Energy Efficiency: Semiconductors' 21st Century Challenge

Worldwide energy use is growing much faster than traditional supplies can match, but the semiconductor industry can help improve the efficiency of energy generation, distribution and consumption.

Pushkar Apte, Daryl Hatano, John Greenagel and George Scalise, Semiconductor Industry Association, San Jose -- Semiconductor International, 4/1/2009

From pre-historic times, energy has been one of the primary driving forces for the advance of civilization. Our earliest human ancestors discovered that fire could protect them from predators, heat their caves, cook their food and expand the habitable areas of the world. High heat was essential to moving from the Stone Age to the Bronze Age, and the 18th century Industrial Revolution — the basis of the modern world — was powered by the steam engine, and its ability to convert heat to mechanical energy. Fossil fuels rose to prominence with the Egyptians using oil as fuel, and with Marco Polo bringing back "black stones" (coal) from China to Europe.

The dependence on fossil fuels through petroleum-driven transportation and coal-driven electricity has endured. For example, >90% of energy used in the United States today still comes from non-renewable sources. Although global attention is now focused on clean and renewable sources, much R&D is needed for these alternative energy sources to become mainstream. Technology will play a key role both in improving the efficiency of the current energy ecosystem, and in enabling alternative ideas to transition from exciting research to widespread implementation.

The global energy challenge

Worldwide energy use is growing much faster than supply — certainly fossil-fuel supply — can match. The U.S. Department of Energy projects that worldwide energy use will increase by ~40% from today to almost 700 quadrillion BTUs by 2030.[1] This increased demand reflects many factors, including the growing prosperity in emerging nations. For example, China is adding 50–80 GW of electricity-generating capacity every year — roughly the equivalent of the entire grid of England.

This growth in energy demand creates economic, environmental and foreign policy challenges. Global energy problems demand a global and comprehensive strategy to seek solutions. Such efforts must involve both governmental initiatives and cooperation between industries. Academia and research institutes can also play a key role, since the challenges are difficult and require new, out-of-the-box ideas. Given the magnitude and urgency of the challenge, it is important that these efforts be coordinated to minimize redundancy.

The strategy should focus on:

- Improving how we generate electricity by increasing the use of renewable sources.
- Improving how we distribute energy by moving toward a smart grid.
- Reducing the energy we consume by increasing the efficiency of our factories, buildings, appliances, computers, automobiles and other products.

Technology can play a key enabling role in each of these areas, allowing us to "do more, using less" — so that people are not forced to lower their expectations of a better life because of energy issues. Semiconductor chips have been the engine behind most technology innovations in recent decades. Since 1978, ICs have helped improve the efficiency of cars by 40%, passenger planes by 121%, lighting by 339%, and computer systems by nearly 3,000,000%.[2] Working together with system and service providers, the semiconductor industry can have a significant positive impact in addressing the global energy challenge.

Generation: Enable viability of renewables

Alternative, renewable energy sources are the focus of much excitement in academia, industry and government. Solar, wind, biological and other sources are being explored with great vigor around the world. Semiconductor technology will play a key role in making these alternative, renewable energy sources more feasible for mainstream applications in a variety of ways.

All energy sources require conversion of energy to electrical power — for example, conversion of the sun's photons to electric current. Obviously, the higher the efficiency of conversion, the more energy we can use productively. Chips often help facilitate this conversion, and research in chip technology has helped improve the efficiency of conversion. For example, solar energy conversion efficiencies as high as 20–40% have been demonstrated using advanced chip technologies. As a comparison, some technologies in production and use today have efficiencies as low as 5%.

A big challenge with most alternative energy sources is that they are not cost-competitive with fossil-fuel sources. The most optimal solar power today is still 2–3× more expensive, per watt, than the best coal power. Semiconductor manufacturing technologies can play a big role in reducing production costs — transferring innovative know-how that has kept the semiconductor industry on track with Moore's Law for decades. The research for nanomaterials, nanoscale devices and manufacturing techniques in the semiconductor industry can be leveraged by alternative energy manufacturing. The bulk of the solar market today is served by solar cells that use the same silicon substrates as chips, and the highest-efficiency cells today use a simplified form of the same manufacturing process.

Some popular alternative energy sources, especially solar and wind, have significant degrees of variability and uncertainty associated with them — one cannot predict with certainty, for example, the intensity of sunshine or wind at any given location and time. Smart semiconductor chip and system design techniques can account for this upfront, model the variability and proactively compensate for it to minimize fluctuations for the power provider and end user.

Distribution: Reduce losses

Nearly two-thirds of electrical power generated is lost in transmission and distribution,[3] which is a staggering statistic. Viewed as an opportunity, however, it means we could (in principle) more than double our energy supply without consuming any additional resources. Electrical grids in most parts of the world are often decades old, if not more than a century old. Turning these old grids into "smart grids" is a priority for most nations, and technology is the key enabler.

A key challenge is ensuring that the power supply is reliable and efficient — the cost of poor reliability is nearly $200B/year in the United States alone.[4] The main issue is that engineers have poor visibility into the grid system as problems occur. Two things are needed to address this problem: first, the ability to identify problems quickly and accurately for the utility engineers; and second, fast analytical and computational techniques to determine solutions. These capabilities can be provided by primarily sensor and processor chips, together with optimized systems and software.

In addition, chip- and system-level optimization is needed to determine how to distribute the computational processing capability between sensors in the field and the central office. By the year 2010, only half of the entire U.S. grid is expected to be digital — implying that there is still a huge potential for savings. The ultimate goal is "self-healing networks" that are able to diagnose and correct their own problems, enabled by complex systems-on-chip (SoCs) that combine sensing, communication, memory and processing capabilities. The potential for cost savings by switching to this smart grid could be more than $100B/year, and the energy savings could be many 100s of gigawatts.

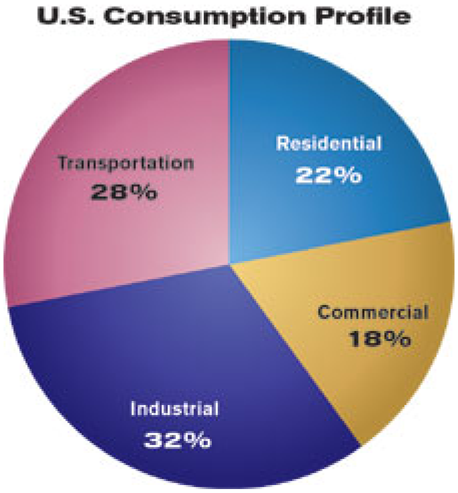
The impact of the chip-enabled smart grid will be even more dramatic when it integrates the improvements in generation, distribution and consumption of energy. For example, solar panels work on sunny days and wind turbines turn on windy days. As these sources begin to generate a larger portion of our total energy, energy storage for night, and cloudy and windless days will become more important.

Hybrid and electric cars can be a solution to this problem. Car batteries could be charged — or perhaps some day hydrogen cells replenished — by renewable sources when those sources are at their peak, and then the cars could provide electricity back to the grid when renewable sources are unavailable. The smart grid will allow consumers, be they businesses, factories or residences, to shift their energy consumption to better balance demand with supply. The smart grid allows a two-way, real-time flow of information between energy producers and consumers, and can use price signals or other mechanisms to alter consumption behavior.

Consumption: Improve efficiency

To determine opportunities for energy savings, it is helpful to examine the energy consumption profile. **Figure 1** shows the profile of U.S. energy consumption. Although this is the profile of a developed nation, and may not be typical of global patterns, it is likely that as emerging economies grow and prosper, they may develop similar energy consumption profiles. Half the energy usage is for industrial and commercial applications, a little less than a third for transportation, and the rest for residential purposes.

There are two complementary elements to reducing energy consumption. One is a mindset and lifestyle change made by individuals; becoming more conscious and careful about energy waste — driving less, switching off lights, etc. The second element is reducing the energy consumption of end products. The first element is necessary, but it is not sufficient because people demand a certain quality of life, which requires energy. As more emerging economies prosper, more people will have the buying power to purchase televisions, refrigerators, washing machines and cars; and energy use is likely to increase rather than decrease — even with a more responsible mindset. Therefore, reducing the energy consumption of end products is critical to addressing the energy challenge. Let us examine the role of technology in each major area of consumption shown in **Figure 1**.

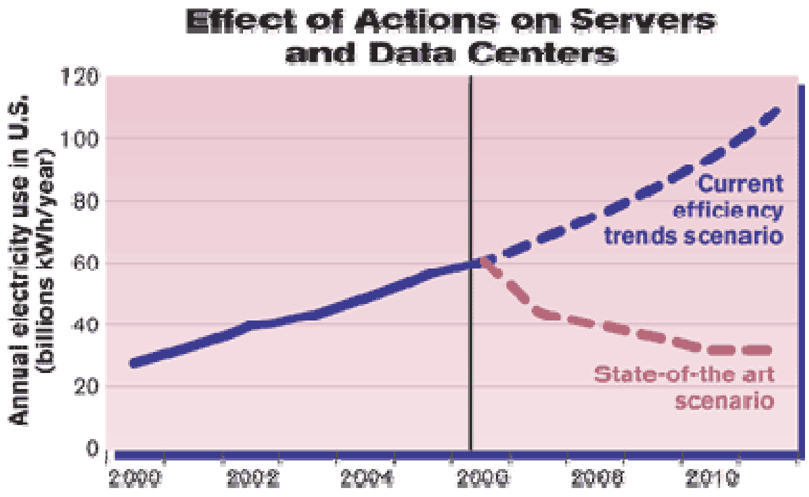


1. Of the 101 quadrillion BTUs of energy consumed in the United States in 2008, about half was used for industrial and commercial applications. (Source: Energy Information Administration, Annual Energy Outlook 2009)

Industrial and commercial

About half the energy consumption is driven by industrial and commercial applications. Semiconductor technology can impact this in multiple ways. One major impact is in improving the efficiency of electric motors, which account for about two-thirds of the world's industrial electricity consumption. Chips enable variable-speed drives for these motors, which consume only one-eighth of the energy that a constant-speed drive motor consumes. Currently only 5% of the electric motors in service use variable-speed drives, and yet they are already saving the energy produced by 10 power plants. If all electric motors were as efficient, we could save the energy of 200 power plants. Equally important is the environmental impact — the efficient motors are already saving almost 68 million tons of greenhouse gases.[5]

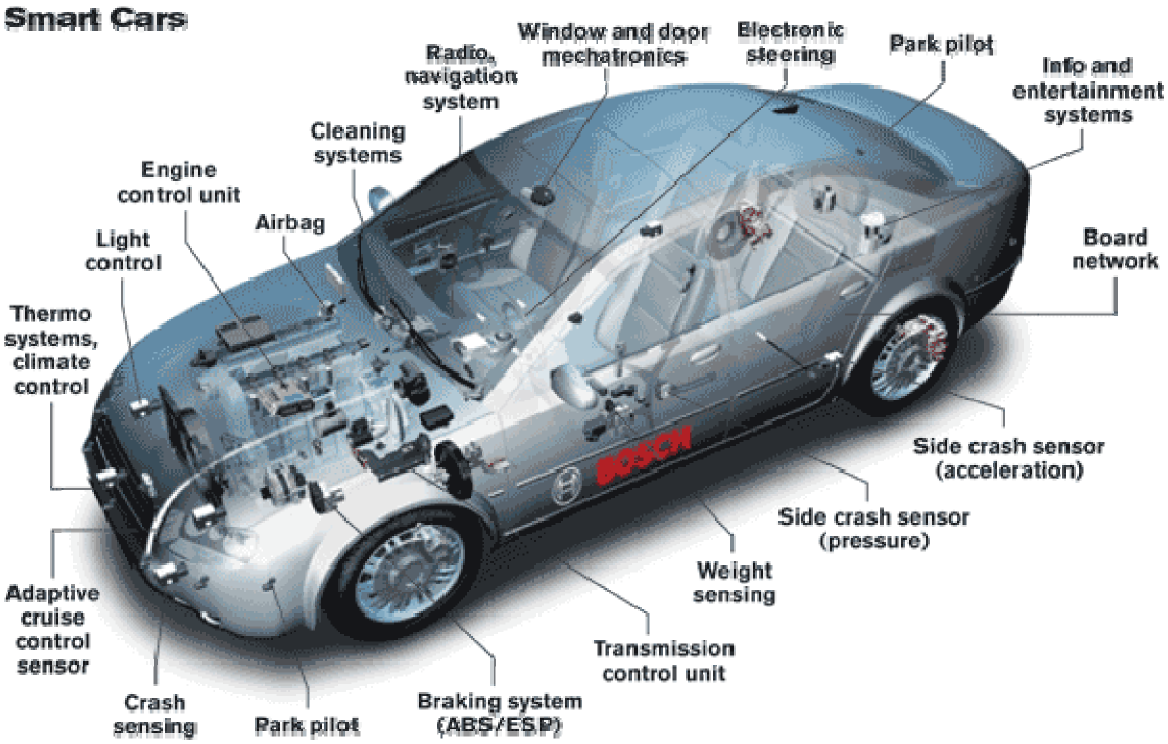
Digital technologies have now become part of people's personal and professional lives across the world. This, in turn, is driving growing energy demand for powering digital systems. For example, servers and data centers consumed 61 billion kWh in 2006 in the United States, double the consumption of 2001 (**Fig. 2**). Energy usage by data centers will double again in five years if we do nothing. However, through innovation in semiconductor chip and system design technologies, we can reduce energy consumption by half, even though the demand will still double. The semiconductor industry has a rich history of enabling drastic power reductions. For example, initial computing devices such as the ENIAC weighed >30 tons and consumed 200 kW of electrical power. That same functionality is now available on a tiny handheld device that weighs a few grams and runs on less than 1 W.



2. U.S. servers and data centers consumed twice the energy in 2006 they did in 2001, and energy usage will double again in five years if we do nothing. Through technological innovation, we can reduce energy consumption by half, even though the demand will still double. (Source: U.S. Environmental Protection Agency, "Report to Congress on Server and Data Center Energy Efficiency Public Law 109-431," Aug. 2, 2007)

Transportation

Chips are at the core of the gradual transformation of planes, trains and automobiles into energy-efficient systems. The modern high-end car, for example, is loaded with electronic devices that make driving safer, more economical, and more enjoyable (Fig. 3). These cars are much more fuel-efficient and environmentally friendly. Just a few examples of the innovative technologies that enable this are electric power steering, an integrated starter and alternator, brushless fuel pumps, traction control and antilock brakes. These systems typically are driven by a combination of sensing, processing and memory chips. Some vehicles have up to 100 computing chips (microprocessors), which is more than a high-end computing system. The rapid reduction in chip cost following Moore's Law ensures that more and more of these benefits keep moving from high-end cars to less expensive ones, and thus benefit an increasing number of global consumers.



3. The modern high-end car is loaded with electronic devices that make driving safer, more economical, and more enjoyable (Source: Bosch)

Semiconductors play a key role in electric and hybrid vehicles. In addition to the pervasive electronics already found in today's standard cars, hybrid/electric cars require significant changes in electrical voltage. These changes are managed and controlled by power ICs — R&D for these chips contributes significantly to building better hybrid/electric vehicles. These cars are already much more fuel-efficient compared with traditional gasoline-powered cars, and have up to 33% less CO_2 emissions. As technology progresses, this performance will improve even further.

Chips also help reduce energy consumed in transportation in indirect ways — by enabling telecommuting, for example. With advanced computing and communication facilities now available at an affordable cost for a growing number of individuals, telecommuting — working at home while maintaining contact with the office — has become an option for many. Today, nearly 4 million American workers regularly work at home via telecommuting, and save about 840 million gallons of gasoline a year. Telecommuting saves the equivalent of 9–14 billion kWh of electricity per year — the amount of energy consumed by ~1 million U.S. households. In terms of environmental impact in the United States alone, it is estimated to have reduced CO_2 emissions by ~14 million tons per year.[6]

Residential

Last, but far from least, chips are beginning to have an impact on residential energy usage. Although residential usage is currently 22% of the total energy pie, it represents more than a third of total U.S. electricity consumption, and on a global scale will rise rapidly because consumers are the primary users of goods and services.

From 2008 to 2018, the number of households in the United States is projected to increase by 11%, while the total consumption of electricity is projected to only increase by 6%, in large part due to the 21% decline in energy used in lighting, one of the largest uses of residential electricity.[7] Semiconductors play a key role in lighting advances, controlling the ballasts for compact fluorescent bulbs and light-emitting diodes (LEDs). LEDs themselves are a semiconductor technology.

Semiconductor technology can help reduce energy used for standby power when our appliances are switched off, including the power drawn by external power supplies such as the transformers we plug into our wall to power our cordless phones. Because standby power is drawing current 24 hours a day, and because so many of our modern appliances consume standby power, it has been estimated that standby power is responsible for 5–10% of total residential electricity consumption.[8]

A significant impact of semiconductor technology will be felt when "smart buildings" begin proliferating (Fig. 4). Smart homes have already moved from being science fiction just a few years ago to reality today, and will have several features such as energy-smart, microprocessor-controlled home appliances, irrigation systems, heating and air conditioning. Also vital will be pervasive sensor chips, which will do everything from controlling lights based on motion, to ensuring the safety of residents. The smart home will enable the resident to control this vast array of electronic systems from virtually anywhere using an Internet-connected PC or PDA, perhaps wirelessly.

4. Smart homes will have several features such as energy-smart, microprocessor-controlled home appliances, irrigation systems, heating and air conditioning.

The smart home also will have chip-enabled "smart meters," interacting with the smart grid. This smart interaction will save energy by improving demand management capabilities, reducing wastage, and enabling better management of usage profiles — for example, encouraging energy use in off-peak hours when it is most economical, and reducing the demand for peak load capacity. In some models, consumers allow utilities to turn down or off some appliances during peak demand periods in exchange for lower rates. In other models, consumers' price per kilowatt hour changes over time and consumers can shift their energy-intensive activities to times when prices are lower. If the smart home is powered by alternative sources such as solar energy, it could also provide energy back to the electrical grid in times of need, and thus balance supply and demand even further.

Toward a smart energy future

Over the next two decades, semiconductor chips will catalyze a revolutionary change in how we generate, distribute and consume energy. This change will be as significant as the transformation that semiconductor chips enabled with the spread of the Internet and mobile communications over the past 20 years. Semiconductor technology is already making significant contributions in addressing the global energy challenge, and balancing the growth in energy demand and supply in an environmentally responsible way. Continued innovation in semiconductor chips will enable further discontinuous innovations such as alternative energy sources, the smart grid and all-electric vehicles to be developed and integrated, and to become practical, affordable and ubiquitous.

Rapid adoption of technology to solve our energy challenges requires funding and careful nurturing of the high-tech ecosystem of research, innovation and investment through close collaboration across industry, government and academia. We need to adopt sound public policies, including tax and other incentive programs for producers and consumers; federal, state and local government procurement of energy-efficient products (lead by example); and increased government support for basic research at universities and national laboratories. If we pursue the "smart energy" opportunity aggressively and wisely, we will generate a historic transformation as significant as the invention of the steam engine, the internal combustion engine, and the spread of electricity to every home.

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