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CleanTX Analysis on Semiconductors

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Abstract

Semiconductors play a key role in clean energy by enabling clean, renewable energy sources and improving energy efficiency. Semiconductor materials are the basis for solar electric energy systems. Semiconductor devices are also used to condition power from solar arrays and wind turbines so the energy can be used by electric equipment and fed onto the electric grid. Semiconductors are playing an increasingly important role in making the electric grid more intelligent through the use of smart meters, sensors, wireless and wire line communications, and control systems. This intelligence enables the electric utilities to more easily detect faults, manage the demand for power when capacity is constrained or costly, and integrate renewable and distributed sources of power into the grid. Of great importance is the role semiconductor devices play in controlling products that consume energy- from simple home appliances to advanced lighting, automobiles and complex factory equipment. Semiconductor devices themselves also use energy, and the proliferation of semiconductors increases the need for these devices to be more energy efficient, and so numerous steps are being taken to help mitigate this impact, from materials and transistor design to efficient software. Ultimately, the transition to clean, renewable energy sources will require significant but achievable technological advancements, investments, and changes in lifestyles and the economy. Semiconductors will play a key role in these areas as well, enabling new modes of commerce and social interaction through, for example, wireless communications, telecommuting, and on line business transactions. This primer provides a background for how semiconductors are used to enable clean energy in different sectors of the economy

I. Introduction

The industrial revolution relied on the availability of plentiful and relatively inexpensive sources of energy, mostly from fossil fuels, as sources of power. From early steam engines to jet engines and the modern electric grid, energy stored in the earth over 100's of millions of years has allowed humans to vastly increase the distances we travel, the amount of work we do, and the goods we produce, and our personal comfort. It is not surprising, that there is a clear link between GDP and energy consumption (figure 1)[1]. Wealthy nations consume 5 to 10 times the energy on a per capita basis than do poor and developing nations. Furthermore, developing countries are undergoing a rapid increase in the amount of energy they consume as they increase the quality of their lives, resulting in more rapid depletion of oil and gas reserves and an increase in the rate of global warming. The correlation between standard of living and energy intensity is not 1 to 1 however. Some countries, such as Japan, are more efficient in their use of energy while others, such as Russia, fall far below the curve. This demonstrates there is substantial room for improvement in energy efficiency. Some of the differences come from location (colder climates require more heating), demographics and social choices, such as where people live, the size of their homes, and the kind of cars they drive. While other differences result from the way people use technology, which can also have an impact on energy consumption.

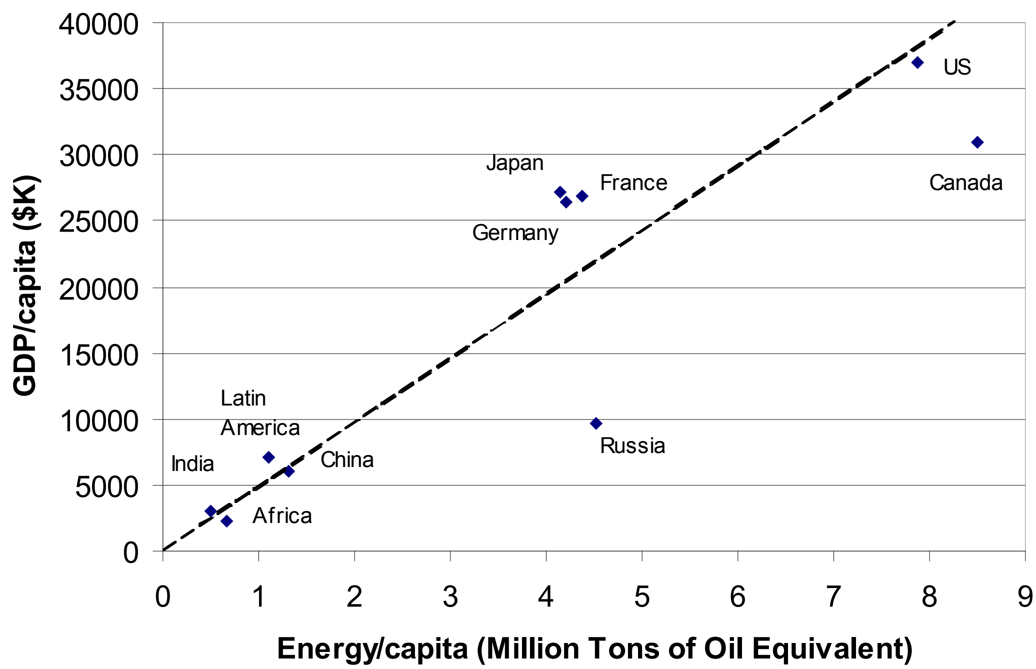


Figure 1. Relationship between GDP and energy consumption

In much the same way that energy has driven the industrial revolution, semiconductors have formed the basis of the technology revolution. Without the inventions of the transistor and integrated circuit, the highly developed society we live in today would not be possible. With over 500 billion semiconductor devices sold each year, they have become ubiquitous in our lives. Semiconductors are prevalent in all sectors of our economy including power generation, transportation, communications, and health care.

Sustaining the advances in quality of life we have achieved from the industrial and technology revolutions while protecting the environment requires clean, renewable sources of energy and improvements in energy efficiency. A range of solutions, both technical and non-technical, are required. Technical solutions will build on advances in materials science, thermodynamics, chemistry, information processing, computer architecture & algorithms, and other fundamental and applied sciences. Advances in the science and technology of semiconductor materials, devices, and integrated circuits and in software to run on the ICs play a key role. Semiconductors are the basis of solar photovoltaic (PV) systems and have become critical components in improving the energy efficiency of most of the machines we use.

The energy industry – the total value of all primary sources of energy that are harvested from the earth and sun - is roughly $6 trillion per year*[2]. This is about 9% of the world

GDP and is expected to grow at an annual rate of 2 to 3% over the next few decades. The total value of the world semiconductor market is $260 billion and is expected to grow at an annual rate of 6% over the next few years. The juncture of these two industries, and in particular the market for semiconductors in clean energy solutions, be it renewable sources or energy efficiency, is very likely to grow relatively faster. This represents significant market opportunity and an important part of the efforts to bring energy supply and demand into balance while protecting the environment.

*The amount can be easily calculated by multiplying the quantity of each type of energy consumed each year by the current pricing and summing across all fuel types – oil, coal, natural gas, nuclear, hydro, and renewables. It does not include the cost of converting fossil and nuclear fuel to electricity.

II. Types of Semiconductors used in Clean Energy Systems

There is a range of materials and semiconductor device types that play a part in clean energy systems. Semiconductor materials include silicon, gallium arsenide, and other compounds. Metal, organic, and inorganic thin films are also used. Device types range from individual diodes and transistors to complex integrated circuits having tens of millions of transistors.

A. Semiconductor Materials used in Clean Energy Systems

Silicon (Si) is the most important semiconductor material for electronics and for clean energy applications. It is used for nearly all integrated circuits and in over 95% of all PV devices. Compound semiconductors (materials with two or more elements) are also playing an increasingly important role in clean energy. Silicon carbide (SiC) and gallium nitride (GaN), for example, are used for high power switches, while gallium arsenide (GaAs) and copper indium gallium di-selenide (CIGS) are used for PV. There are also organic semiconductor materials that were developed for use as photoreceptors xerographic machines and form the basis for organic PV materials.

B. Discrete Devices

Diodes and transistors are the building blocks for integrated circuits, but they can also be used individually in what are known as discrete devices. A diode is a simple device formed by the junction of positively and negatively "doped" semiconductor material*. Current can pass in only one direction in a diode unless an external source of energy such as light or heat is applied. Transistors are simple switches that can turn on and off current flow. Discrete transistors and diodes are typically much larger than the sub micron sized diodes and transistors used in ICs and often handle much more power. There are several types of discrete transistors used for high power applications, known by their acronyms as MOSFETs, IGBTs, and JFETs**. Silicon is used for most of these, but silicon carbide and gallium nitride can also be used. Each technology has its own advantages and is used for certain applications.

*Doping is adding small amounts of other elements to the base semiconductor material to create excess positively and negatively charged carriers which enables the fundamental action of all semiconductor devices.
** MOSFET = Metal Oxide Semiconductor Field Effect Transistor, IGBT = Isolated Gate Bipolar Transistor, JFET = Junction Field Effect Transistor.

An "Inverter" is one example of the important role discrete diodes and transistors play in clean energy. . Inverters transform direct current (DC) to alternating current (AC) and control the phase and frequency of the output power. They are used to control variable speed motors and convert wind and PV power to the AC power that is fed onto the electric grid or used directly in most appliances and equipment. Variable speed motors are more efficient than simple induction or DC motors in certain applications such as refrigeration and industrial processes. Rather than turning the motor on or off, variable speed motors adjust the power to match the load.

Another example of a discrete device helping to conserve energy is in light emitting diodes or LEDs. LEDs emit light when current is passed through a diode in the forward direction. LEDs are more efficient than incandescent bulbs and can be more efficient than even compact fluorescent lights (CFLs). LED lighting has an additional advantage over CFLs: they contain no traces of mercury.

C. Sensors

Many modern day sensors are based on semiconductor materials. These devices measure a wide range of physical conditions including temperature, pressure, vibration, light intensity, and the chemistry of the surrounding environment which enable more precise and efficient computer control. Following are a few examples of these sensors and how they are used for clean energy applications.

Semiconductor temperature sensors rely on the change in resistance of a semiconductor material with temperature. They can be used to keep air conditioning and refrigeration systems operating a peak performance. Pressure and vibration sensors use micro-machined silicon structures that change shape and stress with a resulting change in electrical resistance. A pressure sensor can be used to monitor automotive tire pressure and signal when it is time to put air in the tire, resulting in improved fuel efficiency. Chemical sensors combine chemically active (usually organic) thin films with a semiconductor substrate to measure the type and concentration of certain chemicals, including water vapor. Chemical sensors can measure the ambient humidity and control industrial processes, or reduce the amount of clean water required to irrigate plants. A light sensor relies on the photoelectric effect and can be used to turn off lights when no one is in a room.

D. Analog and Mixed Signal Devices

Analog and mixed signal integrated circuits measure analog, or continuously variable, electrical signals, convert them to digital values, and process the information. They are often combined with sensors on a single piece of silicon to form a complete measurement device. The digital information is processed to help monitor and control the analog variables. Examples of mixed signal devices are power management ICs and drivers. Power management ICs are key to helping conserve energy in other ICs in a system. A cell phone, for example, relies on a power management IC to reduce power consumption and extend battery life. Driver circuits are used to switch or "drive" the power transistors found in inverters and motors.

E. Digital Integrated Circuits

Digital integrated circuits include microprocessors, microcontrollers, and digital signal processors (DSPs). Combined with programming software, these devices form the heart of all computing and telecommunications equipment. Most energy consuming equipment these days use at least one digital IC to provide control.

III. Applications of Semiconductors in Clean Energy Systems

All sectors in the economy use semiconductors to either help generate, transmit or distribute power or reduce the need for energy.

A. Energy Sources

The world consumes around 500 quadrillion (that's 500,000,000,000,000,000) BTUs of energy per year*[1]. Known as the total primary energy supply (TPES) this is the energy equivalent of 82 billion barrels of oil per year. Thirty five percent of that energy actually comes from oil, with 25% coming from coal, 21% from natural gas, 6.3% from nuclear, 2.2% from large scale hydroelectric, and roughly 10% from what are referred to as renewable sources. These include biomass, biofuels, small hydro, geothermal, solar thermal, wind, and PV, the largest of these being biomass (the burning of wood for heat and cooking). For non-renewable energy sources, semiconductor-based electronic equipment helps make them cleaner from an environmental perspective. For example, the capture and sequestration carbon from coal burning power plants is a complex process that requires many ICs for measurement and control. Even though wind and solar make up a very small percentage of the total energy supply today, they are the fastest growing among all sources of energy and some of the most interesting in terms of semiconductor applications. (wave power , geothermal, controlled growth of algae for biofuels..etc are other examples of interesting future applications).

*a BTU is the amount of energy required to raise one pound of liquid of water by 1 degree F.

1. Photovoltaics

Photovoltaic cells, the basic component of PV systems, are essentially large area diodes that take advantage of the photoelectric effect. Photons, or "particles of light", from the sun strike the layers of the diode creating negatively charged electrons and positively charged "holes" which become the current in the external circuit (figure 2)[4]. The invention of the PV cell and and the continuous improvement in performance have drawn heavily from the fundamental understanding of the physics of semiconductors developed for the electronics industry. The first working solar cell had an efficiency of 6% and was developed in 1954 by Bell Labs, the same lab that invented the transistor.[5] Since then, the efficiency of PV cells has improved significantly (figure 3)[6].

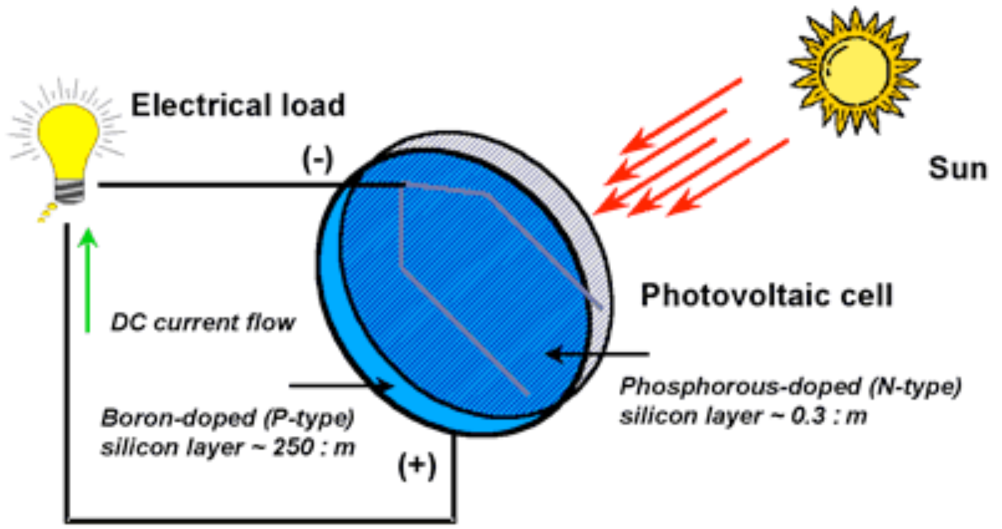


Figure 2. A photovoltaic sell consisting of positively doped and negatively doped Si. Ref. http://www.blueplanet-energy.com/

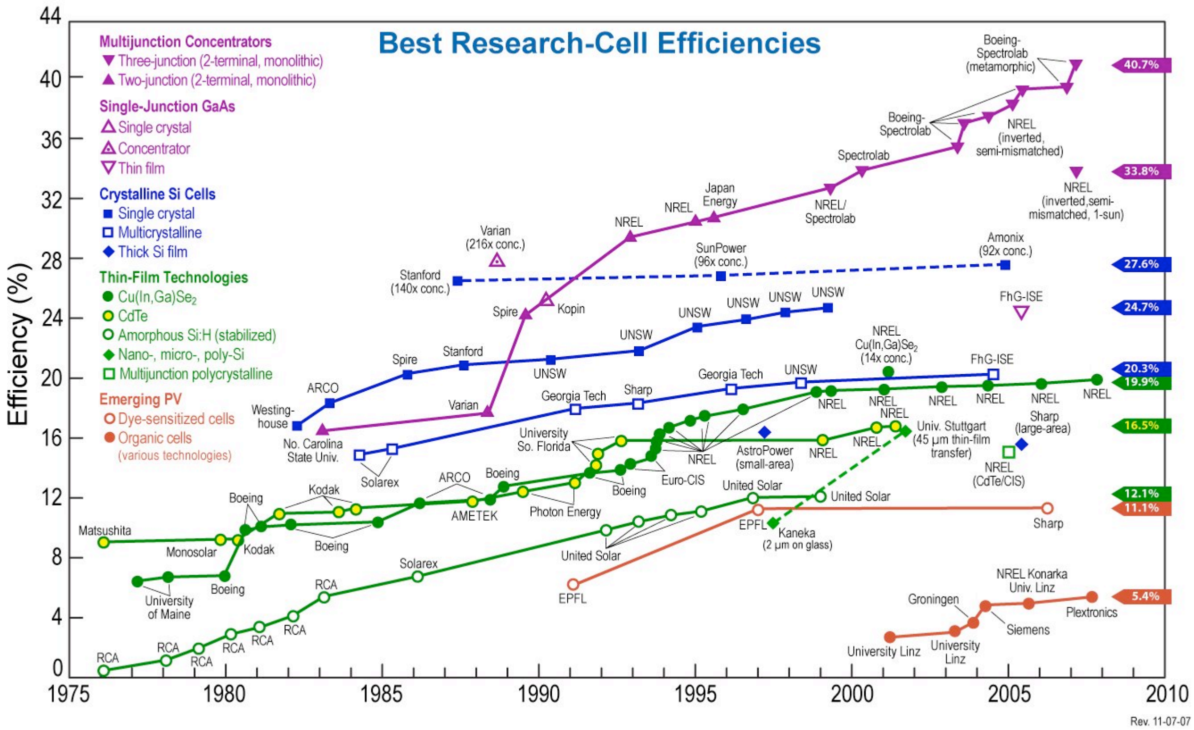


Figure 3. Improvement in solar cell efficiency over time.[6]

Over 95% of the PV market today is based on silicon, the same material used for integrated circuits. Originally PV cells were made using scrap single-crystal Si wafers from the electronics industry, but demand outstripped supply and now most PV cells use multi-crystalline Si wafers made specifically for the PV industry. Interestingly, the total wafer area used in PV manufacturing now outnumbers the amount used in electronic applications. Although the purity requirement is not as high as it is for electronics grade silicon, the processes used to convert silicon dioxide to poly silicon (the input material for making the wafers) are similar. In recent years, the growing demand for poly silicon for PV has resulted in increased prices for both the solar and electronics industry. The major suppliers of poly silicon and silicon wafers for the semiconductor industry also supply material to the solar industry. Companies like MEMC and Hemlock in the US and Wacker in Germany have benefited from the increased demand. Newer companies like REC in Norway and a host of companies in China are entering the market specifically for solar and are expected to ease the poly Si supply constraint.

Newer technologies are being developed that use semiconductor materials and understanding of their behavior, but are targeted specifically at the PV market. Thin films of semiconductor material can be deposited on inexpensive substrates like glass and stainless steel. These products use much less material, and take much less energy to manufacture as the PV cells that use single-crystal or mutli-crystal wafers. Amorphous silicon is one such material, as is Copper Indium Gallium Selenium (CIGS). The efficiency of these thin film solar panels is not as high as it is for crystalline solar cells, but the potential is there for these materials to provide much lower cost PV solutions.

Newer still are organic photovoltaic materials. Originally developed as materials that coat the drums of photocopy machines, these materials can be deposited on flexible substrates using simple printing techniques and offer still lower prices. However the efficiency and stability of these materials needs to be improved before they become commercially viable.

All of these new materials benefit greatly from the fundamental understanding of semiconductors that has been developed over the last 50 years for the electronics industry. However, a new generation of scientists and engineers, focused specifically on PV, is needed to solve materials and manufacturing challenges and bring down the cost of PV.

Most PV devices use single junctions or layers of positively and negatively doped material as shown in figure 2. However, efficiency can be increased by creating two or more layers, or junctions. In this approach, each junction can be tuned to capture a different part of the solar spectrum. This is the approach used by Spectrolab, a division of Boeing, to achieve a conversion efficiency of 40.7%.[7] Fabrication of these cells is very complex and requires many of the techniques developed for creating multiple layers on semiconductor devices for the electronics industry.

The size of the PV market is expected to grow from 4 GW (billions of watts) of added capacity in 2008 to over 22 GW in 2012.[8] This represents a 50% annual growth rate. The total installed capacity at the end of 2007 was 12 GW. In dollar terms, the value of the market for complete PV systems is expected to grow from $26 billion in 2008 to $90 billion in 2012. The total world wide electrical generating capacity is 4 terawatts (4 billion kilowatts).[9] PV represents a fraction of one percent of that total, so there is still plenty of room left for PV to continue its meteoric growth.

In order for the PV industry to achieve these growth rates, there needs to be constant improvements in efficiency and reduction in prices. Additionally, long term fundamental and applied research into the behavior and manufacturing of PV systems is required. It is likely that many of the resources currently being applied to the semiconductor electronics industry will shift focus to the PV industry.

The most notable example a company taking advantage of the strong link between photovoltaics and semiconductors is Applied Materials. Applied is the world's leading supplier of semiconductor manufacturing equipment. Two years ago Applied announced they were entering the market for equipment to produce PV cells – both the crystalline and thin film type.[10] Applied is leveraging their expertise in semiconductors in general, and in thin film process technology in particular. The company booked orders of $400M in their first year, doubling their original forecast. Mark Fitzgerald, analyst at Banc of America Securities, has predicted that the company's solar revenue could reach $1.2 billion in 2009.

Intel, the world's leading semiconductor manufacturer, recently announced they were spinning off a new PV company called Spectrawatt that will commercialize technology developed inside the company.[11] The company will develop and sell PV cells to solar module makers. Intel is also leading a $50 million investment round in the company and will be joined by Goldman Sachs and others. According to Andrew Wilson, SpectraWatt's CEO and former general manager of the Intel New Business Initiatives group, "The solar industry is akin to where the microprocessor industry was in the late 1970s. There is a lot to be figured out and improved," Intel also recently announced it is investing $38M in Sulfurcell, a thin film solar company based in Germany.

IBM has also announced they are entering the PV business by developing a process to deposit thin films of CIGS[12]. Although they have no plans to manufacture PV modules themselves, they will license the technology to PV manufacturers. According to Supratic Gupta, the lead scientist for photovoltaics at IBM research, "we have the skills that we have developed in other areas — standard silicon semiconductors, materials chemistry — and we're looking to utilize those skills in the photovoltaic space and develop IP [intellectual property] and know-how that other people don't have". Other companies that use CIGS are Heliovolt, Nanosolar, and Miasole.

Given the intermittent nature of solar and wind power, a fundamental technological breakthrough in mass energy storage would positively and radically alter the economics of both of these attractive renewable power sources for the grid.

2. Wind

Semiconductors also play a role in wind energy. There are two basic types of turbines used today – those with mechanical drives and those with electric drives. The mechanical drive turbines rely on a hydro-mechanical transmission to translate the slow, variable speed of the turbine to the speed of the rotor in the generator that produces AC power at the desired frequency. There is a relatively modest amount of semiconductor content in these turbines, similar to the content found in conventional electrical generation equipment. Most turbines today, however, use electronic means for converting the variable speed wind energy to AC power with tightly controlled frequencies of either 50 or 60 Hz, depending on the country. These turbines use high power discrete devices, drivers, and controllers similar to what are found in solar inverters and variable speed motors.

The market for wind energy was 20 GW in 2007 and is expected to grow at an annual rate of 12% to 36 GW by 2012.[13]

A. Electric Utilities – the Smart Grid

The modern electric grid is one of the crowning achievements of engineering in the 20th century. Of the world's TPES, forty percent goes into electricity generation.[14] This percentage is projected to rise to 42% by 2030 as our economy continues to rely more heavily on electrical gear including IT equipment[51]. That fraction will likely increase even faster than forecasted as the transportation sector starts to rely on electricity as a prime mover (see following section). We have become accustomed to highly reliable, universally available, and relatively inexpensive electric energy to power our homes, offices, shops, and factories. The grid, however, is faced with some real challenges, including aging infrastructure, increasing demand, increasingly expensive fuel, and the need to accommodate renewable and distributed energy sources. Renewable energy sources present a challenge to utilities because they are non-dispatchable - they can not always be turned on at will. Making the electric utility industry cleaner by integrating solar and wind energy, reducing transmission losses, and allowing demand side management to match the load to the capacity on a real time basis are key elements to a clean energy economy. The industry is responding in part by developing what is come to be known as the smart grid.[15]

Equipment (nodes) on the grid, including utility meters, switches, transformers, and even end point devices on the customer's premises are being equipped with sensors, microcontrollers, and communications devices. These nodes are being given IP addresses and linked to central control stations using technology borrowed from the internet, thereby allowing the utilities to monitor and control their assets. Semiconductors play a key role in this transformation and the market opportunity is substantial. All of the major semiconductor manufacturers including Freescale, IBM, Intel, and Texas Instruments are playing a role in the smart grid.

Smart meters use semiconductor devices to replace the electro-mechanical current sensors and allow digital readout of kW-hrs consumed as well as instantaneous power. They can also be equipped with communications devices, either wireless or wired, to allow remote reading. One popular wireless technology is known as Zigbee, a short-range protocol that uses very low energy to transmit the data. Zigbee can be used to allow utilities to read meters remotely and can connect the meter to appliances in the home for demand side management. Companies such as Texas Instruments and Freescale provide ICs for both the controllers and the Zigbee communications in smart meters.

Wired communications on the smart grid uses something called broadband over powerline, or BPL. This technology allows very high speed digital signals to run over existing power lines, both inside the home and for short distances on the utility power lines.

B. Transportation

The transportation sector consumes 20% of the world's TPES and over 60% of the oil.[1] Transportation also accounts for 25% of the CO_2 emissions coming from fossil fuels. Improving the energy efficiency of the transportation sector and reducing its dependence on oil are essential elements of a clean energy society. Semiconductors have played a key role in making vehicles more fuel efficient and will play an increasingly important role as vehicle powertrains become more advanced and hybridized and transportation systems rely more on electric energy.

The basic mechanical design principles of the four-stroke internal combustion engine have remained essentially the same since patented in 1884. However, the electrical systems in automotive engines have changed dramatically over the years. The first use of semiconductors to improve automotive fuel efficiency was in electronic fuel injection (EFI) systems. First introduced in the late 1950's, EFI totally replaced mechanical carburetors by the early 1980s and continues to evolve with more sophisticated control of the air/fuel mixture and combustion process in both gasoline and diesel engines. Modern electronic control systems are designed to meet legislative mandated exhaust emission and fuel economy levels. Today, high end vehicles can have 80 - 100 microcontrollers and hundreds more analog, discrete, sensor components. These devices are used throughout the vehicle, from power train and engine management to body control, safety, passenger comfort, and entertainment systems. Powerful microcontrollers running at over 100 MHz control the air/fuel mixture and timing of engines. These devices have helped improve fuel efficiency in the US from 12 mpg in 1970 to 19 mpg by 2000 (figure 4)[47].

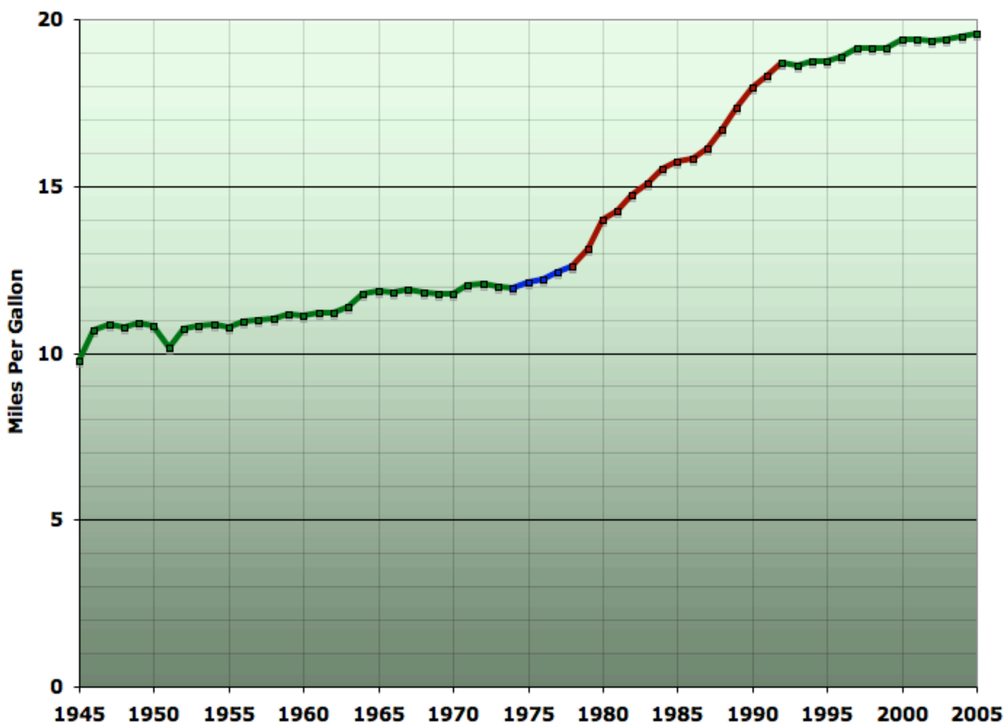


Figure 4. Estimated fuel efficiency for all deployed gasoline vehicles in the United States by year, 1945 – 2005 [ref. US fuel efficiency. [ref. 47]

Some of the increase was due to improved aerodynamics and reduced weight, while, most is due to advanced powertrain control. Since that time, mileage has stagnated due to increased vehicle mass from additional safety, comfort, and entertainment systems as well as a shift in the American buying habit during the 1990's away from cars toward light trucks and SUVs. However, we are seeing a rapid and substantial shift back to more fuel efficient vehicles and new efficient powertrain technologies in response to the recent run up in gasoline prices.

Automotive tire pressure monitoring is another valuable example of semiconductors being used to improve fuel efficiency[57]. These devices measure tire pressure with MEMS sensors and wirelessly transmit the signal so the driver knows when the air pressure is low.

The most promising role for semiconductors in making transportation systems radically cleaner is to replace traditional fuel-based systems with electric drives. The first step has been the introduction of the hybrid electric vehicle (HEV). Sales of HEVs are expected to rise from 1 million cars in 2008 to over 2 million in 2012 (figure 5)[16].

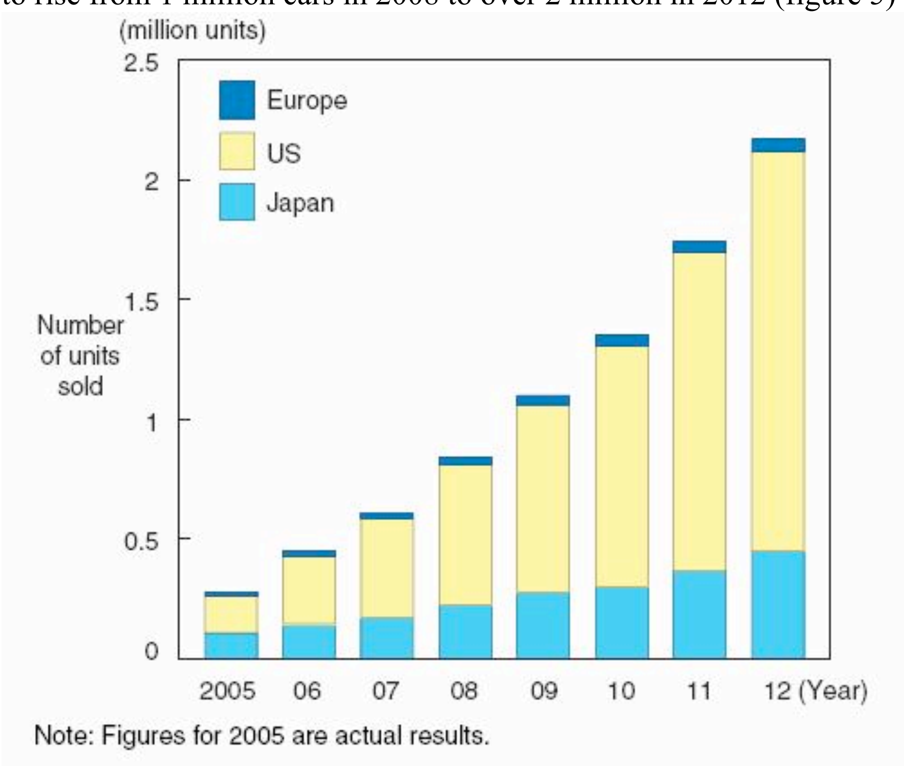


Figure 5. Forecast of worldwide HEV sales. [ref. 16]

Although HEVs still rely on gasoline fuel for 100% of their energy, they make significant use of semiconductor technology to substantially improve fuel efficiency, particularly in city driving. HEVs like the Toyota Prius use electric motors in addition to internal combustion engines for power. Improved efficiency is a result of several features, including shutting off the internal combustion engine when the vehicle is not moving, keeping the engine running at an optimal speed, and using regenerative braking, which converts the cars kinetic energy into battery energy during braking, rather than wasting it as heat in normal brakes. A typical car today contains around $300 worth of semiconductors. A HEV contains around twice that amount, the added content going into the inverters, battery chargers, and electric drive management. Figure 6 shows complexity of the Prius inverter. Discrete power devices, mixed signal, and high performance microprocessors and microcontrollers are all used.

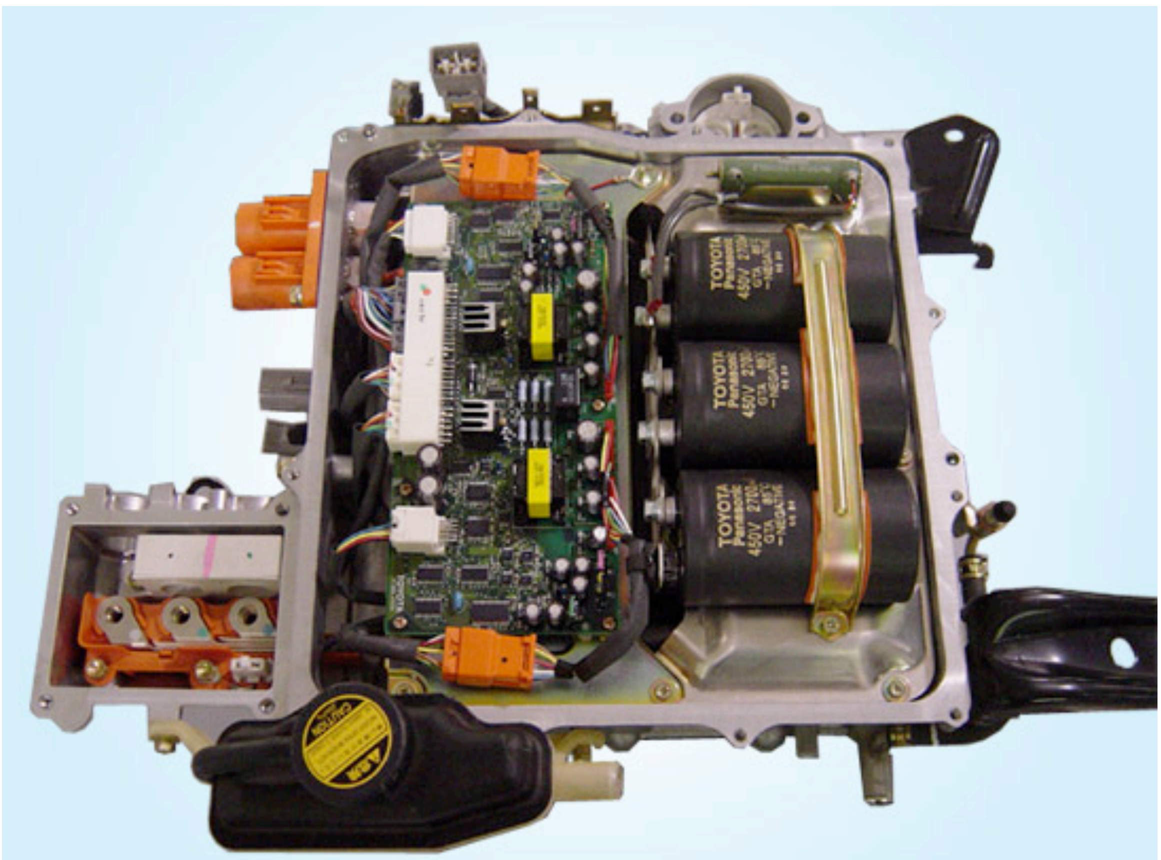


Figure 6. Toyota Prius Inverter. [ref. 48].

The next step in the electrification of the transportation sector and migration away from fossil fuels will be with plug-in hybrid electric vehicles (PHEV) or extended range electric vehicles (eREVs). Functionally, these are HEVs with much larger batteries that can be charged with power from the electric grid. Depending on the size of the battery and the length of a commute, it is possible with PHEVs to greatly reduce or eliminate the use of gasoline. Even with the source of the electrical energy from coal, gas, nuclear power plants as well as renewable solar, wind, and hydro sources overall emissions is still expected to be reduced through the deployment of PHEVs. (source NREL, EPRI..) PHEVs will require even more semiconductors than HEVs to manage the larger battery and communicate with the utility for charging.

C. Lighting

Lighting consumes 8% of the total world primary energy supply and 19% of all electric energy produced. The electricity used in lighting contributes 70% as much green house gasses as those from all cars.[17] Energy efficient lighting is a key clean energy technology. Today, most light bulbs are incandescent, which are only 5-10% efficient. These bulbs are being replaced by compact fluorescent lights (CFL), which are 4 times as efficient. It is estimated that a complete shift from incandescent bulbs to CFLs would save 3% of all electric energy. Governmental agencies are starting to require the use of CFLs. Australia has taken the lead by banning the sale of incandescent bulbs by 2010 and the US will ban the sale by 2012 under the energy law passed by Congress in 2007. Semiconductors play an important role in the migration from incandescent lighting to CFLs because incandescent bulbs use no semiconductors while many fluorescent bulbs use electronic ballasts, which have discrete power devices and small integrated circuits.
LEDs, as mentioned earlier, can be even more efficient than CFLs for some applications such as flashlights, traffic lights, and automotive lights. There is heavy investment to develop LEDs for general area lighting but so far the technology has not advanced to the point where they are capturing market share from CFLs or linear tube fluorescent lights. High brightness LEDs use the compound semiconductor gallium nitride. Cree Semiconductor is one company that provides high brightness LEDs for general area lighting.[18]

Another role for semiconductors in reducing the amount of energy consumed by lighting is through automatic lighting control based on time of day or by sensing the presence of people in the room or entryway. These solutions involve infrared sensors and control ICs. Not only does this reduce lighting costs but also air-conditioning costs associated with the heat created by lighting

D. Motors

In 2004, motors accounted for 40% of all electrical energy and 16% of the worlds TPES[50], and for nearly half of all energy used by industry[19]. There are many different types and sizes of motors, so making blanket statements about their efficiency and the potential for improvements by using semiconductors is difficult. One simple classification is AC vs DC. Over 90% of all motors are AC induction motors. They are found in air conditioners, washers, dryers, industrial machinery, fans, blowers, vacuum cleaners, and many, many other applications. AC motors are reliable and inexpensive, but they have a limitation: the speed can not be controlled independently of torque without the addition of a variable speed drive. This is an electronic device very similar to the inverters found in solar systems. Adding a variable speed drive to an AC motor can result in substantial energy savings depending on the application and the range over which the speed is being controlled[52]. Today, less than 5% of all AC induction motors have variable speed drives. This represents a significant opportunity for energy savings and for companies that make semiconductors for motor drives. The most expensive semiconductor components in a motor drive are the discrete power devices, described in section IIB. Companies like International Rectifier, Infineon, Fairchild, and On Semiconductor all make discrete power devices for this market. Motor drives also require microcontrollers and analog circuits to control and drive the switching of the discrete devices.

E. Consumer Electronics.

Demand for more powerful consumer electronics has, in-turn driven demand in the semiconductor industry. In 2003, consumer electronics industry revenue in the United States was $107.4 billion, according to the Consumer Electronics Association. Based on a July 2007 projection, revenue is expected to increase to $170.1 billion in 2008. This year, the consumer segment will lead growth for semiconductors at 5.9 percent[20]. Continued growth in this segment, and demand for more powerful devices that consume less power and have longer battery life, will fuel future growth for semiconductors that can improve upon balancing the power consumption-performance tradeoff.

While creating handheld devices with longer battery life has been the focus in the electronics and semiconductor industry, companies and consumers are just beginning to pay an increasing amount of attention to the amount of electricity consumed by products such as televisions, game consoles and personal computers. There are ample opportunities for semiconductors and software to play a role in managing the power of these devices, as 11.4 percent of integrated circuits sold in 2009 will be used in consumer electronics (including computers)[21]. Another focus is the "standby power" consumed when devices are not being used by consumers but are idling, ready to be quickly turned on.

On average, a microdisplay rear projection TV uses 0.14 watt per square inch, a liquid crystal display (LCD) TV uses 0.29 watt per square inch, and a plasma TV uses 0.35 watt per square inch[25]. That means a Sharp 65-inch LCD TV consumes 583 watts when powered on and 76 watts when powered off. Running the TV 365 days per year, turned on 8 hours per days equates to annual cost of $227 per year at 10.6 cents per kilowatt hour (the average price of electricity in the US). The watt per inch is higher for this model than other LCDs on average[22].

As energy prices rise, designing for energy efficiency will likely become a key differentiator in consumers' purchase decisions. One company is already leading the way — Phillips recently introduced a 42-inch LCD Eco TV with power saving features.

According to the EPA, beginning Nov. 1, new Energy Star standards will apply to televisions that "save energy while they are on and when they are off."

F. Smart Home/Appliances

According to the EPA program Energy Star, more than a third of the electricity produced in the United States is consumed in households, producing about 17 percent of the nation's greenhouse gas emissions. Air conditioners consume the most energy followed by refrigerators, water heaters, washers and dryers[23].

Installation of "smart appliances," which monitor how much energy they are using and have the capability to shut down or be turned on and off remotely using a web or mobile-phone interface, can have a significant impact in not only reducing energy costs, but warding off large-scale failures of power grids. Smart appliances are connected to digital thermostats which are controlled through the internet.

A January 2008 study by the Pacific Northwest National Laboratory of the Energy Department found that energy usage dropped 10 percent from the use of smart water heaters and dryers. If used nationwide, these technologies could save $70 billion and eliminate the construction of 30 new coal-fired power plants over 20 years[24].

There are more than 100 million households in the United States. With retrofits to these homes, there is an opportunity to save 25 to 30 percent on energy compared with current consumption[25].

Demand is increasing for more energy efficient home appliances, thus increasing the electronic content in the appliances, and demand for semiconductors that enable energy efficiency. Specifically, manufacturers are incorporating inverter-based variable speed control solutions, electronic displays, network-connected appliances and power management devices to improve energy efficiency[26].

MEMS valves also can improve the energy efficiency of refrigerators and air conditioners. Companies such as Microstaq, based in Austin, are using a silicon expansion valve, based on MEMS technology, to achieve up to a 25 to 30 percent improvement in energy efficiency in an air conditioner[27].

IV. Energy Consumption in Semiconductor Devices

With the proliferation of semiconductors in our daily lives, the electronics industry is beginning to recognize the additional cost of their products' carbon footprints. Moving away from the moniker, "performance at all cost," energy cost is now a major consideration. Beyond the environmental impact of this increased consumption, it makes economic and business sense to reduce the amount of power consumed by electronics as energy costs continue to rise and renewable, alternative energies have yet to become mainstream energy sources.

More efficient semiconductors can play a significant role in creating products that use less energy. While continued scaling will require the design and production of more energy efficient semiconductors to improve performance, as semiconductor content increases with each new generation of applications, its contribution to application energy consumption tends to increase accordingly[28]. To reduce the amount of energy consumed by semiconductors, chip designers are focusing on lower power architecture to minimize the voltage required, dynamic voltage and frequency scaling and improvements in standby power and auto shut-off transistors at the logical design level, new materials to reduce current leakage at the process technology level. However, the greatest opportunity to reduce a system's power consumption and in turn, the world's energy consumption, is at the system design and software levels.

A. Product Design, Applications and Software

Product design can have a significant impact on power consumption. Energy Star — a joint program of the U.S. Environmental Protection Agency and the U.S. Department of Energy — promotes energy efficient products and services to help save businesses and consumers money as well as protect the environment. Using these products in 2007, Americans saved $16 billion on their utility bills and saved energy equivalent to the greenhouse gas emissions from 27 million cars[29]. There are more than 50 product categories with products that qualify to carry the Energy Star label.

Designing products so they do not draw more power than necessary when in the "Off" mode and still plugged in, is one way companies can design for energy efficiency. Hewlett Packard's LaserJet printers require no more than 1 watt of power when in off mode. According to Gartner (Sept. 2007), printers account for 6 percent of global carbon dioxide emissions in the information and communications technology (ICT) area. Carbon dioxide emissions from ICT make up approximately 2 percent of global emissions — roughly equivalent to that of the aviation industry. PCs and monitors account for 40 percent (excluding embedded energy) of ICT emissions[30]. Power management features in desktop PCs, such as automatically switching a monitor or CPU into standby after certain period of inactivity, can save up to 381 kWh for a monitor and 294 kWh for a desktop PC each year, which is enough energy to power a 75-watt light bulb burning continuously for one year[31].

From a software standpoint, power efficiency techniques such as reordering instructions, exploiting system architectures and application-specific optimization can improve energy efficiency[32]. As can developing software with better computational efficiency, which allows the CPU to idle, by writing more efficient algorithms and multi-threading; employing data efficiency by reducing the frequency of disk accesses and reading only what is necessary; and building context awareness into software design by subscribing to and responding appropriately to platform power events[33].

Software is an essential piece in the move to more efficient, multi-core servers. Servers (including cooling) account for 23 percent of global carbon dioxide emissions from

ICT[34]. To improve energy efficiency and performance, servers are moving to multi-core processors. However, most client software today is single-threaded and cannot take full advantage of multiple cores to speed up compute cycles[35].

B. System/Chip Architecture

At the system level, optimizing the input and output (I/O) interfaces of user-facing devices in the system can reduce power consumption. Devices, such as self-refreshing displays and audio, are synched to processing cycles of the overall system. Reducing their dependency on these cycles can put these functions into an idle state more frequently, thus reducing power consumption.

Up to 50 percent of the power used in a computer is wasted on repeated power conversions from the power source to the circuit. With as little as 50 percent of the power arriving at the circuit, there is significant room for improvement. Intel is working on ways to improve efficiency, with a target of 90 percent efficiency.

While putting computers to "sleep" is not a new concept, there is an opportunity to optimize how and when different components in a system are put to sleep when they are not needed[36].

Keeping pace with Moore's Law — the prediction made by Intel Co-Founder Gordon Moore that the number of transistors on a chip will double every 18 to 24 months — will require the semiconductor industry to reduce chip power consumption through the use of lower power chip architecture. As scaling continues each transistor consumes more power and produces more heat. This presents one of the largest challenges for continued scaling. For example, an Intel Pentium processor in 1993 had approximately 3 million transistors. Today, the Intel Itanium 2 processor has over 1 billion transistors. If this rate of scaling continues, high performance microprocessors processors will soon produce more heat per square centimeter than the surface of the sun.

For that reason, IBM, AMD, Sun, Freescale, Intel and other chipmakers are moving to multiple core processors, which as Intel states, it "adds two or more brains to each processor. A multi-core processor architecture has two or more execution cores — or computational engines — within a single processor. The multi-core processor plugs directly into a single processor socket, but the operating system perceives each of its execution cores as a discrete logical processor with all the associated execution resources."

This architecture enables more the chips to do more work per clock cycle, with lower frequencies. This, in turn, reduces power consumption, which increases proportionally with frequency. The reduced power consumption has the added benefit of reducing air conditioning needs and costs[37].

Putting an entire system on a chip, known as an SOC, has resulted in improved power efficiency in systems. An SOC is a chip which includes an entire system such as a processor core, memory unit, programmable logic and high performance bus. Putting all of these components on one chip reduces the amount of power conversion in a system, thus reducing power consumption[38].

At the 2008 International Solid States Circuit Conference, Massachusetts Institute of Technology and Texas Instruments introduced a complete SOC that is up to ten times more energy efficient than current technology. . The design includes an on-chip DC-to-DC converter which converts voltages to the required levels.   Incorporating this converter onto the chip results in improved power efficiency.

In designing circuits, there is an ever-present performance-power tradeoff. An often used solution is dynamic voltage/frequency scaling (DVFS), which allows just enough voltage and frequency to ensure performance, while conserving power. It automatically adjusts clock frequencies — the speed at which a microprocessor executes instructions — and supply voltages in response to processor activity within the system, essentially linking power management to software activity[39].

A Carnegie Mellon University study showed that DVFS can further improve the energy efficiency of chip-multiprocessors running multithreaded commercial and scientific workloads. Cooperative hardware/software schemes have been deployed to achieve increased energy-efficiency in virtually every laptop computer sold today as well as the highest performance servers and embedded processors.   The potential for improved software to contribute to increased energy efficiency cannot be overstated as well as to fully leverage the advantages of multi-threading[40].

Using a lower frequency frequency and voltage leads to less heat output, thus reducing the need for cooling fans, and ultimately, power consumption. DVFS also enables longer batter life and "quiet computing." Advanced Micro Devices' (AMD) Cool n' Quiet technology is a prime example of DVFS. AMD's technology has several features including a multi-point thermal control which reduces heat output; and AMD CoolCore™ Technology which turns off parts of the microprocessor when they are not needed. The frequency scaling feature is the Independent Dynamic Core Technology which adjusts individual core frequencies as required by utilization (DVFS). This technology also is an Energy Star product[41].

C. Logical/ Physical Circuit Design

Combining energy efficient software with the right energy efficient hardware can further optimize a product's power consumption. For hardware, sequential analysis at the register transfer level and clock gating give designers the opportunity to improve energy efficiency. This includes shutting off redundant writes, reducing the frequency of operations while increasing parallelism to maintain throughput and disabling pipeline stages when the results are not being used in subsequent calculations[42].

Even when a device is in standby mode, there is current leakage. To reduce leakage integrated circuit designers can shut off power to the section of logic that is not needed to perform a task. This is called power gating and enables the implementation of sleep transistors, which further reduces power consumption[43].

D. Process Technology

As chip geometries continue to shrink, the industry faces two major power consumption issues: increased heat generation due to the increase in speed and transistor density and current leakage — the continued flow of current leakage even when the transistor is off[44].

In 2007, Intel and IBM announced their plans to implement high-k dielectrics and metal gates at the 45-nanometer node. The use of a high-k dielectric material improves the gate field effect and allows the use of thicker dielectric layer to reduce current leakage. When combined with a metal gate, which also improves the gate field effect, the chip has more than 20 percent greater performance and reduces source drain leakage more than five times and gate oxide leakage more than 10 times[45].

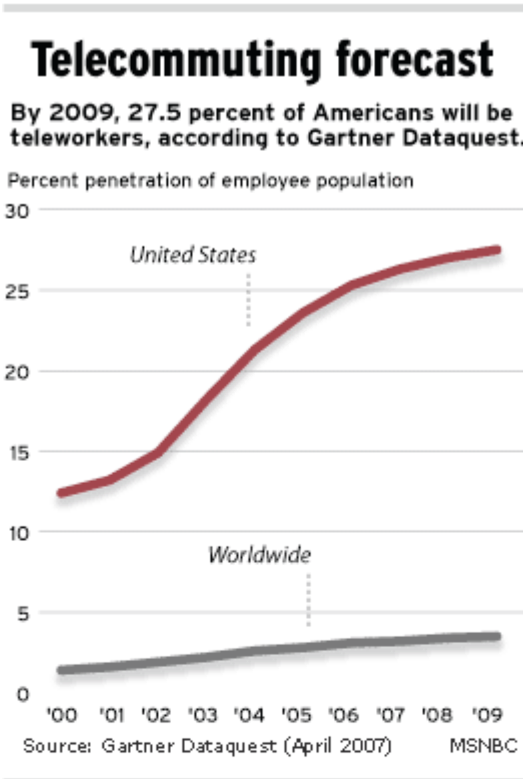
The implementation of high-k/metal gate, in addition to enabling continued scaling, will reduce the amount of power consumed by semiconductors and the need for cooling systems in electronics and appliances. This means longer-lasting batteries in laptops and more functionality in computers.

According to an estimate by Applied Materials in July 2007, if all the microchips shipped in 2006 used high-k dielectric and metal gate technology, the total power saved could provide electricity to more than 4.5 million homes for a year[46]. (Estimate based on one year, 12-hour/day chip usage.)

V. The Role of Semiconductors in a new Economy

Enabling renewable energy sources and improving energy efficiency of existing products are not the only ways that semiconductors are helping to reduce our dependence on fossil fuels and reduce the resulting greenhouse gas emissions. The technology revolution, based heavily on semiconductors, is allowing new ways of doing business and living our lives. The internet and modern telecommunications are enabling teleconferencing, telecommuting, and on-line consumer business, all of which can reduce the need to travel. And since transportation accounts for 20% of the global energy demand, these activities can have a substantial reduction in energy use without compromising economic growth or quality of life. The number of telecommuters is difficult to measure and depends on how you define the term. According to Gartner, the number of workers in the US who telecommute more than 8 hours per week will reach 14 million by 2009, up from 6 million in 2000 (figure 8) .

Worldwide, the number of telecommuters is more than 100 million. While this is still a small part of the total working population, the trend is likely to continue.



Telecommuting not only saves on fuel expenses, but also on net office energy consumption. Sun Microsystems recently announced the results of its Open Work Energy Measurement Project[53]. Nearly 19,000 of Sun's employees from around the world, representing 56% of their employees, use some form of telecommuting. By skipping the commute to work 2.5 days per week, Sun figures that each employee saved $1,700 in gas and vehicle wear and tear per year. They also saved 2.5 weeks of commute time. On average, employees who took part in the study saved 125 gallons of gasoline and reduced CO2 emissions by more than one metric ton. In addition, Sun found that the office equipment in a typical Sun office used energy at two times the rate of the home office equipment that their telecommuters were using (about 64 watts per hour at home vs. 130 watts per hour in the office). By skipping the commute to work 2.5 days per work, Sun figures that each employee reduces the energy consumed for work activities by 5,400 kilowatt hours per year.

Videoconferencing and teleconferencing are two other ways that companies are using the internet to reduce energy consumption. British Telecom claims to have reduced its carbon footprint by 97,000 metric tons by using videoconferencing to replace air and ground travel to face-to-face meetings. These modes of commerce would not be possible without the advances made in semiconductor technologies.

VI. Summary

The industrial revolution was based on the supply of inexpensive and plentiful energy from fossil fuels. These fuels are non renewable. We are at or near the peak in world oil production[55], the effects of which are being felt today in oil prices. What oil remains is heavily concentrated in a relatively small number of countries which threatens the security and stability of many others. Natural gas is being increasingly used for our energy needs but it too is in short supply. Coal, while the most plentiful fossil fuel, is also by far the dirtiest from an environmental perspective. We also know that by burning these fossil fuels we are injecting large amounts of carbon dioxide into the atmosphere, causing global warming. The rapid advances in the economies of India and China are causing these problems to accelerate. We must find clean, renewable sources of energy, and use what energy we have more efficiently and wisely, if we are to continue to grow, or even sustain, our quality of life and not cause irreversible damage to the environment.

Semiconductors form the basis of the technological revolution. Nearly all of the modern conveniences we have use some type of semiconductor device. Telecommunications, computers, the internet, mobile phones, health care equipment, and consumer devices all rely heavily on semiconductor technology. And nearly all products that consume energy rely on semiconductors for their operation today. Transportation, which consumes 20% of all energy, makes extensive use of semiconductors and is expected to use even more as we move towards HEVs, plug-in HEVs, and all electric vehicles. Electric lighting and motors are also large users of energy and are becoming increasingly reliant on semiconductors to improve their efficiency. Solar and wind are renewable sources of energy and are the two fastest growing energy sources world wide. Both of these rely heavily on semiconductor technology for their operation. Photovoltaic solar, in particular, is fundamentally based on semiconductors and is growing at 50% per year. Semiconductor devices also use energy, and making these devices more energy efficient is a key area of focus for semiconductor manufacturers. Advances are being made at all levels, from fundamental materials and devices to efficient software coding.

We face the significant challenge of increasing the supply of clean, renewable energy while reducing our energy needs until these are brought into balance. Technology alone will not solve this problem; it will require changes in lifestyle, in how business gets done, and in government policies[56]. But technical advances can make significant contributions, and the science and technology of semiconductors will play a key role. Developing semiconductor solutions for a clean energy society is an important endeavor and is one that is likely to grow rapidly, providing opportunities to businesses, employees, and communities.

References

1. International Energy Agency Key World Energy Statistics 2007 http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1199
2. Doerr, John, Kleiner Perkins, Caufield and Beyers quoted in Web 2.0 Summit http://blog.eightblack.com/2007/web-20-john-doerr/.
3. World Semiconductor Trade Statistics http://www.wsts.org/
4. http://www.blueplanet-energy.com/
5. AT&T Labs technology timeline, found at http://www.corp.att.com/attlabs/reputation/timeline/54solar.html].
6. National Renewable Energy Lab http://www.internet-public-library.org/carbon-reduction/painless-carbon-reduction.htm

7. Boeing press release.
   http://www.boeing.com/ids/news/2006/q4/061206b_nr.html
8. Shah, Vishal, et. al, Lehman Brothers Solar Energy Coverage Initiation Energy, November, 2007
9. US DOE Energy Information Administration data on Electricity Installed Capacity. http://www.eia.doe.gov/emeu/international/electricitycapacity.html.
10. Applied Materials press release
    http://www.appliedmaterials.com/news/solar_strategy.html
11. Intel Corporation press release
    http://www.intel.com/pressroom/archive/releases/20080616corp.htm?iid=SEARCH
12. IBM Corporation press release
    http://www.ibm.com/news/us/en/2008/06/2008_06_16.html
13. Global Wind Energy Council, Global Wind 2007 Report, May 2008.
    http://www.gwec.net/index.php?id=90
14. US DOE Energy Information Administration data on Electricity Generation http://www.eia.doe.gov/emeu/international/electricitygeneration.html
15. CleanTX Forum, The Smart Grid, Feb. 2008, http://cleantx.org/wp-content/uploads/2008/02/final_smart_grid_primer_kf.pdf
16. University of Portsmouth Department of Electrical Engineering http://mosaic.cnfolio.com/M528Coursework2007A204
17. International Energy Agency "Lights Labors Lost", June 2006.
    http://www.iea.org/textbase/press/pressdetail.asp?PRESS_REL_ID=182].
18. Cree Semiconductor. [ref. http://www.creells.com/index.aspx]
19. www.eecabusiness.govt.nz
20. Global Semiconductor End-Use Forecast - Market Diversity, It's a Good Thing. Jim McGregor. Electronics Industry Market Research and Knowledge Network. February 2008.
    http://www.electronics.ca/reports/semiconductor_applications/end_use_forecast.html
21. IC Market Drivers. IC Insights. 2008 edition.
    http://www.icinsights.com/prodsrvs/marketdrivers/marketdrivers_part1.html
22. The Basics of TV Power. Brian Nadel and Matthew Moskovciak. CNet Reviews, 2008. http://reviews.cnet.com/4520-6475_7-6400401-2.html
23. U.S. Household Electricity Report, Energy Information Administration. July 2005. http://www.eia.doe.gov/emeu/reps/enduse/er01_us.html
24. Digital Tools Help Users Save Energy, Study Finds, by Steve Lohr. New York Times. January 2008.
    http://www.nytimes.com/2008/01/10/technology/10energy.htm
25. Energy Star®— The Power to Protect the Environment Through Energy Efficiency, United States Energy Protection Administration. August 2003.
    http://www.energystar.gov/ia/partners/downloads/energy_star_report_aug_2003.pdf

26. The Worldwide Market for Major Home Appliances – 2007 Edition, Research Report # IMS4505, IMS Research Group, March 2007.
27. Fluid Handling: Big Gains from Tiny Valve, by Steve Booth and Rachid Kaina. Appliance Design, April 2008. http://www.appliancedesign.com/CDA/Articles/Feature_Article/BNP_GUID_9-5-2006_A_10000000000000292838
28. Freescale Semiconductor. Freescale Technologies for Energy Efficiency, 2007 Overview. http://www.freescale.com/files/shared/doc/ENERGYEFFWP.pdf
29. Energy Star Overview of 2007 Achievements, U.S. Environmental Protection Agency
30. Conceptualizing 'Green' IT and Data Center Power and Cooling Issues, by: Rakesh Kumar and Laras Mieritz, Gartner, Inc., September 2007
31. Saving Energy with HP, Hewlett Packard, 2006
32. Designing Energy Efficient Consumer Electronics, by Devadas Varma, Calypto Design Systems. Portable Design, 2007. <http://www.portabledesign.com/article?article_id=134>
33. Introduction to Energy Efficient Software, Second Life Talk, Bob Steigerwald and Taylor Kidd, Intel Software and Solutions Group, Intel Corporation, November 2007
34. Conceptualizing 'Green' IT and Data Center Power and Cooling Issues, by: Rakesh Kumar and Laras Mieritz, Gartner, Inc., September 2007
35. Increasing Data Center Density While Driving Down Power and Cooling Costs White Paper, Intel Corporation, June 2006
36. Energy-Efficient System Architecture Aims to Improve System Energy Efficiencies, by Ravi Nagaraj. Technology@Intel Magazine, Intel Corporation, March 2006, http://www.intel.com/technology/magazine/systems/eesa-0306.htm
37. Intel's Road to Multi-Core Chip Architecture, by Geoff Koch, Intel Corporation, 2006. <http://cache-www.intel.com/cd/00/00/22/09/220997_220997.pdf>
38. System on Chip, Electronics Information Online, January 2007. <http://www.electronics-manufacturers.com/info/circuits-and-processors/system-on-chip-soc.html>
39. How to Squeeze More Battery Life Out of Your Wireless Design, by Henk Derks, Ronald van Cleef and Reinier van der Lee, Philips Semiconductor, Wireless Net Design Line, August 2006. <http://www.wirelessnetdesignline.com/192200084;jsessionid=0B25YQ2UCMZJQQSNDLQCKIKCJUNN2JVN?pgno=3>
40. Analysis of Dynamic Voltage/Frequency Scaling in Chip-Multiprocessors, Sebastian Herbert and Diana Marculescu, Carnegie Mellon University, ACM, New York, NY. International Symposium on Low Power Electronics and Design, 2007.
41. Energy Efficiency with AMD Cool n' Quiet Technology, AMD, 2008. http://www.amd.com/us-en/Processors/ProductInformation/0,,30_118_9485_9487%5E10272,00.html

42. Designing Energy Efficient Consumer Electronics, by Devadas Varma, Calypto Design Systems. Portable Design, 2007 <http://www.portabledesign.com/article?article_id=134>
43. Dual threshold voltages and power-gating design flows offer good results, by Kaijian Shi, Synopsys Professional Services, EDN, February 2006. http://www.edn.com/index.asp?layout=article&articleid=CA6301624
44. From Moore's Law to Intel Innovation — Prediction to Reality by Radhakrishna Hiremane, Technology@Intel Magazine, Intel Corporation, April 2005 <http://www.intel.com/technology/magazine/silicon/moores-law-0405.htm>
45. Intel and IBM Commit to High-k, Metal Gates, by Peter Singer, Semiconductor International, January 2007. http://www.semiconductor.net/article/CA6410945.html
46. Applied Materials Makes the Transistor Cool Again with Integrated High-k/Metal Gate Technology, Applied Materials News Release, July 2007. http://www.businesswire.com/portal/site/appliedmaterials/index.jsp?epi-content=GENERIC&newsId=20070717005426&ndmHsc=v2*A1167656400000*B1206143686000*C1199192399000*DgroupByDate*J2*N1010872&newsLang=en&beanID=2009756526&viewID=news_view
47. The Oil Drum. http://www.theoildrum.com/story/2006/12/17/1377/0132
48. The Clean Green Car Company. http://www.cleangreencar.co.nz/page/prius-technical-info
49. Gartner Dataquest 2007 data as reported by MSNBC. http://www.msnbc.msn.com/id/20281475/
50. Arun Mattel of Infineon as quoted in EDN news. See also BP Wold Energy Review. http://www.edn.com/blog/1470000147/post/70007407.html
51. Energy Information Administration International Energy Outlook 2008. http://www.eia.doe.gov/oiaf/ieo/ieoenduse.html
52. http://www.aps.com/main/_files/services/BusWaysToSave/Motors.pdf
53. Sun Microsystems Open Work Energy Measurement Project. http://www.sun.com/aboutsun/pr/2008-06/sunflash.20080609.2.xml
54. British Telecom May 2007. http://www.businessweek.com/globalbiz/content/may2007/gb20070521_706772.htm?chan=globalbiz_europe+index+page_top+stories
55. Hubbert’s Peak: The Impending World Oil Shortage, Princeton Press, 2001. http://www.amazon.com/Hubberts-Peak-Impending-World-Shortage/dp/0691116253/ref=sr_1_1?ie=UTF8&s=books&qid=1216650114&sr=8-1
56. See for example, http://news.yahoo.com/s/ap/20080717/ap_on_go_ot/gore_electricity
57. Freescale Semiconductor Tire Pressure Monitoring System http://www.freescale.com/webapp/sps/site/application.jsp?nodeId=02Wcbf123FQ1Dg