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The Potential of Energy Efficiency: An Overview

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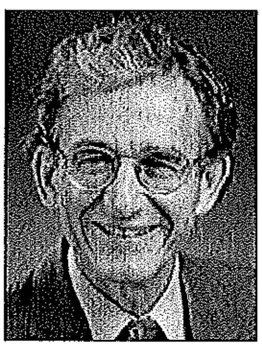
Overcoming formidable barriers to energy efficiency will require public and private support.

The Potential of Energy Efficiency
An Overview



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Efficient technology that requires less energy than is currently used to get the same or better output has fueled the growth of our economy for more than a century. But while America was building its infrastructure and developing its industry and service sectors, the energy intensity of the economy, BTU per dollar of output, fell dramatically. If this had not happened, it would now take four times as much petroleum, coal, and natural gas to produce current GDP, at the 1919 energy-intensity level. This would amount to 85 percent of the current world production of fossil fuels—just to support the U.S. economy. Producing, transporting, and using that much energy, even if it were technically feasible, would devastate the natural environment and contribute to carbon dioxide emissions that would exceed the atmospheric concentration some scientists think would be catastrophic.

Figure 1 suggests the potential for improving energy efficiency to reduce our consumption and emissions. U.S. energy intensity dropped by half from 1919 to 1973 and then dropped by half again from 1973 to 2006, rates of 1.6 percent and 2.1 percent per year, respectively. Thus energy intensity decreased in the last three decades almost twice as fast as during the previous five decades. Since GDP is projected to grow at 2.5 percent per year through 2030, unless we continue to lower our energy intensity, the United States will use 69 percent more energy in 21 years than it uses today. That would require more than doubling our imports of oil and vastly increasing our imports of natural gas.

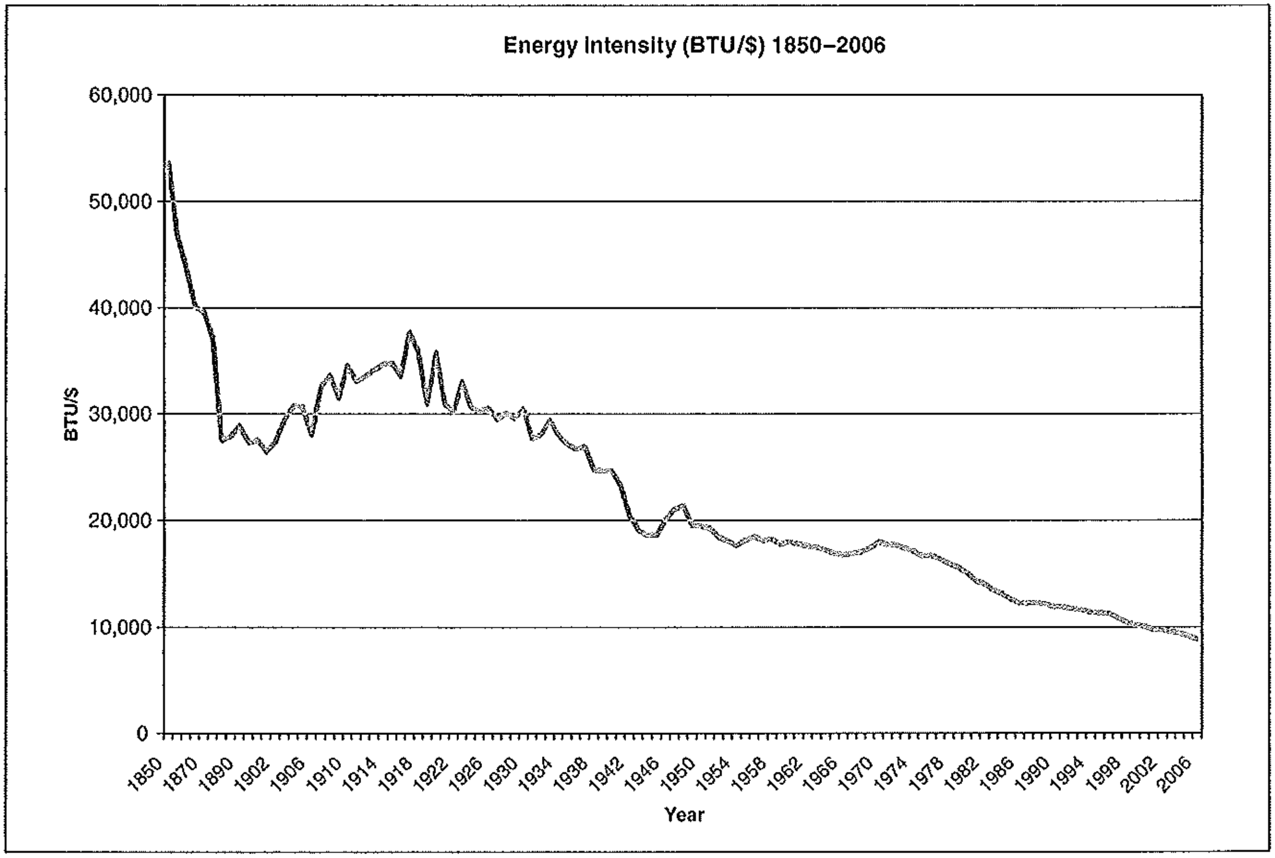

FIGURE 1 U.S. energy use per dollar of GDP, 1850–2006. Sources: based on EIA, 2008b; Schurr and Netschert, 1960.

If energy intensity continues to drop at an annual rate of 2.1 percent, as it did from 1973 to 2006, total energy use in the economy would rise by only 8 percent by 2030, putting less pressure on our imports and the environment. If we could find a way to reduce energy intensity even more, to 2.5 percent per year instead of 2.1 percent, we could keep energy use from growing, despite a growing economy. This would have enormous benefits for environmental quality (including reducing greenhouse gas emissions), energy security, and our balance of payments. However, this decrease is not likely unless policies are adopted that motivate investments in energy efficiency.

The potential for realistic conservation, as well as for greater energy efficiency, is suggested by comparisons of energy intensity in the United States and energy intensity in other advanced nations. Table 1 shows energy use per capita and per dollar of GDP for the United States, Japan, Denmark, France, and Germany. Japan and Denmark use about half the energy per capita, and France and Germany use a bit more than half of the per capita energy used in this country. In Japan and Denmark, energy use per dollar of GDP is half the U.S. level, and in France and Germany, it is about three-quarters of the U.S. level. An analysis by the International Energy Agency concludes that about half the difference between the United States and Europe is attributable to energy efficiency and about half to other factors, such as life style (IEA, 2004).

TABLE 1 Energy Use in 2005—Per Capita and Per Dollar of GDP

	BTU per person (million BTUs)	BTU per dollar of GDP
United States	340	9,113
Japan	177	4,519
Denmark	153	4,845
France	182	7,994
Germany	176	7,396

Source: EIA, 2009b,c.

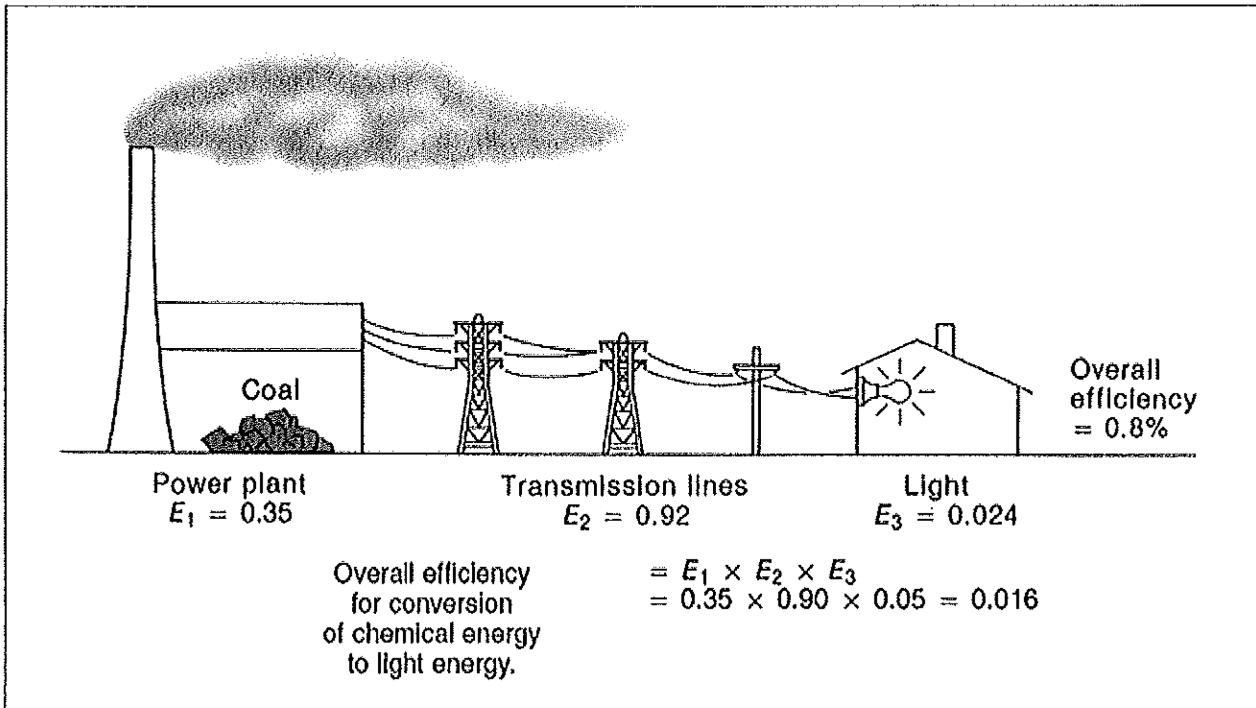

FIGURE 2 Lighting efficiency. Source: NRC, 2009.

Japan, France, and Germany are highly industrialized nations, and Denmark, France, and Germany have income levels comparable to ours. To be sure, this sort of aggregate comparison does not account for the GDP mix, climate, size, or passenger and freight transport for each nation. Nevertheless, the comparisons suggest that Americans might be able to cut energy use per capita by almost half if we were to adopt a European life style and European levels of energy efficiency.

In *Real Prospects for Energy Efficiency in the United States*, published as part of a National Academies project called America's Energy Future, a panel of experts evaluates the prospects for energy efficiency through the first half of this century, with a focus on the next decade. The panel details efficiency increases that could be achieved by making buildings, transportation, and industry more energy efficient and concludes that, compared to current projections of energy use in 2020 and 2030, additional energy savings of 30 percent are possible by 2030. About half of those savings could be realized in the next decade. In terms of cost, the panel concludes that saving energy would be far less expensive than buying additional energy at mid-2008 prices (NRC, 2009).

Examples of improvements in energy efficiency are plentiful. Figure 2 shows that burning coal to produce electricity to generate light is perhaps 0.8 percent efficient. A modern compact fluorescent lamp (CFL) is roughly four times as efficient as an incandescent lamp. The *New York Times* reports that manufacturers are displaying light-emitting diodes (LEDs) that are 10 times as efficient as an incandescent lamp (Taub, 2009). Another example, shown in Figure 3, is the annual energy use of a refrigerator. Compared to a 1974 model, a new refrigerator, which is both larger and cheaper, would use only 31 percent as much electricity.

The point is that, measured at the aggregate level, whether we look at energy use in the United States over time or compare it to energy use in other nations, or at the process level (e.g., lighting, refrigerators, other appliances), tremendous progress in energy efficiency has been made, and there is a huge potential for more progress in the future.

In the remainder of this article, I describe energy efficiency in buildings, the industrial sector, and, briefly, the transportation sector.[1] I then identify barriers to implementing energy-efficient technologies and the drivers of energy efficiency.

[1] Energy efficiency in light-duty vehicles is explored in the article on p.22 by Don Sperling, a member of the Energy Efficiency Panel, and Nic Lutsey.

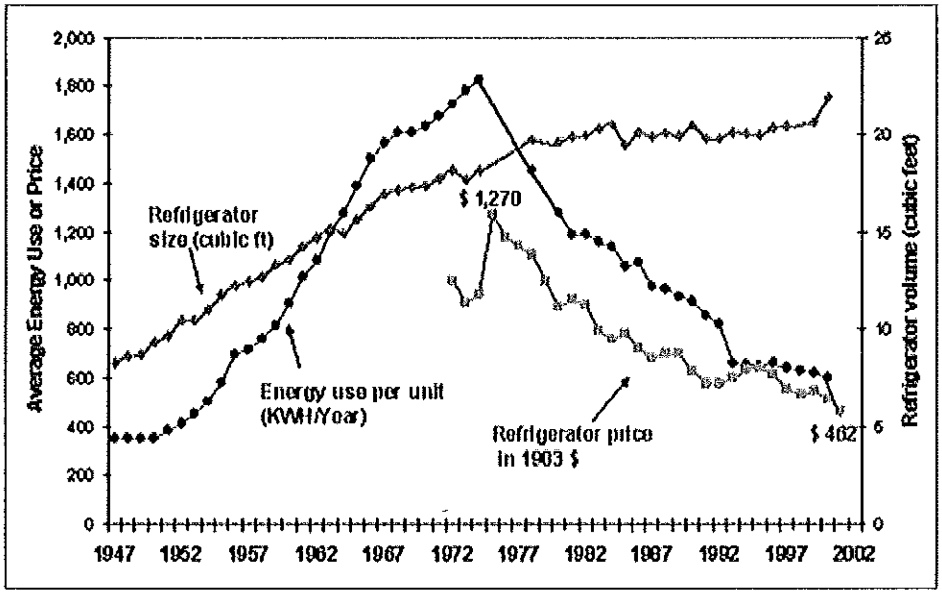

FIGURE 3 Efficiency of refrigerators. Source: NRC, 2009.

Energy Use in Buildings

The 81 million single-family houses, 25 million multifamily residences, and 7 million mobile homes, together with 75 billion square feet of commercial floor space account for 73 percent of electricity use and 40 percent of total energy use in the United States. From 1975 to 2005, despite increased energy efficiencies, an increase in the number of residences and the amount of commercial space led to substantial increases in total energy use—15 percent in residential buildings and 50 percent in commercial buildings.

The efficiency gains, which were made in refrigerators and lighting, as well as in air conditioners, building envelopes, and many appliances, were promoted by Energy Star labeling of appliances and even of buildings. For example, the number of new residences that attained Energy Star status increased from 57,000 in 2001 to 189,000 in 2006. For buildings, the median cost-effective and achievable potential (taking barriers to implementation into account) are 24 percent for electricity and 9 percent for natural gas. Unfortunately, this potential is sensitive to price, especially for natural gas.

Although potential gains from individual projects (e.g., appliances) are significant, the gains would be much greater if an integrated whole-building approach were adopted. Buildings can achieve much more substantial savings if they are designed to take advantage of natural light and if equipment is placed to reduce heating and cooling energy. A small but growing number of buildings have achieved a 50 percent savings in the energy used for heating, cooling, and hot water. Energy use for some buildings can be reduced by putting solar photovoltaic cells on the roof, which can transform a building into a net energy generator, although this is unlikely to be cost effective.

One way to view possible energy savings in buildings is to use "conservation supply curves" that estimate the cost of the energy conserved by using energy-efficient appliances or by renovating a structure. However, because conservation supply curves do not use an integrated approach, they are likely to understate the amount of efficiency that is cost effective. For example, switching from incandescent lamps to CFLs not only reduces energy use for lighting, but also reduces the air conditioning load in commercial buildings, allowing for downsizing of equipment and reducing the amount of energy required to cool the building. All of these technologies are generally available in the marketplace and are well proven.

Figure 4 is a representative conservation supply curve for residences. The figure shows how much electricity can be saved for all U.S. residences with various expenditures, beginning with the most cost-effective changes. For example, if all consumers selected energy-efficient color televisions rather than standard ones, they would save a total of 70 TWh of electricity per year at a cost of 1 cent per kWh, a 90 percent reduction in operating cost. Energy-efficient lighting, such as CFLs, could save an additional 160 TWh at a cost of just over 1 cent per kWh. In total, choosing the 12 appliances listed in Figure 4 rather than their less efficient models could save more than 600 TWh per year (about 15 percent of total electricity use) at a cost of 8 cents per kWh or less, leading to substantial dollar savings as well as substantial energy savings.

Unfortunately, realizing these energy and dollar savings will take many years. The analysis assumes that the purchaser chooses the more efficient alternative over the less efficient alternative when it is time to buy a new appliance. However, because furnaces and air conditioners can last for decades, many years may elapse before all current appliances are replaced. An ancillary point is that when a long-lived appliance is replaced, there is a singular opportunity to increase efficiency by choosing a more efficient model. If this opportunity is missed, it might be decades before another one arises.

Energy Use in U.S. Industry

The $2.6 trillion output of U.S. industry in 2006 was produced by diverse businesses with a wide array of products, processes, and ways of using energy. U.S. industry spends $200 billion per year to purchase 33 percent of the total energy used. About 8 quads of that energy are for feedstocks into the production of products, such as petrochemicals, fertilizer, and asphalt. The most energy-intensive industries are metals (iron, steel, and aluminum), petroleum refining, basic chemicals and intermediate products, glass, pulp and paper, and mineral products (cement, lime, limestone, and soda ash). In 2002, petroleum supplied 40 percent of industrial energy, and natural gas supplied 44 percent. Almost all of the coal used in the United States is for electricity generation, rather than for industrial use.

Because of a shift toward services and greater energy efficiency, energy use by industry is forecast to grow only 4 percent from 2007 to 2030 (EIA, 2009a). Nevertheless, U.S. industry is markedly less efficient in using energy than industry in other industrialized nations, due in part to the historical abundance of low-priced energy in this country. In addition, other industrialized nations impose high taxes on energy. In 2000, the Intergovernmental Working Group on Energy-Efficient and Clean Energy Technologies estimated that a portfolio of advanced technologies could reduce energy use by 16.6 percent by 2020. Using the latest projections by the Energy Information Agency, the savings would be 5.7 quads plus an additional 2 quads due to the increase in the use of combined heat and power (NRC, 2009). Table 2 is a summary of various estimates of increases in energy efficiency in U.S. industry by 2020.

Cross-cutting technologies, such as combined heat and power, better separation processes, advanced materials that resist corrosion and can withstand high temperatures, better steam and process heating technologies, new fabrication processes, and better sensors could lower energy use in many industries. As shown in Table 3, by 2020, improvements in energy efficiency could reduce energy use by 14 to 22 percent, compared to the usual projection, with rates of return of at least 10 percent. However, major barriers would have to be overcome to achieve these levels of improvement:

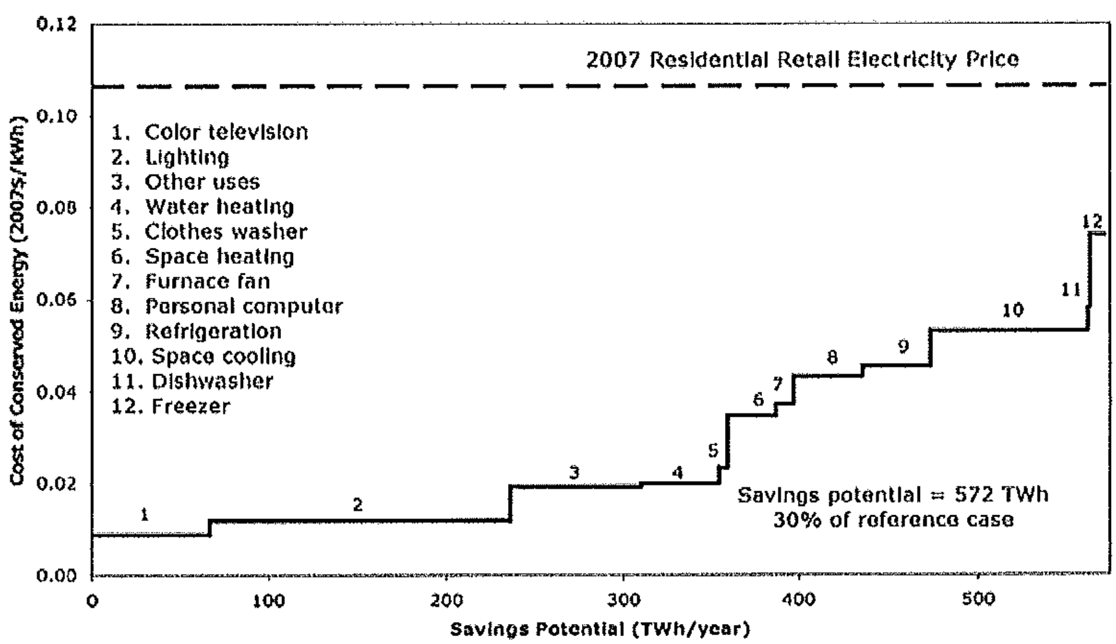

FIGURE 4 Potential electricity savings for residential products. Source: NRC, 2009.

TABLE 2 Potential for Energy-Efficiency Improvements in Industry by 2020: Sector-wide and for Selected Subsectors and Technologies (in Quads)

	CEF Study[a] Scaled to AEO 2008[b]	McKinsey and Company (2008)	Other U.S. Studies	Global Estimates from IEA (2007)
Petroleum refining	N/A	0.3	0.07–1.46 to 1.68–3.94	13–16%
Pulp and paper	0.14	0.6	0.53–0.85	15–18%
Iron and steel	0.21	0.3	0.76	9–18%
Cement	0.08	0.1	0.04 to 0.65	28–33%
Chemical manufacturing	N/A	0.3	N/A	13–16%
Combined heat and power	2.0	0.7		
Total Industrial Sector	7.7	4.9		18–26%
	(22.4%)	(14.3%)		

Source: Based on NRC, 2009.
[a] For CEF study, see Intergovernmental Working Group, 2000.
[b] AEO 2008, see EIA, 2008a.

- Because each industrial plant is unique, new technologies pose technical risks and may interrupt production or lower the quality of a product, even if they have been proven effective in other plants.
- Industry is looking for a much higher rate of return than 10 percent in allocating investment funds among competing projects.
- Plant managers are unlikely to have the discretion to invest in energy efficiency or reductions in emissions unless they are required to do so by regulation or ordered to do so by company management.
- Efficiency innovations often require specialized knowledge that many current plant managers do not have.
- If a new technology interrupts production, lowers product quality, or otherwise lowers the value of plant output, the costs could be much higher than the savings from energy efficiency.

Energy Use in Transportation

Modest improvements in efficiency will be made in some modes of transportation as new technologies are introduced and as research results are transferred. For example, the new 787 and 747-8 jets will provide a 15 to 20 percent increase in fuel economy compared to the models they replace. However, an increase in air traffic is expected to far outweigh improvements in efficiency, leading to greater fuel consumption overall.

Fuel accounts for a major proportion of annual costs in the trucking industry, which has always made fuel economy a priority. Modest improvements are expected in this sector, mostly from truckers shutting off their engines rather than idling when a truck is not moving.

Rail transportation and marine shipping have also put a premium on efficiency, and diesel-electric locomotives and diesel ship engines have improved efficiency over time in both sectors. The major potential for reducing fuel use in freight transport in the future will be from slower speeds and better integration among shipping modes. For example, freight could be carried by rail for the long part of a haul, with local pickup and delivery by truck. The widespread use of containers has removed many of the barriers to intermodal coordination.

Barriers to Energy Efficiency

Formidable barriers stand in the way of the implementation of energy-efficient changes. First, energy prices are artificially low because they do not account

TABLE 3 Summary of Potential Savings in Industry (estimated energy savings due to energy-efficiency improvements in industry)[a] (in Quads)

	Energy Use in Industry			Savings over Business as Usual (BAU) in 2020[a,b]
		BAU Projection (DOE/EIA Reference Case)		
Industry	2007	2020	2030	Savings in 2020[a,b]
Petroleum refining	4.09	6.07	7.27	0.77–2.81
Iron and steel	1.38	1.36	1.29	0.21–0.76
Cement	0.44	0.43	0.41	0.04–0.39
Bulk chemicals	6.85	6.08	5.60	0.30
Pulp and paper	2.15	2.31	2.49	0.53–0.85
Total savings for all industries (including those not shown)				4.9–7.7[c] 14%–22%

Source: NRC, 2009.

[a] Based on review of studies for specific major energy-using industries, for industrial combined heat and power (CHP), and for industry as a whole.

[b] Savings shown are for cost-effective technologies, defined as those providing an internal rate-of-return of at least 10 percent.

[c] Includes 0.7–2.0 quads from CHP systems.

for environmental or energy-security externalities, such as air and water pollution, greenhouse gas emissions, and other environmental effects, and the costs of ensuring a stable supply of energy imports. A high price for energy, such as the prices in July 2008 for gasoline, natural gas, and coal, would justify the implementation of more efficiency measures. In addition, high prices tend to focus attention on efficiency and conservation, an important factor in potential savings. Unfortunately, wildly fluctuating prices in 2008 wound up undermining the ability of producers and consumers to predict future prices and thus tended to also undermine arguments for investments in efficiency.

Second, current tax policies encourage expenditures on energy rather than on greater efficiency. Energy expenses are considered a current cost while expenditures for efficiency must be depreciated over time.

Third, in most states, utilities' profits go up when they sell more electricity or natural gas, and, logically, they go down by encouraging efficiency. Some states, such as California, have changed the compensation rules to motivate utilities to invest in efficiency rather than increasing energy use. A related issue has been that each utility has exclusive rights to sell its product in its service area, which has impeded the development of combined heat and power, microgrids, and other energy-efficient technologies.

Fourth, the decision about whether to invest in energy efficiency is often made by someone other than the person paying the energy bill. For example, a landlord may select appliances, but the tenant pays for electricity. Similarly, architects and builders, who are motivated to keep the price of a building down, may choose windows, insulation, and other materials with a focus on minimizing first costs rather than minimizing lifetime costs.

Fifth, architects, builders, workers, and customers all need more and better information. If they do not understand the benefits of alternatives, they cannot make informed choices.

Sixth, because energy expenditures are often a small part of the cost of occupying a residence or running a business, they often get little attention.

Seventh, energy-efficient appliances must be mass produced to be competitive with less efficient appliances. This cannot happen, however, until a substantial number of customers express a desire for these products. This chicken-and-egg problem can keep products with important advances from entering the market.

Finally, energy-efficient alternatives often have a higher initial price tag than less efficient products. If

TABLE 4 Estimates of Energy Savings from Major Energy-Efficiency Policies and Programs

Policy or Program	Electricity Savings (TWh/yr)	Primary Energy Savings (Quads/yr)	Year
CAFÉ vehicle-efficiency standards	—	4.80	2006
Appliance efficiency standards	196	2.58	2006
PURPA and other CHP initiatives	—	1.68	2006
ENERGY STAR labeling and promotion	132	1.52	2006
Building energy codes	—	1.08	2006
Utility and state end-use efficiency programs	90	1.06	2006
DOE industrial efficiency programs	—	0.40	2005
Weatherization Assistance Program	—	0.14	2006
Federal Energy Management Program	—	0.11	2005
TOTAL	—	13.37	—

Source: NRC, 2009.

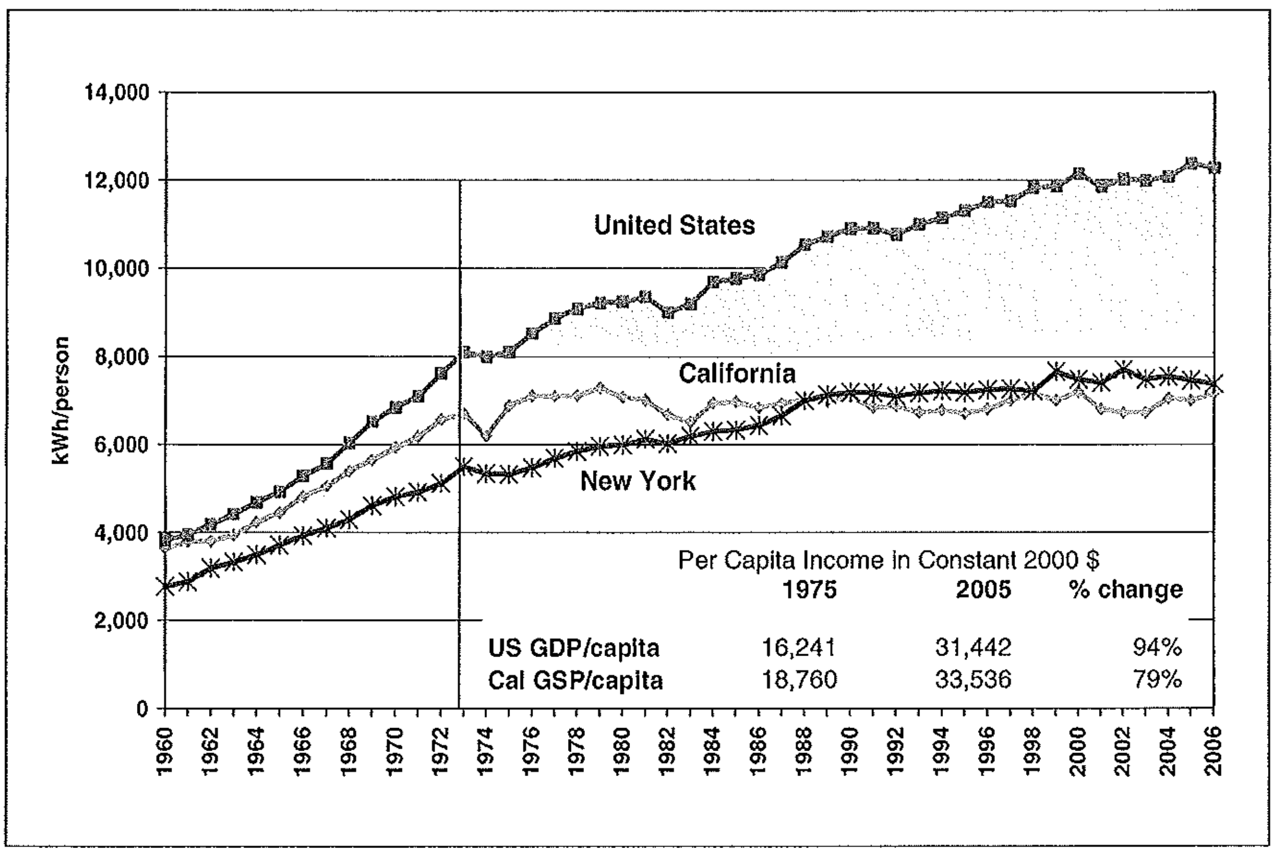

FIGURE 5 Per-capita electricity consumption in California, New York, and the United States as a whole, 1960–2006 (not including on-site generation). Source: NRC, 2009.

customers cannot afford the higher price or if they have to pay credit card interest rates, they are not likely to choose the energy-efficient alternative.

Drivers of Energy Efficiency

Despite these barriers, substantial progress has been made in energy efficiency, as shown by the drop in energy intensity of the U.S. economy. New energy-efficient technologies (e.g., electric arch furnaces rather than integrated steel mills) are being adopted, even though energy efficiency is not the major reason. Another driver has been intense competition. Sometimes, although energy savings for a plant may be small, they can make the difference between a facility that becomes profitable and one that cannot compete.

Regulations, such as vehicle fuel-economy standards address energy efficiency directly. Since environmental emissions generally consist of waste raw materials and fuel, regulations for air and water pollution discharges often encourage more efficient use of these inputs, including better energy efficiency.

Appliance and building codes have been particularly important in improving energy efficiency (see Figure 3 for refrigerators). In these cases, standards have overcome barriers to bringing more efficient, cheaper products to market. However, regulation is a deceptively simple tool for change; in fact, it cannot work without the cooperation of both industry and consumers.

A less heavy-handed innovation has been providing customers with information (e.g., Energy Star labels) about how much energy a product uses. However, customers must also be educated about how to use this information. Pressure from educated consumers and investors has motivated many companies to improve their energy efficiency and the energy efficiency of their products.

Table 4 shows estimates of energy savings as a result of government policies. California and New York, which have aggressively promoted electricity savings, have held electricity use per capita nearly constant for more than two decades. As a result, their use per capita is 40 percent below the national average (Figure 5).

Conclusion

The AEF Energy Efficiency Panel concluded that existing technology, or technologies that will be developed in the normal course of business, could save 30 percent of the energy that would have been used by 2030 under current policies and assumptions. About half of that efficiency increase could be achieved by 2020. The energy savings represent a savings in dollars as well as in energy. However, formidable obstacles must be overcome to realize these savings, which will require major public and private support, including product labeling, efficiency regulation, changes in tax policy, and educating and informing designers, builders, operations personnel, and customers about the benefits of energy efficiency.

Finally, special attention must be paid to the design and purchase of long-lived assets, from buildings and automobiles to refrigerators and air conditioners. Because of their long lifetimes, when an energy-inefficient product is purchased, the inefficiency cannot be eliminated until the product is replaced, which may take decades. Therefore, the energy efficiency of long-lived products should be improved, and purchasers should not only have the information they need to appreciate their energy efficiency, but should also have incentives to choose them over less efficient, often lower priced, competitors.

References

EIA (Energy Information Administration). 2008a. Annual Energy Outlook 2008 with Projections to 2030. Available online at *http://www.eia.doe.gov/oiaf/archive/aeo08/index.html*.

EIA. 2008b. Short-Term Energy Outlook. Available online at *http://www.eia.doe.gov/emeu//aer/pdf/pages/sec1_5.pdf*.

EIA. 2009a. Annual Energy Outlook 2009 with Projections to 2030. Available online at *http://www.eia.doe.gov/oiaf/aeo/demand.html*.

EIA. 2009b. Energy Intensity Using Purchasing Power Parities (Btu per Year (2000) U.S. Dollars Market Exchange Rates). International Energy Statistics. Available online at *http://tonto.eia.doe.gov/cfapps/ipdbproject/iedindex3.cfm?tid=44&pid=47&aid=2&cid=&syid=2002&eyid=2006&unit=BTUPUSDM*.

EIA. 2009c. Total Primary Energy Consumption per Capita (Btu per year (2000) U.S. Dollars Purchasing Power Parities). Available online at *http://tonto.eia.doe.gov/cfapps/ipdbproject/iedindex3.cfm?tid=44&pid=45&aid=2&cid=&syid=2002&eyid=2006&unit=BTUPUSDP*.

IEA (International Energy Agency). 2004. Oil Crises and Climate Challenges: 30 Years of Energy Use in IEA Countries. Paris: Organization for Economic Cooperation and Development.

Intergovernmental Working Group on Energy-Efficient and Clean Energy Technologies. 2000. Scenarios for a Clean

Energy Future. ORNL/CON-476. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

McKinsey and Company. 2008. The Untapped Energy Efficiency Opportunity of the U.S. Industrial Sector: Details of Research, 2008. New York: McKinsey and Company.

NRC (National Research Council). 2009. Realistic Prospects for Energy Efficiency in the United States. Washington, D.C.: National Academies Press.

Schurr, S., and B. Netschert. 1960. Energy in the American Economy, 1850–1975: An Economic Study of Its History and Prospects. Baltimore, Md.: Johns Hopkins University Press.

Taub, E.A. 2009. Industry Looks to LED Bulbs for the Home. New York Times, May 11, 2009, p. B6.