Semiconductor Technologies:
The Potential to Revolutionize U.S. Energy Productivity

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FOREWORD: SEMICONDUCTOR TECHNOLOGIES AND ENERGY PRODUCTIVITY

By the end of 2009, the United States will have expanded its economic output by nearly 62 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 less than 20 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 semiconductor devices and related technology systems 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 we previously have called "the high tech energy paradox" whereby analysts tend to pay more attention to the energy-consuming characteristics of semiconductor devices than to their broader, economy-wide, energy-saving capacity.

While it is easy to imagine that the proliferation of semiconductor technologies would lead to an increase in power demand across sectors, calculating their net effect on economy-wide 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 his team present in this report, historical measures of energy efficiency provide clear evidence of the dramatic reductions in energy intensity (energy per constant dollar of GDP) during recent historical periods. While important advancements in efficiency were undoubtedly made between 1950 and 1995 (when energy intensity declined by an average of 1.2 percent annually), the most dramatic advancements occurred during the past 14 years when the level of U.S. energy intensity declined by 2.1 percent annually.

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 technologies and the related shift in the predominant technological paradigm. The authors build their case for energy productivity on the pioneering work of Dale Jorgenson and his colleagues (2005) as well as drawing from a previous analytical study on the link between information and communication technologies and energy productivity gains (Laitner and Ehrhardt-Martinez 2008).

Based on available data, the analytical team provides a reasoned assessment of the high-tech energy paradox, and they make a compelling case that much of the current efficiency gains have resulted from the proliferation of technology systems supported by semiconductor devices and products. Nevertheless, the authors also argue that continued progress in achieving economy-wide energy productivity gains is dependent on our policies, our institutional framework, and our cultural capacity to direct these technologies toward addressing our most pressing energy and climate problems.

Overall, this study provides readers with critical research on the relationship between semiconductor technologies and their larger energy productivity benefits. Although preliminary in nature, the analysis provides highly useful insights into this important linkage. As such, it represents a valuable foundation for future research on this topic.

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

EXECUTIVE SUMMARY

On any given day a consultant might use his home-office to "telecommute" rather than drive to the office, or a business executive may video-conference with her clients in Europe and avoid a flight across the Atlantic. A downed power line may trigger a series of actions to prevent an area blackout, an industrial motor may slow down to adjust to a decreased load, or a GPS navigation system may give instructions to a delivery truck driver on the shortest route to cover all of his deliveries. These many different events all share one thing in common—semiconductor technologies that enable energy savings. From the use of cellular phones and online banking to managing industrial operations and product testing, semiconductor technologies have transformed our economy and our lives. In some surprising and unexpected ways they also have revolutionized the relationship between economic production and energy consumption.

Based on the available data and statistics, the evidence is compelling. In this report we estimate that the deployment of semiconductor technologies since 1976 has generated a sizeable energy productivity benefit across the U.S. economy. Whether we are producing better consumer products or managing our commercial and industrial operations more productively, we are able to meet the nation's demands for goods and services more efficiently. Compared to the technologies available in 1976, we estimate that the entire family of semiconductor-enabled technologies has generated a net savings of about 775 billion kilowatt-hours (kWh) of electricity in the year 2006 alone. Although it is hard to precisely assess the impact, had we expanded the size and scope of the U.S. economy based on 1976 technologies, it appears that the U.S. would be using about 20 percent more electricity than actually consumed in 2006. Stated differently, had we continued to rely on 1976 technologies to support the U.S. economy today, we might have had to build another 184 large electric power plants to satisfy the demand for goods and services.

While deployment of the now ubiquitous semiconductor has created new economic activities and powered the development of the U.S. and the international economies, it has also made our economy more productive. The family of semiconductor technologies now at work in our economy has amplified the use of our buildings and equipment, our labor, and our energy resources well beyond the normally expected returns. Computers and servers show us that it can be easier to make decisions, and that it is easier to move electrons around than it is to physically move people and goods. More robust telecommunication systems facilitate business decisions and connections with friends and families in ways that save energy. The efficiency of wall packs and power supplies that charge our many electronic devices are greatly improved with smart electronics.

More robust telecommunication systems facilitate business decisions and connections with friends and families in ways that save energy. Semiconductors enable the improved operation of motors and the motor systems that heat and cool our homes, and that provide pumping and mechanical power in our industrial facilities. Light-emitting diodes can completely replace incandescent lighting with a significant level of energy savings. Any energy solution that is described as "smart," from smart buildings to smart appliances to the Smart Grid, have semiconductor sensors to measure temperature or other variables, communications chips to receive and transmit data, memory chips to store the information and microcontrollers, microprocessors, and power management chips to adjust energy loads.

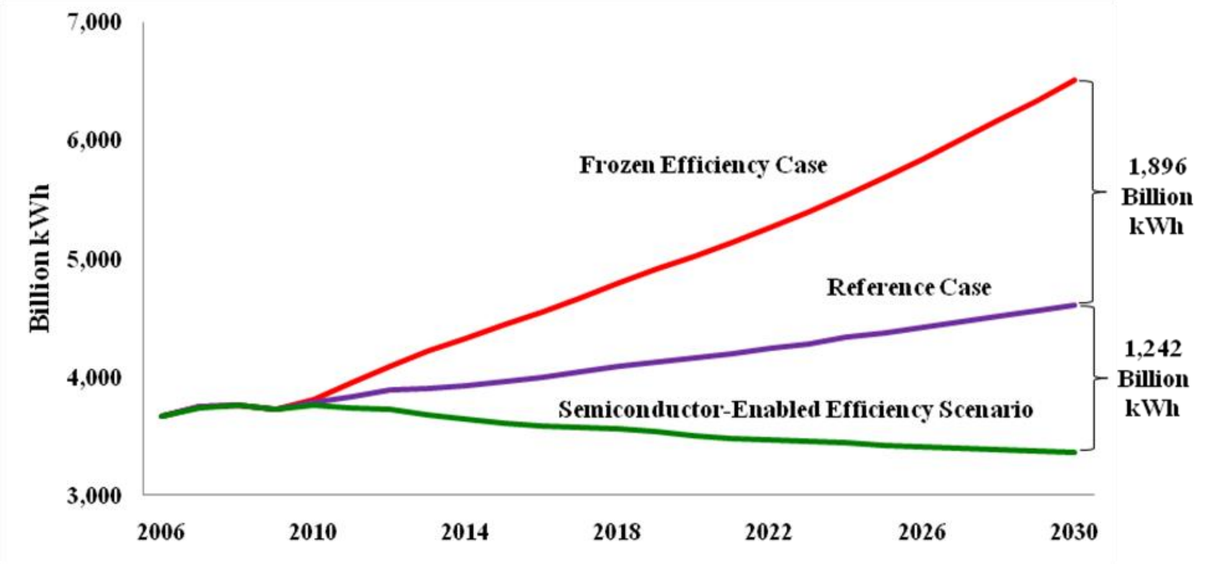
Smart grid technologies also enable a more cost-effective deployment of decentralized but cleaner renewable energy resources such as solar panels and wind turbines, which are also enabled by semiconductors. In the future, smart grids may also enable plug-in hybrid cars to stretch our gasoline dollars, and provide battery storage units for the nation's electric generation system. And

semiconductors also may enable smoother, more fuel-efficient performance in our nation's many vehicle fleets. In fact, a new car today may have as many as 50 to 80 microprocessors and microchips to more efficiently and safely navigate our national transportation system.

The impact of energy productivity gains, although not immediately obvious to the average consumer, has already been significant. But we extend this analysis to generate a sense of how much more the semiconductor industry might shape the nation's future productivity gains. To accomplish that task, our study sets up a series of analytical frameworks to provide reasonable estimates of future energy savings that might result from policies that drive greater efficiency gains—powered largely by semiconductor-enabled devices and technologies. We show that, supported by smart policies, we can reasonably extrapolate past energy saving growth in the semiconductor industry to result in 27 percent total energy savings in 2030.

We first create a "frozen efficiency" scenario to more clearly see how the next two decades might look if we were to rely on today's technologies and freeze their performance even as we try to grow the economy out to the year 2030. We use the latest "official forecast" of the U.S. Energy Information Administration (EIA) as a reference case to further guide our assessment. We then model a Semiconductor-Enabled Efficiency Scenario (SEES), which features public policy measures that drive a greater level of productive investments in semiconductor technologies which, in turn, results in a further 27 percent energy savings. Figure ES-1 below illustrates these different scenario outcomes.

Figure ES-1. Future Electricity Scenarios for the U.S.



In 2010, the EIA estimates the U.S. economy will consume about 3,789 billion kWh of electricity. As Figure ES-1 suggests, this might increase to 6,502 billion kWh by 2030 if technology advances were "frozen" in performance. What this indicates is that normal energy productivity improvements in both technologies and in the market—driven heavily by the deployment of semiconductor technologies and devices—will reduce electricity consumption down to a "moderate level" of 4,606 billion kWh that is assumed in the EIA reference case. This will be a productive savings of 1,896 billion kWh by the year 2030. The evidence indicates, however, that we can do better. Smart energy policies, enabled by the development and deployment of semiconductor technologies, can reduce electricity requirements significantly below the reference case. As both Figure ES-1 and Table ES-1 (below) summarize the suggested opportunity, our analysis implies that a full suite of smart efficiency policies has the potential to save an additional 652 billion kWh by 2020 and 1,242 billion kWh by 2030.

Table ES-1. Trends in U.S. Electricity Consumption (Billion kWh)

	2008	2010	2015	2020	2025	2030
EIA Reference Case	3,763	3,789	3,959	4,161	4,372	4,606
Semiconductor-Enabled Efficiency Case	3,763	3,765	3,614	3,509	3,424	3,364
Savings from the Reference Case	0	24	345	652	948	1,242

As it turns out, there are a variety of policies and incentives that might stimulate a greater investment in semiconductor-enabled efficiency technologies. These are described more fully in the main report. And as the analysis reveals, given the right mix of investment-led policies that drive what we call a Semiconductor-Enabled Efficiency Scenario, the market could facilitate productivity gains that reduce electricity use below current levels—to only 3,364 billion kWh by 2030. The resulting savings of 1,242 billion kWh in 2030 means that the economy may actually consume 11 percent less electricity than it did in 2008. In other words, semiconductor-related technologies may support an economy in 2020 that is 35 percent larger than today, but one that uses 7 percent less electricity. And by 2030 those policies may support an economy that is over 70 percent larger but uses 11 percent less electricity than in 2008.

Given these sizeable efficiency returns, the question naturally arises: how specifically might this affect our annual electricity bills, the nation's job market, and perhaps even carbon emissions? The full details that underpin our assessment are shown in the appendices to this study. Table ES-2, however, provides an initial insight into the net returns that are made possible from a smarter deployment of more energy-efficient technologies.

As we show, the energy efficiency benefits clearly require significant outlays of capital in all years of our analysis. We estimate these to begin with a modest $7.1 billion of incremental investments in 2010, rising to as much as $28.7 billion by 2030. The average annual investment over the next two decades is estimated at about $22.5 billion. Cumulatively, the market for these new technology investments is about $472 billion over the period 2010 through 2030. Notably, however, there is a hefty return on these investments. We estimate the electricity bill savings to average just over $61 billion during that same period of analysis, producing a cumulative electricity bill savings on the order of $1.3 trillion. What's the bottom line? The savings are about 2.7 times the investment cost. Even if we include program and administration costs in this assessment, the net savings are still more than twice the cost of our SEES case.

Table ES-2. Macroeconomic Impacts of Savings Compared to Reference Case

	2010	2015	2020	2025	2030	Average Annual
Annual Investment (Billion 2006 $)	7.1	20.6	21.9	24.5	28.7	22.5
Electricity Bill Savings (Billion 2006 $)	2.1	30.4	59.6	90.8	126.4	61.3
Reductions in Carbon Dioxide (MMT)	15	212	391	557	733	383
Net Job Impacts (Thousands)	80	344	568	780	935	553

Perhaps an even more compelling outcome from our analysis is the impact on carbon dioxide emissions and employment. Using average carbon emissions intensities found within the EIA reference case, it appears the electricity savings from the policy case will reduce carbon dioxide emissions by an average 383 million metric tons over the period of study. This is a substantial benefit that can positively impact global climate change. We can also map our estimates of the added technology costs and the resulting energy bill savings into the DEEPER modeling framework (or the

Dynamic Energy Efficiency Policy Evaluation Routine, which is explained in the full report). Because energy-related expenditures are so much less labor intensive than almost all other consumer expenditures within the U.S. economy, our working analysis suggests a net increase of 80,000 jobs in 2010, which increases to 935,000 net jobs per year by 2030. Over the time horizon, the net employment gain will average about 553,000 jobs. This suggests an important additional benefit from the deployment of semiconductor technologies.

As we noted early in this executive summary, the evidence is compelling. A combination of smart policies, supported by the family of semiconductor devices and technologies, can deliver significant productivity benefits that provide large savings on our electricity bills, significant reductions in carbon dioxide emissions, and a source of new job creation—but only if we choose to develop those options.

ABOUT ACEEE

The American Council for an Energy-Efficient Economy (ACEEE) is a nonprofit research organization dedicated to advancing energy efficiency as a means of promoting economic prosperity, energy security, and environmental protection. For more information, see http://www.aceee.org. ACEEE fulfills its mission by:

- Conducting in-depth technical and policy assessments
- Advising businesses, policymakers, and program managers
- Working collaboratively with businesses, public interest groups, and other organizations
- Organizing technical conferences and workshops
- Publishing books, conference proceedings, and reports
- Educating consumers and businesses

Projects are carried out by staff and selected energy efficiency experts from universities, national laboratories, and the private sector. Collaboration is the key to ACEEE's on-going success. We collaborate on projects and initiatives with dozens of organizations including international, federal, and state agencies as well as businesses, utilities, research institutions, and public interest groups.

Support for our work comes from a broad range of foundations, governmental organizations, research institutes, utilities, and corporations.

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Finally, we would like to express our appreciation to ACEEE's own Associate Research Director Neal Elliott who greatly helped us understand the possibilities for efficiency gains in motor systems, and Executive Director Steve Nadel for his early insights and research support that proved invaluable in getting this study underway. 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 SIA committee members' commitment to developing 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. Many thanks!

I. INTRODUCTION

On any given day a consultant might use his home-office to "telecommute" rather than drive to the office, or a business executive may video-conference with her clients in Europe and avoid a flight across the Atlantic. A downed power line may trigger a series of actions to prevent an area blackout, an industrial motor may slow down to adjust to a decreased load, or a GPS navigation system may give instructions to a delivery truck driver on the shortest route to cover all of his deliveries. These many different events all share one thing in common—the reliance on semiconductor-related technologies that also enable energy savings. From the use of cellular phones and online banking to managing industrial operations and product testing, semiconductor technologies have transformed our economy and our lives. In some surprising and unexpected ways they also have revolutionized the relationship between economic production and energy consumption.

Since the development of the first practical transistor in the late 1940s, and especially since the introduction of the microprocessor in the early 1970s, the huge cost and performance breakthroughs and the many new innovations in semiconductor-related devices have worked to drive the expansion and diffusion of new technology applications and systems. These innovations, in turn, have enabled the development of new high-tech products and services, new investments, and new ways of doing things. In other words, the positive economic returns generated by these new innovations have stimulated higher levels of economic productivity. In perhaps some surprising ways, these innovations have also driven net gains in cost-effective energy savings throughout the U.S. economy. How big of an impact might we suggest?

The available data and statistics now collected by various governmental agencies do not allow a precise estimate. Nonetheless, the evidence is compelling. Looking only at productivity gains in electricity consumption, we estimate that deployment of semiconductor technologies—whether in consumer goods, industrial operations, or the production of alternative energy resources—has generated a net savings of about 775 billion kilowatt-hours (kWh) of electricity in the year 2006 alone. This is on the order of a 20 percent savings for the entire U.S. economy. A large 600 megawatt coal-fired power plant might generate just over 4 billion kWh in a year's time. So stated differently, our national economy might have required the construction and operation of 184 large electric generating power plants "but for" the widespread use of semiconductor technologies. Yes, while deployment of the now ubiquitous semiconductor has created new economic activities and powered the development of the U.S. and the international economies, it has also made our economy more productive. In short, the family of semiconductor technologies now at work in our economy has leveraged and amplified the use of our capital, labor, and energy resources beyond normally expected returns. Energy productivity gains, although not immediately obvious to the average consumer, have been especially large.

In this report we explore both the deployment and use of the full array of semiconductor technologies now hard at work within our economy. We especially note the historical contribution of semiconductor devices to the energy productivity benefits that have accrued. We then look to gather some idea of the larger benefits that might accrue in the near future should U.S. energy policy emphasize more productive investments in our nation's equipment, buildings, industrial plants, transportation system, and energy infrastructure through investment in semiconductor-enabled technologies. To accomplish this purpose, we first examine the nature of semiconductor technologies and how they assist in the production of our nation's goods and services. We then set up a series of analytical frameworks that help us generate reasonable estimates of the historical energy savings that have resulted from the use of semiconductor devices and technologies. Finally we use the latest "official forecast" of U.S. energy consumption to see how semiconductor technologies might contribute to further energy productivity gains—especially projections of future energy saving benefits should we choose to develop smart investment policies that accelerate the development and diffusion of smart, new technology systems based on semiconductor technologies. In completing this larger exercise to quantify future benefits, we will also provide a series of short appendices to summarize and describe the analytical methods that underpin our assessments.

II. BACKGROUND AND TRENDS: DRIVING INCREASED PRODUCTIVITY

We can get an idea of the macroeconomic impacts of semiconductor technologies by reviewing published data made available by the various federal agencies responsible for tracking our nation's economic progress. In the following section we examine, first, the larger economic productivities which appear to be driven in large part by the growing ubiquity of semiconductor technologies. From there we examine evidence of growing energy efficiencies enabled by these more productive technologies. Finally, we open the discussion with asking the right questions about how investment and policy decisions will impact energy use.

A. Semiconductor Technologies and the Larger Productivity Trends

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 has been significant and has 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 information and communications technologies 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 the rate of four percent annually.

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[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 on the next page. 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.

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 output per hour in all business sectors of the economy. The data is adapted from the Bureau of Labor Statistics.

During the years immediately 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 per year. As we've already alluded, the productivity growth rate in the immediate past decade (1995 to 2006) rebounded to 2.8 percent annually. This period, in particular, benefitted from what economists sometimes refer to as "capital deepening." By this we mean that the rate of investment as a percentage of annual growth in GDP expanded rapidly—especially, in our view, as the use of semiconductor-based technologies expanded. This expansion 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 sensors and microprocessors as well as in information and communications technologies beginning in 1995. Although there have been some year-to-year changes over this past decade, the growth in overall labor productivity has been robust. Moreover, this productivity growth has also been coupled with other technological and structural changes as consumers, businesses, and the market have found new ways to exploit the new technologies and information and as they have transformed the worldwide web from a means of communication to a platform for service delivery. Analysts have dubbed this "the new economy."

This very pronounced relationship between economy-wide productivity growth and the use of semiconductor-based technologies has been documented in a variety of studies on the topic. In a succession of pioneering reports, Dale Jorgenson and his colleagues specifically cited the importance of information and communication technologies (ICT) as driving 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 and colleagues have noted, 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). Laitner and Ehrhardt-Martinez (2008) point to the recent body of evidence that confirms the importance of an emerging generation of semiconductor technologies and ICT systems as the means to strengthen economic productivity.

Table 2, for example (adapted from Jorgenson and Stiroh 2002), highlights the growing influence of ICT as they sustain overall economic activity or output of the economy. The level of investments and

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[2] The evidence indicates that the "digital" information and communication technologies—enabled by an array of semiconductor devices—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 suggests it is likely to grow to 10 percent by 2012. See Knast (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 which, 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 semiconductor investment and performance provides a basis for continuing productivity gains.

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 shown in Table 3 (below), Jorgenson and his colleagues again demonstrate that U.S. productivity growth has 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 1995-2003 suggests that the production and use of information technology account for a large share of the 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. 2004. 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 first think of these productivity technologies as 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, on net, "energy saving" across the broader U.S. economy. 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]

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[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 which 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.

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

Sector	**1998**	**2000**	**2002**	**2003**	**2005**	**2007**	**CAGR**
Energy Production	96.1	100.0	99.9	98.2	103.0	105.8	1.1%
Semiconductor-Related Production	62.2	100.0	83.9	91.9	108.9	142.5	9.6%
Semiconductor-Related Services	74.1	100.0	108.0	110.9	136.3	170.5	9.7%
All Other Economic Sectors	92.9	100.0	101.2	103.6	111.7	116.1	2.5%
Total	91.4	100.0	101.1	103.5	112.6	119.2	3.0%

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

Initial evidence of the link between semiconductor-related 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 and totaling about 90 percent of the larger economy (omitting households and non-profit organizations), energy production has grown at approximately 1.1 percent annually over the period 1998 through 2005. On the other hand, producers of semiconductor-related equipment and appliances expanded about 9.6 percent while semiconductor-related services grew at 9.7 percent. All remaining sectors of the economy grew at about 2.5 percent annually while the combined industrial and government sectors grew 3 percent per year.

Perhaps more interesting is that, in 1998, the two aggregate semiconductor sectors accounted for about ten percent of the total economic activity represented in Table 4. Yet, they were responsible for about 25 percent of the total growth in the economy over the years 1998 through 2007—even while energy production decreased as a share of overall economic activity. This provides a solid basis for further review of the net energy saving potential of ICT investments which we explore more fully later in this study.

B. Evidence of Energy Productivity Gains

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 more productivity. 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 achieving cost-effective reductions in wasted energy.

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 below).

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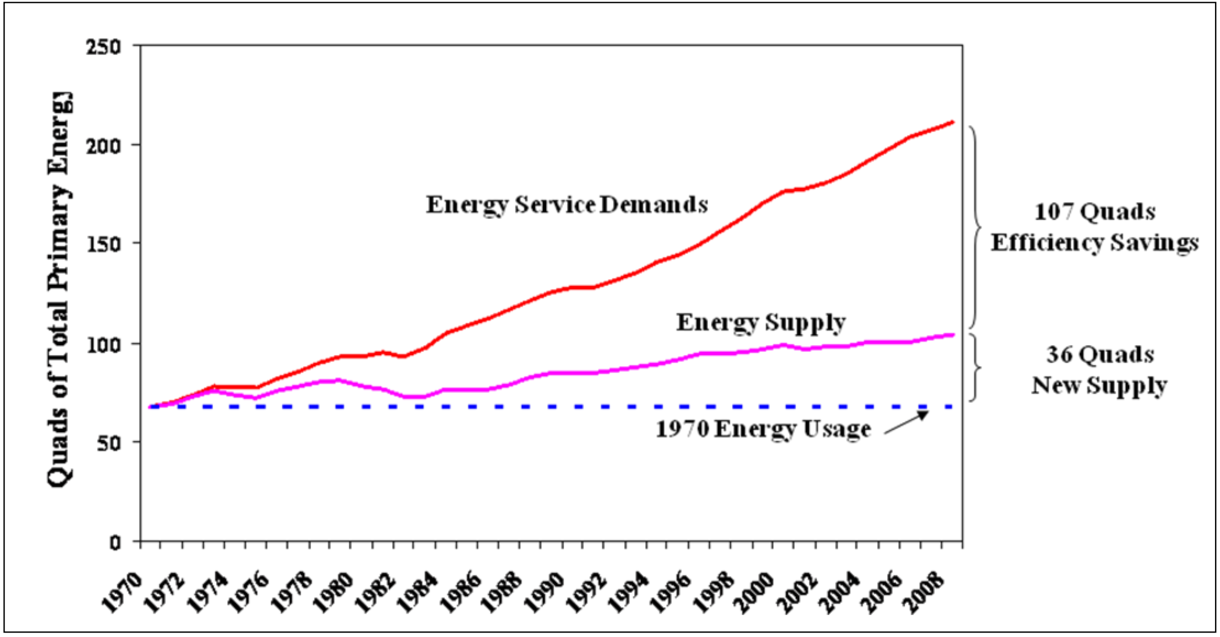
[5] For those who might want a more complete description of the aggregation scheme used in this table, contact the report authors. Note, however, that a new definition of what might be included among either the energy or the semiconductor-related sectors is unlikely to change the overall results indicated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

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



Source: Authors' calculations based on data from the Energy Information Administration (2008)

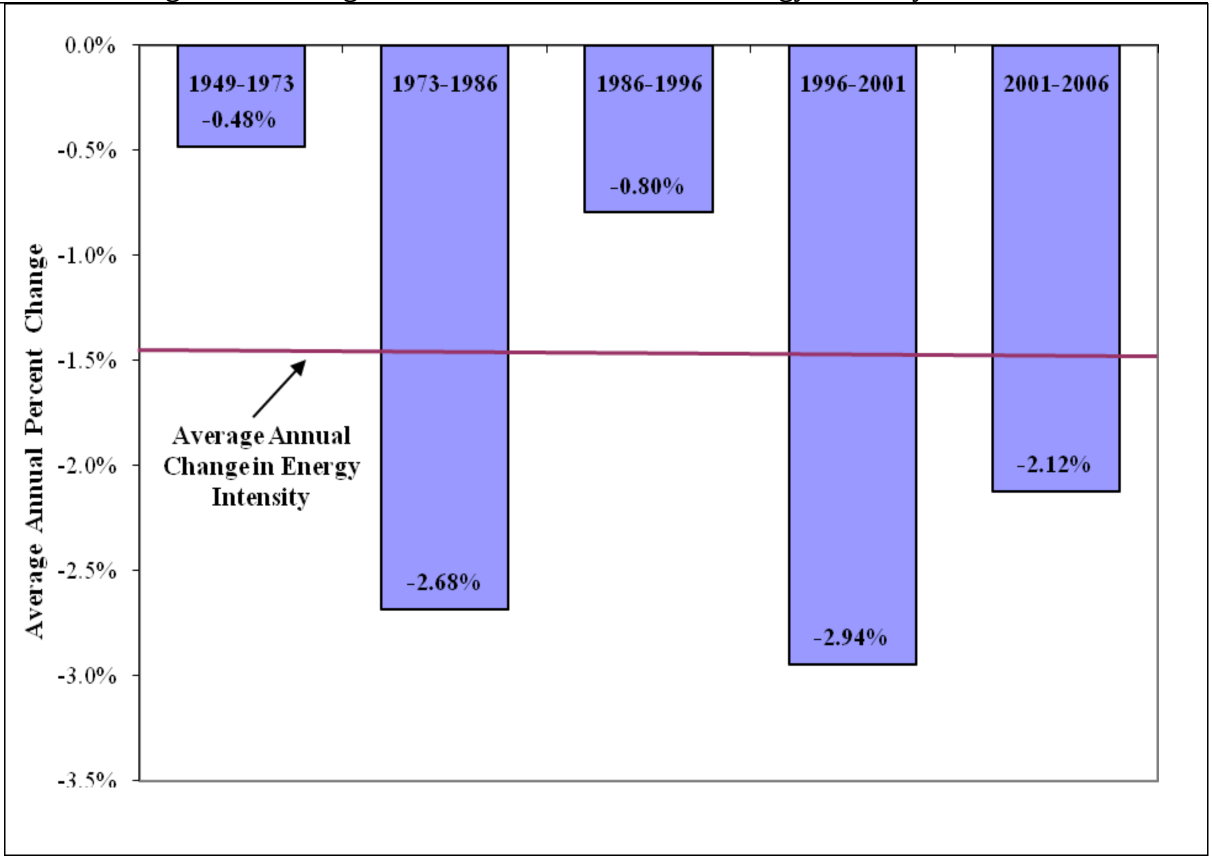
Importantly however, historical data from as early as 1949 suggest five distinct periods of change in the nation's energy intensity (see Figure 2 on the following page). In the early, long-term historical period between 1949 and 1973, energy intensity fell by roughly 0.5 percent per year—a trend that 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. Whether new fuel efficiency standards for cars, or new building code standards or new research and development initiatives, these new policies, in turn, spurred efficiency improvements in the residential, commercial, industrial, and transportation sectors.

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 merely "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—the process we previously described 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 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.[6]

In the most recent period of our review (2001-2006) energy intensity has 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—as a result of uncertainties in the financial markets and mounting concerns in the Middle East. Still, the growing ubiquity of ICT systems have 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, the decline in energy intensity 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.

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



Source: Authors' calculations based on data from the Energy Information Administration (2008)

In recent periods, there is no doubt that semiconductor production and services—perhaps exemplified by the rapid growth in the role of information and communications technologies in the global economy—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

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[6] We should note a distinction between energy efficiency that follows structural change and efficiency gains that follow reduced unit energy consumption, but also make the point—especially in today's information-based economy—that shifting toward high-value added economic sectors that are also significantly less energy intensive should be seen as a smart energy efficiency strategy on a par with more efficient equipment.

technologies, semiconductor technologies have 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 such devices. The most recent trends in sector-specific energy consumption patterns illustrate this trend.

C. 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.[7]

Wheeler’s comment is particularly relevant to our understanding of the relationship between technology, energy, and the environment. In the case of global climate change, the proliferation of energy-using technologies is cited as a source of increased atmospheric concentrations of greenhouse gases. The premise is that as more energy-using technologies are purchased, they 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 definition, microprocessors, computers, servers and telecommunications equipment are among the technologies that, at least initially, contribute to the problem when viewed on a product-specific level. In effect, they are using growing amounts of electricity to meet the growing demand for goods and services.

Over the course of the past two decades, semiconductor technologies have become an integral part of our everyday lives. From computers to cell phones, to fax machines, Information and Communication Technologies are 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-2008 there were more than 1.2 billion PCs, representing a ten-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 nearly 1.6 billion users on the Internet, a 400-fold increase in the last 19 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) embedded within the various appliances used within the home. Those devices manage a dynamic array of widely divergent but reliable technologies as lighting, telephones, 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 information and communications technologies and the growing evidence that human activity is changing the global climate, the natural question to ask is

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[7] 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). We might note the situation has not improved—indeed, the constraints have only tightened—since the release of this report in 2006.

"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?

But, first, to generate better insights into how the family of semiconductor devices and technologies enhance overall energy and economic productivity, we describe those technologies and characterize their economic contributions in the section that follows.

III. SEMICONDUCTOR APPLICATIONS AND EFFICIENCY OPPORTUNITIES

We tend to think of semiconductors as a relatively new technology. Yet, the semiconductor industry has a long and extensive history of innovation and advancement. Modern semiconductor devices, like transistors, diodes, resistors, and capacitors all have their roots of discovery as far back as the 1700s. As one case in point, Dutch professor Pieter van Musschenbroek at the University of Leyden came up with the so-called Leyden jar in 1745. This very simple device, which Benjamin Franklin also used to conduct his experiments with electricity, is typically credited as the first capacitor.[8] Since that time universities, private laboratories, and research and development teams across the U.S. and around the world have all had a major role in shaping how these technologies are used today. A wide range of products and devices utilize semiconductor technologies in various configurations to improve the quality of our home life, our business and personal communications, and industrial productivity and energy use. But what exactly is a semiconductor and how does it figure into these many uses?

The semiconductor is a material that takes advantage of the movement of electrons between materials with various conductive properties. Most semiconductor devises are silicon chips with impurities embedded to conduct electricity under some conditions and not others—hence the name "semiconductor." Typical semiconductor circuits are a combination of transistors, diodes, resistors and capacitors which switch, regulate, resist, and store electricity. These smaller circuits, in turn, are combined into items like integrated circuits, sensors, and microcontroller chips that make their way into a wide-range of consumer products and business equipment.

Diodes are the simplest form of semiconductor devices. In effect, they block electrical current in one direction while letting it flow in another direction. The term diode draws from two Greek words meaning "two paths." They can be used in a number of ways. For example, a device that uses batteries often contains a diode that protects the device if the batteries are accidently inserted backwards. The first properties of the diode were discovered as early as 1879. Today, diodes have a wide range of applications from lighting technologies such as light emitting diodes (LEDs) and uninterruptible power supplies. These applications allow significantly more efficient use of electricity within many different applications.

Transistor is an abbreviated combination of the words "transconductance" or "transfer," and "varistor" (variable resistor). Transistors are perhaps the fundamental building blocks of the circuitry that governs the operation of computers, cellular phones, and all other modern electronics. Because of quick response, accuracy, and easy integration into other aspects of electronic components, the transistor may be used in a wide variety of functions including amplification, switching, voltage regulation, and signal modulation. Transistors may be packaged individually or as part of generic or application-specific integrated circuits. These latter devices may hold a billion or more transistors in

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[8] There are records that indicate a German scientist named Ewald Georg von Kleist invented a similar device to the Leyden jar some months before. However, Kleist did not keep detailed records or notes and as a result his contribution is often overlooked as a contributor to the capacitor's evolution. More recent studies credit both as their research was independent of each other.

a very small area. Within integrated circuits, transistors amplify or change a given electronic signal into an output signal. The first patent for a transistor was filed in 1925, and William Shockley, John Bardeen and Walter Brattain succeeded in building the first practical “point-contact transistor” at Bell Labs in late 1947. Over time, the transistor replaced vacuum tubes that were used in radios and televisions. Transistors were a superior technology that was not only more reliable, but used significantly less electricity

Resistors are two-terminal electronic component that oppose an electric current by producing a voltage drop between its terminals. They are used as part of electrical networks and electronic circuits and they are extremely commonplace in most electronic equipment.

The primary characteristics of resistors are their resistance and the power they can dissipate. Other characteristics include temperature coefficient, noise, and inductance. Less well-known is critical resistance, the value below which power dissipation limits the maximum permitted current flow, and above which the limit is applied voltage. Critical resistance depends upon the materials constituting the resistor as well as its physical dimensions; it's determined by design.

Resistors can be integrated into hybrid and printed circuits, as well as integrated circuits. Size, and position of leads (or terminals) are relevant to equipment designers; resistors must be physically large enough not to overheat when dissipating their power.

Capacitors have a history that reaches all the way back to ancient Greece. Unlike batteries which use chemical reactions to generate electrons, capacitors only store electrons which have been deposited within their volume. Capacitors are composed of layers of conductive and non-conductive material that hold an electric charge, filter noise or process signals. Capacitors are an essential component in electric motors, enabling them to start. Capacitors can also sense the temperature and humidity of our surroundings. Sensors with capacitors can then control the energy output we use from industrial processes to household heating and cooling.

The properties of capacitors in a circuit may determine the resonant frequency and quality factor of a resonant circuit, power dissipation and operating frequency in a digital logic circuit, energy capacity in a high-power system, and many other important aspects.

Integrated circuits combined these semiconductor technologies into one unit. One of the first ICs commercially available was Intel's 4004. Released in 1971 for use in calculators, this central processing unit (CPU) was only improved upon in the years to come. Over time computing power, speed and capacity of these devices would mostly hold to "Moore's Law," doubling every two years. Other devices such as recent graphics processing units (GPUs) have shown four-fold energy efficiency improvements over a one-year period (Robison 2008). ICs are embedded in a number of devices that we use today and provide a degree of automation and control that would otherwise not exist.

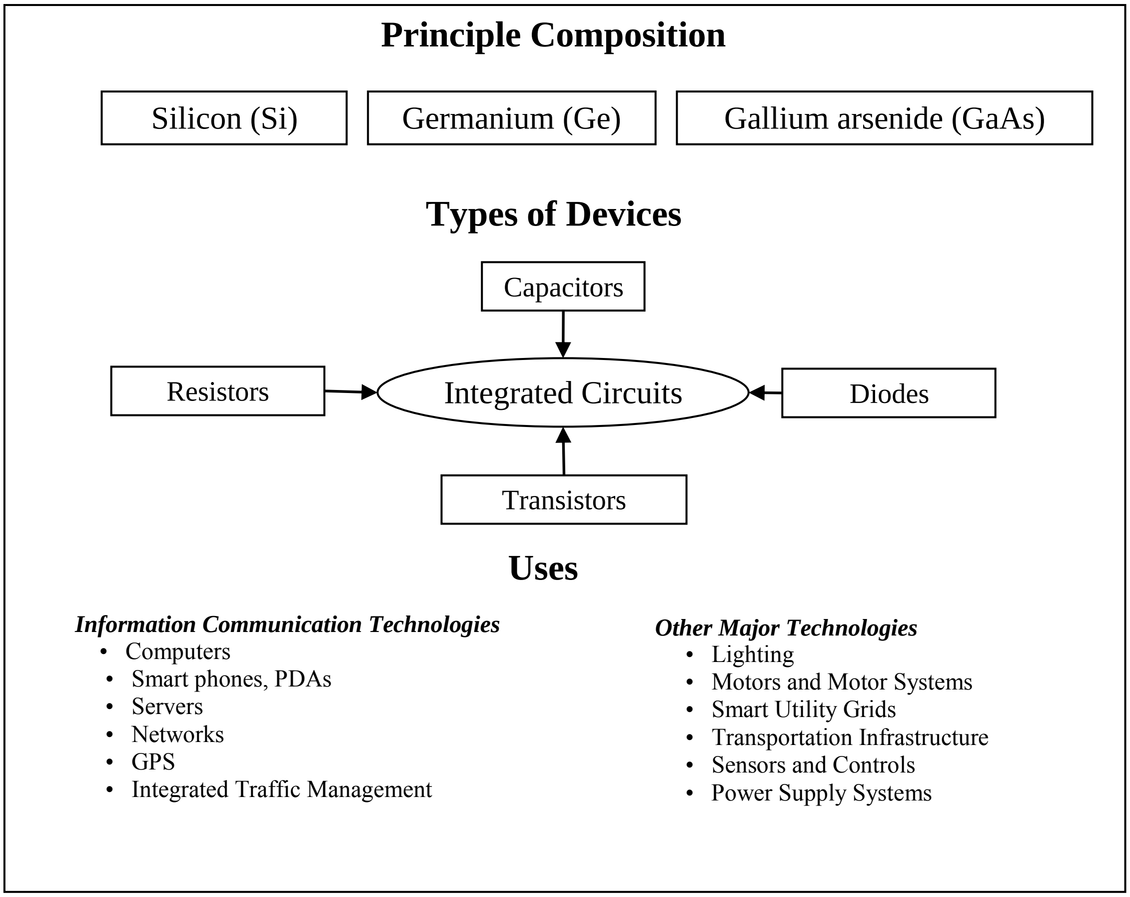
- **Ubiquity in Military Applications.** Like many cutting edge technologies, the use of semiconductors began mainly in military applications. Worldwide communication and information networks as well as opportunities for intercepting information from other countries were a common use of semiconductors and later ICs. The development of the diode, allowed the military's radar to utilize ever higher frequencies for communication. Additionally, the reliable and sturdy diode allowed radios to move into smaller, portable devices. A new age of communication was brought about by the Advanced Research Projects Agency (ARPA), a division of the U.S. Department of Defense. This Agency's network, commonly referred to as ARPAnet, was the first operational data network and a precursor to today's Internet.

Semiconductors also played a role in advancing transportation technologies across land, air and sea. Today, flying the most advanced, often unmanned military aircraft is not possible without the extensive use of on-board computers to control and direct flight. Both military and commercial flights are also supported by an extensive satellite communications network. Most importantly, these devices and communication systems allow the military to achieve new standards in technology that perform better, provide more information, and do so with fewer resources than equipment of just a few decades ago.

- **Ubiquity in Consumer Applications.** The average consumer encounters semiconductor technology at home, in the workspace and when enjoying leisure time. Beginning in the 1950s and 60s consumers began to see an influx of new household devices that utilized semiconductor technologies. Most visibly these devices were intended for communication and entertainment. Beginning with transistor radios in the 1950s, televisions and now home video recorders are widely available to the general public. Although most consumers could not afford the most advanced technologies of the time, economies of scale eventually brought down the price of these devices. Economies of scale also aided the further expansion of integrated circuits (IC) into other devices, including common household appliances and even our many different modes of transportation. As both the scope and the scale of ICs and microprocessors expanded, they progressively impacted the use the energy, allowing consumers the ability to purchase ever more advanced items with improved performance and a greatly improved use of energy.

- **Ubiquity in Commerce and Industry.** And, semiconductor-enabled technologies have also made their way into the workplace. There are a number of developments that can be cited, but a few noteworthy milestones are the introduction of the IBM 360 mainframe computer in 1964, which was widely adopted for business tasks such as billing and data base management, the advent of automated teller machines that allowed consumers to “self serve” rather than rely on bank tellers, and the growth of computer aided design tools to enable manufacturers to “see” a product and minimize the expense of physical prototypes. The introduction of the personal computer, laptops and the internet have all spawned new business models, including downloading music instead of compact disks, and ordering merchandise and airline tickets on-line. Information and communication technologies—ranging from computers and smartphones to data networks and servers—have enabled growth in economic and energy productivity (Laitner and Eharhardt-Martinez 2008).

Figure 3. Critical Aspects and Ubiquity of Semiconductor Technologies



- **New Areas of Use.** Although there are many current uses of semiconductors, their application in future devices appears to be unlimited. New microprocessors and controllers will enable many devices to become 'smart' in ways that anticipate our needs and provide us with “to-the-minute” information. Already in testing, semiconductor technologies will further enable the nation's utility grid to provide customers with “real time” pricing and feedback on their energy use. Several metropolitan areas are using traffic monitoring devices to enhance to flow of traffic in rush hour or inclement weather. With this broad review of both the technologies and their potential applications, we now explore nine different areas that will be better served by smart semiconductor-enabled technologies.

A. Computers and Servers

Computers are the bedrock of energy efficiency, both present and future. For decades, personal computers and data centers have been processing information more quickly and with less energy. The use of computing devices enables large increases in productivity and energy efficiency in applications ranging from home energy management to supply chain optimization. Emerging computer models such as cloud computing and accelerated computing, and new technologies which include virtualization, are allowing for even greater gains in system efficiency (IDC 2009, Richie 2009, AMD 2007, Scheffy 2007). Relatively energy-intensive computer applications such as data centers should be seen in proper context, and managed through smart policy. If we lose sight of the contributions of computers to energy efficiency goals we risk a less robust economy that drives higher prices for both energy and other consumer goods.

Personal Computers

Personal computers are at the core of the information and communication technologies that are reshaping the global economy. Their components account for just under half of the $250 billion global semiconductor market. From 2006 to 2010 the stock of global personal computers is expected to double. By the end of this decade, there will be an estimated 2.9 billion personal computers worldwide, roughly half the global population at that time (Britton and McGonegal 2007).

The continuing strength of the computing market is driven by rapid improvements in computer performance combined with drastic reductions in cost and energy use. Amazingly, over the last 5 decades the power requirements of a computer chip of a given capacity haven fallen by half every 18 months while computing power has doubled. This has huge implications: that the energy intensity of computing power falls by a factor of 4 every year and a half (Economist 2007). This rapid technological advance is also reflected in the price of a computing operation, which has declined by 36 percent annually over the last 60 years.[9] As a result, a computer's energy efficiency improvement, as measured in instructions per second/watt, has improved by 2,857,000 percent from 1978 to 2008. In contrast, miles per gallon for automobiles have only improved by 40 percent over the same time period (Laitner and Ehrhardt-Martinez 2008).

Inside a data center

These trends may very well continue as companies innovate in energy saving hardware and software. Multi-core processors, common in personal and laptop computers today, use 40 to 60 percent less energy than single-core chips (ENERGY STAR 2007). Current Central Processing Unit (CPU) and Graphics Processing Unit (GPU) technologies reduce computer power consumption by adjusting performance according to demand (Hildebrand 2008). Large companies with many computers such as Verizon and GE are each saving millions after implementing power management algorithms. Dell is saving $1.8 million a year in electricity costs after reducing desktop power consumption by over 90 percent (ENERGY STAR 2007).

Data Centers

As a result of miraculous technological advances, computers have become more popular and therefore, in aggregate, more energy intensive. This is particularly true of data centers, the large groups of servers and storage devices, and supporting infrastructure, used by organizations to manage information. It is true that data centers information processing demands are increasing and therefore electricity use can also increase if data centers are not optimized. Their demand for electricity has doubled since 2000 and, without optimization, is expected to double again by 2011 (ENERGY STAR 2007).

But data center energy demand may be reduced with smart policies and practices. Using best available technology in data centers such as 98 percent efficient transformers, 95 percent efficient

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[9] Laitner and Ehrhardt-Martinez (2008) calculate that the price per computing operation per second has declined by 36 percent annually on average over the last 60 years.

uninterruptible power supplies (UPS), variable speed fans and pumps, server virtualization,[10] and Combined Heat and Power (CHP) systems would reduce data center energy demand in 2011 by 56 percent compared to business-as-usual estimates (ENERGY STAR 2007). The best available technologies are all made possible by semiconductor devices. The first stages of implementation of these technologies have already resulted in substantial energy savings. Thanks in part to better data center energy management, the amount of energy used to transfer a bit of information over the internet has been decreasing by 30 percent per year over the last decade (Koomey 2009). Further improvements can be enabled by smart public policy. Government R&D funding for emerging server and data center technologies has the potential to promote future energy efficiency gains.

Context

More importantly, judging the energy impact of computers and data centers only on what they consume is akin to judging the benefit-cost ratio of a productive research and development investment based on the first year private returns: while diffuse, the magnitude of the lagged benefits vastly outweighs the initial investment. Likewise, personal computers and data centers should instead be viewed in the context of the efficient macro-economies they have helped build.

Looking from macroeconomic perspective, economies that rely heavily on the manufacture and use of computers for their incomes are less energy-intensive than average. This follows from the fact that computing is a high value-added industry that creates significant economic return with a relatively small amount of material. This, in part, is why California requires 40 percent less energy to produce $1 of economic activity (measured in constant dollars of gross domestic product) than the rest of the nation.

But the impact of computers is magnified because they promote efficiency recursively. Computers are not only high-value added goods to produce, but their use within a given economy further reduces energy consumption. Computers are used to optimize the design, manufacture, distribution, and operation of a variety of products (Laitner and Ehrhardt-Martinez 2008).

Statistical analysis shows that the combined direct and recursive affects of computers vigorously increase energy efficiency. For every 1 kilowatt-hour (kWh) of electricity consumed by information technologies in the US over the period of 1949 to 2006, an estimated 8.6 kWh were saved economy-wide. Thus, the energy "benefit-cost" ratio for computing technologies is very favorable (Laitner and Ehrhardt-Martinez 2008).[11]

The great challenge for policymakers is to increase the net energy savings from computers by pressing for higher system efficiencies while putting computing power to work in important applications such as the "smart grid" (about which we say more later). Seen in context, personal computers and data centers have low levels of energy consumption. Taking into account their society-wide impact, they are more accurately characterized as energy-saving devices than energy consuming ones. Through appreciating their contributions to energy productivity while pressing for further gains from smart applications, we can provide the highest likelihood that computers will fulfill their efficiency promise.

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[10] Using virtualization, the hardware of individual low-utilization servers is virtualized and incorporated as software in the high-utilization machine. Virtualization may result in 70 to 80 percent reduction in data center space, power, and cooling (Laitner and Ehrhardt-Martinez 2008).

[11] We should point out that the energy benefit-cost ratio is significantly different than the monetary benefit-cost ratio. Since all commercial activity requires other capital, labor and other materials to build and operate any given production system, the monetary benefit-cost ratio is on the order of 3:1.

B. Power Supply and Management

Semiconductor-based power electronics are crucial tools in the US battle for energy efficiency. The electricity of 47 power plants flows through power supplies each year, charging our phones and powering our computers[12] (Calwell 2002). As it stands with the low-tech power supplies we currently use, over half of this energy is wasted. High efficiency and wireless power supplies can transform the $30 billion global power supply market and save consumers billions.

Contrary to popular perception, power supplies are not battery packs. Rather, they are power electronics that convert the higher voltage alternating current electricity flowing through home and business wiring systems into the lower voltage direct current electricity used to power stereos, or to charge cell phones and other devices.

Power supplies may be small, but with $17 billion worth of electricity flowing through them annually, they have a big impact on energy use. With the dated technology used in many power supplies, 60 percent of this electricity flow is wasted, costing consumers over $10 billion per year (Calwell 2002).

Through rapid market transformation of the $30 billion global power supply market, advanced power supplies can provide a radical increase in energy efficiency (Hochman 2009). The simplest switch is to adopt the latest semiconductor-based power supplies. These would cut the $10 billion in annual power supply electricity losses by two-thirds, putting over $6 billion back into consumers' pockets.[13]

Next generation power supplies include wireless systems that are able to charge cordless devices from up to 85 feet away with up to 90 percent efficiency. Using technologies such as inductive coupling and radio-frequency harvesting, wireless power supplies only charge selected appliances, and prevent over-charging (Hochman 2009). This can save wear and tear on consumer electronics in addition to saving the consumer money.

External Power Supplies

C. Information and Telecommunications Infrastructure

Telecommunications, the transmission of signals to a receiver for interpretation into usable information and action, have fundamentally altered how we live, work, and play. Semiconductor technologies have enabled both performance and energy efficiency improvements in a dynamic array of telecommunication devices: radios, televisions, emergency response networks, and the increasingly fast delivery of digital information into our home and handheld devices.

The telegraph and telephone, the earliest telecommunications devices available, connected individuals at significant distances with relatively quick information carried by wires. With the telegraph, at

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[12] Assuming 500MW power plants

[13] Using Calwell's figure of $17 billion flowing through U.S. supplies annually with common efficiency in the 40 percent range, then increasing efficiency to 80 percent will reduce losses by 2/3.

either end of the signal, people coded and interpreted the message with Morse Code. The telegraph and early telephones required an array of electromagnets and mechanical switches to send signals, but were largely obsolete by the time the modern form of semiconductors devices were mass produced and developed. In fact, the first semiconductor transistor was invented at Bell Labs because of a rapidly growing telephone network needed much more reliable switching devices.

The first telecommunication device to utilize over the air signals was the radio. The first radios were employed mainly for military efforts, prior to their introduction into typical households. The first household radios were rather expensive, incorporated large, energy-intensive vacuum tubes and required specialized, short-life batteries. Modern radios are inexpensive, compact, and require a relatively miniscule amount of electricity in order to operate. Semiconductor devices have enabled the radio's transition into small compact devices, which are still essential for military and emergency communications today.

Radios were the first commercially available devices to entertain and inform large audiences, but soon to follow was the introduction of the television. With the gradual replacement of boxy cathode ray tube sets by semiconductor-enabled flat screens, televisions have become much slimmer and are providing better picture quality with less energy. Liquid Crystal Display (LCD) televisions are very complex devices enabled by a wide array of semiconductor controls and switches that process and display a picture. Even with such complexity, LCD televisions of 40 inches or less operate on less power than traditional televisions of the same size (Thorne-Amann et al. 2008). The cost for consumers to purchase LCD televisions continues to drop as more units are purchased, leading to economies of scale. In 2007 an estimated 72.5 million LCD televisions were sold in the U.S and the average price of a 40-inch LCD television fell by 37 percent (Britton and McGonegal 2007).

Smarter-Two Way Communication

But semiconductor-enabled technologies have yet to reach the full potential to improve *net* energy savings. Through smarter-two way communication, the energy associated with an activity—whether paying bills, shopping online, conducting business meetings or working remotely—can now be done through electronic communication rather than in person. And because it is easier to move electrons than either people or goods, the energy and material savings are potentially very large. With e-commerce, teleconferencing and teleworking, a person will be substituting the energy associated with car and air travel in favor of electronic channels that can deliver goods and services more efficiently. Less net energy use is therefore the result of individuals performing economic activities through energy efficient devices *and* foregoing the excess energy associated with transportation. Indeed, the productivity gains from semiconductor-enabled technologies and services, largely through the growing reliance on information and communication technologies, have been responsible for nearly all of the growth in labor productivity since the 1990s (Atkinson and McKay 2007).

The Telecommuting Office

E-commerce and e-billing represent a large opportunity for net energy savings. Semiconductors enable ICT devices to safely and securely deliver goods and services through more efficient channels. In 2005, e-commerce sales totaled 2.2 trillion dollars in business-to-business and 189 billion dollars in business-to-consumer transactions (Britton and McGonegal 2007). Although these transactions are only 22.3 percent and 2 percent of total sales for business-to-business and business-to-consumer transactions respectively, e-commerce creates net energy savings. First, business transactions that are done online forego many of the costs of running a traditional store. This action also spares the expense of consumer travel to a traditional storefront. Second, traffic congestion associated with trips to the store is reduced. But, more importantly, the distribution channels that deliver goods to consumers are increasingly more efficient when equipped with ICT devices.

As our economy becomes increasingly computer-driven, transportation service demand will shift away from motor vehicles towards energy efficient cyber-travel such as telecommuting and video conferencing. Laitner and Ehrhardt-Martinez (2008) find that our "normal" working habits may dramatically shift as continued advances in information and communication technologies enable more widespread and creative forms of telecommunication and the digitization of services such as banking. Firms and employees are seeing a mutual gain from higher worker satisfaction and productivity, and therefore are increasingly following the telecommuting motto "undress for success."

These developments have resulted in some powerful trends and possibilities. About 3.9 million households in 2006 had at least one telecommuter, and their actions reduced US annual gasoline consumption by about 840 million gallons (CEA 2007). Matthew and Williams (2005) find that 40 percent of the U.S. workforce—about 53 million people—could telecommute to work. The American Consumer Institute finds that current rates of telecommuting could double and that this would save 588 million tons of greenhouse gas emissions over a 10-year period (Fuhr and Pociask 2007). And looking to the airways, if frequent flyers can eliminate 1 in 7 trips through some combination of video- and/or tele-conferencing, we might save an estimated 180,000 barrels of oil per day (Komanoff 2002).

Furthermore, in addition to telecommuting and videoconferencing, the increased use of virtual worlds for engagements such as meetings or discussion forums has the potential for significant future energy savings as an alternative to travel for off-site meetings. It has been estimated that by the end of 2011, around 80% of active internet users will experience a "second life" in a virtual world (Reuters 2007).

Smartphones

Cell phones and smart phones which use 3G channels can provide net energy savings because they transfer digital data through the internet and other digital wireless networks. These devices have advanced substantially over the years with the Semiconductor Industry Association (2008) noting: "Twenty years ago, a mobile phone made only calls, required its own carrying case, and weighed as much as most hardback bestsellers." Today, smartphone users can browse the internet, read e-mails and access digital work-related documents in addition to making a simple phone call—all from a device that fits in their palm. Because of these energy and time savings capabilities, smart phones are making up a larger and larger share of the US handset market (NPD Group 2009). The number of smartphones sold in five years will more than triple to 60 million as multimedia devices go mainstream (Walsh 2009). And high-speed data transfer functions are becoming more central to smartphones. In fact, two-thirds of smartphones now use 3G networks, compared to just 46 percent a year ago (NPD Group 2009). But smartphones are just one of a variety of mobile devices that make use of such broadband networks.

Soon, a wider array of digital communication channels will be open to faster, more technologically advanced ICT devices, many making use of wireless 3G networks. 3G networks provide the horsepower to transmit large packets of data efficiently to wireless devices. From 2003 to 2008, 3G device shipments grew at an annual rate of 48.4 percent, and 2G device shipments grew at a 10.4 percent annual rate (Britton and McGonegal 2007). Currently, PC data cards, USB modems, USB sticks, phones with data modems and portable devices with built-in support for Mobile Broadband, like notebooks, netbooks and Mobile Internet Devices (MIDs), are all making use of 3G networks. By 2013, more than 140 million U.S. consumers will be paying for mobile broadband services—up from 46 million in 2008—as they become more comfortable with broadband-enabled devices (Walsh 2009).

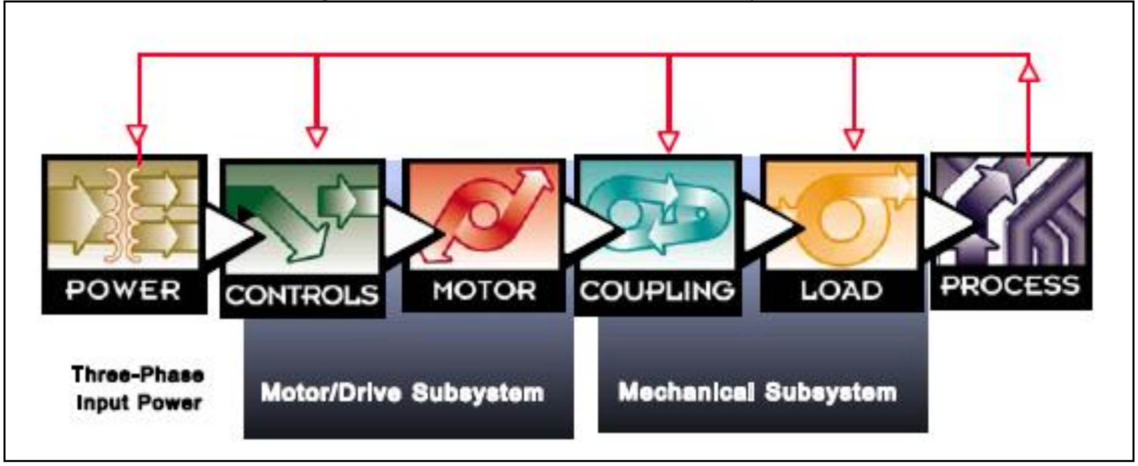
D. Motors and Motor Systems

Motors play an important role in everyday life. More than half of all U.S. electricity produced in the United States flows through motors (Nadel et al. 2002). Their existence and their continued improvements over time enable the many conveniences of modern life. Motors not only get us from place to place, but they are a critical tool in the manufacture our goods and consumer products. They also enable us to heat and cool our homes, wash our clothes and keep our foods from perishing. Because of their ubiquity throughout all aspects of in our lives, motors are hugely varied in size and power. Semiconductors facilitate greater efficiencies within motors and motor drives in differing ways—all depending on a specific motor's application and use.

Semiconductors play an important role in controlling *motor systems* and the mechanical subsystems they drive (see Figure 4). Semiconductors optimize a wide-array of manufacturing and industrial motor systems responsible for the production of many diverse goods. Almost all motors are part of a motor system that can loosely be viewed as being constituted of the following elements:

1. power supply and conditioning
2. motor controls
3. the motor itself
4. coupling or the transmission from motor to the driven device (e.g., belts, gearbox, pumps)
5. the load or driven device (e.g., pump, conveyor belt, rollers)
6. process (e.g., piping system or steel rolling mill)

Figure 4. The Elements of a Motor System



Worrell et al. (2004)

Each of the elements of a motor system has been improved by advances in semiconductor technology. For example, semiconductors have improved the drive power devices that supply the motor with optimal voltage and current for maximum efficiency. There is a wide-array of motors available on the market, but the most advanced motors incorporate and rely on semiconductor technologies.

Motors

An electric motor is a device that transforms electricity into mechanical power through a rotation shaft. These devices range from fractional horsepower, or units with less than one horsepower (hp) to large industrial systems generating 5,000 hp of shaft power and beyond. While semiconductor technologies have contributed to energy efficiency advances in the application of motors in the home, on the road, and in manufacturing, new advanced motor designs have emerged more recently that move beyond alternating current or AC induction motors with an adjustable speed drive, to direct current or DC motor designs that rely upon semiconductor power conditioning. Variable speed motors that avoid some of the inefficiencies of previous designs include brushless, electronically commutated permanent magnet and switched-reluctance commercial motors. When coupled with powerful sensors and distributed processing capability, motor systems with both new capabilities and greater efficiencies can be installed. While these advanced motors represent a small fraction of the current installed motor energy use, domestic motor manufacturers have committed to building advanced designs and which are made possible by powerful and more affordable semiconductors.

Motors in the household are typically found in the large appliances such as refrigerators, heating, ventilation and air-conditioning systems (HVACs), dishwashers, and clothes washers and dryers. The motors in these devices performing differing tasks yet are typically fractional horsepower motors. Because of the abundance of home appliances and other small motor applications, 95 percent of all motors in use in the U.S. are less than 1 horsepower (Nadel et al. 2002). Historically, motors in large household goods use wire brushes to keep constant power contact with the motor's stator, resulting in electricity losses as a result of friction and resistance. Now, permanent-magnet motors, or more specifically electronically commutated permanent-magnet motors utilize solid-state power and feedback devices to replace brushes. In addition to energy efficiency improvements, the permanent-magnet motor has a lower operating temperature, prolonging motor life and precise speed control.

The switch reluctance motor bridges the gap between white goods and transportation. These motors are highly efficient with the capability to produce needed torque in appliances ranging from copiers to Horizontal-axis clothes washers, to larger applications in electronic vehicles. Semiconductor devices enable these motors to have precision control in applications where variable speed is needed. The switch reluctance motor's design, despite its name, is very simple, allowing this type of motor to operate from a low of 50 revolutions per minute (RPM) to as many as 100,000 RPM (E Source, Inc. 1999). Similar switching devices, such as the switched-mode power supply, optimize control, but are capable of producing a desirable level of voltage from full on, to full off. This capability has been realized with semiconductor technology (Elliot 2009).

Motors play a large role in American industry. Two-thirds of the electricity that flows through U.S. industry is utilized by motors. Thankfully, the energy efficient motors that service this sector are some of the most technologically advanced and efficient motors offered. For example, particularly large advanced motors, in excess of 500 hp, have efficiencies of 98-99 percent (Elliot 2009).

Advanced motors in industry incorporate semiconductor technology within copper rotor, amorphous core, and superconducting motors. These motors are all large polyphase induction motors in excess of 100 hp. Advanced motors in this size range utilize a wide range of motor technologies, given the application at hand. These motors are often built to specification and employed in a facility, full-time, for decades. So, although energy efficiency improvements for motors are reaching diminishing returns, slight improvements add-up to big energy savings. Semiconductor technology also enables benefits outsides of energy use reductions such as: longer operating life, greater safety, higher overload thresholds, reduction in friction, reduced noise, size, volume and weight (Worrell et al. 2004).

Drive System

The frontier of energy savings possibilities for semiconductors lies within the drive control of industrial motors. Because of the size of industrial motors, three-phase power supplies are needed to provide adequate power to start and run these motors. The optimal power that is specified on a motor can be achieved through semiconductor drive systems. Drive systems condition the power coming into an industrial facility so the motor's specified voltage and current needs are met. The American National Standards Institute, standard C84.1 specifies that utilities supply power within +/- 5 percent of 120 volts. Drive systems bring variances in voltage to within +/- 2 percent of 120 V. Without an adequate drive system to correct for utility variances, large industrial motors will have a significantly lower efficiency and lifespan. Drive systems are essential to operating and maintaining both the life and the efficiency of a motor.

Motor Systems

Motors systems include all of the actions that occur as the result of the motor's mechanical output. Motors systems power multiple manufacturing and industrial processes with the resulting mechanical energy driving fans, compressed air, pumps and other actions. Motor systems are very specialized, so much so that often no two systems are alike. But semiconductor technologies can be employed at key junctions within a given motor system.

Most motors are also single speed, and thus can not vary their speed without resorting to inefficient mechanical transmissions. This lack of motor speed variability is important because among the most important motor system loads are centrifugal devices, such as fans, pumps and compressors. The energy use of centrifugal devices varies in proportion to the cube of the speed, while the flow is directly proportional to the speed. This relationship referred to as the "affinity law" means that small changes in motor speed can result in large changes in energy. Centrifugal loads represent about two-thirds of total motor energy use. Thus, it is important to closely match the output from the driven device to match the requirements of the load.

Historically, matching output and loads was achieved by adjusting the transmission speed of the driven device. While mechanical variable transmissions have been available, they have frequently been costly, unreliable and inefficient. They relied upon mechanical sensors and controls to change speeds to adjust output to meet varying conditions. Also, there were direct current (DC) motors that offered variable speed operations, but again these were costly, unreliable and inefficient.

Beginning in the 1970s, power semiconductor technology developed to the point that electronic variable speed drives could be commercially deployed in the marketplace. These devices, while introducing electric inefficiencies into the motor system, allowed for better motor speed control while also reducing the maintenance problems associated with DC drives or mechanical transmissions. In addition, these devices could be combined with electronic sensors and controls that were emerging in the marketplace made possible by advances in semiconductor technologies that further reduced costs. Initially, these systems were deployed in large industrial and power generation applications where the cost of the systems could be justified. As power semiconductor technology continued to advance, the cost and performance of these systems improved which made smaller systems practical. Increases in distributed computing power also broadened the application of this technology. In appropriate variable speed applications, energy savings in excess of 50 percent have been verified.

Because motor systems are long processes with large loads, simply turning on a motor system can present a challenge. This challenge, referred to as *in-rush*, places a large load on the motor. The loads on a motor remain high until the kinetic energy of devices within the system are fully operational. Semiconductor technologies provide a solution to the in-rush problem by moderating a *soft-start* of motor systems. Semiconductors enable soft-starts by controlling the flow of current into the motor. Electrical current levels gradually increase as the motor system reaches its operating level. Semiconductor components minimize in-rush which can significantly lower the efficiency of motors and shorten their lifetime.

Other semiconductor devices take feedback signals from the motors system to control how the motor operates. Digital signal processors are designed to provide valuable controls that increase motor performance, and do so in ways that withstand the vibration that many motor systems create. These processors run algorithms that not only control the operation of individual motors but they also monitor the system as a whole, providing valuable information to system operators.

It's important to realize that within motor systems semiconductors *enable* energy savings. Semiconductors in these applications result in savings only when technicians and engineers can properly install and monitor the feedback that semiconductors in motor systems provide.

Semiconductor Benefits

Because of semiconductor technology, motor and motor system operators are better able to monitor their equipment and make minor adjustments that can result in large energy-efficiency improvements. But, beyond the energy savings highlighted in the paragraphs above, semiconductors also enable non-energy productive benefits. Semiconductors increase the reliability of motors and motor systems. Semiconductor feedback allows operators to respond quickly, and sometime predict, motor burnout events. Knowing when to replace a motor maximizes the availability of motors and motor systems in manufacturing and industrial processes, minimizing costly downtime. Semiconductor technology enables a systematic approach to improving energy-efficiency and productivity

The full impact of semiconductors is difficult to assess because of the complexity of motor systems. This problem is complicated by the fact that the Federal Government has discontinued collecting information on many manufactured products, such as motors, and has not expanded their collection of market data to reflect technology evolution. While the application of semiconductor technologies remains a fraction of all motor systems, the systems where they are applied are among the most energy intensive, so their fraction of motor electricity use is more significant. ACEEE estimates that about 20 percent of motor loads currently benefit from semiconductor technologies. While some applications produce dramatic savings, most systems experience more modest benefits. We estimate that the energy savings benefits enabled by semiconductor technology were on the order of 40 billion kilowatt hours for 2006. This is about two percent of the total electricity consumed by motors within the U.S.

It is likely that semiconductor technologies will play an increasingly critical role in the coming decades. New motor systems will replace existing technologies (motors last about 25 years) and as a significant share of new motor loads will turn over. By 2030, ACEEE estimates the benefits in electricity savings are likely to exceed 100 billion kilowatt hours, in large part driven by the shift toward semiconductor technology within the industry. Aggressive policies that shift a larger fraction of the motor systems to benefit from semiconductor technologies would modestly increase savings to almost 130 billion kilowatt hours in 2030

E. Lighting and Lighting Systems

Solid-state lighting (SSL) is a form of lighting technology that is dramatically more efficient than conventional lighting technologies, such as incandescent and fluorescent bulbs. Light emitting diodes

(LEDs) are the form of SSL that hold the most market potential. Colored light LEDs have been on the market for several years—they are often used in traffic lights, exit signs, and other lights that remain on almost constantly. As research has progressed, costs have gone down steadily. However, the development of white light LEDs is a recent technological breakthrough.

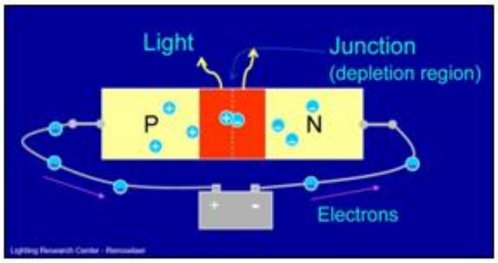


Diagram of a Light Emitting Diode

Unlike other lighting technologies, LEDs use electric current passed through semiconductors to produce light. Different colors of light are created by using different materials in the diode. Technology improvements are expected to bring brighter white light LEDs that provide light as good as or better than existing lighting fixtures with significantly percent electricity. Compared to a standard halogen desk lamp, for example, an LED lamp with an efficient power supply can provide 12.5 times the lighting out per watt of electricity (Williams 2009). With successful research and development in these products, energy savings nationwide over all sectors could be as high as 50 to 70 percent of total lighting demands for electricity (Navigant Consulting 2006). As SSL technology advances, it is likely to become better suited to a broader array of applications. Future R&D goals include improving the light quality, increasing further efficiencies, and reducing prices.

The potential energy savings will depend on how quickly and to what extent these developments occur. Although the technology's greatest impact will likely be in the commercial sector, SSL is also expected to transform residential and industrial lighting demand. Therefore, our analysis of the LED potential includes all three sectors.

Table 5. Lighting Technologies: Projected Lumens per Watt

	2007	**2012**	**2017**	**2022**	**2027**
Light Emitting Diodes	53.1	111	155.3	175	183.1
Lighting Upgrades	40.9	66.2	80.3	95.4	107.8
AEO 2009 (EIA 2009)	43.8	48.1	49.6	50.5	51.4
Lighting upgrades are only applicable to commercial sector efficiency improvements. The AEO 2009 forecast for commercial sector lighting efficiency is included for comparison.					

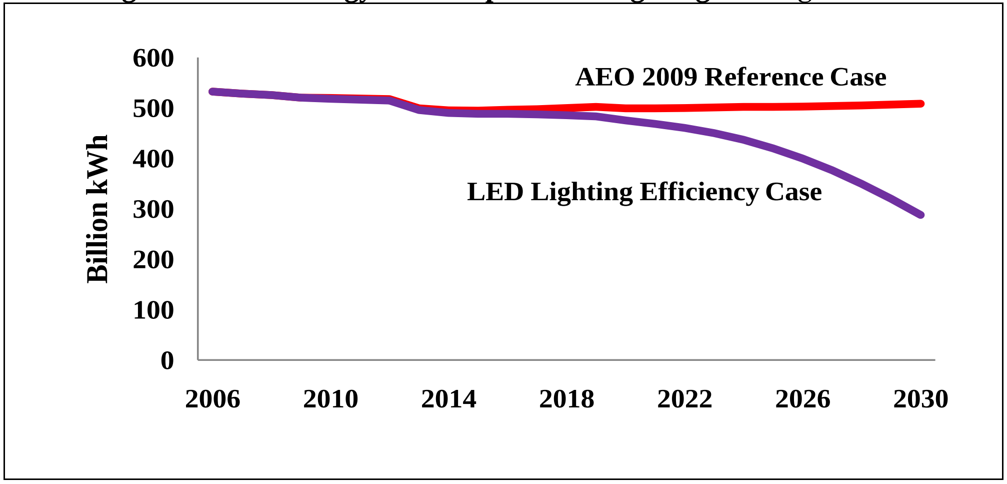
Under the aggressive research and development agenda being pursued by the U.S. Department of Energy, these substantial energy savings are very possible. A recent study on the market potential of SSL technology by Navigant Consulting (2006) determined that by 2027, LEDs could completely replace incandescent lighting and substantially replace most other forms of lighting in all sectors—residential, commercial, and industrial. Because incandescent bulbs are the least efficient form of lighting currently on the market, replacement of these bulbs with LEDs translates into tremendous savings of electricity. Table 5 above illustrates the different efficiencies (expressed in lumens of light output per watt of power) of LEDs compared to lighting upgrades and the projections of the *Annual Energy Outlook 2009* (EIA 2009). Clearly, LEDs are much more energy efficient than other technologies. With proper incentives, total LED market penetration potential by 2027 is estimated at 89 percent to 95 percent, depending on the sector (Navigant Consulting 2006). With this level of the market switching to LEDs, other forms of lighting would be rendered almost obsolete.

Table 6. Electricity and Lighting Demand in the United States

	2008	2010	2020	2030
Total Electricity Demand (Billion kWh)	3,763	3,789	4,161	4,606
Percent Electricity Used in Lighting	14.0	13.7	12.0	11.0
Electricity Used in Lighting (Billion kWh)	526	520	499	509
Lighting Efficiency Case (Billion kWh)	526	519	475	288

Overall, the Navigant Consulting (2006) study estimates that LEDs could lead to 30 percent or more electricity saved annually. Following AEO 2009 estimates published by the Energy Information Administration (2009), in 2008 residential and commercial building lighting accounted for approximately 14 percent of electricity usage within the United States. By 2030 its share is expected to drop to 11 percent. This is due, in part, to recent Congressional action on lighting standards, and also to anticipated higher prices for electricity.[14] If we assume that by 2030 we can deploy technologies which reduce lighting requirements roughly in half, and that 70 percent of the market is transformed by that time, the last row of Table 6 suggests that total lighting demands might be reduced from 509 to 288 billion kWh. This implies a potential 43 percent electricity savings by that year. Figure 5 provides a look at the savings trajectory on an annual based over the period 2008 through 2030.

Figure 5. U.S. Energy Consumption for Lighting Through 2030



So, with current projections for electricity consumption, lighting demand within the United States is expected to remain essentially unchanged between 2008 and 2030 (EIA 2009). However, with a "high efficiency LED" scenario, lighting demand might decrease by more than 40 percent. The interesting aspect is that such a scenario does not even come close to "maxing out" the likely potential by 2030. For example, if cost-effective lighting efficacy increases from 51 to 183 lumens per watt by 2030 (as suggested in the last column of Table 5), and if the market reaches 90 percent saturation by 2030, then we might envision lighting demands dropping even further—to 158 billion kWh by that year. That would reflect a 69 percent savings compared to the reference case forecast.

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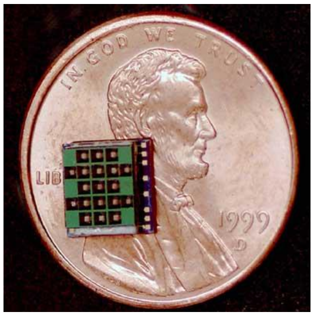
[14] According to the AEO 2009 forecast, the average price of electricity is expected to go from 8.7 to 10.2 cents per kWh (using constant 2006 dollars). In real terms, this is a 17 percent increase in average electricity prices.

F. Sensors/ Controllers

Without sensors and controllers, humans would be restricted to completing tasks manually in real time. No matter how much we could learn about something on our computers, if we wanted to measure or move something, someone would have to do it in person. This might work in a society that undertook few complex and large-scale tasks, but in any advanced setting would be extremely problematic. Thankfully, mechanical and electrical sensing and control systems empower humans through extending their awareness and field of action. Semiconductor-based sensors and controls augment basic sensing and control functions through providing seamless interaction with a digital society, facilitating greater flexibility and more precise measurement.

Semiconductor-based sensing and control systems have useful applications at all scales of analysis. Some of them are described here, from the exotic to the everyday:

From the micro-scale…
The picture below is of thruster for miniature satellites made using MEMS technology. Micro-electromechanical systems (MEMS) combine the "thinking" power of computer chips with sensing and control abilities (Memsnet 2009). MEMS are used in sensing applications such as detecting levels or acceleration or inertia, but may also be viewed as energy efficient tools that use extreme levels of precision to execute tasks with less waste than before. Some experts think these tiny instruments may eventually change our lives as much as computers have to date (Vittorio 2001).



A MEMS thruster for miniature satellites

To the meso…
Through optimizing the timing of operations, manufacturing controls increase production efficiency and are recognized to be a major contribution of semiconductors to energy savings (Laitner and Ehrhardt-Martinez 2008). Wireless sensors provide these advantages but do so with much lower wiring and installation costs. Applications include advanced industrial motor controls, and better communication with ultra-small productivity enhancing devices such as MEMS (DOE 2002). Large firms such as GE are currently pursuing industrial applications for wireless sensors (InTech 2004).

To the macro…
Wireless sensing and control systems have the potential to take the energy efficiency of large systems, industrial or otherwise, to the next level. Through distributed intelligence, highly-networked groups of wireless sensors can eliminate single points-of-failure and provide emergent performance characteristics that are not indicated by any individual sensor. This has implications for efficient transportation in the form of smart cars such as Toyota's futuristic Personal Mobility Vehicles and appliances that communicate through peer-to-peer networks (Cascio 2004). For instance, sensors and automatic controls will allow cars to coordinate their travel with one another, enhancing safety and fuel economy.

Toyota's Personal Mobility Vehicle

And the everyday…
On the more mundane side, sensors also help people manage their forgetfulness. This is most commonly in the form of automated switches for energy-consuming devices, usually lighting. The US Department of Energy estimates that motion sensing lights use between 17 percent and 60 percent less energy than non-motion sensing lights (NEMA 2001).

More recent sensing innovations include the use of motion sensing devices for HVAC control in hotel rooms and self-dimming residential lights. In fact, the electric utility PG&E recently entered into a multi-million dollar contract with Honeywell to install motion sensing controls in hotels within its service territory. The installations are expected to save $140 dollars in electricity expenses annually for each room (EnvLeader 2007). If this was carried out at all US hotels rooms it could save the industry $616 million dollars.[15]

Sensing technology has also resulted in smart lights and computer screens that react to the brightness of their environment. Many laptops have auto-dimming screens, and Panasonic has recently introduced large residential lights that are able to dim and brighten in response to light bouncing off the floor (Heimbuch 2009).

One of the largest uses for sensing technology is in reducing the energy impact of computing data centers, which are explored in detail in another section of this report. Data centers use a significant amount of electricity, about half of which is for cooling (ENERGY STAR 2007). IBM is developing sensors to determine when individual data center computers are being overheated or overcooled, and which incorporate algorithms that put servers to sleep when they're not needed (Richard 2008).

G. Alternative Energy Resources

In spite of their low-carbon emission and energy security advantages, alternative energy systems are fighting an uphill battle. With 85 percent of worldwide energy provided by fossil fuels, the burden is on alternative energy systems to prove that they can provide cheap and reliable power. This is nowhere clearer than in the case of "variable" renewables such as wind turbines and solar photovoltaics. Not only do they struggle to compete on a price basis, but they must also overcome the variability of their power production. Semiconductors have provided vital assistance in helping these energy sources penetrate an electricity grid designed around centralized power plant technologies.

Wind

Without semiconductors, wind turbines would still be a niche power source. Hampered by fixed speed operation, unable to produce reactive power, and isolated from control centers, turbines would be little more than novelty items. T. Boone Pickens would not be planning multi-billion dollar wind turbine investments, and the U.S. Department of Energy (DOE) and the American Wind Energy Association (AWEA) could not have produced their report arguing for the feasibility of a grid with 20 percent wind power in good conscience.

Instead, wind turbines have become one of the fastest growing electric power sources in the industrialzed world in 2008, representing 42 and 43 percent of new capacity in the US, and in Europe, respectively (Appleyard 2009, AWEA 2009). The mastermind behind this incredible feat is the power electronics that have squeezed more juice per dollar invested in turbines, and also allowed large wind "farms" to connect to the grid without destabilizing it.

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[15] According to the American Hotel & Lodging Association, there are about 4.4 million hotel rooms nationwide.

Power and stability. One crucial advance in recent years is the growth of variable-speed turbines from a luxury item to the status quo. From a power perspective, variable speed turbines are superior, producing 10 to 20 percent more power than fixed speed systems. (Takashi et al.1999, Kanellos et al. 2006). However variable speed turbines produce variable current that is not matched to the grid. Semiconductor-based power electronics such as inverters and transformers adjust it to appropriate levels. As a side benefit, these electronics also allow turbines to stabilize levels of reactive power in the grid, a function which used to be restricted to fossil fuel power plants. Reactive power is extra electrical current that sloshes back and forth on power lines and can impede the deliver of electricity to consumers. Through stabilizing the movement of reactive power, advanced wind turbines help make sure that the movement of reactive power does not interfere with power quality.

Wind Turbine Transformers

Remote sensing and control. Because wind turbines are often located high off the ground and in rural areas, it is not practical for on-site crews to continuously monitor them. Modern wind farm performance is monitored through the use of remote sensors, and commands are sent from afar via personal computers. Between 100 and 500 parameters in modern wind turbines can be monitored remotely, and improved monitoring and control is behind much of the increase in wind turbine performance in recent years (DWIA 2009).

Future developments in wind technology will also rely on semiconductors. Smart variable electric generators are currently under development that selectively magnetize themselves in response to changing flows and thus allow up to 50 percent more power capture and 57 percent more revenue for wind farm owners (Bullis 2008).

Photovoltaics

The market for photovoltaic (PV) systems grew 60 percent in 2007 (Solarbuzz 2008). This kind of growth is not possible for an energy system without seamless grid integration. Semiconductors have been critical in that regard. While PV systems have not had to surmount the many grid-destabilization challenges in the same way that wind has, they have faced the hurdle of being a distributed resource that requires “plug and play” interconnection systems. Progress in these interconnection technologies, particularly inverters, has been crucial to their growth. Continued developments improving PV system performance will support additional growth.

Power optimizers: high performance PV

Without inverters—which “invert” the direct current electricity produced by solar panels to the alternating current form used by the grid—solar PV systems would be restricted to isolated applications such as cell phone towers, oil rigs, and rural homes. Unable to interface with the grid, the solar PV market would be a fraction of its present size. PV systems would also be less efficient because electricity utilization from stand-alone PV systems is limited by the storage capacity of batteries. The grid, however, functions as a limitless battery so none of the power produced is wasted (Goudey 2009).

Just like in wind turbines, semiconductors also enable maximum power output of PV systems. The computerized components of inverters manage the performance of all modules in a group to optimize the electricity output of the system – given the technology available. This now is typically carried out by a centralized inverter; in the future the power to the centralized inverter will likely be optimized through smart inverters located on every panel. In this more productive configuration, power optimizers can harvest up to 57 percent of the power normally lost. Such optimizers work by helping solar panels achieve their maximum potential in the face of real world impediments such as clouds, dirt, and bird droppings. PV systems are only as efficient as their weakest link, so a few shaded or degraded panels can impact an entire array, much as a section of Christmas lights wired in series is vulnerable to the failure of a single light. Power optimizers allow the array to harvest the energy of each panel independently, so that a shaded or dirty panel contributes what it can while the remaining panels contribute their full potential (Muenster 2009).

H. The Smart Grid

The "smart grid" is the most talked about new infrastructure development in decades, but it is probably the most easily confusing reference as well. Much of this is because the different groups talking about the smart grid are actually talking about different things. Silicon Valley start-ups tend to focus on the "smart" aspect, talking about feedback, advanced metering, and smart appliances. Utilities focus on the "grid," explaining how billions of dollars in transmission investment are needed to ensure reliable delivery of electric power. And futurists focus on emergent properties of the smart grid system, explaining how it will be self-healing and adaptive. Setting this partisanship aside, from an energy efficiency perspective it is the advanced metering, communications, display, and control technologies that are crucial: it is more the smarts that are needed than the grid (although transmission investment may be necessary for other reasons, e.g., location constrained resources).

If the grid only had a brain…

The market for these smart technologies is expected grow from $2.7 billion in 2008 to $4.7 billion in 2013 (Fehrenbacher 2008). These figures comprise less than 10 percent of the estimated value of the larger smart grid market, but it is here that the most energy saving potential can be found. It is these technologies that will allow consumers to react to displays of price signals—such as through Google's new Power Meter application, and to then program their household consumption according to their activity cycles. It will also enable smart appliances to adjust their consumption during times of peak demand, stabilizing the grid and preventing construction of expensive "peaking" power plants. A radically different and more dynamic grid could save consumers more than $300 billion over 20 years through the reduction of peaking power plants alone (Talbot 2009).

The Utility Side of the Meter

Currently, mechanical switches and close monitoring are needed to keep the nation's grid operating. Even with close supervision there have been more than a few notable blackouts as well as rolling brownout events which have occurred across the country in recent years. Also, the grid's transmission and distribution network cannot identify how that electricity makes it to customers and be predictive about their short-term needs. In response to customer's short-term needs, utilities will turn to peak generation facilities to provide grid stability. Peak generating facilities sit idle for most of year, yet 10 percent of all power plants are peak plants (Foundation Capital 2009). Peak facilities are often inefficient, least cost methods of generating power which result in relatively high greenhouse gas emissions per unit of power generated.

Semiconductor devices can build communication links between distribution and transmission lines. These devices will be able to dispatch energy to keep the grid operating, preventing localized lapses in power quality. Communication between transmission networks will also be able to identify how an amount of electricity is delivered to customers while utilizing past information to predict their needs. If more power is needed during peak periods of demand, the smart grid can access reserve power from combined heat and power (CHP) units, recycled energy systems, and other distributed generation or batteries with energy that has been stored from wind and solar farms, or even plug-in vehicles (Parks et al. 2007). This can go a long way to reduce the need for peaking power plants.

The Consumer Side of the Meter

There are multiple semiconductor-enabled technologies that will allow a smart grid to increase the efficient use of electricity. The story begins with smart meters that respond to signals sent by the utility and will give the end-use customer a real-time price for electricity. The information transmitted through the smart meter can they be displayed on an in-home computer screen. Seeing the consumption of individual appliances increases energy-consciousness and alerts consumers to energy hogs. Furthermore, when regulations are updated to reflect these new technologies, advanced electricity metering allows real-time pricing that better reflects the actual cost of generation. When the average price per kWh is decomposed into minute-by-minute marginal costs and displayed, consumers often choose to reduce their consumption during peak-demand periods, typically on the order of 5 to 15 percent (Darby 2006). That could produce a significant savings for both consumers and the utilities. And the same real time pricing that makes electricity bills more transparent will also allow greater profits from solar photovoltaic systems with net-metering. Because the sun shines the brightest during times of peak demand—typically summer afternoons—that is when photovoltaic systems generate the most electricity and real-time prices are at their highest.

More advanced smart grid technologies offer even more impressive energy savings. Emerging computer programs allow major energy appliances to be monitored and controlled from personal computers, resulting in significant energy savings. Consumers that can program their water heater and climate control systems from their personal computers reduce their electricity bills 10 percent on average (Lohr 2008). Computer chips embedded in appliances allow water heaters and air conditioners to respond to grid disturbances by sensing the frequency of the electricity they are using. Under times of grid distress, they reduce their consumption automatically (PNNL 2009). There are even semiconductor technologies that will allow appliances to coordinate their grid-savings efforts; in effect, working as a team of appliances. Advanced power electronics can allow refrigerators in commercial applications to talk to each other, and in residential applications to talk to the utility meter. In both cases this allows “the system” to determine how much they should each reduce demand to deal with fluctuations in both price and supply (CSIRO 2009).

Perhaps equally intriguing, the technologies that make the grid "smart" are overwhelmingly the same type of semiconductor-enabled information, communication, sensing, and control technologies that are also needed to create smart roads, bridges, and levees. For instance, wireless communication protocols such as ZigBee, EnOcean, or Z-wave can be applied to a variety of infrastructure applications. Developing and deploying wireless communication platforms for one application in infrastructure systems will help their integration in others. The same goes for the devices that interact with these networks. Car displays that predict traffic problems ahead may utilize similar technologies as household energy monitors do. Developing sensors that detect strained levees may contribute to the development of temperature sensors that will allow for more targeted heating and cooling of homes, which currently accounts for 23 percent of residential electricity demand. And eventually these devices may even be consolidated. It is not hard to imagine a car equipped with a navigation system that is integrated with household sensors, alerting drivers in case they left their heater on too high or their stove lit. Rather than focus on the smart grid alone, we should begin thinking about policies and behaviors that can bring all of our infrastructure systems into the Twenty-First Century.

I. Transportation Systems

In 2007, the US transportation sector consumed 28 percent of our national energy supply, the vast majority in the form of petroleum. This demand drove the importation of 7 million barrels of oil per day. Much of that oil was from the Middle East, and its consumption resulted in over 2,000 megatons of greenhouse gas emissions (ORNL 2008). Not surprisingly then, and for a variety of economic and political reasons, policymakers have focused on ways of increasing the efficiency of our transportation practices. Yet the policy debate has largely focused on new fuel economy regulations and the promotion of alternative transportation, ignoring the potential savings from the smart application of semiconductor technologies. We have discussed above the potential of telecommuting and teleconferencing as attractive modes of energy efficient commerce above. In this section, we identify two important ways that semiconductor-based technologies enable increased energy efficiency in non-virtual transportation. Namely, they optimize the performance of transportation technologies, and they help more efficiently coordinate vehicle movement and the delivery of goods. These two practices are already working to increase the energy productivity of the US economy, and will do so more extensively in the future.

Transportation demands within the United States—whether by land, sea, and air—can be met more efficiently through wide variety of semiconductor technologies and applications. This has been the case with automobiles, which have increased their fuel economy 70 percent over the last three decades (Laitner 2008). With 50 to 80 or more microprocessors and controllers now used even in today's low-end cars, there is more computing power in a single car than in the Apollo spacecraft used to get our astronauts to the moon in the 1960s. Semiconductors play a vital role in improving powertrain efficiencies through optimizing gasoline engines with such features as SIDI (Spark Ignition, Direct Injection), V.V.T. (Variable Valve Timing), Combined Combustion, and Turbo/Super-charging (Tuttle 2008). Semiconductor sensors measure a tire's pressure and communicate the information to the dashboard—fuel efficiency is reduced by one percent for every three pounds per square inch that the tire is underinflated (DOT 2007). Semiconductors can also "network" an automobile's electrical system and avoid separate wiring from the locks, windows, mirror, seats, lights, and other devices to their respective switches, reducing the weight of a car as much as 60 pounds and thereby improving fuel efficiency (Huang, Thomas 2008). By the end of 2009, one-quarter of the value of the average car will be comprised of electrical and electronics components, half of which will be semiconductors. The worldwide automotive semiconductor market will reach $25 billion in 2009 and continue to grow despite a slowing auto market (Industrial Equipment News 2009).

Still, as evidenced by past rates of energy progress, in subsequent decades cars will learn many more things from computing technologies. If energy efficiency in cars from the 1950s had improved at the same rate as in computers (50 billion-fold), today we might need only 15 gallons of gasoline to provide for the entire world's annual transportation needs[16] (UM 2008). If we began to seek this same relentless progress in our automobiles, perhaps we could inch more quickly towards best practices in efficiency. In fact, fuel economies over 10,000 miles per gallon have been achieved for a gasoline engine-powered vehicle, and in 2006 all top 8 finishers in Shell's eco-marathon achieved over 4700 mpg (ENS 2006). Besides helping to achieve radical motor and design efficiency increases, semiconductor-based technologies can also enable smarter behavior that reduces vehicle energy use. Intelligent cars of the future may use global positioning systems (GPSs), sensors, and on-board communications equipment to help drivers maintain efficient speeds and find the least congested routes to their destination.

Learning from computers: 10,000 mpg

Another important contribution of semiconductors to transportation is in plug-in hybrid electric vehicles (PHEVs). Because of their ability to store large amounts of power, PHEVs can feed excess power back into the grid during increase periods of electricity demand. PHEVs would automatically respond to price signals such that charging would occur during off-peak times when electricity prices are low, generally very early in the morning. Smart grids would then be able to dispatch stored energy from PHEVs when energy prices are high and electricity resources are limited. With semiconductor technology, the smart grid would be able to communicate and tap smaller resources like PHEVs creating a stable grid and savings for consumers. During these events, the utility could potentially be paying the owner a higher price for the energy put back into the grid than the price paid to charge the vehicle (Kempton and Tomić 2005). PHEVs also incorporate semiconductor devices that enable PHEVs to operate in their most efficient state. It is estimated that a PHEV with a 9 kWh battery could save owners up to $450 in fuel costs each year. Also, with a large number of PHEVs on the road, carbon dioxide emissions from vehicles would be cut in half (Parks et al. 2007).

Some of the largest energy savings potentials in transportation are external to the vehicles themselves; these can create system-wide benefits from the better coordination of travel. For instance, while average US automobile fuel economy has doubled since the 1970s, the miles traveled per cars have greatly increased as well. While much of the solution to this is in better community planning practices to reduce the distance of commutes, some of it is also in using semiconductor-based technologies to reduce inefficiencies. As but one example, upgrading US traffic signal infrastructure to optimize traffic flow would have a benefit-cost ratio of 40 to 1. Combining basic signal upgrades with the installation of advanced sensing and computing technologies at intersections would save the US about 20 billion gallons of gas per year (Clayton 2008).

Better coordination of transportation can also benefit businesses. Increasingly long and complex business supply chains under globalization means computers have an important role to play in logistics coordination. UPS employs a "package flow" algorithm to find ways to reduce the total miles traveled by its delivery fleet, including by avoiding left-hand turns. Reducing the need for inefficient left-hand turns saved the company 3 million gallons of gas in 2006. Other energy savings

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[16] The article cited finds that 1 liter would provide for UK consumption for a year. Judging by a chart in the Economist, the UK took up about 1/54 of worldwide gasoline consumption in 2003, and 54 liters is about 14.2 gallons. See http://www.economist.com/images/ga/2007w27/Petrol.jpg.

will come as advanced logistics technologies better help firms utilize intermodal transportation strategies, reduce the “backhaul” of empty trailers, and keep better track of inventories so that only necessary orders are made. Among these, the use of intermodal transport for long distance shipping is projected to reduce greenhouse gas emissions 65 percent per trip compared to ordinary truck-only transport (Laitner 2008).

J. The Larger Infrastructure

With all the recent talk about the smart grid, it’s easy to forget that semiconductors have applications in a variety of infrastructure systems, not just electricity-related ones. As we noted in our Smart Grid section, many of the sensing and communication technologies used in making the grid smart can be applied to other infrastructure systems as well. This is fortunate because our infrastructure is in dire need of modernization.

In the past, an outdated perception of infrastructure systems has led to outdated policies and consequently infrastructure systems have not benefited significantly from information and communication technologies (ICT). While business and financial services have enjoyed ever faster and more complex accounting software and real time information flows, infrastructure-related industries have continued to deploy low-tech assets that remain low-tech throughout their very long lives. And every year, we see the consequences of these outdated understanding and practices in the form of traffic congestion, energy waste, and structural failure. The technologies exist, largely in the form of advanced sensing and communication systems, for us to build a more productive infrastructure future. These can be applied to bridges, levees, and roads to improve economic productivity and energy efficiency.

The new I-35 "smart" bridge

One area that semiconductors could be used in is critical structure monitoring such as in bridges and levees. The I-35 bridge collapse in Minnesota took 13 lives and cost the state $60 million dollars in lost output (Positively Minnesota 2008). Weak levees played a major role in the destruction of Hurricane Katrina in Louisiana, which caused over $150 billion dollars in damages (Burton and Hicks 2005). Currently, engineers use a slow and inconsistent process of visual inspection to determine the integrity of these structures. As a result, valuable resources are squandered on replacing structurally sound bridges while those with invisible structural deficiencies may go unrepaired. Embedded advanced sensing technologies—such as vibration powered wireless sensors or a nanotube-powered sensing spray coating—transmit data to computers which can then precisely gauge safety (Steinberg 2009, Science Daily 2007). The rebuilt I-35 bridge, which passed a visual inspection one year before its collapse, now has about 320 new sensors (Science Daily 2007, News Hour 2008). These sensors render expensive inspections by skilled engineers unnecessary while reducing rates of structural failure. Besides the increased safety of these structures, through decreasing the risk of unpredicted structural failures investments in sensing technologies free up economic activity to move in more energy efficient directions.

All of this suggests that Twenty-First Century transportation doesn’t need to have all the worst aspects of the Twentieth Century. Traffic jams, frequent accidents, unexpected street closures: all of these unforeseen road risks cost drivers time, risk their safety, and waste a lot of energy. In 2005, congestion cost US driver 2.9 billion gallons of gasoline worth $78 billion (TTI 2007). But most of these can be mitigated through semiconductor technology. In addition to the telecommuting opportunities discussed earlier in this report, the impact of traffic can be lessened through roadside sensors that provide information to traffic control centers and directly to drivers (Totty 2009). Traffic centers can then post information on roadside signs and drivers, especially if empowered through GPS systems, could change their routes. Sensors can also lessen traffic through enabling traffic lights to work together to optimize traffic flow, which can lower our gasoline consumption by 5 to 10 percent (Laitner 2008). Another way to save drivers money is by preventing accidents. Embedding sensors and advanced displays in cars can help avoid traffic accidents by providing warnings to drivers when they are approaching the car in front of them (Staedter 2008). Just as in the case of preventing bridge and levee failures, preventing automobile accidents—which cost the economy $164 billion each year—creates opportunities for productive investments in other sectors (AAA 2008).

IV. QUANTIFYING FUTURE ENERGY AND OTHER PRODUCTIVITY IMPACTS

At this point in the assessment we ask the question, what additional energy productivity gains might semiconductor technologies support within the U.S. economy? We delve into that question by examining different scenarios of future electricity growth. In the comparison that follows, we explore how different assumptions might impact future electricity demand. In this next assessment, we build on the latest set of forecasts published by the U.S. Energy Information Administration (EIA 2009).

In the "most likely" reference case forecast, the EIA projects electricity consumption to grow at an average rate of about 1 percent annually from 2008 through 2030. This means that total electricity consumption will increase 22 percent from 3,763 to 4,606 billion kilowatt-hours (kWh) in that period. This "business-as-usual" forecast is largely predicated on three things: (i) an economy that will grow at an average annual rate of about 2.5 percent; (ii) an average electricity price that grows (in constant dollars) from 9.6 to 10.5 cents per kWh; and (iii) a 27 percent decline in the nation's electricity intensity (as measured by in kWh per real dollar of GDP). The forecast incorporates estimated impacts of currently legislated building codes and appliance standards (including those in the Energy Independence and Security Act of 2007) as well as normal market-driven improvements in energy efficiency. It also assumes continued contributions of utility- and government-sponsored energy efficiency programs established prior to 2009.

The specific questions we ask in this section of the report are two-fold:

1. How much electricity might be saved through normal rates of innovation and on-going improvements in semiconductor-enabled technology, and with existing government and industry programs?
2. How much additional electricity might be saved through accelerated investments in more productive semiconductor-enabled technologies?

Under the assumption that significant changes cannot be implemented in 2009, we explore those questions by looking at the period 2010 through 2030. Our further assumption is that additional energy productivity gains are not likely to happen without new policies being put into place. The reason is that it will require a new set of policies to provide the incentives necessary for driving cost-effective changes in the nation's energy productivity. (For a more complete discussion on the need for policies to drive further gains in energy efficiency, see Brown and Chandler 2008, and also Geller et al. 2006).

While Appendix B provides the background details which underpin our findings, both Table 7 on page 35 and Figure 6 on page 36 highlight the results that emerge from our analysis. We begin with Table 7 which summarizes the four different trends in electricity consumption patterns over the period 2010 through 2030.

A. Frozen Efficiency and Reference Case Scenarios

The first trend is a "frozen efficiency" scenario. This represents a working estimate of what electricity consumption might be if there are no further improvements in the nation's energy productivity. In other words, if the economy were to grow in ways that the intensity of electricity demand was held at 2009 levels—in effect, if today's electricity use remained fixed at 0.32 kWh per dollar of real GDP. In that case, total electricity consumption would grow at the rate of the national economy which is now pegged at 2.5 percent annually through 2030. Under that assumption, electricity demand would increase from 3,922 billion kWh in the 2008 historical year to 6,502 billion kWh by 2030.

The good news is that there are market trends and a variety of policies, now in place, that will catalyze larger but still cost-effective investments in energy-efficient technologies. Such investments will slow the demand for electricity compared to the technologies being used today. Those market trends and policies have prompted the Energy Information Administration, in effect, to modify the frozen efficiency case so that electricity demand in the reference case will grow to only 4,606 billion kWh by 2030. In other words, "normal improvements" in the energy market will reduce electricity demand by about 29 percent compared to the frozen efficiency scenario. A majority of the savings will be driven by the many semiconductor technologies we've previously described. The reference case assumes, for example, that lighting will transition away from incandescent bulbs to compact florescent and light emitting diodes as required under the Energy Independence and Security Act of 2007—a savings of some 70 billion kWh (EPRI 2009).[17]

While there are sizeable savings for the U.S. economy that are expected to be achieved in the reference case, the evidence strongly suggests that we can do much better—given the right mix of incentives and policies.

B. EPRI Scenario

In January 2009, the Electric Power Research Institute released a study which suggested a 5 to 8 percent savings from the EIA reference case forecast by 2030 (EPRI 2009). The EPRI study includes a list of technologies that can be implemented together with their associated electricity savings at the end use (See Table D-1 in Appendix D for a modified version of this list). There are a significant number of semiconductor-enabled technologies among the more than two dozen listed. These technologies include (listed in order of their potential energy savings): commercial lighting, high efficiency industrial motors and motor systems, residential color TVs, residential programmable thermostats, commercial central air conditioners (AC), residential lighting, commercial monitors, residential refrigerators, reduction in residential standby wattages, commercial personal computers, residential central AC, industrial high intensity discharge lamps, commercial energy management systems, commercial color copiers/printers, commercial other electronics, industrial fluorescent lamps, commercial programmable thermostats, residential personal computers, commercial variable air volume systems, industrial heating and cooling of buildings, residential water heating, residential

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[17] Although not easy to reconcile, even with the EPRI savings of 70 billion kWh noted here, examining Table 6 and the subsequent discussion in the lighting section of this report, we might suggest still another 150 to 200 billion kWh of savings and more might be possible—with the right set of policy signals and incentives.

dishwashers, and industrial process heating. In cases such as space cooling, the savings are a combination of semiconductor-enabled smart building controls and measures that are not related to semiconductors such as improved insulation (EPRI 2009, Figure ES-7).

In most cases, then, the energy savings are coming primarily from the semiconductor-enabled technology. The importance of semiconductors becomes even more apparent when we realize that even the design and system optimization of integrated technologies, which include insulation and ducting, also benefit from computer-aided design tools and smart energy management systems. In the aggregate, a review of the EPRI list shows the largest opportunity in residential end use is consumer electronics. In commercial end use it is lighting and electronic equipment, and in industrial end use it is machine drive and motor systems (EPRI 2009, Figure ES-6).

C. Semiconductor-Enabled Efficiency Scenario

While the EPRI study demonstrates significant energy savings from semiconductor-related technologies, it assumes no further policies and no new technologies. In effect, the EPRI study provides a backdrop for further savings only if electric utilities decide to modestly "ramp up" existing programs, or if consumers increase their "voluntary efficiency efforts" for other reasons beyond those identified in the EIA reference case. This perspective views efficiency improvements as essentially a growth management tool rather than a productive investment strategy. Yes, energy efficiency can moderate the demand for electricity to make it easier to plan and build new generation units at an easier pace. Yet, the evidence points to a large remaining efficiency resource which can save consumers and businesses more money—if we choose to make those more productive investments.

The EPRI tables of technologies and energy-efficiency measures are useful to review again, this time for what is not on the list. As noted in the preceding chapter, a Smart Grid offers revolutionary opportunities to reduce electricity consumption by providing consumers with real time information on their electricity usage, moving electricity more efficiently to reduce transmission losses, and automatically adjusting networks of electricity loads to off peak-hours. As but one example of this potential magnitude, a study previously cited in the Smart Grid discussion of this report (Darby 2006), suggests that consumers might save between 5 and 15 percent of electricity consumption with positive feedback and real-time price information made possible by the Smart Grid. If we assume only a 10 percent savings by 2030, across all sectors, that translates into a 460 billion kWh savings made possible the system of semiconductor-enabled technologies. This single impact is larger than the entire estimate suggested by the EPRI analysis. Again referencing earlier discussions from Chapter III of this study, there are large savings from data centers (ENERGY STAR 2007), power optimizer technologies (Muenster 2009), virtualization (Koomey 2009), and even greater lighting opportunities with solid state lighting technologies (Navigant Consulting 2006). Navigant Consulting (2006) suggests ultimately we might see a 70 percent reduction in energy consumption of lighting from popular deployment of LEDs and Organic Light Emitting Diodes by 2027. None of the manifold future technological opportunities detailed in our report are captured in the EPRI study.[18]

With proper policies and investments—in effect, policies which encourage greater productive investment that inevitably depend on semiconductor devices and technologies—our analysis points to semiconductor-enabled energy savings that can reduce electricity use to about 27 percent below the EIA's 2030 reference case projections. The analytical assumptions embrace not only the underutilized current generation of technologies (such as those included in the EPRI report mentioned above) but also the "next generation" devices and systems which will eventually permeate both public

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[18] For a further detailed review of the EPRI study, see also ACEEE et al. (2009).

and private sectors. The analysis also accounts for the increased energy required from the greater production of semiconductors. (This is further discussed in Appendix E.)

Our basic approach to estimating the future energy impact of semiconductor-enabled technologies involves extrapolating a historical pattern of industry growth and technological progress into the future, while accounting for new policies and changing industry growth rates (note that Appendixes A and B provide a detailed description of our modeling approach). The total electricity savings of over 27 percent by 2030 may see seem ambitious when compared with studies such as EPRI has published, but it is consistent with the findings of a number of recent analytical exercises including reports released by ACEEE (Laitner 2009, Eldridge et al. 2008a), the American Physical Society (APS 2008), the Lawrence Berkeley National Laboratory (Brown et al. 2008), the United Nations Foundation (Expert Group on Energy Efficiency 2007), and The Climate Group (2008). All of these studies suggest savings in the range of 30 percent is both achievable and cost-effective.

D. Over One Trillion KWh of Efficiency Gains

As we've previously indicated, Table 7 below summarizes the results from both the Semiconductor-Enabled Efficiency Scenario and the other three scenarios that we've previously described.

Table 7. Trends in U.S. Electricity Consumption (Billion kWh)

	2008	2010	2015	2020	2025	2030
Frozen Efficiency (Based on 2009 Data)	3,763	3,813	4,437	5,015	5,685	6,502
EIA Reference Case	3,763	3,789	3,959	4,161	4,372	4,606
EPRI Growth Management Case	3,763	3,765	3,825	3,930	4,058	4,220
Semiconductor-Enabled Efficiency	3,763	3,765	3,614	3,509	3,424	3,364
SEES Savings from the Reference Case	0	24	345	652	948	1,242

Even a cursory review of the trends in Table 7 underscores several critical insights. First, on-going energy efficiency improvements already provide a sizeable benefit in the reference case compared to the frozen efficiency scenario**.** As a result of semiconductor and other efficiency measures that are already on track, by 2030 we will have an economy that is about 70 percent larger, but one that uses only 22 percent more electricity. Total energy savings in 2030 are nearly 2,000 terawatt-hours.[19] And although the reference case impacts are large, the technologies exist to actually reduce future electricity demand even further. Again, should we choose to develop the energy efficiency resource, the associated productivity gains can actually reduce electricity requirements but that can also continue to ensure additional economic growth by 2030. Figure 6 below graphically illustrates these different scenarios.

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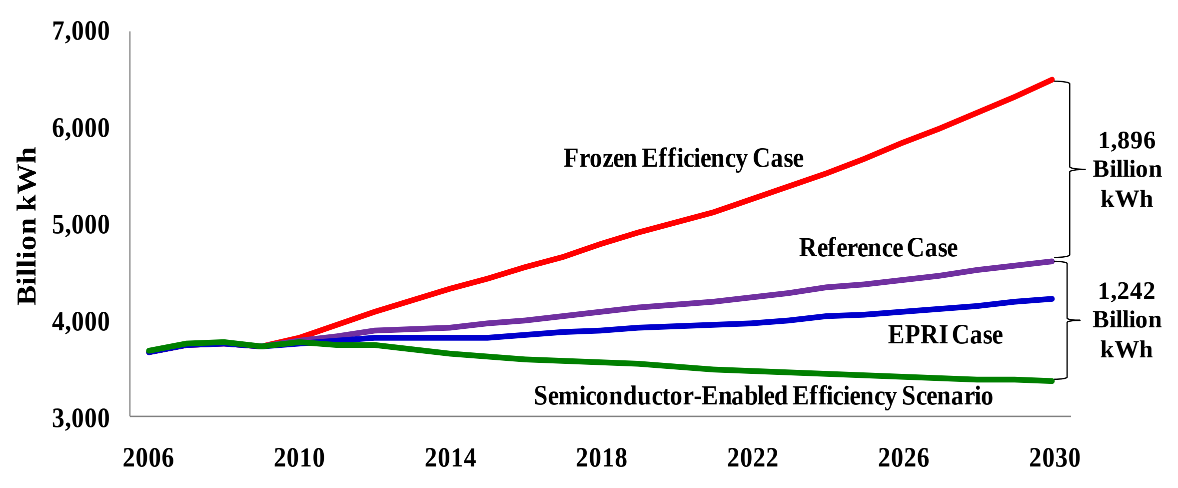
[19] Note that one billion kWh is the same as one trillion watt-hours (also sometimes referred to a one Terawatt-hour). Hence, as suggested in Figure 6, the savings of 1,896 Billion kWh is nearly two trillion kWh or 2,000 terawatt-hours.

Figure 6. Scenarios of U.S. Electricity Growth



Given these larger productive returns the question naturally arises, how might this affect electricity bill savings and even the nation's employment base? While, again, the full details that underpin our assessment are shown Appendix B, Table 8 below summarizes the net returns that are made possible from a smarter deployment of energy efficiency investments—and especially including semiconductor-enabled technologies. As we show, the productivity benefits clearly do require greater level of outlays in all years of the analysis. We estimate these to begin with a modest $7.1 billion of incremental investments in 2010, rising to as much as $28.7 billion by 2030. The average annual investment is on the order of $22.5 billion (with all values shown in constant 2006 dollars). But the returns on those investments are large. We estimate the electricity bill savings to average just over $61 billion over that same period of analysis.

Table 8. Macroeconomic Impacts of SEES Savings Compared to Reference Case

	2010	2015	2020	2025	2030	Average Annual	Cumulative 2010-2030
Annual Investment (Billion 2006 $)	7.1	20.6	21.9	24.5	28.7	22.5	472
Electricity Bill Savings (Billion 2006 $)	2.1	30.4	59.6	90.8	126.4	61.3	1,287
Net Job Impacts (Thousands)	80	344	568	780	935	553	n/a

Perhaps an even more compelling outcome from our analysis is the impact on employment. We can map our estimates of the added technology investments and the resulting energy bill savings into the DEEPER Modeling framework (Laitner and Knight 2009). Because energy-related expenditures are so much less labor-intensive than almost all other consumer expenditures within the U.S. economy, our working analysis suggests a net increase of 80,000 jobs in 2010 which increases to 935,000 net jobs in 2030. This suggests an important additional benefit in the deployment of semiconductor technologies.

Table 9. Environmental Benefits of SEES Savings Compared to Reference Case

	2008	2010	2015	2020	2025	2030
SEES Savings from Reference Case (Billion kWh)	0	24	345	652	948	1,242
Number of 600 Megawatt Power Plants Not Built	0	6	82	155	226	296
Carbon Dioxide Saving (Million Metric Tons)	0	15	212	391	557	733

As shown in Table 9, the environmental benefits from the Semiconductor-Enabled Efficiency Scenario are also dramatic. By 2030, we would need to build 296 fewer power plants. That would, in turn save 733 million metric tons of carbon dioxide emissions in 2030 alone. Over the full period of analysis the cumulative CO_2 emissions reductions would be on the order of 8,000 million metric tons. That would provide a huge boost to the larger well-being of planet—all in a way that will likely save consumers and businesses a good deal of money.

The semiconductor-enabled carbon savings are, of course, even greater than the efficiency savings alone because the savings in this calculation does not include the CO_2 savings from semiconductor enabled renewable energy such as solar panels and wind turbines. The calculation also does not include the CO_2 savings from semiconductor enabled technologies in motor vehicles such as improved engine controllers, wiring weight reduction, tire pressure gauges, and other technologies that improve gas mileage; nor technologies such as telecommuting and GPS navigation that reduce the miles driven. Finally, the calculation does not include the combination of renewable energy, a Smart Grid, and electric cars; whereby car batteries are able to store electricity generated from renewable sources as described in Section III of this report.

V. CONCLUSION

Semiconductor-enabled technologies have been the backbone of our nation's economic productivity, especially in the last three decades. And despite the immediate growth in electricity demands to power the growing number of devices and technologies, semiconductors have enabled a surprisingly larger energy productivity benefit in that same period. Both normal market innovations and existing policies promise an even greater set of efficiency improvements. Yet, the opportunity remains surprisingly large—with the right set of market-based policies and incentives. If we choose to develop those opportunities, the net impacts will be significantly positive. By our calculation here, the cumulative net electricity bill savings enabled by semiconductors might exceed $1.3 trillion through 2030. Perhaps not surprising, a more productive economy might also support some 935,000 more jobs while substantially reducing environmental impacts—notably a reduction in energy-related carbon dioxide emissions that would exceed 700 million metric tons, also by 2030. There are really only two questions at this point. First, will we choose to develop the enormous power of semiconductor-enabled technologies? And second, what policies and incentives are we willing to support that will ensure this more productive investment opportunity?

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APPENDIX A: WORKING ESTIMATE OF 2006 ELECTRICITY SAVINGS

To establish a working hypothesis about the level of energy productivity gains associated with the deployment of semiconductor technologies, we set up a regression equation to evaluate the effect of economic growth and semiconductor investments as they, in turn, impact electricity consumption. Using a combination of information from the Bureau of Economic Analysis and the Energy Information Administration, we collected data for the years 1949 through 2006. Economic growth was reflected in the growth of the nation's Gross Domestic Product, or GDP. However, economic accounting data are not collected on the full array of semiconductor technologies. To overcome that lack of information, we developed a semiconductor proxy dataset (SPD) which consisted of the capital stock associated with computers, telecommunication equipment and software. The values for both GDP and SPD were converted into billions of constant 2000 dollars.

The two independent GDP and SPD variables were found to be statistically significant at the one percent level. More specifically, GDP had a positive effect on the change in electricity consumption while SPD had a small negative (i.e., productivity enhancing) effect on electricity consumption. The test of this working hypothesis resulted in the following equation (with t-statistics shown in parentheses):

$$\text{Total Electricity Use} = \underset{(-23.79)}{-713.2} + \underset{(68.38)}{0.562} * \text{GDP} - \underset{(-21.26)}{0.993} * \text{SPD}$$

For this equation, the adjusted R-square of 0.997 suggests that these two variables explain nearly all of the change in total electricity consumption (measured in billions of kilowatt-hours).[20] For example, GDP in 2006 was estimated at $11,319 billion. Total SPD capital stock was estimated at $1,771 billion for 2006. Plugging in these values suggest at total U.S. electricity consumption of 3,887 billion kWh for 2006.[21] The question of interest, however, is what the electricity use might have been "but for" the deployment of semiconductor technologies—or in this case, the proxy variable that "represents" semiconductor technologies.

Exploring the Impact of Semiconductor Technologies

Examining the SPD dataset over the period 1949 through 2006 there appears to be four distinct market trends over that time horizon. In the period 1949 through 1976 (about 5 years after Intel introduced its first microprocessor), for example, the technologies characterized by SPD increased at a rate of 9.0 percent per year. Over the period 1976-1995 (just before the big price drops associated with semiconductors and integrated chips) the rate increased to 10.7 percent. In the years 1995 through 2001 that SPD capital stock increased by 13.0 percent annually. Over the years 2001 through 2006 the rate of increase grew more slowly at 5.8 percent. But if we accept the pre-1976 time horizon as a reasonable description of technology before the introduction of semiconductor technologies, we can then compare the rate of technology penetration post-1976.

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[20] To be clear, we are not suggesting that these two variables alone actually drive electricity consumption. Rather, they can be used to "explain the demand" in a way that allows us to see how that demand would be different with an entirely different technology stock as well as a different rate of market penetration.

[21] In fact, the actual electricity consumption for 2006 was reported as 3,820 billion kWh. This represents a 1.7 percent difference from what is reported using our model. From a statistical perspective this is not an especially troublesome difference. And because we want to use our model as the basis to compare the "but for the deployment of semiconductor technologies," we report changes from the model's baseline value of 3,887 billion kWh rather than the historical account of 3,820 billion kWh.

It turns out that the average rate of increase over the time horizon 1976 through 2006 was 10.2 percent annually. At the pre-1976 rate of growth, it turns out that the SPD capital stock would have been more like $990 billion in 2006 rather than the $1,771 billion dollars referenced above. By substituting the lower SPD value in our working model we find that the implied use of electricity would have been 4,662 billion kWh. This would be true “but for the deployment of semiconductor technologies.” In other words, the economy would have been less productive so that electricity use would have been about 20 percent greater.[22]

Some Initial Conclusions

We can at this point, ask the question, what might be the economic impact of this higher level of electricity consumption. As one simple measure, we can multiply the higher demand for electricity by an average price of electricity to see how big the energy bill might appear to be. According to the Energy Information the average price of electricity in 2006 was about 8.9 cents per kWh (also in 2006 dollars). So the reduced energy productivity suggested above indicates a greater electricity consumption of about 775 billion kWh in 2006. Multiplying this value times the average electricity price implies an electricity bill that might have been $69 billion higher “but for” semiconductor technologies.[23] In other words, it appears that the deployment of semiconductor technologies has produced significant electricity cost savings for businesses and consumers through 2006.

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[22] Some observers might comment that had the SPD proxy maintained the slower 1949-1976 growth rate the economy might also have grown slower. In effect, the slower rate of economic growth might have changed electricity consumption to be less than otherwise suggested. However, it turns out that GDP grew at a very healthy 3.9 percent in the pre-semiconductor phase through 1976 while it has averaged only 3.2 percent since 1976. This suggests any variety of other possible “economic recipes” might have emerged “but for” the emergence of semiconductor technologies. From an analytical perspective, however, this higher GDP growth rate before 1976 validates our model as one way to estimate our “working hypothesis.” That said, more work clearly needs to be done in this regard.

[23] Indeed, the evidence suggests that the average price of electricity would have been much higher since more expensive generation units and more demand for coal and natural gas would likely have forced up the unit costs of electricity. At this point we make no judgment about how much higher those prices would have been. Hence, the resulting impact is a conservative estimate.

APPENDIX B: METHODOLOGY FOR QUANTIFYING FUTURE IMPACTS

As we've suggested in the main part of this report, there is a huge potential for cost-effective investments in energy efficiency throughout all sectors of the U.S. economy. If we make a working estimate of the possible electricity, oil, and natural gas efficiency gains between now and 2030, and then convert them to barrels of oil equivalent, one working estimate suggests that we might have on the order of 45 to 50 billion barrels of oil equivalent between now and 2030. This is about 2.5 times bigger than what some have suggested might be available from off-shore drilling in U.S. coastal waters (Laitner 2009). And from the perspective of semiconductor-enabled technologies and other potential gains with electricity savings, it appears we might have another 296 power plants equivalent (see Table 9 in the main report). These are gains that we are unlikely to generate without further policies or incentives. (Again, as we note in the main text of the report, for a further discussion on why policies are needed to overcome market and information barriers, see Brown and Chandler 2008, and also Geller et al. 2006.) This appendix describes how we arrive at our estimate of future semiconductor-enabled energy savings, and depicts the kinds of policies that will be necessary to increase the probability that these efficiency gains might actually occur.

The Reference Case

We start by laying out our reference case assumptions. Here we turn to the 2009 version of the Annual Energy Outlook published by the Energy Information Administration (EIA 2009). This document describes the outlook for the economy through the year 2030, providing annual estimates of the Gross Domestic Product (GDP), energy prices, and energy quantities. The prices and quantities are provided for a range of energy resources whether they are kilowatt-hours (kWh) of electricity, barrels of oil per day, or one million British Thermal Units (Btu) of natural gas.

The most common unit of energy quantity is a quadrillion Btus (also known as a "quad"). With an average fuel economy of 20.5 miles per gallon, one quad of gasoline will provide sufficient energy to fuel the nation's light duty cars and trucks for about 21 days. And assuming a 600 megawatt power plant (see Appendix C), one quad is sufficient energy to power 22 coal-fired power plants for one year.

The most common energy price is in constant 2007 dollars per million Btus. If the average price of gasoline is now (as of this writing) about $2.04 per gallon, and we know there are 125,000 Btus of energy in each gallon of gasoline, then the average price of gasoline is also equivalent to $16.32 per Million Btu. If the average price of electricity if 8.7 cents per kWh, and we know there are 293 kWh per million Btu, then the average price of electricity is also equivalent to $25.49 per million Btu.

The AEO 2009 Reference Case assumes an economy that will grow on average 2.5 percent annually from 2008 through 2030. Given current prices and technologies, the AEO anticipates that the nation's electric intensity will decrease 1.5 percent annually so that electricity sales will grow from 3,763 billion kWh in 2008 to an estimated 4,606 billion kWh in 2030. This base case assumption implies that sales of electricity grow by only 0.9 percent annually. Table B-1 below summarizes the key results, including the average electricity price and the carbon dioxide emissions from electricity sales.

Table B-1. Key Results from the AEO 2009 Reference Case Forecast

	2008	**2010**	**2020**	**2030**	**CAGR**
GDP (Billion 2000 $)	11,677	11,793	15,511	20,112	2.5%
Average Electricity Price (in 2006 $/kWh)	0.094	0.087	0.092	0.102	0.4%
Electricity Intensity (kWh per dollar of GDP)	0.322	0.321	0.268	0.229	-1.5%
Total electricity sales (billion kWh)	3,763	3,789	4,161	4,606	0.9%
Carbon Dioxide Emissions for Electricity (MMTCO2e)	2,380	2,388	2,495	2,720	0.6%

Note: CAGR in the last column of the above table means the compound annual growth rate.

From the perspective of the semiconductor industry, however, the issue is how semiconductor-enabled devices and technologies might reduce the nation's electricity intensity. And what will be the associated benefits and costs to businesses and consumers?

Estimating Future Costs and Electricity Bill Savings

Based on the many efficiency potential studies that have been done to date[24] it appears that we might anticipate a 27 percent savings over the reference case assumption for electricity use by 2030. More critically, it appears this is a level of savings that is both achievable and cost-effective. If our Semiconductor-Enabled Efficiency Scenario plays out, this means that the nation's electricity intensity would decline from 0.229 kWh per dollar of GDP (shown in the 2030 column of Table B-1) to an intensity that might be as low as 0.16 kWh per dollar of GDP.

To determine the potential investment cost of that target we turn both to past assessments completed by ACEEE (see Eldridge et al. 2008b, for example) to a recent study completed by the Lazard financial analysis firm. In an assessment provided by the National Association for Regulatory Utility Commissioners (NARUC), Lazard Ltd. (2008) provided a cost assessment for a number of electricity resource options. For conventional electricity generation options, for example (ranging from natural gas peaking units to baseload coal and nuclear plants), Lazard suggested levelized costs that ranged from a low of about $0.07 to $0.14 per kWh for baseload generating units to a high of $0.22 to $0.33 per kWh for peaking units. For renewable energy technologies, including both photovoltaic and wind energy systems, Lazard suggested a cost that might range from $0.04 to $0.15/kWh.

For energy efficiency investments, Lazard found a range of $0.0 to $0.05/kWh. ACEEE generally finds a levelized cost for efficiency investments on the order of $0.03/kWh. For this analysis we assume a levelized cost that starts at $0.03/kWh in 2010 and rises slowing to $0.05/kWh by 2030. These latter costs translate into investment costs of $0.29 to $0.48/kWh, respectively. Assuming a 2010 cost of electricity of $0.087/kWh (see Table B-1 above), these first costs imply an average payback of 3.3 to 5.6 years, respectively. And, of course, as the cost of electricity slowly rises to $0.102/kWh by 2030, the simple payback for these investments falls to 2.8 and 4.7 years, respectively.

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[24] In the main text of the report we cite Laitner (2009), Eldridge et al. (2008a), the American Physical Society (APS 2008), the Lawrence Berkeley National Laboratory (Brown et al 2008), the United Nations Foundation (Expert Group on Energy Efficiency 2007), and Navigant Consulting (2006), among others. We again refer to them here.

Mapping the EPRI Case

The Electric Power Research Institute (EPRI 2009) published two scenarios which it described as a "Realistic Achievable Potential" and a "Maximum Achievable Potential." Compared to the AEO 2008 forecast, EPRI suggests that these efficiency scenarios would generate a 5 percent and an 8 percent reduction, respectively, from the electricity consumption that was projected for 2030. We note two things in this regard. First, in describing its two scenarios, EPRI comments that "this potential does not include the impact of future codes and standards not yet enacted, or any other regulatory or policy changes." Second, because of its assumption of frozen technology, nor does it anticipate any of the advances in semiconductor-enabled devices and systems anticipated in this study. These range from the potentially large impacts through smart grid investments to dramatic improvements in lighting, information and communication technologies, power optimizing systems, and the like (see the discussion in chapter three in the main part of this report).

Despite these limitations, the EPRI study does provide a useful set of "marker scenarios" that help establish the possibility of additional efficiency gains even with a limited technology regime and assuming no further policies, regulations, or incentives. To map an EPRI-like scenario we generally followed a trajectory from the AEO 2009 reference case (EPRI used the AEO 2008 case) that reduced electricity use by about 8 percent by 2030, or what they identified as the Maximum Achievable Potential. Because EPRI used a different set of assumptions and a model to which we have no access, it was not possible to reproduce the specific results EPRI obtained. However, we found an approximate 8 percent savings that gives us a reasonable proxy for the EPRI Maximum Achievable Potential.

Semiconductor-Enabled Efficiency Scenario

At this point we might note that neither the AEO 2009 reference case, nor the EPRI Maximum Achievable Potential scenario comes close to closing the US efficiency gap. A more economically plausible and politically attractive approach is to imagine a scenario in which historic trends of growth in the semiconductor industry are supported and accelerated by smart energy policies. In this case, extrapolating the historical relationship between US electricity consumption and the capital stock of semiconductor technologies, we can forecast different scenarios of semiconductor penetration and energy efficiency.

As the econometric model in Appendix A shows, growth in GDP is positively related to electricity consumption while growth in semiconductors—which we modeled through our semiconductor proxy dataset (SPD)—is negatively related to energy use. In the past, the huge size of the US economy has meant that energy use from increased economic growth has overwhelmed the energy savings from increased accumulation of semiconductor technologies. While the increased penetration of semiconductor computing, sensing, and communications devices has led to the declining energy intensity of our Gross Domestic Product, our total energy use has therefore increased in absolute magnitude. Depending on public policies however, in the future the large and rapidly increasing productive use of semiconductor technologies could actually result in decreasing absolute energy use[25].

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[25] In the econometric equation suggested in Appendix A, the first term is growing slowly while the second is growing very quickly. However, since the first term is very large, its magnitude of change (growth rate * qty.) is still larger than the magnitude of change in the second term. This means total energy growth is positive, but because the second term is growing faster than the first, the ratio of the second to first terms is increasing, reducing the energy intensity of GDP. Future decline in the total quantity of energy consumption will occur when the magnitude of change in the second term becomes larger than that of the first.

To project economic growth we will assume, as the EIA's Annual Energy Outlook 2009 predicts, that real GDP grows at a rate of 2.5 percent from 2006 to 2030. This is a somewhat slower than the 2.9 percent growth rate that occurred in the period 1990 to 2006, for example. Long term forecasts of growth in the semiconductor industry are more difficult to make than GDP forecasts, as individual industries are much more volatile and sensitive that national economies.[26] Still, historical data gives us a reasonable launching point for our predictions. From 1976 to 2006, the semiconductor capital stock (modeled by our proxy dataset) has increased at an average annual rate of 10.2 percent. However, from 2000 to 2006, this rate fell to 5.8 percent. While part of this falling rate may be explained by the bust of the "dot-com" bubble in the first years of the 21th century, a maturing industry coupled with less aggressive policies to accelerate productivity gains, may also have slow investment in semiconductor technologies. At the same time we can fit our model in Appendix A to determine what the Annual Energy Outlook 2009 might have suggested the growth in semiconductor-related capital stock would be to support the GDP trajectory and electricity consumption found in the reference case of that report. It turns out that substituting EIA's suggested GDP and electricity consumption values for the year 2030, the growth in semiconductor capital stock appears move at an average annual rate of 5.2 percent—only slightly smaller that the recent historical rate of 5.8 percent. This lower growth rate is nicely explained, at least in part, by a slower growth in GDP.

Reflecting the recent global economic difficulties with the positive long-term outlook for energy efficient semiconductor-technologies, in this analysis we ask the simple question: "what if we use a variety of policy mechanisms that accelerate the growth in semiconductor-related capital stock by one percent per year—that is, from an average annual growth rate of 5.2 percent to 6.2 percent. In this case, electricity sales might drop to as little as 3,173 billion kWh by 2030. At the same time, however, the greater use of semiconductor technologies will themselves use electricity. Drawing from separate data provided by Wade (2008), we estimate that each dollar of capital stock will require about 0.13 kWh of electricity to support the use of related equipment. Hence, the anticipated electricity consumption, net of the electricity use associated with semiconductor-related equipment, would be about 3,362 billion kWh in the 2030 "semiconductor-enabled efficiency scenario," or SEES. It turns out, then, that an electricity demand of 3,362 billion kWh is about 27 percent less than the reference case assumptions postulated by the EIA. And as we might imagine, actually achieving this level of energy efficiency will require smart policies to promote investments in a more productive capital stock. Without advocating any specific policy to actually increase the rate of investment in these technologies from 5.2 to 6.2 percent, we highlight the kinds of policies that are likely to catalyze this end result.

Representative Policies

There are a number of potentially effective energy efficiency policies being implemented across the country that might also be harnessed to leverage semiconductor technologies to deliver further energy savings in the coming years. The impacts of these policies have been modeled frequently in state and regional reports produced by ACEEE and others. Moderate to aggressive policy bundles featuring these measures typically result in cost-effective energy savings of 20 to 30 percent of future energy demand (see, for example, Laitner and McKinney 2008, and The Climate Group 2008). Efficiency policies may be enacted individually, or in conjunction with an overarching initiative such as an

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[26] One of the few to venture here is UC Berkeley Professor of Engineering Dr. Chenming Hu, who predicted in 1996 that semiconductor industry would be growing at an 8 percent rate in 2030. See his presentation http://www.eecs.berkeley.edu/~newton/presentations/EECSColloq11_96/tsld005.htm.

Energy Efficiency Resource Standard (EERS)[27] or some form of a carbon pricing program. If enacted preceding a carbon pricing program as lead-in measures, these policies can reduce its economic burden significantly. In general, effective energy efficiency policies involve a strategic combination of energy performance standards and targets, incentives for productive investments by consumers and business, and federal government leadership.[28]

In the residential sector: Improved Building Energy Code with Third Party Verification and Compliance Incentive; Expanded Weatherization Assistance Programs; Residential Retrofit Incentive with Resale Energy Labeling and Incremental Tax and Other Cost Incentives; and Tightened Residential Appliance Standards with Incentives.

For commercial buildings: Commercial Building Energy Codes with Third Party Verification and Compliance Incentives; Support for Commissioning of Existing Commercial Buildings; Efficient Commercial Heating, Ventilation, and Air Conditioning (HVAC), Lighting and Whole Building Retrofit Incentives; and Tightened Office Equipment Standards with Use Tax and Other Financial Incentives.

For industry: Incentives for high performance/high efficiency motors; Expanded Industrial Assessment Centers which promote high performance/high efficiency motors; Increased Energy Savings Assessments; Support Combined Heat and Power (CHP) with Appropriate Incentives

For the electricity grid: Reformed regulatory structures that promote the inclusion of distributed generation resources such as CHP and a variety of waste to energy technologies, and that provide incentives to incorporate and fully use an advanced metering infrastructure (AMI); Support for the research, development, and demonstration of electricity storage technologies.

In the earlier section of this appendix we describe our assumptions about the magnitude of investments required to drive actual investments needed in response to these kinds of policies. To summarize, we assume investment costs of $0.29 to $0.48/kWh, covering the period 2010 through 2030, respectively. Assuming a 2010 cost of electricity of $0.087/kWh (as suggested by Table B-1), these first costs imply an average payback of 3.3 to 5.6 years in that same period of time. As the cost of electricity rises slowly to $0.102/kWh by 2030 (again shown in Table B-1), the simple payback for these investments falls to 2.8 and 4.7 years, respectively.

Still, there is a more to this story. We also assume that it requires program funds to promote, monitor and evaluate our various policy efforts around the country. For our purposes we adopt a high end cost which suggests that it requires about 15 percent of the investment dollar to adequately run and evaluate programs at this scale. But with experience and a slow market transformation, these costs decline to perhaps 10 percent of the investment needed to drive the suggested growth in technology-related capital stock. Over the period of analysis it turns out that program costs would run at an estimated $1.0 billion beginning in 2010 and rising slowing to about $2.8 billion in 2030 (with all values in constant 2006 dollars). From a total resource perspective then, the benefits now outweigh

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[27] If enacted, an EERS would require the nation's electric utilities to lower electricity demand through energy efficiency services and programs. A moderate version of this proposal would require the utilities to lower their electricity demand by 15 percent from the 2020 reference case levels through a variety of energy efficiency programs and investments (Furrey, Nadel and Laitner 2009).

[28] These policies are consistent with those of the US Addendum to the Smart 2020 report by The Climate Group (2008), which models their use for driving information and communication technologies (ICT) investments that cut annual carbon dioxide emissions in the U.S. by 13 to 22 percent from a business-as-usual scenario in 2020. In the analysis here, we do not include any specific effects of a carbon price in our projection. We merely assume a mix of policies that might drive a 6.2 percent annual growth rate in the semiconductor-related capital stock. One can imagine this result being driven completely without "the price mechanism," but more economists agree (as do we) that some form of price signal might provide a useful complement to other non-price policies such as we describe above.

the costs by about 2 to 1. Still, that is a highly positive result that indicates a strong return for the U.S. economy.[29]

Assessing the Job Impacts

For the last several years ACEEE has been developing and using what we call the DEEPER modeling framework to evaluate the net employment impacts of our various policy scenarios and programs (for the employment impacts, see both Eldridge et al. 2008b and Laitner, Furry, and Nadel 2009). DEEPER is the Dynamic Energy Efficiency Policy Evaluation Routine, a quasi-dynamic input-output model now calibrated to the 2006 economic accounts for the United States (Laitner and Knight 2009). Based on those 2006 economic accounts for the U.S. it turns out that the electric and natural gas utilities support fewer than 8 direct and indirect jobs per million dollars of revenue. All other sectors of the economy support about 19 direct and indirect jobs per million dollars of revenue. Hence, a cost-effective movement away from energy consumption should support a small but net positive gain in the nation’s employment base. In simple terms, if an electric utility has $1 million in less revenue because of efficiency gains, it may support on average 8 fewer jobs in the economy. But if businesses and consumers have a savings of $1 million jobs, then their re-spending of that savings will support on average 19 jobs. In that case the economy is better off by 11 net jobs on the positive side of the ledger.

In this case, we use the DEEPER modeling framework to match both the positive and negative changes in revenues to the appropriate sector multipliers to determine the net job impacts found in Table 8. These multipliers are modified over time to reflect changes in labor productivity as reported by the AEO 2009 reference case. As it now reports for the period 2010 through 2020, the AEO suggests that labor productivity will increase by about 1.9 percent per annum. This means that $1 million in spending in 2030 will support only 63 percent of the jobs yielded in the base year of the model. In the example above, a net gain of 11 jobs in 2006 might be only 7 jobs by 2030.

Finally, we can estimate carbon dioxide savings by using the values shown in Table B-1 above. In 2030, for example, the reference case suggests that electric utilities might have 2,720 million metric tons of carbon dioxide emissions resulting from the sale of 4,606 billion kWh of electricity. This implies a carbon dioxide intensity of 0.59 metric tons for each 1,000 kWh of electricity sold. As we note from Table 8, our policy would increase efficiency gains by 1,242 billion kWh. Multiplying the two figures suggests that we will be reducing carbon dioxide emissions on average by 733 million metric tons in 2030. Assume that a typical car generates about 5.4 metric tons per vehicle, that CO2 emissions reduction from improved efficiency within the electric utility sector would be the equivalent of taking 105 million automobiles off the road for that year.

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[29] It is worth noting two things here. First, our investment cost assumptions are conservative in that innovation within the semiconductor and other technology industries and services are likely to keep costs closer to what we might expect in 2010 rather than in 2030. And program costs may likely decline substantially more over time than we’ve suggested here—especially as performance standards and other policies slowly transform the market over the next two decades. Finally, this level of efficiency gain is likely to drive down the cost of electricity for both those who take advantage of these new efficiency gains and those who choose to stay with less efficient equipment. By one estimation developed in this analysis, for example, electricity prices in 2030 might be pushed down to closer to their 2010 values—measured in constant dollars and absent any charge for greenhouse gas emissions. This means the economy benefits not only from electricity savings times an avoided cost, but that those who still use electricity will also see a lower price for the electricity they do consume. If that highly desirable outcome holds, that might imply a total savings that is something closer to $170 or $180 billion in 2030 rather than $126 billion savings that we report here. Finally, if we were to discount both the costs and the benefits over time the net present value would fall somewhat compared to the constant dollar comparison. For example, if we use a societal real discount rate of 3 percent, the benefit-cost ratio would fall from 2.4:1 to about 2.2:1. Similarly, if we were to use a much higher rate of 7 percent, the impact the benefit-cost ratio would then fall to 1.98:1. In all cases, however, the returns are significantly positive for the U.S. economy.

APPENDIX C: METRICS TO CHARACTERIZE PRODUCTIVITY GAINS

The ability to convert between metrics of energy allows the construction of more meaningful statistics, which comes in handy when developing a bottoms-up analysis of the effects of energy savings technologies, such as we do within this study. With a bottoms-up study, dealing directly with technologies means that output is typically expressed as the quantity of energy saved in standard units such as kilowatt-hours (kWh) or British thermal units (BTUs). Quantities of energy expressed in standard units, however, are often not the most publicly salient aspect of the energy industry.

While one large coal-fired power plant may represent the annual functional equivalent of 4 billion kWh of electricity, the public and policymakers are often much more interested in the former, particularly when we are proposing to build less of them. The same goes for the costs of electricity. Most people can relate to concrete and meaningful measures such as dollars and coal plants more readily than standard units of energy consumption or production. Converting among these metrics only require statistics that are readily available from public and non-profit agencies specializing in the gathering and analysis of energy data. These include the United States Energy Information Administration (EIA) or the International Energy Agency (IEA). In this case, all data used here have been taken from various EIA reports for the year 2006.

As it turns out, the estimated 775 billion kWh savings in the year 2006 (referenced in Appendix B), can be expressed a number of different ways. We identify five different metrics and explain how we arrived at these numbers.

184 power plants equivalent prevented

One of the most powerful metrics in energy efficiency analysis is the number of power plants that have been avoided by energy savings. To find the number of power plants prevented we simply divide the amount of electricity saved by the electricity delivered by the average power plant. The calculation begins with finding the power production capacity of the average power plant. From a capacity perspective, we compromise between smaller rural power plants and nuclear mega-plants and use a 600 megawatt (MW) plant equivalent (this is the same as a 600,000 kilowatt unit). This is the maximum capacity that a plant can produce at any given time. But as a base load unit, it might typically operate at about 80 percent of its maximum capacity. This is referred to as a "capacity factor" of 80 percent. So, we then have the equivalent of 480 full-capacity megawatts operating per year.

Multiplying the resulting adjusted production per power plant by the number of hours in a year gives its average annual production in kilowatt-hours. Thus, the total electricity produced by the average power plant is 600MW * 0.8 capacity factor * 8,760 hours in a (non-leap) year = 4,204,800 megawatt-hours (MWh). Since a MWh is 1,000 kWh, and when we round the final calculation, we derive an estimate of 4.2 billion kWh per power plant equivalent per year. If we then divide our total semiconductor-enabled electricity savings of 775 billion kWh by 4.2 billion kWh, this yields 184 power plant equivalents.

69.0 billion dollars in business and consumer savings

To find consumer and business savings we multiply the total electricity savings enabled by semiconductor technologies by the average price of electricity paid by end-users. In 2006, this yields: 775 billion kWh savings * .089 dollars per kilowatt-hour = $69 billion (in rounded 2006$) in total consumer and business savings.

613 dollars in savings per household

If we are interested in the dollars saved per household, we simply divide the total consumer and business electricity bill savings by the number of households. In that case, $69 billion in total savings divided by an estimated 112.5 million households reported by EIA for 2006 yields 613 dollars per household.

64.5 million households equivalent powered

Alternatively, we might be interested in expressing the number of households that could be powered by the electricity saved by through semiconductor-enabled technologies. In 2006, we again start with the estimate of 112.5 million households in the United States. Their total electricity consumption, as indicated by total residential sector electricity consumption, was 1,352 billion kWh. This means that each household consumed 1,352,000 million kWh divided by 112.5 million households which equals 12,014 kWh of electricity use per average household. Dividing our total savings of 775 billion kWh by 12,014 kWh then yields 64.5 million households equivalent. So, in 2006 semiconductor-enabled savings could have powered, on average, 64.5 million households.

479 million metric tons CO_2 equivalent emissions prevented

Another important, if not as publicly familiar, metric is the amount of greenhouse gases that have been prevented by energy saving technologies. This only requires that we find the total energy-related carbon dioxide greenhouse gas emissions (GHG) emitted by the electric generating system in the US, and then multiply this by the share of greenhouse emissions that have been prevented by a given technology. In this case, the total output of carbon dioxide emissions from electricity production of electricity was 2,364 million metric tons of CO_2 equivalent.

The share of energy-related GHG emissions that have been prevented by semiconductors is, on average, the same as the share of national electricity production that has been prevented. In 2006, total US electricity consumption was 3,826 billion kWh and, as we have previously calculated, semiconductors were responsible for 775 billion kWh of electricity savings that year. This means that semiconductors saved about 775/3826, or about 20 percent of US energy consumption in 2006. In terms of CO_2 emissions for 2006, we can then say that semiconductor-enabled technologies were responsible for the savings of 479 million metric tons, or 20 percent of the 2,364 million metric tons otherwise emitted in that year.

APPENDIX D: THE ENERGY PRODUCTIVITY IMPACT OF SEMICONDUCTOR-ENABLED TECHNOLOGIES

Semiconductors are ubiquitous. These devices are found within and greatly influence the use of a full spectrum of consumer and business products. Indeed, only 42 percent of semiconductor revenues in 2007 were for devices used in computers. About 21 percent were from sales made to produce a rapidly expanding array of communication technologies while an estimated 20 percent were for use in a variety of other consumer products. Automobiles and industrial products each provided about 8 percent of the market. The small remaining balance (about 0.6 percent) is used to supply the residual needs of the military (WSTS 2008).

And what of the overall scale of these many technologies? By one estimate there were more than 257 billion integrated circuits produced in 2008 alone. Depending on the economy, industry analysts forecast the number of units to rise to 330 billion by 2012. If that trend holds, that will imply the sale of nearly 50 integrated circuits globally per person on an annual basis. This is nearly a 25-fold increase in the number of per capita integrated circuits since 1998 (Smolan 1998). As if that one measure of growth wasn't of sufficient scale to underscore the influence of semiconductor technologies, the recent growth of the Radio Frequency Identification (RFID) industry has been even more staggering. From the period 1955 to 2005, cumulative sales of radio tags totaled 2.4 billion. In the last year alone an estimated 2.24 billion tags were sold worldwide, and analysts project that by 2017 cumulative sales will top 1 trillion—generating more than $25 billion in annual revenues for the industry (Iconocast 2008).

And their capacity and power? The Semiconductor Industry Association (2007) notes that "today's typical personal computer costs less than a third of the typical unit of a decade ago but is 100 times more powerful." So, whether new air conditioners using advanced motor control techniques, power supplies that provide accurately regulated outputs for motors and control electronics, or industrial processes and equipment that benefit from improved operation and equipment reliability, semiconductors are integral to the productivity and the growing energy efficiency of our economy. In today's economy, almost anything associated with the use of energy and electronics—from electric motors and automobiles to computers, cell phones, iPods and consumer appliances—involves the use of semiconductor-related technologies to improve both cost and performance. The table on the following page underscores this point.

In the recent study by the Electric Power Research Institute on achievable energy efficiency (EPRI 2009), a large number of technology options were listed together with their potential savings. Some 30 of those discrete technologies are listed in the table together with estimates of their efficiency potential by 2030. Omitted are insulation, double pane windows, and improved ducting. But for these last three options, all technologies in the table depend on semiconductor-related devices to maintain optimal performance.

But the story moves well beyond a discrete listing of efficiency measures that are enabled by semiconductor technologies. The use of software programs such as eQuest (2009) improves building design in ways that integrate passive (non-energy using) insulation and double pane windows together with powered technologies whether lighting and consumer appliances or heating, ventilation, and air conditioning (HVAC) systems.

One example is particularly revealing of the emerging indirect impact of semiconductor-enabled technologies. Using computer models, engineers and biologists discovered that the fin of a humpback whale has a trailing edge with special bumps on it that decrease their drag and increase their maneuverability. With this insight, entrepreneurs created wind turbine blades that annually can produce 20 percent more energy than turbine blades of a more regular design (Hamilton 2008).

Similar computerized modeling techniques are used in minimizing the travel distance and material inputs in business supply chains. Whether modeling fluid dynamics or supply chains, it is impossible to be a productive business in the modern economy without semiconductor-enabled tools. And finally, there are technology platforms which can further improve system efficiencies—whether energy management systems, utility load dispatch routines, or the emerging use of advanced meters and smart grid technologies.

Given this backdrop, what might we say about the impact of semiconductor technologies? While there are any number of significant contributions to future gains in energy productivity, ranging from advanced materials and sophisticated technology designs, very little of those improvements would likely be possible in today's economy without the use of semiconductor-enabled devices and technologies.

Table D-1. Semiconductor-Enabled Energy-Efficient Technologies

Improved Efficiency In…	Could Reduce Specific 2008 End-Use Demand by:
Residential Color TV	30.0%
Residential Programmable Thermostat	12.0%
Residential Personal Computers	20.0%
Residential Water Heating	20.0%
Residential Whole House Fan	20.0%
Residential Low Flow Shower Heads	14.6%
Residential Refrigerators	15.0%
Residential Dishwashers	35.0%
Residential Central AC	8.3%
Clothes Dryers w/Moisture Sensor	10.0%
Light Emitting Diodes	67.8%
Reduce Standby Wattage	4.5%
Occupancy Sensors	9.0%
Energy Management System	20.8%
Variable Air Volume System	33.7%
Commercial Copiers and Printers	25.0%
Commercial Other Electronics	13.0%
Commercial Central AC	24.3%
Commercial Programmable Thermostat	7.9%
Commercial Computer Monitors	25.0%
Commercial Variable Speed Pump	4.8%
Commercial Personal Computers	30.0%
Commercial Water Temperature Reset	15.2%
Commercial HVAC Economizer	18.0%
Commercial Servers	15.0%
Industrial Process Heating	8.5% to 25.0%
Industrial HVAC Improvements	9.5% to 20.0%
Industrial 1-20 hp motors	10.0% to 30.0%
Industrial 20-1000 hp motors	.5% to 10.0%
Industrial Efficient Lighting Retrofit	28.0% to 76.0%

Source: EPRI 2009

APPENDIX E: INDUSTRY USE OF ELECTRICITY IN THE PRODUCTION OF SEMICONDUCTORS

In discussing the ways that semiconductor technology can reduce totally energy consumption, one might ask, "what about the electricity used to manufacture semiconductors themselves?"

According to data from the U.S. Census Bureau's Annual Survey of Manufacturers (2006), the semiconductor industry purchased 11.8 billion kilowatt hours of electricity in 2006, which was about 1.3 percent of manufacturer consumption and 0.3 percent of total US consumption. Perhaps even more impressive, the Bureau of Economic Analysis (2007) reports that while the economy as a whole increased energy use by 13 percent over the period 1997 through 2007, the semiconductor industry actually cut energy use by half over that same period.

In spite of this relatively low and declining amount of consumption, the semiconductor industry is seeking new ways to save energy in its factories. In 2008 the World Semiconductor Council, made up of the Semiconductor Industry Associations in China, Chinese Taipei, Europe, Japan, Korea and the U.S., announced that they have reached a voluntary agreement on expectation levels for normalized reductions of electricity by 30 percent by 2010 from the baseline of 2001 (WSC 2008).

The semiconductor industry has made significant progress in lowering the energy used to recirculate air in the factory "clean rooms" which prevent dust and other fine particles from interfering with the process of etching billions of microscopic circuits on each silicon chip. Air handling used to account for 11 percent of a chip factory's energy consumption, but as of 2007 that has now dropped to only 3.9 percent. Today about 40-50 percent of the energy used in a semiconductor factory is for running semiconductor manufacturing equipment, so cooperation with the makers of that equipment is important for the industry to lower its energy demand (Huang, Frank 2008). In both air handling and process equipment that includes vacuum pumps, the variable speed motors mentioned in Chapter 3 of this report are an important contributor to reducing electricity consumption. We thus have the intriguing loop of semiconductors enabling energy efficient motors that enable energy efficient fans and pumps that enable energy efficient production of semiconductors.

To make further progress with reductions in electricity usage in semiconductor process equipment, the World Semiconductor Council has established an energy conservation partnership with suppliers to the semiconductor industry, represented by the Semiconductor Equipment and Materials International, in a joint effort to achieve further energy-savings equipment used to make semiconductors. The initiative will identify the drivers and obstacles for advancing energy conservation of semiconductor tools and processes, leading to a roadmap to lay out the "path forward" toward achieving those results.