Information Technology and U.S. Energy Consumption

Energy Hog, Productivity Tool, or Both?

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Summary

A significant debate has emerged with respect to the energy requirements of the Internet. The popular literature has echoed a misleading study that incorrectly suggests the growth of the information economy will require huge amounts of new energy resources. Even correcting the misleading assumptions in that study, discussion on this topic tends to result in a highly limited and unsatisfactory review of many larger issues. Although the evidence suggests a relatively small amount of energy is required to power today's information needs—about 3% of total electricity consumption in the United States—the complexity and connectivity of the Internet, and, more generally, the information economy, yield a deep uncertainty about the eventual long-term impact on energy consumption. Although we may not yet be able to generalize about the future long-term energy needs associated with the information economy, the evidence points to continuing technical changes and the growing substitution of knowledge for material resources. These interrelated trends will likely generate small decreases in energy intensity and reduce subsequent environmental impacts relative to many baseline projections. Despite these trends, a number of questions need to be addressed before any solid long-term conclusions might be forthcoming. The article reviews some of the dimensions of these possible changes and suggests further directions for research that may help answer these important questions.

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Introduction

In his speech "The American Scholar," philosopher Ralph Waldo Emerson noted an ancient oracle that said, "All things have two handles: beware of the wrong one" (Emerson 1837). The emerging debate about the direct energy requirements associated with the growing use of information and communication technologies (ICTs) may be grabbing for the wrong handle.[1] Such a narrow focus yields only limited usefulness to policy makers, who must wrestle with questions about the appropriate balance between economic activity and environmental quality. Perhaps a more complete question with respect to energy consumption might be, What impact will the information age have on our ability to produce goods and services within our economy; and what impact will it have, in turn, on the nation's overall energy requirements? In short, will the information economy prove to be an energy hog, a productivity tool, or both?[2]

Table 1 shows the key energy and economic data for the United States for selected years over the period 1960 through 2001, including gross domestic product (GDP), energy consumption, and energy-related carbon emissions (U.S. EIA 2001a, 2001b, 2002). Also shown are the estimated energy intensities of the U.S. economy for the different years as well as the average annual change in energy intensity in the intervening years. The years of interest are 1960, which provides the historical benchmark data; 1973, which is the first year of the 1973–1974 oil embargo launched by the Organization of Arab Petroleum Exporting Countries; 1986, which generally reflects the bottoming out of oil and energy prices resulting from both the oil embargo and the so-called 1979 Iranian oil shutoff; 1996, which is the year many believe the influence of the Internet was firmly established; and 2001, which is the last year for which we have complete historical data.

Since 1960, U.S. energy consumption has increased at roughly half the rate at which the nation's economy has grown. The reason for the slower rate of growth in energy use is that the nation's energy intensity has also declined. For example, in the years 1960 through 1996, energy intensity declined at an average rate of 1.3% annually. For the years 1996 through 2001, this trend took a sharp turn, and energy intensity declined at the rate of 2.8% per year. In absolute terms, this is a greater rate of decline in the nation's energy intensity compared to that which occurred in the "oil crisis" years of 1973–1986. Carbon emissions, driven by changes in energy consumption, generally follow a similar pattern.

The sharp decline in energy use per dollar of GDP in the years 1996–2001 has generated strong interest among analysts. Some attribute the majority of the change to weather. Boyd and Laitner (2001), however, suggested structural change in the economy—the continued shift from the extraction of raw materials and the production of goods to the delivery of high-end, value-added services, including, but not limited to, Internet-related services—as a major influence. A separate analysis by Davis and colleagues (2001) indicated that weather accounts for only

Table 1 Key U.S. energy and economic data for selected years

Year	*GDP*	*Energy*	*Intensity*	*AAGR*	*Carbon*
1960	2,377	47.6	20.0	–	792
1973	4,123	78.0	19.4	−0.2	1,265
1986	5,912	81.3	13.8	−2.6	1,255
1996	7,813	99.1	12.7	−0.8	1,472
2001	9,334	102.4	11.0	−2.8	1,540

Source: Adapted from EIA 2001a, 2001b, and 2002.

Note: GDP is gross domestic product in billions of 1996 dollars. Energy is total primary energy consumption in exajoules. Intensity is the energy use per dollar of GDP in megajoules. AAGR is the average annual growth rate in energy intensity for the intervening years. Finally, carbon is the energy-related carbon emissions in million metric tons.

a limited change in the nation's energy intensity. Even with a small correction to reflect the influence of weather, it appears that the annual rate of change in 1996–2001 was surprisingly larger than many analysts might have expected on the basis of past trends.[3] This is all the more surprising because it occurred in the absence of any significant price signals or major energy policy initiatives within the United States.

Clearly, five years of data is not sufficient to confirm whether the rate of change in the nation's energy intensity is a real trend rather than a simple anomaly. Yet, a number of analysts suggest that, even if temporary, the change is significant and real. Such change, in fact, may be driven by structural changes catalyzed by investments in ICTs (Romm 2001; Laitner et al. 2001; Laitner 2000; Koomey et al. 1999; Romm et al. 1999).

This article provides a further review of whether the explosive growth of software, information resources, and communication technologies have significantly reduced the nation's energy intensity (with concomitant reductions in energy consumption, energy-related carbon emissions, and other atmospheric pollutants). More important, are these reduced energy intensities ones that enhance the larger economic well-being?

Background

In 1970, the Internet consisted of just four university campuses connected by a highly limited network largely for e-mail purposes. In 1999, the Buyer's Index provided an on-line search engine that listed 8,000 buyers' sites with 19 million products for sale (Rejeski 1999). Today it now lists 20,000 sites with 300 million products (Buyers Index 2002). Perhaps more important, the various channels of the Internet economy now support more than a half trillion dollars in electronic commerce revenues within the United States. The Gartner Group further suggested that by 2004, worldwide business-to-business commerce revenues will grow to \$6.0 trillion (Goodman 2001). And equally intriguing, Forrester Research continues to believe that on-line business will approach \$7.0 trillion in worldwide transactions by 2006 (Kirkpatrick 2001). This is about one-third of total current U.S. output.

Although various ratings from Standard and Poor's or the Fortune e-50, and markets such as the NASDAQ, all suggest that "the era of the dot-coms" may be over, the long-term prospects of the information economy are still enormous. Indeed, contrary to public perception, many of the dot-com enterprises succeeded. One industry estimate indicates that at most, 10% of significant Internet companies have failed as a result of the shakeout in 2000 and 2001 (Mosquera 2001). And although the Internet may not emerge as a "disruptive" technology as quickly as some believed early on, the larger information economy promises to reduce consumer and business costs; change the nature of markets, institutions, and other social and business relationships; and affect the way we do our jobs. Because technologies tend to wander along unexpected development paths, never quite moving in straight lines (Saffo 2002), all of these changes are likely to occur in ways that cannot be fully anticipated at this point in time. By implication, then, it is hard to know with any precision how information technologies might impact the many dimensions of potential energy use over the coming decades. At the same time, however, we can reasonably frame or highlight key issues so that we at least have a manageable handle to explore possible outcomes.

Possible Energy Impacts from the Information Economy

The immediate impact of ICTs appears to be in four interrelated areas. None of these is mutually exclusive, and the examples provided are by no means exhaustive.

New Insights

The first area is their ability to generate new insights that provide us with new materials and new ways to sustain our economic livelihood. Applications include genetic algorithms, neural networks, and other advanced computational methods (practical only because of increases in computing power) to assist engineers in the design of new engines and industrial processes. For example, using Sun Microsystems workstations, researchers at the University of Wisconsin's Energy Research Center employed a computer-aided design tool based on a genetic algorithm (using "survival of the fittest" principles) to design truck engines that pollute less while also consuming less energy. Usually, engineers optimize system design for either fuel efficiency or for reduced pollution levels, but the genetic algorithm was able to help engineers simultaneously improve both attributes. The new engine design cut nitric oxide emissions by 3 times and soot emissions by 50% while simultaneously reducing fuel consumption by 15% (Johnson 2000). At the same time, the world of materials science has exploded in recent years, leading to the design of new products for information storage, new biomedical resources and equipment, and smart materials that evolve in real time in response to changes in load, light, temperature, and humidity. The design and application of these new materials is made possible, in large part, by an emerging science that draws heavily on information technologies (Ball 1997).

Reduced Energy Use

The second area is the reduction of direct energy use by equipment that benefits from computer-aided optimization. New electronics and software technologies allow the more efficient use of energy in almost all equipment and appliances. Electronic appliances such as TV sets, computers, and cellular phones and their adapters have been characterized as energy vampires, using up to 20 W of power even when turned off. A new chip and new equipment design can reduce the use of standby power by up to 90% (Takashi 1998). The new Toyota Prius, among the first generation of fuel-efficient hybrid electric vehicles, has an electronic control and software system that continuously "talks" to and optimizes the operation of all the car's key components. This ensures that the vehicle always operates in its most efficient mode, obtaining as much as 45 to 52 miles per gallon of gasoline (U.S. OEERE 2001).

Real-Time Data

The third is the ability to provide real-time data that reduces both time and distance (as in the remote monitoring of building energy consumption patterns 24 hours/day, 7 days/week). Interactive, Web-based tools allow energy service providers to monitor and evaluate energy needs in real time, and then allow them to make adjustments to optimize performance, reducing both cost and energy use. For example, District Energy St. Paul, Inc., manages the largest hot water district heating system in the United States. It uses a comprehensive energy analysis tool that accesses meter data less than 1 hr old to diagnose and pinpoint efficiency problems, all at a net savings of energy and money (Anderson 2001). Ford Motor Company is using network distribution tools to ship and track the delivery of new automobiles, and has plans to allow a Ford product to be shipped with a General Motors product if both are going to dealers in the same city. Logistics is not an area in which Ford competes with General Motors, and a shared distribution network would reduce both material and energy costs in the delivery of automobiles (Greenleaf 2000).

Value-Added Materialization

The fourth, but not necessarily final, area is the growing influence of knowledge and information systems and their ability to catalyze higher levels of added value for a given resource. Examples might include the greater value inherent in the manufacture of pharmaceuticals and computers compared to the mining of the sand, petroleum, and various other minerals and metallic ores that provided the material basis for their production and use.

In the so-called new economy, value is embodied in knowledge, innovation, and speed, rather than material presence. This is changing the composition of the economy, as well as changing the value-to-weight ratio of major goods that underpin our economic activities. For example, sand costs about 1¢/lb or less. Crude oil now costs about 7¢/lb, whereas steel is now about 11¢/lb. As these raw materials are fashioned into automobiles, however, the value increases to perhaps $6 to $10/lb. Semiconductor materials in the form of a processor chip for computers might cost more than $10,000/lb. And medicines might range from $200 to more than $20,000/lb.[4] Hence, the growing knowledge base and information economy allow us to generate more value added per pound of raw material in ways that should lead to less energy required per dollar of GDP—although not necessarily less energy use overall—compared to traditional energy and economic forecasts.[5]

An Unfortunate Distraction in the Dialogue

Some researchers argue that growth in the Internet implies a huge and increasing demand for electricity. Huber and Mills (1999) have suggested, for example, that current computer, office equipment, and Internet energy requirements amount to 8% to 13% of total U.S. electricity consumption. Their estimates included both the energy required to produce the various devices connected to the Internet and the energy needed to power all the servers, network equipment, and a portion of telephone office electricity use attributed to the Internet. Building on this assessment, Mills suggested in a recent article in *American Spectator* (Mills 2001) that a wireless Palm Pilot used as much energy as a refrigerator when connected to the Internet.[6] These alleged facts have been repeated in numerous magazine and newspaper articles, to the point that they appeared to be common knowledge (Koomey et al. 2002).

A detailed analysis by Kawamoto and colleagues (2001), however, indicated that Mills's estimates were significantly higher than what might be supported by the data. Analysts with consulting firm Arthur D. Little, Inc. (Roth et al. 2002), further demonstrated that the Mills hypothesis was not supported by the evidence. In a study completed for the U.S. Department of Energy, Roth and his colleagues found that Mills "consistently selects power draw levels that lie at or beyond the end of the equipment considered and applies that assumption to the entire stock of devices" (Roth et al. 2002, 105). For example, the Mills analysis assumes that the routers consume 1,000 W of power. This number does apply to the high-end routers, but it is the low-end routers that dominate the market. The low-end routers require as little as 15 W when operating. Similarly, the Mills analysis assumes that the average personal computer and associated peripheral equipment also draw 1,000 W. As Roth and his colleagues note, "this assumption would be true—but only for a PC with a large CRT monitor, hooked up to a computer network, and printing continuously from an office-class laser printer. In reality, most printers are shared resources and do not print continuously" (Roth et al. 2002, 106). Romm (2001) also pointed out that the actual growth in the nation's demand for electricity seems to contradict the Mills assertion. Indeed, the Arthur D. Little assessment indicated that "office and communication equipment consumes about 2.7% of delivered electricity nationwide, or just less than 9% of all electricity consumed in commercial buildings" (Roth et al. 2002, 96).

Romm (2001) and Laitner (2000) further suggested that Mills's view failed to accurately capture the systemic effect and structural change, respectively. The systemic use of energy refers to both the direct and all of the indirect uses of energy associated with changes in the economy, whereas structural change refers to a change in the composition and output of the economy. The unfortunate aspect of the Mills analysis is that he did raise some important questions with respect to these last two issues. But as we shall see further in the discussion, the greatly exaggerated claims about overall electricity demand make it difficult to put other relevant issues into a useful context.

A Thought Experiment on the Magnitude of Potential Savings

At this point, we can ask questions about the magnitude of potential energy savings and environmental impact of the information economy. For this exercise, we turn to the U.S. Energy Information Administration's *Annual Energy Outlook 2002 (AEO 2002)* (U.S. EIA 2001b). That forecast suggested total energy use in the United

States will increase from 105 EJ of primary energy in the year 2000 to 122 EJ by the year 2010.[7]

Given the increased demand for energy and the mix of fossil fuel resources necessary to meet that demand, the *AEO 2002* (U.S. EIA 2001b) suggested that energy-related carbon emissions in the United States, now at about 1,540 MMT, will increase to perhaps 1,835 MMT in 2010. At the same time, however, the growth in the information economy appears to be facilitating the deployment of more energy-efficient equipment. This is occurring directly through the successes of voluntary programs such as the U.S. Environmental Protection Agency's (U.S. EPA's) Energy Star initiative and indirectly through the accelerated diffusion of the more energy-efficient equipment made possible by a variety of ICTs. By 2010, for example, the U.S. EPA estimated that its voluntary programs will reduce total greenhouse gas emissions by 100 MMT (CPPD 2002).[8]

In a separate paper by Laitner and colleagues (2001), researchers from the U.S. EPA and the Lawrence Berkeley National Laboratory suggested that a shift in the conventional modeling assumptions might generate a forecast of a net reduction of at least 95 MMT in carbon emissions otherwise forecasted for the year 2010, effectively lowering projected emissions to 1,728 MMT in that year. Table 2 summarizes these results.

The U.S. EPA–Lawrence Berkeley National Laboratory analysis provides estimates that lower carbon emissions by about 6 MMT as a result of reduced paper and cement consumption by 2010.

Table 2 Information economy adjustments in a 2010 reference case forecast

Sector category	*Carbon emissions (MT)*
Reference case forecast	1,835
Industrial commodity production	−6
Transportation	−16
Commercial floorspace	−18
Combined heat and power	−8
Voluntary programs	−40
Structural change	−31
Integrating/rebound effect	+12
Adjusted reference case forecast	1,728

At the same time, forecasts of improved shipping practices and altered shopping patterns through on-line purchases provide small reductions in vehicle miles traveled, such that transportation emissions would be reduced by about 16 MMT. Changing product inventories, telecommuting, and other business practices might reduce total commercial building space to produce another savings of about 18 MMT. An additional impact stems from the Web-based brokering of electricity sales together with other influences that increased the penetration of more energy-efficient industrial cogeneration and distributed energy resources. This provides an estimated savings of 8 MMT compared to standard forecasts. In addition, structural change within the economy (meaning a more rapid growth in the less energy-intensive service sectors compared to the growth in heavy industry) was forecast to contribute reductions of another 31 MMT compared to standard forecasts. Finally, the conventional forecasts currently reflect only partial credit for the anticipated success of the information-based voluntary programs. Should they give full recognition for program impacts as documented by the U.S. EPA, energy-related carbon emissions might be reduced by perhaps another 40 MMT in the year 2010.

When the combined 107 MMT of carbon emission reductions are integrated into a modeling exercise, including an expected rebound effect that tends to increased energy use as more income is generated for businesses and consumers, a net reduction of about 95 MMT might be expected compared to the 2010 reference case. Hence, an alternative 2010 projection might suggest total energy-related carbon emissions of only 1,728 MMT, instead of the current estimate of 1,835 MMT.[9]

Three important points should be noted in this exercise. First, even with the expected acceleration in the growth of the information economy, energy use and carbon emissions are still expected to grow by about 12% compared to emissions in the year 2001; it is just that they might grow less quickly in the 10-year forecast reflected in the *AEO 2002* (U.S. EIA 2001b). Second, the reduced growth in carbon emissions is comparable to the estimates provided in the *AEO 1997* (U.S. EIA 1996) projections for the year 2010 (U.S. EIA 1996). In effect, the higher average annual economic growth rate assumed in the current forecast—3% in the *AEO 2002* versus 2% in the *AEO 1997*—may be partially offset by an increasing energy productivity that reduces the overall growth of energy use and carbon emissions. Finally, there are a large number of uncertainties that may indirectly tip the balance either toward greater energy consumption or toward an even lower use of energy. These trends will be greatly affected by energy and environmental policies yet to be enacted. The following discussion highlights the impact of many different futures that might emerge, given the complex interactions of social and economic influences that drive energy consumption over time.

Many Different Futures

Notwithstanding the current infrastructure, technology systems, and cultural preferences, the past is consistent with many different futures (Robalino and Lempert 1999). In other words, despite the assumption of a fixed capital stock and social preferences, there are a large number of plausible economic and environmental landscapes that might emerge as a result of the complexity and connectivity of both the Web and the information economy (Rejeski 1999; Lempert 2000; Merry 2000). In effect, we have moved from the merely complicated to the highly complex in ways such that the information economy makes possible even more and varied futures than are typically captured in routine economic forecasts.

The specific energy outcomes will depend on many little and currently unknown (and even unknowable) choices that we will make in the future. Figure 1 provides an illustration of this perspective. It highlights the many possible energy paths that are consistent with past trends and variables. These trends are based on the projections found in the *AEO 2002* (U.S. EIA 2001b), but they are greatly affected by the many uncertainties surrounding the otherwise expected energy future.

Standard forecasts of future energy use suggest that U.S. energy consumption might roughly double from about 105 EJ in the year 2000 to about 211 EJ by the year 2050. A 95% confidence interval around the standard forecast might suggest a lower and upper range from 183 to 240 EJ, also by 2050 (shown in figure 1 as an index of 1.75 to 2.29, where the year 2000 equals 1.00).[10] But these formal models tend to reflect only complicated data rather than the many complex and emergent relationships that may surprise and confound the standard forecasts.[11] Allowing just three key drivers of energy consumption (population, per capita income, and anticipated efficiency gains) to vary in a Monte Carlo simulation according to the historical range of values indicates a broader range of energy futures that might emerge. The ranges of annual rates of change that are assumed in these projections, adapted from historical data documented by the U.S. Energy Information Administration (U.S. EIA 2001a), are shown in table 3. The results of these simulations, shown in figure 1, provide a year 2050 index ranging from 1.00 to more than 3.00, reflecting the impact of these variations and resulting in high and low index values of about 1.25 and 3.00, respectively, for the year 2050. These roughly correspond to projections of energy consumption ranging from 131 to 315 EJ, respectively.

How might the information economy broaden the range of possible outcomes compared to standard forecasts? Rejeski (1999) suggested that with a phenomenon such as the Internet, the notions of property and ownership, the dynamics of value creation, and the nature of competition may all have significantly different impacts than are commonly understood. Separate discussions by Merry (2000) and Cilliers (2000) on the inherent complexities of the information age suggest the phenomena described by Rejeski (1999), Merry (2000), Matthews (2001), and others may all give rise to so-called third- and fourth-order effects not presently anticipated in standard forecasts. These effects can either increase or decrease total energy use beyond any initial reductions made possible by ICTs. For example, changes in wealth and travel patterns may drive an unexpectedly larger energy use than might otherwise be anticipated. On the other hand, changes in community structures and market arrangements (made possible by information technologies) may substantially alter land-use patterns such that energy

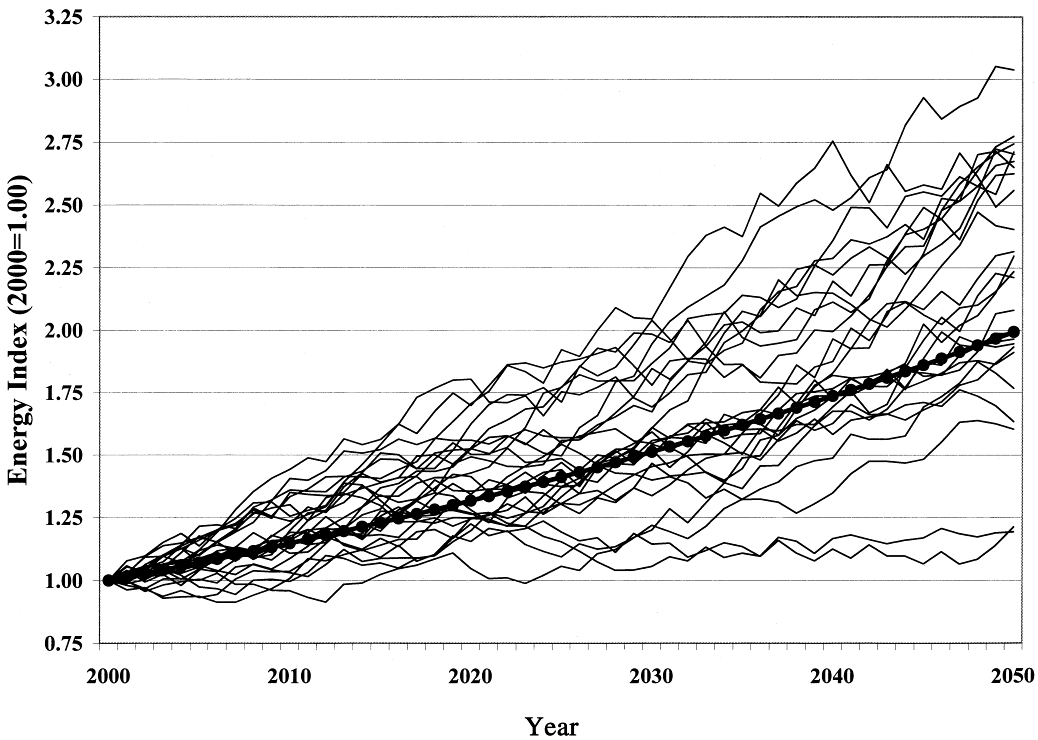

Figure 1 Many different energy futures consistent with past changes in economic variables.

demand over the longer time horizon is significantly reduced. Also, a number of technological "wildcards" might contribute to disruptive change. Some examples might include low-temperature fusion, high-temperature superconductivity, and nanoscale manufacturing. All of these are likely to depend heavily on advances in computation and information-age technologies.

Third- and fourth-order effects of disruptive technologies and institutional changes are typically not explored in the standard modeling exercises with respect to energy consumption and its larger impacts. Yet, it is the very real possibility of these surprises that prompted Lempert and colleagues (2002) to promote what they refer to as a robust adaptive planning approach in thinking through future energy options. Under "conditions of complexity and deep uncertainty that normally defeat other analytic approaches," Lempert and his colleagues encourage the use of robust adaptive planning methods to evaluate large ensembles of scenarios that help identify candidate strategies that may enable the production of goods and services regardless of unexpected disruptions. Such exercises can enhance decision makers' ability to construct hedging strategies that may actually strengthen the economy while mitigating or minimizing the effects of surprise.

Conclusions and Recommendations

The initial evidence with respect to information technologies appears to support a trend toward decreasing energy intensity compared to the trends now represented in conventional forecasts. Nonetheless, as long as GDP grows faster than the decline in energy intensity, overall energy consumption will continue to increase, albeit at a smaller rate. At the same time, the more important question should be raised about whether society is adequately prepared to confront either a 100 or a 300 EJ future compared to an assumed 200 EJ economy by 2050. Other questions might include whether energy consumption matters if we move toward cleaner re-

Table 3 Range of assumed annual rates of change for U.S. energy projections, 2000–2050

	Population	*Per capita GDP*	*Energy intensity*
Lower range	0.35%	−2.56%	−4.40%
AEO average	0.83%	2.11%	−1.52%
Upper range	1.01%	6.78%	2.44%

Source: U.S. EIA 2001a, 2001b.

Note: The values in this table represent average annual changes from a previous year. The AEO average reflects the average rate of change in the AEO 2002 forecast for the period 2000 through 2020. The lower and upper ranges reflect the lower and upper historical rates of change documented in the period 1970 through 2000. As shown in figure 1, these values were used to generate the range of projections over the longer period 2000 through 2050.

newable energy resources. And how can we position ourselves today such that the negative impact of future surprises can be minimized? Or, said differently, how can we anticipate future opportunities opened up by ICTs that might enhance the quality of economic activity? Research questions that would provide greater insights into a robust set of future policy options include the following:

- What are the reasonable estimates of long-term growth in the ICT sectors of the economy?
- How will such growth influence activity elsewhere in the economy?
- How will competition and innovation within the ICT sectors affect productivity gains throughout the larger economy?
- Will we see managed but positive reconstruction of a new economy or wild and woolly creative destruction of the old economy?
- Will the resources devoted to ICT infrastructure improvements reduce the opportunities for improvement in other sectors of the economy?
- Are there other trade-offs not anticipated by the transition to an information-age economy, including changes in distributional benefits, consumer or producer surpluses, the increased reliance on imported or critical materials, or other environmental and economic impacts?
- What are the technical limits to the efficiency gains that might be associated with an information economy?
- How important will the reliability and security of our energy system be, and how can information technology improve such attributes of the technology?
- And, finally, are there cleaner, more renewable energy-supply technologies that minimize the need to reduce the nation's energy intensity?

In short, how will the so-called hypereconomy (Kelly 1997), facilitated by information technologies and changing social networks, shape both the direct and indirect long-term energy use? And what will be the resulting environmental impacts? Just as any highly rated corporate enterprise adjusts its investment and technology portfolios to reflect risk and uncertainty, what management strategies and energy policy options should society be exploring to maintain economic and environmental prosperity in light of the greater complexities implied by the information age? As the great English economist, John Maynard Keynes, might note, "The difficulty lies, not in the new ideas, but in escaping from the old ones" (Keynes [1936] 1964, viii).

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Notes

1. Direct energy requirements refer to the energy necessary to operate computers, routers, servers, and other equipment associated with the information economy. System energy requirements

would also include the energy to manufacture the technologies, the ancillary economic activities that support the information economy, and the energy associated with changes in wealth and output catalyzed by the transition to an information-based economy.

2. Ideally, the issue should reflect a broader array of environmental impacts rather than a more limited review of the energy requirements associated with the Internet or information economy. At the same time, however, energy consumption provides a useful first-order estimate of the likely impact in that energy production and consumption generate significant environmental impacts. For example, the combustion of energy resources contributes more than 80% of total U.S. greenhouse gas emissions in the form of carbon dioxide (U.S. EPA 2002). Energy use also contributes more than 90% of total nitrogen oxide and sulfur dioxide emissions in the United States (U.S. EPA 2000).
3. This point was brought home in a recent journal article by Kydes (1999), who, based on a series of runs from the *Annual Energy Outlook 1997* (U.S. EIA 1996), forecast that in the period 1996 through 2015, the annual rate of decline in the nation's energy intensity would be "bounded by 1.25 percent when real energy prices are relatively stable" p. 119. Yet in the period 1996 through 2001, when prices were relatively stable, the rate averaged 2.9%, more than double Kydes's estimated bound.
4. The various cost-to-weight ratios are estimates that I generated from my own survey of prices and quantities for the different materials referenced in the text.
5. This is one of the key claims in the discussion of the environmental impact of the information economy. In terms of life-cycle impact, the items with high value-to-weight ratios (computer chips, pharmaceuticals, and the like) are quite often the ones we end up shipping around the globe with airfreight. What we save in direct energy use may be lost in the logging of more transportation miles. For a further discussion on this larger perspective, see, for example, work by Cleveland and Ruth (1999). Their article did not address dematerialization engendered specifically by the information economy, but it illustrated the importance of a life-cycle perspective in evaluating overall impacts. Rejeski (1999) and Matthews (2001) also raised a similar perspective.
6. Lawrence Berkeley National Laboratory senior scientist Jonathan Koomey has repeatedly requested documentation of this claim, which Mills has failed to provide. For a series of historical documents related to this controversy, including a copy of the ninth unanswered e-mail request that Koomey sent to obtain such documentation, visit the Web site http://enduse.lbl.gov/Projects/InfoTech.html.
7. An exajoule is 10^{18} J; there are 1055.056 J per British thermal unit (Btu). Hence, to convert exajoules to quadrillion (10^{15}) Btu or quads, the unit of reference used within the United States, multiply exajoules by 0.9478.
8. The success of the Energy Star program stems from closing both the information gap and the efficiency gap (Laitner and Sullivan 2001). The information gap refers to the lack of timely and credible knowledge about options that might otherwise prompt investment in cost-effective energy-efficient technologies in our homes and businesses. The efficiency gap refers to the difference between average and best practice regarding the use of appliances and equipment. Diffusion of that knowledge depends heavily on the information technologies. For example, Web-based tools allow managers of commercial properties to assess the overall energy performance of their buildings. Consumers can search the Internet to locate Energy Star refrigerators and other appliances.
9. To put this into perspective, the Kyoto Protocol would require the U.S. to reduce energy-related carbon emissions by about 580 MMT, using a conventional 2010 forecast of emissions compared to a target of 7% below its 1990 level of emissions. Thus, the thought experiment shown here suggests that reductions of only 485 MMT might actually be needed.
10. This reference case projection reflects an assumption that the values contained in the *AEO 2002* (U.S. EIA 2001b) might be extended from its terminal year of 2020 to the year 2050. Allowing key economic drivers to generally follow the low and high economic growth scenarios reflected in the *AEO 2002* provides the lower and upper range of 183 to 240 EJ when extended to the year 2050 for this thought experiment.
11. A recent article by Laitner and colleagues (2002) provides a review of past energy forecasts, suggesting a large variation in actual versus predicted outcomes. The primary reasons include underestimating technological change and changes in market structure. See also work by Shlyakhter and colleagues (1994) for a further discussion of the large variations in modeling outcomes.

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