per year.

Table 4. Quantity Index of Gross Sector Output (Index 2000 = 100)

Sector	1998	1999	2000	2001	2002	2003	2004	2005	CAGR
Energy Production	96.7	96.8	100.0	100.6	100.5	98.0	98.9	96.0	-0.1%
ICT Producers	58.6	76.0	100.0	97.3	87.5	97.8	106.5	121.6	11.0%
ICT Services	75.0	88.7	100.0	108.7	108.2	110.2	117.6	131.2	8.3%
All Other Sectors	92.7	96.5	100.0	98.8	99.8	102.2	106.1	109.4	2.4%
Total	91.0	95.5	100.0	99.6	100.2	102.5	106.6	110.6	2.8%

Note: "CAGR" refers to the compound annual growth rate.
Source: Author calculations based on date from the Bureau of Economic Analysis.

[4] The fax machine is an early example in which the use of small energy-using ICT equipment replaced the need for big energy-using equipment. Instead of sending a document by U.P.S. or FedEx (i.e., using land and air vehicles that consume relatively large amounts of energy), people can now fax (or email) a document across the country. This reduces energy consumption by several orders of magnitude.

[5] For those who might want a more complete description of the aggregation scheme used in this table, contact the report authors. Note, however, that a new definition of what might be included among the energy or ICT sectors is unlikely to change the overall results indicated here.

Perhaps more interesting is that, in 1998, the two aggregate ICT sectors accounted for about 7 percent of the total economic activity represented in Table 4. Yet they were responsible for about 26 percent of the total growth in the economy over the years 1998 through 2005—even while energy production remained essentially flat. This provides a solid basis for further review of the net energy-saving potential of ICT investments, which we explore more fully below.

Technological Revolutions, Energy Efficiency, and the Paradox of ICT

As we implied in the previous section, ICT have not only *transformed* our economy and our lives, they have also reinvigorated economic productivity. What is less well-recognized is that ICT systems have *revolutionized* the relationship between economic production and energy consumption. As such, the array of ICT applications has become a major economic and social force as well as a critical energy and economic productivity tool. Notwithstanding these critical insights, the still-evolving relationship between ICT services and economic activity also provides a range of potential solutions to the growing problem of greenhouse gas emissions. Although some recent attention has been paid to the potential climate change solutions associated with energy efficiency (Expert Group on Energy Efficiency 2007; Bressand et al. 2007; Laitner 2007a), little attention has been given the potential contributions of ICT as a cost-effective emissions reduction strategy.

We attribute the failure to acknowledge the energy-saving potential of ICT to what might be called "the ICT energy paradox." In short, analysts of all stripes tend to focus on the energy-consuming characteristics of ICT while overlooking the economy-wide, energy-saving capacity of those same technologies. As such, the shift toward an information-based economy has raised concerns about the energy demand associated with the explosion in the number of computers and other electronic devices—especially against the backdrop of impending climate change and the growing constraints on the stable production and delivery of needed energy resources. Moreover, some of the early studies done on this topic misinformed policymakers and contributed to serious misperceptions regarding the potential role for ICT investments in the global climate change equation.

To more fully explore the ICT paradox and to gain a better understanding of the potential net energy benefits provided by ICT, this report explores the following questions: What is the enabling role of ICT investments and how might they be expanded to increase energy productivity beyond current patterns of improvement? How might a productivity-led ICT strategy provide greater energy security while contributing toward climate change mitigation efforts? What do current energy and efficiency trends look like and how do ICT provide a positive complement within the emerging trends? We begin by assessing where ICT fit within the historical and technological context and by discussing our working definition of the term "energy efficiency."

The ICT Revolution

If we take a step back and look at the larger trends of our so-called "industrial age," we might better characterize the period from the late 18th century to the present as a succession of at least five distinct technological eras. One especially insightful review (Perez 2002) suggests that we are currently in the middle of a fifth major technological period—what she refers to as the Age of Information and Telecommunications. This pattern is shown in Table 5.

Table 5. Five Successive Technological Revolutions, 1770s to 2000s

Technological Revolution	Popular Name for the Period	Core Country or Countries	Catalyst Initiating the Revolution	Year
FIRST	The "Industrial Revolution"	Britain	Arkwright's mill opens in Cromford	1771
SECOND	Age of Steam and Railways	Britain, spreading to Continent and USA	Test of the "Rocket" steam engine for the Liverpool-Manchester railway	1829
THIRD	Age of Steel, Electricity, and Heavy Engineering	USA and Germany forging ahead and overtaking Britain	The Carnegie Bessemer steel plant opens in Pittsburgh, Pennsylvania	1875
FOURTH	Age of Oil, the Automobile, and Mass Production	USA (with Germany at first vying for world leadership), later spreading to Europe	First Model-T comes out of the Ford plan in Detroit, Michigan	1908
FIFTH	Age of Information and Telecommunications	USA (spreading to Europe and Asia)	The Intel microprocessor is announced in Santa Clara, California	1971
Adapted from Perez (2002)				

As we quickly observe in the Table 5 outline, our "modern history" generally begins with what people commonly label the "Industrial Revolution." This covers roughly the period from 1771 to 1829. This phase of our technological history was then followed by the Age of Steam and Railways (to 1875), the Age of Steel, Electricity, and Heavy Engineering (to 1908), and the Age of Oil, the Automobile, and Mass Production (to the early 1970s).[6] While the influence of oil, automobiles, and mass production remains clearly palpable in today's economy,[7] Perez and others suggest that Intel's 1971 announcement of the microprocessor enabled a new industrial paradigm to take hold. Still at a midpoint in its longer-term horizon, the emerging paradigm is now shaped by a rather incredible array of information and communication tools and technologies. The tools, devices, and equipment of this Age of Information and Telecommunications range from the thumbnail microchips and sensors that might be found in our cars and refrigerators to the Internet and the growth of online transactions and social networking. In ways that we discuss below, one of the apparent benefits of the information and communications technology infrastructure has been the many productive ICT investments that cost-effectively substitute for the inefficient use of energy.

[6] The life cycle of each technological revolution begins with the irruption of a new technology followed by intensive investment, coherent growth, and market saturation. The complete cycle lasts roughly 50 years. During the tail end of each cycle, the conditions become favorable for the irruption of a new technological revolution such that the beginning of the next great technological surge overlaps in time with the late stages of the previous revolution. In this way, each new revolution overlaps with the revolution that preceded it.

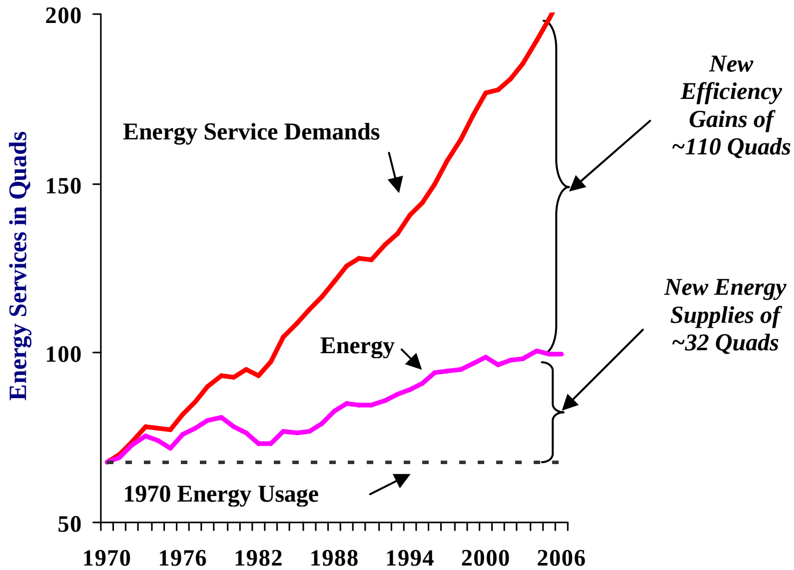
[7] Indeed it might be said that we continue to have "Oil on the Brain" (Margonelli 2007) as automobiles are still very much part of our culture and our lifestyles.

What Is Energy Efficiency?

Energy efficiency is a process that achieves the same ends with fewer energy inputs. It's about producing, transporting, traveling, lighting, cooking, heating, and communicating in ways that maintain or increase our productivity for every unit of energy consumed. In other words, energy efficiency is about providing the same goods and services using less energy.

Energy efficiency and energy conservation are not the same. By definition, conservation is about refraining from use, while efficiency is about using energy wisely. Energy efficiency is not about doing without energy resources but about extracting greater value from our energy resources whether we put them to work as kilowatt-hours of electricity or gallons of gasoline. In short, energy efficiency is about the many cost-effective reductions in wasted energy.

Figure 1. U.S. Energy Service Demands, Energy Efficiency Gains, and Energy Supplies



Source: Adapted from Energy Information Administration data (2007).

U.S. Trends in Energy Efficiency

Since 1970, the U.S. has succeeded in providing dramatically more energy services for each unit of energy consumed. In fact, energy efficiency has contributed more value to the economy in recent decades than any conventional energy resource, meeting three-fourths of all new demand for energy services since that time. During this period, U.S. energy consumption per dollar of economic output has declined by 50 percent (from 18,000 Btus in 1970 to less than 9,000 Btus by the end of 2008). In other words, current U.S. energy consumption is only half of what it would have been if levels of energy efficiency and energy productivity had remained unchanged (see Figure 1 above).

Importantly, however, historical data from as early as 1949 suggest five distinct periods of change in the nation's energy intensity (see Figure 2 below). In the early, long-term historical period between 1949 and 1973, energy intensity fell by roughly 0.5 percent per year—a trend that can best be characterized as one of slow decline. Not surprisingly, this trend changed dramatically after the first oil price shocks in 1973.

Between 1973 and 1986, annual declines in U.S. energy intensity were more than five times larger than in the preceding period, falling by an average of 2.7 percent per year. These gains were made in response to high oil prices, as well as increased political will and leadership that fostered new energy policies and technological changes that, in turn, spurred efficiency improvements in residential, commercial, and industrial energy consumption.

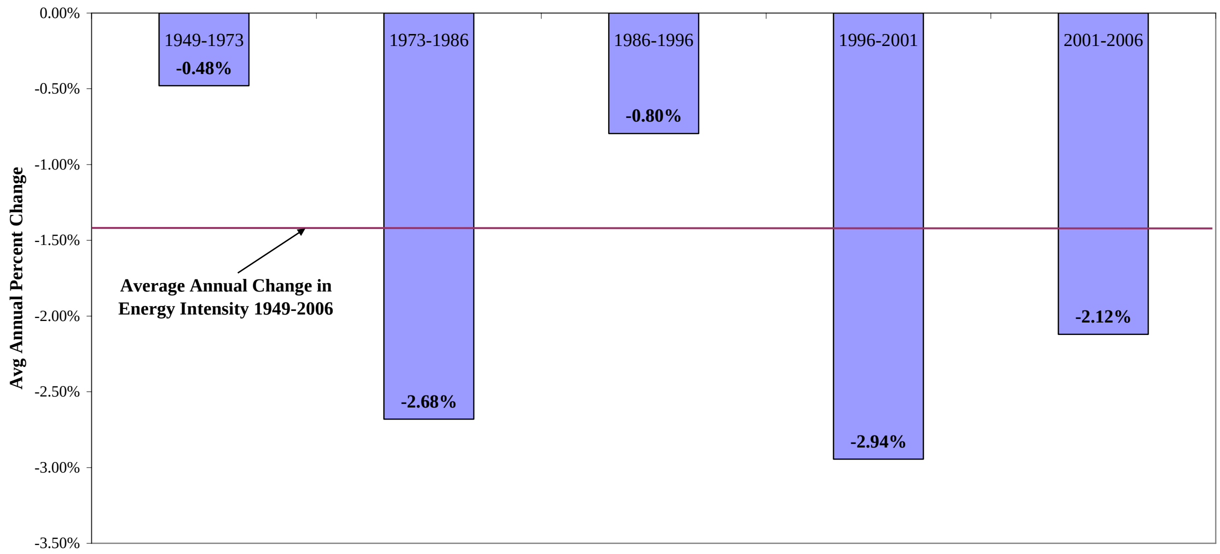
Despite the dramatic efficiency gains achieved in the mid-1970s and early 1980s, falling energy prices weakened interest in what most people believed to be mostly “a conservation ethic.” A mild recession and a general economic malaise further distracted interest in so-called “energy issues.” While the decline in the nation’s energy intensity continued in the post-Oil Embargo years 1986-1996, it fell at a much slower annual rate of only 0.8 percent.

By 1996 a turnaround had begun. Spurred by significantly lower prices for semiconductors and ICT equipment beginning in 1995, the nation accelerated its rate of investment—a process economists refer to as capital deepening. Those new investments brought online and into widespread use dramatic new technologies associated with high-speed processing and communications. These investments—remarkable in the absence of rising prices and the presence of relative stable energy supplies—contributed to significant increases in both productivity and gains in energy efficiency. Between 1996 and 2001, the nation’s energy intensity declined significantly, not as a result of changes in energy prices or supply constraints, but in substantial part as a response to technological innovation and highly productive ICT investments. During this period, energy intensity fell by an average of 2.9 percent per year.[8]

In the most recent period of our review (2001-2006), energy intensity continued to decline but at a somewhat slower pace. In the aftermath of the 9/11 terrorist attacks, consumers and businesses faced both rising energy prices and continued innovation. Moreover, the rate of capital deepening has slowed, given uncertainties in the financial markets and mounting concerns regarding the Middle East. Still, the growing ubiquity of ICT has helped reduce the level of energy resources consumed for each dollar of economic output, resulting in an average annual decline in energy intensity of 2.4 percent. While a significant drop from the previous period, it is still almost five times greater than the average rate over the period 1949 to 1973. Moreover, recent declines have been further catalyzed by growing concerns over global warming and nagging worries about international energy security. The trends are summarized in Figure 2.

[8] Changes in energy intensity since the mid-1980s are related to three important trends in the U.S. economy: (1) the implementation of new means of production that reduce energy consumption per unit of energy service delivered; (2) the shifting of the U.S. economic structure in favor of less energy-intensive industries; and (3) the offshoring of energy-intensive production to areas outside of the U.S. The first two trends provide the opportunity to reduce our carbon footprint by making production processes more energy efficient and by redirecting our economy toward high, value-added economic sectors that are also significantly less energy intensive. ICT facilitates both processes. The third trend, offshoring, also holds the potential of reducing carbon emissions if we choose to offshore production through the export of modern and energy-efficient production technologies that allow less developed countries to “leap-frog” into a more advanced technological paradigm. The net carbon impact of this third trend is a function of the types of technologies that are exported as well as their impact on global levels of production and consumption. To the extent that gains in productivity can accelerate cost-effective efficiency improvements here "at home," ICT can help minimize this problem as well.

Figure 2. Average Annual Reductions in U.S. Energy Intensity, 1949-2006



Source: Authors' calculations based on data from the Energy Information Administration (2007)

In recent periods, there is no doubt that ICT have played a critical role in reducing energy waste and increasing energy efficiency throughout the economy. From sensors and microprocessors to smart grid and virtualization technologies, ICT has revolutionized the relationship between economic production and energy consumption. And while discrete technologies have successfully enabled significant energy savings in all sectors, additional, system-wide energy savings have also emerged from the growing ubiquity of ICT technologies. The most recent trends in sector-specific energy consumption patterns illustrate this trend.

Asking the Right Questions

Physicist and now Princeton Emeritus Professor John Wheeler once commented, "We shape the world by the questions we ask." Wheeler's statement concisely expresses the idea that our current perceptions and perspectives of the world around us shape our very understanding of how the world works by constraining the range and types of questions to which we seek answers, the information that we collect and study, and the ways in which we interpret research results. Almost by definition, then, if we're not asking the right set of questions, we may be getting a less-than-satisfying set of answers. This notion is an especially salient one as scientists and political leaders seek to understand and promote smart global climate change policies and ease the growing set of energy constraints.[9]

Wheeler's comment is particularly relevant to our understanding of the relationship among technology, energy, and the environment. In the case of global climate change, the proliferation of energy-using technologies is among the sources of increased atmospheric concentrations of greenhouse gases. More energy-using technologies require more energy and, by default, increase the total amount of energy that is consumed. Because the vast majority of energy-consuming technologies rely on fossil fuel-based sources of energy (whether coal-burning power plants, gasoline in our cars, or natural gas in our homes, schools, or manufacturing plants), their operation also implies an increase in carbon dioxide emissions. By

[9] For a particularly good review of the many and perhaps surprising set of energy supply constraints that impact our economy, see *America's Energy Straightjacket* (Elliott 2006).

definition, computers and other ICT equipment are among the technologies that, at least initially, contribute to the problem.

Over the course of the past two decades, ICT have become an integral part of our everyday lives. From computers to cell phones, to fax machines, ICT is present in our homes, schools, offices, industries, and automobiles. If we look back to 1990, for example, there were fewer than 120 million personal computers worldwide. As of mid-2007, there were more than one billion PCs, representing more than an eight-fold increase. As a forerunner to the World Wide Web in 1990, there were perhaps fewer than four million users logging in to the "ARPANET" and other such systems. Today there are more than 1.3 billion users on the Internet, a 325-fold increase in the last 17 years.

But the world of advanced technologies goes well beyond the Internet. A typical household in the United States may have two dozen or more microcontrollers (computer chips) in their various appliances within the home. Those devices manage a dynamic array of widely divergent but reliable technologies as lighting, telephones, and DVD players, and are even found in washing machines, refrigerators, and microwave ovens. A typical car has as many as 50 or more microcontrollers embedded within its many different components.

Given this environment of rapidly expanding ICT and the growing evidence that human activity is changing the global climate, the natural question to ask is: "How much energy do such technologies consume and how much do they therefore contribute to the problem of global climate change?" But is this the right question?

Analyzing ICT and Energy Use: The Standard Approach

In a well-known and oft-cited article published in *Forbes*, Peter Huber and Mark Mills (1999) considered the impact of personal computers and peripherals on energy demand. They contended that "the Internet and all associated computer equipment were responsible for 8 percent of all electricity use in the United States" and that an additional 5 percent of total U.S. electricity use was consumed by computing equipment not associated with the Internet. In other words, their estimates indicated that a total of 13 percent of all electricity use was driven by computer-related equipment and the operation of the Internet. Moreover, they predicted that in the next 10-20 years, the total share could grow to half of all electricity use.

Subsequent research and reports undertook a more robust analysis of the data, debunking the "digital energy hog myth" suggested by Huber and Mills. In one of the more detailed assessments provided at that time, Jonathan Koomey (2002) concluded that "such activities consume only 3 percent of the nation's electricity."[10] Koomey arrived at this conclusion after working with a more complete set of data and checking with a number of other researchers to examine the Huber and Mills estimates. His review consistently found that the two overestimated electricity use by a substantial margin. Fortunately, later studies of ICT energy consumption were based on a more rigorous analytical framework and were able to provide a more reasonable estimate of the ICT demand for energy associated with the growth in those

[10] The 3 percent estimate that Koomey provides was for the year 2000. While there were differences, his findings were generally supported by other studies such as Roth et al. (2002). It should be noted that more recent estimates provided by the Energy Information Administration (Wade 2008) suggest that the number may now be closer to 6 percent, reflecting the continued investment in ICT technologies and systems. Koomey (2007) generally concurs but notes that 6 percent now 7 years later is a significantly different number than 13 percent in 1999 or 2000. Moreover, the EIA projections suggest that this percentage will remain under 9 percent through 2030. This, of course, is also significantly different than the suggested 50 percent figure cited by Huber and Mills for roughly the year 2020. At the same time, we continue to ask whether this is really the right question.

technologies (e.g., Koomey et al. 2002; Roth et al. 2004; Wade 2008). However, the story doesn't end there.

We contend that even this understanding of the impact of ICT is limited by the framing of the question: "How much energy do such technologies consume?" A more appropriate question might ask: "What is the *net* impact of ICT on energy demand?" This rephrasing of the question allows for the consideration of (1) the potential of energy savings provided through the use of more energy-efficient ICT equipment, and (2) possible net reductions in economy-wide energy use.

A More Robust Analysis of ICT and Energy

The primary goal of this report is to identify the answer to the second question: "What is the net impact of ICT on energy demand?" In other words, what is the net energy impact of each kilowatt-hour of energy consumed by ICT? While case studies and other quantitative data sources clearly suggest that ICT enables the efficient use of business inputs including energy resources, the size of those savings remains less well known. Could the ICT-enabled savings possibly offset the use of energy to power ICT equipment? In order to answer that question, we must first assess the growing ubiquity of ICT and measure the range of energy savings associated with the application of new ICT-based technologies.[11]

The Growing Ubiquity of ICT

By one estimate, only 2 percent of all the microprocessors and chips sold in the world today are for use in traditional servers, desktops, laptops, and mainframes (Schwartz 2004). The other 98 percent are in devices as divergent as refrigerators, cars, and lighting systems and that span telecom switches, iPhones, ATMs, and industrial machinery. Increasingly, all of them are linked so that they provide real-time information in ways that facilitate business transactions, social networks, and the production of our nation's goods and services. This staggering penetration of ICT is being driven by significant price drops, principally since 1995. These lower prices, in succession, catalyze new innovations and inspire new ways of getting things done. The continued development and expansion of such technologies will increase the likelihood of an economic development path that is both economically dynamic and environmentally sustainable. Further enhancement and deployment of ICT and other advanced technologies can provide the foundation for the many new innovations that can set a trajectory for a low-carbon path to the future.

By way of illustration, let's turn to one of the more familiar technologies, the family car, to understand the extent to which ICT sensors, devices, and technologies are already beginning to improve the way we use energy. We've previously noted that even standard cars today might have as many as 50 microprocessors at work. Managing engine performance may be the most processor-intensive and that job falls to the engine control unit, or ECU. This usually is the most powerful computer on cars. The ECU monitors and manages fuel consumption emissions. It relies on dozens of different sensors to pull information on the coolant temperature, the rate of fuel consumption, the demand for greater speed or acceleration, and the amount of oxygen in the exhaust. With all of this data, the ECU performs millions of calculations each second as it consults lookup tables for appropriate values. It calculates long equations to decide on the best spark timing and determine how long the fuel injector is open. The ECU does all of this to ensure the lowest emissions and best mileage.[12] And that is only part of the story.

[11] In setting up this question, we immediately note that the complexity and interconnectivity of the Internet, and more generally, the information economy, yield a deep uncertainty about any eventual estimate. In the spirit of Princeton's John Wheeler, it is our hope that we're at least asking the better question.

[12] As one of our reviewer notes, however, even with all this new technology cars today still get about the same mileage as cars in 1982. At the same time, Congressional passage of the 2007 Energy Bill will increase fuel

There are sensors and processors that govern air conditioning or operate the radio and the DVD player, cruise control to take the burden off some of the driving, and (for those who now use them) global positioning systems to help get you to an unknown destination with the least possible hassle.

In the near future? At some point it will be easy to order groceries while out and about, and then have them ready for pickup after running other errands. While we are used to cruise control systems to assist our driving, the next generation may be "adaptive" cruise control that uses lasers to detect the distance to any vehicle on the road ahead, and automatically slows the car down if it gets too close. And then there is the use of wireless technology to connect cars to each other. So, for example, if one car detected slippery road conditions, cars behind it would receive the information and slow down. The same wireless system could be used to send corrective commands to the car's ECU to improve performance by way of the GPS system. And while today's self-parking cars might seem like a frivolous luxury, they're actually the next step in the evolution of automotive technology.

Finally, GMC has come up with a solution to the rising costs of gas and rent—the GMC PAD. Created for the California Design Challenge, the PAD is a mobile urban loft intended to ease the difficulties of living in Southern California. This six-wheeled behemoth is basically a futuristic motor home—part urban loft, part vehicle, and part telecommunications center. A fully computerized resource management system allows the PAD to wring every last drop out of fuel and potable water supplies, with the projected time between refills lasting weeks or months. To supplement energy demands, six square meters of photovoltaic cells cover the top of the PAD, charging on-board batteries with energy collected from the sun. The computers also control the suspension, giving the PAD a smooth, easy ride and leveling it out automatically in what GMC calls LiveMode.

The Interaction of ICT Across Livelihoods and the Economy

In a very fundamental sense, all business and consumer activities can be distilled down to three things: obtaining information, processing it, and then acting on it. This is true whether we feed and care for our families and ourselves, whether we work to secure the means to do so, or whether we are interacting with family and friends for fun and entertainment. Unlike other technologies used in agriculture, transportation, or steelmaking, it is the continual need to obtain information and act on it, second by second, that invites our growing dependence—one might almost say our growing "interdependence"—on information and communication technologies. The huge decline in costs, and the resulting innovations that have been enabled by these cost reductions, has meant the growing penetration of sensors, microprocessors, microcontrollers, and communication linkages in all aspects of our lives.

In 1971, as Intel was about to announce the production of its first microprocessor, we might have awakened to a mechanical alarm clock. Even if powered by electricity, the alarm clock in 1971 was still an essentially mechanical device. Today we are more likely to be awakened by our cellphones or a radio or CD player set to go off at a previously set but variable time. Our coffee pots click on perhaps a few minutes before we get up in the morning. And before we head off to work, school, or errands and activities for the day, we may go online to learn the latest news, and perhaps to get caught up with our family and friends by instant messaging, e-mail, or checking out Facebook or MySpace. Even though they may be a continent away, we can maintain a real-time interaction through voice and video connections. And while we are checking into our social world, we may also be ordering books, groceries, and furniture online. And as a quick afterthought, we may electronically transfer funds from our personal checking account into our son's or daughter's university account so that they can pay the semester tuition.

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economy standards from the current 27.5 miles per gallon to 35 mpg by 2020. Research indicates that the technology exists to extend fuel economy to 50 mpg or more (Laitner 2007b). These advanced technologies will be a critical part of any new advances in fuel economy.

As we arrive for work (either online or on-site), we might repeat several of these same tasks to get caught up on assignments, check the status of inventories and supplies, or begin processing accounts or researching new information. Whether by cellphones and remote terminals, or through the use of desktop computers with an Internet connection, we are using sensors, microprocessors, and telecommunication equipment to facilitate and act on a flow of information. We may download a 3-D print file that enables a small machine to produce a new part for a Harley-Davidson motorcycle, or we may call up a spreadsheet to check the company budget and pass on key information to the chief financial officer. We may both begin and end the work day with conference calls, and increasingly with videoconferences. In short, there are few places in which ICT equipment and devices have not already begun to merge and interact with our way of living, working, or playing.

Case Studies and Company Information

Given the growing ubiquity of high-tech information and communications technologies in every aspect of our lives, a growing proportion of our nation's total energy demand is being used to power these new technologies. While the proportion of energy consumed by ICT (mostly electricity) has been growing, these same technologies have themselves become more energy efficient. This tends to minimize the need for energy despite the growing reliance on the technologies. Moreover, they have enabled other processes to become more efficient, and they have proven effective substitutes for more energy-intensive activities within the economy. For example, instead of flying from Chicago to New York City, businesses are choosing to use videoconferencing in ways that save jet fuel and work time. On a national level, the result has been a leveling out of the historical growth in primary energy consumption.[13]

Here we explore five efforts to increase energy efficiency through the smart application of ICT: data center optimization and virtualization, which increase the efficiency of ICT services directly; advanced metering initiatives; double-sided thermal printing; hardware power management, which optimizes existing systems in its use of energy; and telework, which effectively substitutes for travel demands. The examples demonstrate ways in which investments in ICT have been used to yield great energy savings despite the fact that they themselves use energy.

Data Center Optimization and Virtualization

As businesses have become increasingly information intensive, the infrastructure required to support them has also grown. While unmanaged growth in computing infrastructure can be associated with rapidly increasing energy demands and growing carbon footprints, there are a variety of initiatives underway to manage and significantly reduce the energy requirements of computing technologies through data center optimization and virtualization.

Data center optimization can be thought of as the convergence of various data resources (servers, storage, networks, business applications, and infrastructure products) combined with specific management actions to refresh, consolidate, retire, or virtualize information and data (Muirhead 2006). Refreshing a resource simply involves replacing old technologies with newer technologies, such as smaller, faster, and more energy-efficient servers. Consolidating resources refers to the management of processing location and generally involves reducing the number of servers required to perform similar tasks, such as consolidating databases running on multiple servers onto a single server.

[13] One note of caution may be appropriate here. Despite the significant productivity gains associated with ICT services and their boost to the larger economy, the annual investment in ICT equipment at this point is insufficient to compensate for the much larger mix of investments in less efficient technologies. Hence, the contribution to an economy-wide productivity is sufficient to slow but not offset the annual growth in energy consumption.

The economic retirement or displacement of resources allows data center managers to reduce the total amount of hardware and software in the system by getting rid of resources that are no longer used, or necessary. Finally, a range of virtualization techniques (described below) can also be used to reduce the amount of hardware required to achieve desired performance standards by replacing physical servers through the creation of multiple virtual servers—saving energy, equipment costs, space, and operating costs in the process. Moreover, data center cooling can be managed by dividing the data center into thermal zones and then using technology to dynamically manage the workload, turning specific zones on and off as appropriate to manage energy use and cooling demands.

Virtualization uses a combination of computer hardware and software to reduce the number of physical servers and the amount of energy required to perform the same amount of work by separating the software from the underlying hardware, so a single computer can run multiple operating systems and applications. In essence, virtualization enables users to maximize their use of existing servers and therefore use fewer servers. The result is lower rates of energy consumption and a significant decline in cooling demands, among other benefits. Virtualization is also a tool that allows for the creation of a more dynamic and flexible ICT environment (one that can adapt faster and more smoothly to changes), which also means less energy wasted.

Table 6. Typical Benefits of Virtualization and Consolidation in a Large Utility System

	Before	**After**
Servers	1,000	80
Storage	270 Terabytes	140 Terabytes
Network	3,000 cables/ports	300 cables/ports
Facilities	200 server racks	10 server racks
Source: Nick (2007)		

Current server utilization rates hover between 5 and 15 percent, providing a vast opportunity for energy savings and equipment consolidation. Drawing on the typical experience of a leading North American utility, virtualization can result in a 70 to 80 percent reduction in data center space, power, and cooling (Nick 2007). All of this adds to a significant reduction of energy demand throughout the United States.

Advanced Metering Initiatives

To ensure the capacity of the nation's electrical grid to continue to meet energy service demands in times of stress, the U.S. Department of Energy has partnered with research institutions and private industry in a nationwide effort to explore the ways in which ICT can improve the performance and efficiency of the current system. The advanced metering initiative, known as GridWise, manages electrical demand through a combination of intelligent technologies and financial incentives (IBM Corporation 2007a, 2007b).

The GridWise demonstration projects are composed of two parts: the Grid Friendly™ Appliance Project (based on intelligent consumer appliance technologies) and the Olympic Peninsula Demand Response Project (based on the use of automated infrastructure technologies). The programs rely on sophisticated ICT systems that allow businesses and consumers to specify individual energy use preferences in relation to specific energy prices. The system automatically regulates energy supply distribution based on near real-time market price signals.

In effect, the application of advanced technologies has created a virtual marketplace in which energy consumers and energy providers use automated ICT devices to "bid" for electricity. On the consumer end, program participants used intelligent, programmable thermostats, water heaters, control modules, and advanced communicating electric meters.

> Consumers program their thermostats and water heaters via the Web, setting temperatures and schedules just as they would if they were manually programming their smart devices. The price signal-based demand management application takes that information, combines it with real-time sensor information and market-trend information, and generates bids into the market for each device. It then sends updated set points and other control signals back to the intelligent devices in response to the market closing price of each market cycle. (IBM 2007a)

The advanced technologies allow consumers to trade flexibility in electricity demand for lower costs when there is a shortage—and it gives providers the demand information they need to determine the actual cost of generation, transmission, and distribution in near real time. The application of these technologies on a larger scale would allow utilities to reduce their use of the least energy-efficient power plants, saving energy and reducing carbon emissions. But there have also been unexpected sources of energy savings. Interestingly, the study found that participants were actually curtailing their energy use and saving energy simply because they had greater control over their energy consumption decisions.

Dematerialization and Double-Sided Thermal Printing

Advanced information and communications technologies can also save energy by reducing the amount of material goods we consume. Because paper is among the most energy-intensive products to produce, technologies that allow us to reduce our paper consumption can also help us to save energy. One new technology being used in grocery stores, two-sided thermal receipt printers, saves a lot of paper.

By printing on both sides of the receipt, stores can cut their paper roll consumption dramatically. According to RMT, Inc. (a nationally recognized environmental management and engineering firm), a 1,000-store chain with four of these printers per store could reduce their paper usage by as much as 40 percent,[14] saving the equivalent of 1,067 trees and more than 100 tons of paper per year (NCR 2007).

Moreover, every 100 tons of paper saved represents an equivalent energy savings of roughly 3,405 kilowatt-hours in paper manufacturing processes alone. In other words, if every grocery store in the U.S. adopted these printers in four of their checkout lanes, the energy savings associated with reduced paper consumption would save up to 16 million kWh of electricity and reduce greenhouse gas emissions by 10 to 15 thousand metric tons of CO_2 equivalent per year.[15]

Additional energy and environmental benefits include the reduction in associated air emissions, waste production, and water consumption associated with the production, transportation, and disposal of the paper.

[14] This assumes an average receipt that has a length of 10 inches.

[15] These calculations are based on an estimated 47,000 grocery stores in the U.S. The exact number of kilowatt-hours of electricity saved and greenhouse gas emissions avoided will vary as a result of a number of factors including the mix of fuels and the amount of recycled paper versus virgin materials used in the paper production process. This estimate is based on the use of 20 percent recycled paper content. These calculations were based on data provided by the Environmental Defense Paper Calculator at http://www2.environmentaldefense.org/papercalculator/index.cfm.

Hardware Power Management

Somewhat ironically, ICT innovations are currently being developed for computers and other high-tech equipment in order to better manage the power demand associated with our increasing reliance on these machines. Of particular note are the new automated hardware power management technologies that are being developed to reduce the amount of energy consumed by advanced electronics when they're not in use.

For example, some PCs may be used 50-60 hrs/week but remain "on" for as many as 24 hours per day. Since the energy usage associated with idle computers adds up quickly, companies began exploring ways to turn systems off when they're not being used and still maintain needed system security.

In order to save energy, Dell responded to this problem by developing a company-wide power management plan that integrates two types of software to shut down computers at night (without data loss or application errors) and repower computers in the morning. The new software has reduced average energy consumption per desktop from 89 to 5 watts per hour and per laptop from 15-25 to just 3 watts per hour.[16] With the use of the new software (manufactured by 1E) on approximately 50,000 of its own office computers, Dell expects as much as a 40 percent reduction in energy costs for desktop and notebook computers. For Dell, that translates into energy savings of roughly $1.8 million per year.

Telework

High-tech telecommunications technologies offer a solution to growing levels of energy consumption and carbon dioxide emissions from the transportation sector. Continuous improvements in the speed, reliability, and options provided through telecommunications facilitate the transition from transportation gridlock to work in the telecommunications fast lane. In short, telework provides high-tech means of substituting telecommunications for work-related travel. Telecommuting and videoconferencing can reduce: (1) the number of passenger miles traveled; (2) traffic congestion (and therefore time spent idling in traffic); and (3) the amount of building-related energy used by reducing the amount of office space required to house employees.

According to a recent study for the Consumer Electronics Association completed by TIAX (2007), there are between four and six million workers in the U.S. who telecommute at least once a week. On average, telecommuting reduces vehicle miles traveled by 40 percent, resulting in a total annual energy savings of 0.1 to 0.2 percent of total primary energy consumption in the U.S. or 100 to 200 trillion Btus of energy per year. In other words, current levels of telecommuting in the U.S. save the energy equivalent of taking 1.5 to 2.1 million light duty vehicles off the road each year. Moreover, a significant increase in energy savings could be achieved through an increased pervasiveness of telecommuting. In fact, a recent study by Mathews and Williams (2005) estimates that about 50 percent of information workers (approximately 20 percent of the U.S. labor force) could telecommute, potentially quadrupling current energy savings.

These case studies illustrate a few of the many ways in which ICT is being applied to reduce energy consumption. On the one hand, the evidence suggests that energy consumption—and especially the use of electricity—has increased as the development of new ICT applications drives the expansion of new devices and appliances in our homes and businesses. On the other hand, the evidence also suggests that the larger, economy-wide productivity gains and efficiency improvements that have been realized through the use of these technologies have more than offset the energy used to power them.

[16] These savings indicate the number of watts saved per hour per computer when idle.

Net Energy Savings: An Emergent Property of ICT

The energy productivity gains generated by the proliferation of ICT appear to be greater than simple observation alone might lead one to conclude. Not only have individual digital age technologies resulted in new, more energy-efficient means of production, transportation, communications, and data processing in many cases,[17] but the use of ICT applications in a *systematic* way (whether by coincidence or by design) has also contributed to greater levels of net energy savings. Thus, as these technologies have (and continue to) become more and more integral to our economy and our everyday lives, *additional gains in net energy productivity are expected to emerge* through the formation of numerous ICT networks and systems.

In this sense, the emergent energy savings associated with the development of ICT systems can be thought of as characteristics, patterns, or features of the system itself: the product of the collective and interactive whole as opposed to a product of its component parts. As such, these types of savings cannot manifest themselves or be observed except in so far as the system is considered in its entirety. In other words, they are macroscopic features of complex ICT systems and cannot be reduced or understood by studying all of the individual component parts of the system.

A few examples include the energy savings that emerge through the expansion of teleworking and teleconferencing or the widespread adoption of e-commerce and e-billing. In the first example, telework, teleconferencing, and video conferencing reduce the number of people traveling to work and business meetings. The obvious result is that fewer people require transportation and less energy needs to be expended with the use of vehicles. In addition, there are likely to be fewer offices and slower growth in the construction of new office buildings, resulting in lower demands for heating, cooling, and lighting. Moreover, fewer roads and parking lots are likely to be constructed and less road maintenance will be required. Finally, as traffic volumes decline, traffic will be less congested, resulting in fewer traffic jams, less idling time, and lower fuel use.

A similar story is likely to emerge with the expansion of e-commerce and e-billing. As costs continue to drop and the frequency and number of people shopping and paying bills on-line increases, the number of traditional shopping trips to the local mall or shopping center will decline, as will the number of cars on the road. Traffic congestion will decrease, reducing idling time and fuel consumption. Improved logistics associated with the management and transportation of shipments will further lessen traffic congestion and miles traveled to deliver the needed groceries or the supplies needed by local manufacturing plants. Eventually, as on-line shopping becomes the norm, there are likely to be fewer retail shops with less floor space requiring less heating, cooling, and lighting. E-commerce combined with ICT production system technologies also allow for smaller retail inventories since products are produced and shipped on demand. Moreover, on-line billing reduces the demand for paper as well as mail volume, thereby reducing the transportation of mail and the production of paper (a very energy-intensive industry).

As ICT technologies have become more integral to the products and services on which we rely, the systems-level energy savings generated by ICT have also continued to grow. The growing ubiquity of ICT has also captured the attention of researchers, and a number of recent studies have sought to identify and document the contributions that ICT has made to productivity growth, energy savings, and reductions

[17] It is important to note that some electronic technologies indeed use lots of energy without obvious productivity benefits—i.e., the new plasma HD TVs and the like. While these efficiencies are likely to be improved over time, the point remains that, in the aggregate, the savings appear to be net positive.

in carbon emissions. We will review their findings and discuss our own macro-level assessment of ICT energy savings in relation to previous studies.

An extensive study released last year by Atkinson and McKay (2007) noted that ICT systems have been the major driver of economic growth since the mid-1990s. According to the authors, between 1995 and 2002, this family of technologies was directly responsible for contributing "two-thirds of total factor growth in productivity and virtually all of the growth in labor productivity." In many ways, this echoes (and cites) the findings of Jorgenson et al. (2005). More critically, the Atkinson-McKay study takes an extra step beyond Jorgenson and his colleagues by contending that as ICT equipment boosts productivity and economic output, it also allows energy and other resources to be used more efficiently.

Indeed, a study by the Lawrence Berkeley National Laboratory found that properly evaluating the contribution of ICT technologies could reduce the growth in carbon emissions by about one-third over what they might otherwise be over a ten-year period (Laitner 2003). In effect, the study suggests that we may need to shift the standard reference case assumptions in ways that lower the expected business-as-usual growth in energy demand and energy-related carbon dioxide emissions. Similarly, the UK's RAC Foundation for Motoring estimates that ICT could reduce commuter travel by 15 percent, heavy freight by 18 percent, and shopping trips by car by 10 percent (British Telecommunications 2005). Another study by Professor Fujimoto (2006) at the University of Tokyo suggested that, over the long term (i.e., out to the year 2050), an ICT-based society could potentially reduce Japan's total carbon dioxide emissions by 40 percent or more.

Along the same lines, an updated study by the McKinsey Global Institute (Bressand et al. 2007) found a clear link among smart technologies, energy productivity, and reduced energy demand. The McKinsey study concluded that investments in smart technologies and energy productivity held the promise of reducing fossil fuel consumption, reducing carbon dioxide emissions, and generating a positive return on investment. More specifically, the study suggested that the right set of investments in the development and application of new technologies could increase energy productivity by 25 percent or more over standard projections during the next two decades. And, in addition to reducing energy use and carbon dioxide emissions, the estimated productivity gains would generate a 10 percent or better net positive return on investment.

Finally, a study by Laitner et al. (2008) explores historical energy efficiency gains in the United States. As summarized in Figures 1 and 2 cited earlier, this study argues that efficiency gains through 2006 have been dramatic. When compared to the development of new energy supplies, efficiency gains "fueled" roughly 75 percent of the new growth demands in the U.S. since 1970. The new energy supply resources, on the other hand, provided less than one-quarter of the annual demands (or about 32 quads, as shown in the figure). This type of assessment indicates that U.S. efficiency gains were responsible for reducing energy consumption by the equivalent of 100 quadrillion Btus in 2006 alone (or roughly 17.2 billion barrels of oil equivalent).

The Impact of Moore's Law

Driving all of this change has been the incredible improvement in ICT characterized by Moore's Law. Before discussing Moore's Law further, however, we think it useful to step back and compare the capacity and performance of computers in 1946, the year before the invention of the transistor, with a typical computer on the market today. Table 7 below contrasts the performance attributes of the Electronic Numerical Integrator and Computer, or ENIAC, with that of the Intel Core Duo Chip that was available in 2006. ENIAC was the first general purpose electronic computer while Duo Chip refers to Intel's x86 64-bit microprocessors targeted at the non-server consumer and business markets.

Table 7. Computer Characteristics, 1946 to 2006

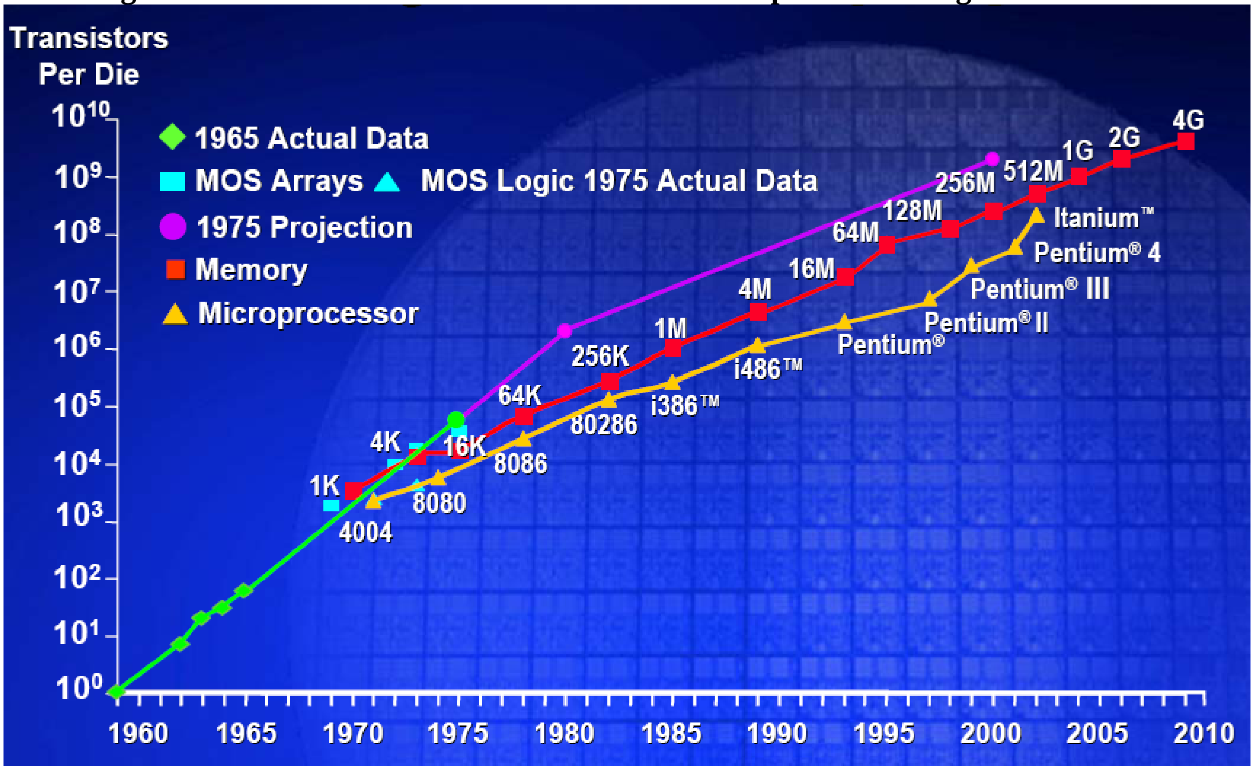
Performance Attribute	Electronic Numerical Integrator and Computer (ENIAC)	Intel Core Duo Chip*
Debut	1946	2006
Performance	5,000 addition problems/sec.	21.6 billion operations/sec.
Power Use	170,000 watts	31 watts max
Weight	28 tons	Negligible
Size	80' wide x 8' high	90.3 sq mm
What's Inside	17,840 vacuum tubes	151.6 million transistors
Cost	$487,000	$637

* The data cited here are given for the Intel Core Duo Chip as shown in Kanellos (2006). To provide a more accurate comparison, the ENIAC should be compared to a modern-day computer using the new Core Duo Chip. Nonetheless, the resulting comparison would show the same degree of technological change as a result of the huge drop in price and the growth in computing performance.

To provide some idea of the dramatic increase in the performance of computers over the last 60 years, we can covert ENIAC's 1946 cost into 2006 dollars and compare its 5,000 operations per second with the 21.6 billion operations that can be carried out by the Duo Chip in that same second of time. Based on this comparison, it turns out that the 1946 cost of roughly $700 per operation declined by an average rate of about 32 percent per year over the last 60 years (authors' calculations). With this perspective, we can now perhaps better appreciate the implications of Moore's Law and its impact on computer and other ICT prices.

In 1965 Gordon Moore was a founder and then research director of Fairchild Semiconductor. In a very short 4-page paper (Moore 1965) he noted that the "future of integrated electronics is the future of electronics itself." By plotting out the data available at that time, he observed that as transistors got smaller, the number of transistors that fit onto an integrated circuit grew exponentially. He then "challenged" the semiconductor industry to continue this exponential growth. Perhaps responding to the dramatic decline in prices as well as the opportunity, industry has risen to that challenge. Each doubling requires innovation, capital expenditure, and risk. In practical terms, the result has been that the computing power of a chip has roughly doubled every 18 months.

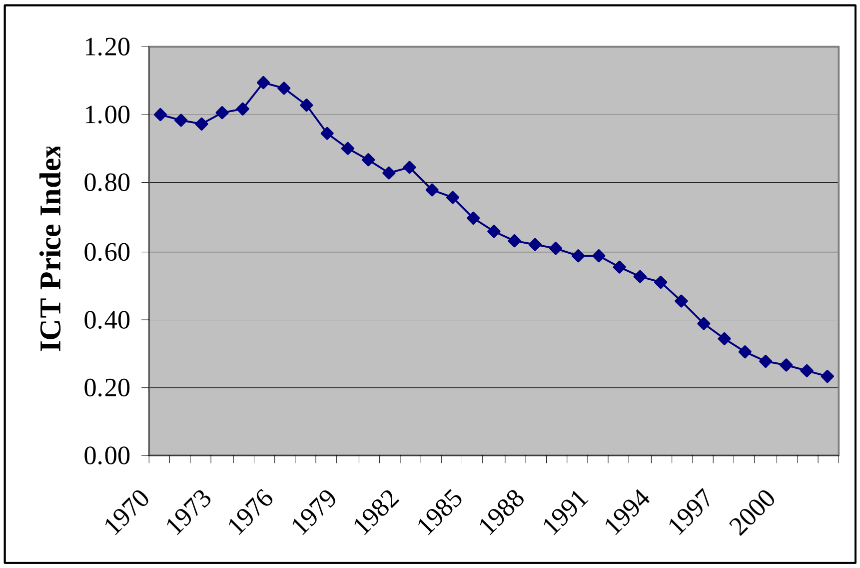
Figure 3. Moore's Law as Reflected in the Development of Integrated Circuits



Source: Moore (2003b)

What we now know as Moore's law has held true for over 40 years. As dramatic as this constant rate of improvement has been, the real impact of Moore's Law has been in terms of the dramatic price reduction in cost. This is illustrated in Figure 4 below, which shows the rate of decline in overall ICT prices over the period 1970 to 2002.

Figure 4. Price Index of ICT Equipment, 1970 to 2002



Source: Jorgenson et al. (2005)

In the figure above, the weighted average of prices for ICT equipment (including computers, software, and telecommunication components) fell to just short of 20 percent of their constant dollar 1970 prices. More decisively, the annual prices fell at a steady 3 percent over the period 1970 through 1995. The rate of price decline accelerated to 9 percent annually beginning in 1995 (Jorgenson et al. 2005). Computers and servers in particular, following an average 13 percent drop in prices through 1995, stepped up the rate of decline to 27 percent from 1995 through 2002. It was this sudden transition of price drops that catalyzed the rapid investments and innovations in ICT equipment and on-line connectivity. It was the link between the number of transistors on a microchip and the declining cost (Moore 2003a) which, in turn, drove the steep price decline beginning in 1995.

The level of progress is continuing across many core ICT technologies (memory, processors, storage, sensors, displays, and communication)**.** For example, the real price of servers fell approximately 30 percent per year between 1996 and 2001 (Van Reenen 2006).

In a similar way to transistors on microchips, hard drive storage capacity has doubled every 19 months while the cost of a stored megabyte of data has fallen 50 percent per year. As a result, the cost of storing one megabyte of information fell from $5,257 in 1975 to 17¢ in 1999 to half a cent in 2002 to less than 1/10th of a cent today (Atkinson and McKay 2007). With this dramatic decline in storage costs, a whole array of devices from portable MP3 video players to digital television recorders have been accelerating in the market.

The increased performance of storage devices is why Hewlett-Packard can sell its Media Vault that stores 300 gigabytes of data— enough to store 150 movies—for around $380 (Atkinson and McKay 2007). It is also why Google, Yahoo, and Microsoft are providing consumers with large amounts of free Web-based storage for their e-mail, photos, and other files. For example, in early 2007 Google provided around 2,700 megabytes of free storage for users of their Gmail e-mail service. Today, it is up over 6,500 megabytes of free storage. Had customers been charged such costs based on 1975 technologies (in 2006 prices), they would be paying on the order of $60,000 per user (authors' calculations). With memory becoming such a negligible cost to companies such as Google, they can afford to give huge amounts of storage for free, paying for it through unobtrusive advertisements.

While much of the growth has been driven by improvements in hardware, software has also improved. One study estimates that software productivity (the writing of code) has more than quadrupled since 1970 (Longstreet 2006). Moreover, an increasing number of software firms are offering more comprehensive, rather than specialized, packages for businesses, which allows for lower-cost implementation and easier use. For example, a new EU project, coordinated by the Royal Institute of Technology in Sweden, is developing a new computer-aided holistic solution for the early phase of aircraft design. Since up to 80 percent of the total cost of an airplane's lifecycle is set during the early design phase, mistakes are expensive. The use of software and a combination of Web-based applications can reduce costs and resources, especially in associated consulting and support (Science Daily 2007).

ICT and Overall Energy Productivity

Interestingly, the expansion of energy productivity gains since 1970, and notably since 1996, coincides with the collective and economic transformation toward a service- and knowledge-based society—in effect, the fifth technological era as described by Carlota Perez (see Table 1 above). One of the principal drivers of increased energy productivity during the past 15 to 20 years has been the emergence and widespread adoption of advanced technologies, including high-tech electronics and a variety of information and communications technologies. But, how big has the contribution of ICT been to this increased productivity?

Our own macro-level analysis, completed specifically for this study, confirms the important contributions of ICT toward the economy-wide increases in energy productivity. To generate a reasonable working estimate of ICT-related energy productivity gains, we collected data on energy use and ICT investments for the U.S. over the years 1949 through 2006. We then used a series of regression analyses to provide a first order impact that ICT investments might have on the annual change in total energy consumed in the United States.

After controlling for the effects of population and economic growth, the mix of ICT technologies was found to have a significant dampening effect on the nation's energy consumption. In effect, while population and economic growth generally increased overall energy usage, the ICT investments increased the overall efficiency of energy use so that the total demand was somewhat dampened. The upshot is that by using 2006 data on investments in information technologies, the series of regression models led us to estimate that for each kilowatt-hour of (mostly) electricity needed to power the use of ICT equipment—whether computers, servers, or telecommunication equipment—approximately 6 to 14 equivalent kilowatt-hours of energy were saved. For example, one kilowatt-hour of electricity used by a variety of ICT devices might enable the saving of a gallon of gasoline as a result of reduced travel demand.

With today's mix of power plant technologies, an electric utility might require about 10,800 Btus of coal or natural gas first to generate that kilowatt-hour and then to transmit it to either the home or the office.[18] A gallon of gasoline has the energy equivalent of about 125,000 Btus. In this illustrative example then, the extra kilowatt-hour of ICT energy use might avoid about 11.5 kilowatt-hours of gasoline equivalent.[19] Given the uncertainty of the data used to derive this estimate, we generally describe the net savings ratio as about 10 to 1. (See the appendix for a complete discussion of regression methodology.)

While current and historical efficiency gains are impressive, the evidence suggests that substantial room for improvement remains—including consumer and business products and information and communication technologies that will be essential to enabling future productivity gains. That today's business leaders and policy makers may be overlooking this broader set of opportunities is not surprising. Public policy specialist Jeffrey Luke (1998) commented almost a decade ago that cognitive research in problem solving shows that individuals usually generate only about 30 percent of the total number of potential options on simple problems. In other words, individuals typically miss 70 percent or more of the potential high-quality alternatives. In the case of energy efficiency opportunities, much of what has been overlooked are the very large productivity gains associated with advanced technologies and ICT-related devices and equipment.

[18] As a matter of interest, a kilowatt-hour of electricity delivered to a home or business is equivalent to 3,412 Btus. If today's electricity utility system requires ~10,800 total Btus to generate and deliver one kWh of electricity, then we would say the system efficiency is about 31.5 percent. Perhaps of even greater interest, the level of efficiency is essentially unchanged since the early 1960s (Energy Information Administration 2007).

[19] While this is a highly positive ratio, the ICT net energy savings is likely to be only a very small part of the overall energy needed by households and businesses. Moreover, because there are additional costs in the form of equipment leasing, labor, and other expenses, the actual financial savings might be more on the order of three dollars saved for every dollar of ICT-related expenditures. For further discussion on this point, see Gallaher et al. (2007).

ICT Productivity Gains: The Four Means of Improvement

For the most part there are four principal ways by which Information and Communication Technologies can improve our overall energy productivity while maintaining a high quality of life and dynamic economy:

- *Reducing the energy needed to design, manufacture, and distribute the ICT devices and equipment.*
- *Increasing the operating efficiency of the ICT technologies once they are installed and on-line.*
- *Optimizing the performance of other energy-using systems.*
- *Substituting ICT-related services for other goods and services within the economy.*

Given the current magnitude of energy productivity gains, how might we anticipate further opportunities? As the box above indicates, there are essentially four different ways that additional productivity gains might unfold. The good news is that industry is hardly standing still. There is active effort that will enhance efficiency opportunities in each of the four categories. We will briefly review these.

The first step toward larger productivity gains is to reduce the energy that is needed for the design, manufacture, and distribution of the ICT devices and equipment themselves. This is an active focus of almost all ICT producers (King 2007). For example, HP set an aggressive goal to reduce global energy consumption of its own products and operations by 20 percent below its 2005 levels by 2010 (Pierce 2007). And this level of commitment is by no means unique.

The second step is to increase the operating efficiency of the ICT technologies once they are installed and on-line. Just as we've seen with Moore's Law, there has been a steady trend in the reduction of energy use by these technologies. The *Economist* magazine (2007) reports, for example, that the electricity requirements of a chip for a given capacity tend to decrease by half every 18 months. In a very concrete way that builds on this tendency, the Climate Savers Computing Initiative (2008) believes that desktop computers waste nearly half the power delivered to them. For that reason, the industry has committed to a 50 percent reduction in the power consumption of computers by 2010. That will greatly improve the efficiency of ICT appliances and equipment.

An impressive third step is to use the ICT capacities to optimize the performance of other energy-using systems. For example, U.P.S. has adopted new package flow software to better organize its routes and, among other things, help its driver avoid left-hand turns. As a result, U.P.S. has taken an estimated 28.5 million miles off its delivery routes. This, in turn, has resulted in savings of roughly three million gallons of gasoline annually (Lovell 2007). Other optimization systems include building energy management systems (Ashford 1998; Hatley et al. 2005). But equally important are industrial optimization systems that can create huge savings to the bottom line there as well (Ondrey 2004; Abramovici 2006).

The last potentially significant step toward greater energy productivity is the substitution of more productive ICT-related services for other goods and services that are less energy efficient. Among the examples that hold particular promise in this category are telework and videoconferencing. Smart-grid technologies can also provide as yet unrealized savings through the refashioning of the nation's entire electricity grid into a digitally controlled network that provides a smart, responsive, flexible generation system that could also save a huge amount of energy. By one estimate, a smart grid could reduce the amount of energy required to produce a dollar of GDP by 30 percent. That would also save the economy an estimated $100 billion (Carey et al. 2003).

In the future, the continued expansion of such technologies can undoubtedly help ensure that economic development will move in a direction that is both economically dynamic and environmentally sustainable. In other words, the further enhancement and deployment of ICT and other advanced technologies can provide the foundation for the many new innovations that can set a trajectory for a low-carbon path to the future.

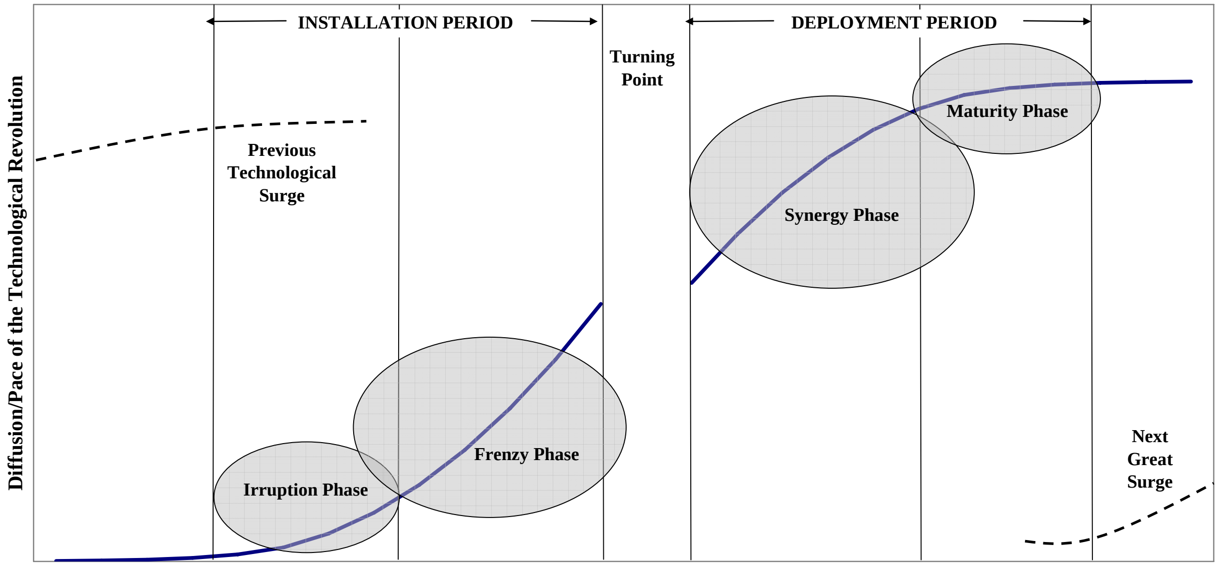
A Technological Era and the Energy Productivity Frontier

Every technological revolution has its own lifecycle that can be thought of as involving four phases (see Figure 5 on the next page). The first two phases are part of the installation period during which new technologies irrupt and advance, disrupting the established social and institutional fabric of society while establishing new networks, infrastructures, and procedures. The installation period is often associated with a period of social and economic polarization, as fortunes diverge and the benefits of increased economic productivity are unevenly distributed. The second two phases are part of the deployment period during which there is a surge of economic development based on the full diffusion of the new technology as well as a more even diffusion of the benefits of economic growth and productivity. The installation period and the deployment period are separated by a critical turning point during which a variety of fundamental changes are required to successfully move the technological revolution forward. According to Perez (2002), it is “a space for social rethinking and reconsidering” as well as “an important crossroads for socio-institutional decision-making.”

The first period (the installation period) begins with the irruption of a transformative new idea that “inflames the imagination of young entrepreneurs.” Generally, this period occurs within the context of the previous technological paradigm and a market that is mature and approaching saturation. However, it isn’t long before the productivity potential of the new technology is recognized, attracting the attention of investors and consumers. The second phase consists of a frenzy of investment activity in the development of the new technology as well as the exploration of related possibilities. Following a successful transition, the third phase—given the proper framework—tends to be characterized by steady and harmonious economic growth. During this phase the emphasis is no longer on financing the new technologies but on maximizing production. In the final phase, the technology in question reaches maturity. Although the signs of success and prosperity still linger, there is also a growing dissatisfaction and frustration on the slowing of social progress, and the political climate becomes ripe for ideological confrontations. Historical evidence suggests that each technological revolution takes approximately 50 years to complete its historical cycle.

This framework is heavily grounded in Everett Rogers’ work on the diffusion of innovations (Rogers 2003). Rogers’ work sought to understand the ways in which new technologies spread throughout a society, theorizing that the pattern of cumulative adoption would form an S-shaped curve. In general, the pattern of adoption would begin with a few early adopters, followed by a more rapid uptake of the new technology, and eventual market saturation and a tapering off of adoption rates. As seen in Figure 5, the diffusion graph illustrates the cumulative percentage of adopters over time.

Figure 5. Illustrating the Pace and Diffusion of the Technological Revolution



Note: This figure denotes a classic diffusion curve (Rogers 2003).
Source: Adapted from Figure 7.1 in Perez (2002)

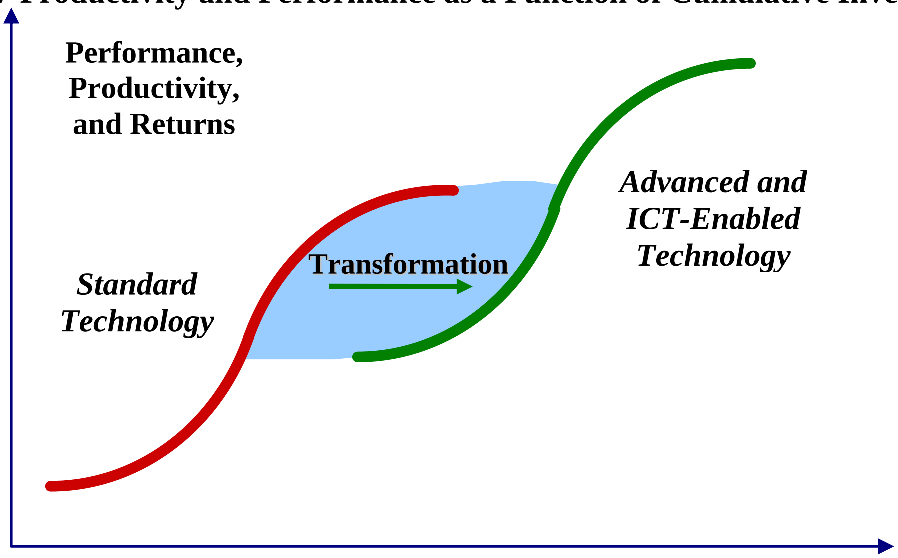
According to Perez's application of the model, the current Age of Information and Telecommunications was begun in the early 1970s. But where in the cycle might we currently find ourselves? Today, U.S. society clearly remains at a critical turning point. And, as described by Perez, "[t]he turning point has to do with the balance between individual and social interests..." and can be seen as "a time when the leading actors in the economy, society and government recognize the excesses as well as the unsustainability of recent practices and trends…" While the future may lead to a more cohesive and equitable period of growth, what lies ahead is not predetermined. A range of outcomes is possible, including a period in which structural tensions and environmental degradation continue unabated or a period of increasing social cohesiveness, improved income distributions, and environmental sustainability.

The Perez analysis suggests the key to unlocking a more equitable (and we would argue, sustainable) future is the ability to implement regulatory interventions via actions on the part of the state and other forms of civil society that result in greater attention to collective well-being. Climate change legislation would be one such type of intervention.

Within the context of this discussion it becomes evident that digital controllers, smart sensors, and adaptive software and operating systems can play an increasingly large role in delivering further energy efficiency gains—if we choose to use them to achieve those ends. In other words, the realization of ICT-driven energy savings has been, and will continue to be, dependent upon our institutional and cultural capacity to direct these technologies toward addressing our most pressing energy and climate problems as much as it is about our technological capacity alone.

Assuming that we choose a path toward a more sustainable future, how might energy productivity benefits expand as a result of accelerated investments as well as expanded efforts? Figure 6 provides a critical insight, especially as it complements the pattern of innovation and diffusion highlighted in the Perez framework show in Figure 5. As shown in Figure 6, ongoing, cumulative investments and the right set of policies can catalyze the advancement in the performance, productivity. and returns of current and future technologies, resulting in a discontinuous jump in the performance path as both the advanced technologies and the markets are transformed. This combination of events also allows for major advances in overall energy productivity, especially as policy and organizational efforts are catalyzing market decisions to move in that direction. While the vertical axis in Figure 5 describes the level of diffusion and penetration, the vertical axis in Figure 6 shows why.

Figure 6. Productivity and Performance as a Function of Cumulative Investment



Source: Authors' Illustration

Indeed there is already strong evidence of this trend in both in the academic literature and in recent industry studies. In one of the seminal papers of its time, economist Edwin Mansfield (1991) notes, for example, that "[d]ozens of economists working independently with quite different sorts of models and entirely different kinds of data have found that the social rate of return from industrial innovations and R&D has been very high, frequently 40 percent or more. This is a remarkable fact, and one that policy-makers should recognize."

Somewhat more recently, researchers Charles Jones and John Williams (1998) asked the question whether there was too much or too little activity in terms of private research and development. Citing a large empirical literature, they found rates of return from R&D investments ranging from 30 percent to over 100 percent. This suggested that there was, indeed, too little investment in such research. Using the framework of an R&D-based economic growth model and a conservative estimate of a 30 percent return for R&D, their analysis suggested that an optimal national investment might be at least four times larger than the normal pattern of such expenditures.

Closer to the point of this study, a team of Northrup Gruman analysts (2006) completed an investigation into the economic returns from investments in intelligent machine technology. Their findings suggested that specific R&D investments directed toward the development of intelligent machine technology would generate productivity gains of 19 percent to 34 percent annually, and that the social rates of returns would be on the order of 70 percent or more annually.

Conclusions

We have entered the age of information and telecommunications. As a society, we currently find ourselves at a point of inflection in this most recent of several important technological eras. From here, the course of action that we choose to follow will not only shape the characteristics of the second half of the present era but also the more distant future. Will it be more or less equitable? Will it be more or less productive? Will it be more or less energy intensive? And finally, will it be more or less environmentally sustainable? The new technologies of the ICT era have opened the doors to many possible futures, but ultimately it is how we make use of them and apply them that determine which path we follow and the consequences of those choices. The data and ideas presented in this report indicate that ICT have increased the economic productivity and energy efficiency of our economy and that they also hold the potential for reducing our energy intensity even more dramatically in the future.

Technological Eras

Although the dot-com bubble may have burst in 2000, as we begin 2008 we still find ourselves in the midst of the current technological era—the age of the microprocessor and other associated innovations. The dissemination of these innovations has indisputably propelled us toward an information revolution based on cheap micro-electronics, computers, software, and telecommunications. In the past 30 years or so, these technologies have allowed us to develop a new socio-economic infrastructure that includes worldwide digital telecommunications, Internet service, electronic mail, and other e-services as well as a variety of modern, electricity networks and high-speed transportation links. They have also enabled us to increase our productivity and our efficient use of energy and raw materials.

ICT and Energy Productivity

ICT has already revolutionized the relationship between economic production and energy consumption, becoming a critical energy and economic productivity tool for consumers and industry alike. For example, in 2006 alone, U.S. capital investments in information equipment totaled $109 million and generated an estimated 2.2 quads of energy savings throughout the U.S. economy (see the appendix). While these investments resulted in the continued proliferation of ICT technologies throughout the economy and expanded the amount of energy consumed by ICT devices, they also increased our economic productivity and our energy efficiency. Thus, for every one kilowatt of energy used by ICT equipment, approximately 10 kilowatts of energy were saved.

Despite the significant energy savings potential that information and communication technologies offer, this attribute of ICT has generated a notable lack of recognition due to what might be called “the ICT energy paradox.” The paradox is one in which more attention tends to be paid to the energy-consuming characteristics of ICT than to its broader, economy-wide, energy-saving capacity that emerges through its widespread and systematic application.

Of equal importance is the growing array of potential solutions that ICT offers for the problem of global climate change and the trend toward growing concentrations of greenhouse gas emissions. By increasing our investments in smart, energy-efficient information and communications technologies, we can reduce our consumption of energy and other production inputs, thereby reducing our impact on the global climate for each of the products we produce and consume.

Inflection Point and Global Climate Change

Importantly, however, while dramatic changes have taken place in the past 35 years, we have yet to realize the full potential of the productivity and efficiency gains that are the promise of this new technological era. In fact, we currently find ourselves merely at the midpoint or turning point in the longer surge of development. As described by Carlota Perez (2002), the turning point is unique because it is "a space for social rethinking and reconsidering. It is an important crossroads for social-institutional decision making." And it is when "the particular mode of growth that will shape the world of the next two or three decades is defined" as well as "… the time when the leading actors in the economy, society and government recognize the excesses as well as the unsustainability of recent practices and trends…"

The inflection point represents an opportunity to address the shared issues of the current era, to consciously choose how best to apply the technologies of this new age not only to maintain robust economic activity but also to enhance our collective social and environmental well-being. While the beginning of every new technological era is characterized by a process of creative destruction, the turning point constitutes the opportunity to adjust and address the social (and now the environmental and climate change) problems that have developed as a result of the economic transition from the previous era. The age of information and telecommunications has introduced many amazing new technologies, expanding our choice of tools for meeting a variety of challenges. Now we must decide to what ends we wish to apply these new tools. What goals will we pursue, and what methods will we employ?

In other words, from here we must decide how to move forward. To what degree will we strive to capture the potential efficiency gains afforded by these new technologies and apply them as solutions to global climate change? To what degree will we choose to invest in technologies that reduce our net energy demand? The choices that we make as we pass through this inflection point are likely to shape the world for generations to come. The new information and communications technologies have given us the ability to dramatically reduce our collective carbon footprint. We recommend that we explore the myriad of ways in which ICT can increase energy efficiency and reduce total energy consumption, as well as the implementation of effective climate change legislation.

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Appendix: Methodology

While case studies can provide us with anecdotal evidence concerning the general direction of ICT productivity gains, additional analysis is required to provide a better sense of the full magnitude of ongoing or potential new benefits. In order to develop more rigorous estimates of the economy-wide impacts of ICT requires the collection and assessment of national level data on a variety of critical measures.

Unfortunately, there is only a limited range of the required statistics available for analysis. In the absence of the preferred data, we have chosen to use proxy variables in order to ascertain the approximate size and direction of the suspected relationships between variables. In this appendix we first set forth the study hypotheses that we are exploring, and we then describe the data that are generally available for review. Finally we describe the different ways of characterizing the net impacts of ICT investments based on a series of regressions that provide us with crude measures of the relationships in question.

This study began with three hypotheses:

H1: Information and communications technologies are transforming the U.S. economy in significant ways.

H2: Information and communications technologies have increased economic productivity in the United States.

H3: Information and communications technologies have increased energy productivity in the United States.

The first hypothesis was assessed through a review of news articles, technical reports, conceptual frameworks, and economic data. These sources suggest that historically recent technological innovations in information and telecommunications technologies have caused a significant shift in the economic structure of our society and resulted in the development of a new techno-economic paradigm based on information intensity, network structures, heterogeneity, and segmentation. National economic data on our nation’s changing sectoral composition and economic growth as well as capital investments in information technologies were also used to assess the relationships between the emergence and diffusion of ICT, on the one hand, and changing economic structures, on the other.

Our assessment of the second hypothesis began with a literature review on the topic, followed by an assessment of case studies and indicative quantitative measurements of the relationship between ICT and changes in economic productivity.

The third hypothesis was evaluated through the use of technological case studies as well as the development of several regression equations in which energy consumption was regressed on a select group of independent variables including population growth, economic growth, and the change in capital investments in information and communications technologies.

More specifically, three regression equations were developed to test the relationship between ICT investments and energy consumption. We describe those efforts next.

First Regression: Link between Electricity Use and ICT-Related Capital Stock

To give us an initial sense of possibilities and magnitudes, we generated a first equation to determine the right sign and magnitude of each of the variables in question. Taking time series data over the period 1949 through 2006, we regressed electricity consumption on GDP and total ICT capital stock based on information available from the Bureau of Economic Analysis.

Based on that estimation, we found the following relationship:

Total Electricity Use = -713.19 + 0.562 * GDP – 0.993 * ICT Capital Stock

With an Adjusted R-square of 0.997, we found all variables to be highly significant. In this equation, electricity will grow with GDP, with that growth being dampened in a small but significant way by the ICT capital stock. Drawing from Wade (2008), we determined that each dollar of ICT capital stock required an estimated 0.131 kWh of electricity. By our estimate, the total ICT capital stock in 2006 (in constant 2000 dollars) was on the order of $1,771 billion within the U.S. That was an increase of $109 billion over 2005 levels. That implied an energy use of 14.2 billion kWh. But the regression indicates that the incremental capital stock saved 0.993 * 109 = 108.2 billion kWh. This implies that for every kWh of electricity needed to power the ICT equipment, 8.6 kWh would be saved.

While a strong pattern, this equation gave us only a partial insight. The hypothesis as supported in this first regression suggests that for each kilowatt-hour of ICT demand for electricity, total energy through out the full economy would decrease. Hence, we then moved to a series of equations that included both capital stock and total primary energy. The subsequent regressions are described next.

Second Regression: Economic Growth, ICT Investments, and Total Energy Use

The second regression equation used annual change score measures of select variables to assess the effect of population change, economic growth, and ICT investments on the change in energy consumption. Data were collected for the years 1949 through 2006 and annual change scores were calculated for the years 1950 through 2006. Census Bureau data on total U.S. population measures were collected from the Energy Information Administration online (*Annual Energy Review*, Table D1, available at http://www.eia.doe.gov/aer/txt/ptb1601.html). Bureau of Economic Analysis data on U.S. gross domestic product (chained 2000 dollars) were also collected from the same reference. Measures of ICT capital investments were collected from the BEA. Measures of energy consumption were collected from Table 1.1 of the 2006 *Annual Energy Review* at http://www.eia.doe.gov/emeu/aer/overview.html.

All three independent variables were found to be statistically significant. Population change and change in economic prosperity (GDP per capita) were both found to have a positive effect on the change in energy consumption although the effect of affluence was much stronger than the population effect. As expected, the change in investment in information equipment was found to have a moderately strong, negative effect on the change in energy consumption. These relationships maintained their direction and significance even in regressions that added various other control measures such as the change in energy prices, or the change in the number of U.S. households.

Test of the second hypothesis resulted in the following equation:

Change in Quads = -1.588 + 0.001 * Change in Population + 0.003 * Change in GDP
- 0.020 * Change in ICT

For this equation, the adjusted R-square of 0.551 suggests that there is more to explain the changes in total primary energy consumption (measured in quads). Nonetheless, all variables appear significant. Multiplying the same $109 billion * -0.020 suggests a total primary energy savings of 2.2 quads. As we found previously, total energy requirements for the net addition to the ICT capital stock implies an energy use of 14.2 billion kWh that must be converted to primary energy. Based on data from the Energy Information Administration (2007), each delivered kilowatt-hour of electricity required a primary energy use of 10,800 Btus. This means the electricity used to power ICT equipment and processes, in turn, uses about 153.4 trillion Btus. Since 2.2 quads are the same as 2,200 trillion Btus, this implies that for every kilowatt-hour (or trillion Btu) of electricity needed to power the ICT equipment that 14.4 kWh (or trillion Btu) would be saved.

At the same time, since there are measurement problems with ICT capital stock, we also decided to apply the Jorgenson et al. (2005) estimates for ICT and re-estimate the capital stock. Here we found that the ratio declined to 6.7 kWh (or trillion Btu) saved for every kilowatt-hour (or trillion Btu) required for the ICT equipment. We chose to treat this as a lower bound.

Third Regression: Expanded Variables and their Impact on Energy Use

While a less satisfying set of relationships, we decided to expand the analysis to include a third regression equation by including two additional independent variables: a measure of a change in investment in industrial equipment and a measure of the change in energy intensity. As anticipated, both measures were positive and significant, indicating that growth in investments in industrial equipment result in bigger changes in energy consumption, all else equal. Similarly the change in energy intensity was found to have a positive impact on the change in energy consumption such that positive changes in energy intensity were associated with positive changes in energy consumption, all else equal.

Change in Quads = -0.908 + 0.001 * Change in Population + 0.003 * Change in GDP
0.019 * Change in ICT + 3.712 * Energy Intensity + 0.160
* Change in Industrial Equipment Investments

For this last equation, the adjusted R-square improved to 0.905 with all other variables statistically significant. By working through the same steps to convert kilowatt-hour to primary energy consumption, and establishing the same comparison, we found that the ratio rose again to 13.5 kWh (or trillion Btu) saved for every kilowatt-hour (or trillion Btu) required for the ICT equipment.

Caveats in the Analysis

As we suggested in the preface to this methodology, the data are not collected in a way that easily allows a precise estimate to be generated for the productivity gains associated with ICT investments. Among the uncertainties are the changing power requirements for ICT capital stock, the growing use of consumer based products such as iPods and Blackberrys that might not be counted in normal ICT capital stock that might reflect more of a commercial or industrial investment pattern, or how one might treat the greatly changing qualities associated with yesterday and today's net capital stock. For that reason, the best we can provide is a highly uncertain range that might run from 6 kWh saved for each one used to as high as 14 kWh (or more). For that reason, we choose to discuss a rule of thumb that suggests a savings of about 10 to 1.