

TECHNOLOGIES TO REDUCE CARBON DIOXIDE EMISSIONS IN THE NEXT DECADE

The rise in the average global temperatures over the past few decades^{1,2} has raised concerns that the warming stems in part from anthropogenic emissions of so-called greenhouse gases, that is, those gases that trap heat near Earth's surface. Dominant among the greenhouse gases caused by human activity is carbon dioxide, even when the gases are compared in terms of their perturbation to the atmosphere, as in figure 1. CO₂ is a natural component of the atmosphere, but its concentration has increased by one-third since the start of the industrial era and continues to rise at about 0.4% per year.¹

Concern about the global impact of greenhouse emissions led representatives from 160 nations to meet in Japan in December 1997 and draft the Kyoto Protocol. The protocol calls on the developed nations to reduce emissions of carbon from CO₂ (or the carbon equivalent of other greenhouse gases) to 5.2% below their 1990 levels between 2008 and 2012. The nations meet again this month at the Conference of the Parties 6, to be held at The Hague, to consider mechanisms for meeting those goals (see the story on page 43 of this issue).

In 1990, the US emissions of carbon dioxide alone amounted to about 1300 million tonnes of carbon (MtC), or 23% of the 5800 MtC spewed out worldwide. (One tonne, or 1000 kilograms, of carbon is equivalent to 3.67 tonnes of CO₂.) Under the Kyoto accord, the US is to reduce its output of carbon and carbon equivalents by the end of this decade to 7% below 1990 levels. But by now, US emissions of carbon from CO₂ have risen 18% above 1990 levels and, if the nation follows current trends for the next decade, it is predicted to increase those emissions by another 16%. Hence, the mandate to *reduce* these emissions poses an ambitious challenge indeed.

We have chosen to focus on CO₂ rather than other greenhouse gases because of its currently dominant role. Almost all of the CO₂ emissions in the US come from burning fossil fuels, which in turn accounts for about 90% of our energy use. Thus we look at the potential of energy-efficient and other low-carbon technologies to help the US reduce its CO₂ output by displacing the need to burn fossil fuels while still enabling the economy to grow. We

The prospects for meeting the Kyoto Protocol for greenhouse-gas reductions will be brighter if the US can develop technologies to lower its energy use.

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believe that such measures can reduce US emissions of carbon from CO₂ to 1990 levels, with the rest of the mandated reductions in carbon-equivalents coming from cuts in other greenhouse gases or from carbon sequestration. Many physicists have participated in the development of conservation technologies, and many more will be needed to reach

the ambitious goals set at Kyoto.

Energy history

In the era of low energy prices preceding 1973, the energy efficiency of many building, transportation, and industrial technologies in the US improved little, so that US energy demand (E) and gross domestic product (GDP) grew in lockstep. This linkage, which many in the US believed to be inexorable, was abruptly broken with the Arab oil embargo of 1973–74. As seen in figure 2, from 1973 to 1986, the energy per dollar of GDP (corrected for inflation) dropped while the nation's energy demand froze at about 74 quads (Q). (A quad is 1 quadrillion British thermal units, or about 10¹⁸ joules.) With the decline in energy prices starting in 1986, energy demand once again rose, from 77 Q in 1986 to 94 Q in 1999 (a rate of 1.7% per year).^{3,4} Carbon emissions have increased at a similar pace. The ratio E/GDP, however, has continued to drop, and in the past three years has done so at an accelerated pace—possibly associated with the rise of information technology and the growth of productivity.

Following 1973, investments in more efficient technologies were facilitated by high and rapidly rising energy prices and by federal and state policies enacted to promote energy efficiency. During this period, Americans purchased more fuel-efficient cars, appliances, and energy-efficient equipment; installed more insulation and high-efficiency windows in their homes and businesses; and adopted more efficient manufacturing processes in factories. Then, in 1985, oil prices collapsed. The lack of progress in energy efficiency in the subsequent 10 years was due mainly to nontechnical factors. The good news is that there is now a backlog of improvements to be had in energy-related technologies.

Five-labs study

Since 1990, four major studies have assessed the US potential to reduce greenhouse-gas emissions using cost-effective, energy-efficient, and low-carbon technologies in the 2010 time frame.^{5–9} We have based this article in part

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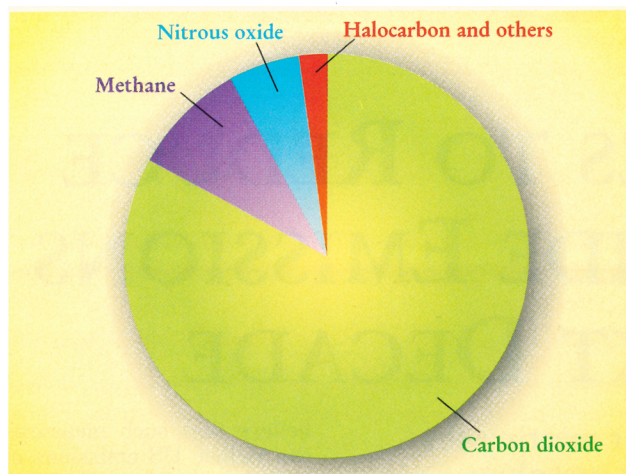


FIGURE 1. US GREENHOUSE-GAS EMISSIONS in 1997. Emissions are given in equivalent-carbon units, which rate the potential contribution of each gas to global warming, relative to the impact of carbon dioxide.⁴ CO₂ accounts for 83% of the total; methane, 9%; nitrous oxides, nearly 6%; and halocarbons and other gases, 2%.

on the 1997 study by five US national laboratories⁵ (which we will call the five-labs study). As participants in that study, we concur with its central conclusion—that a vigorous national commitment to develop and deploy cost-effective, energy-efficient, and low-carbon technologies could reduce carbon dioxide emissions to 1990 levels. We also agree with the study's estimate that the concomitant energy savings might be equal to or perhaps even greater than the cost of deploying the technologies.

As shown in figure 3, the potential carbon reductions estimated in the five-labs study amount to about 400 MtC/yr by 2010. If no carbon-reduction measures are enacted, the US in that year is expected to *exceed* its 1990 carbon emissions by just this amount: 400 MtC/yr.¹⁰ Thus the technologies identified in the five-labs study should just get us back to the 1990 carbon emission levels by 2010.

In figure 3, the potential 2010 annual reductions in carbon emissions for the four energy-use sectors are rated as a function of the cost of each measure, in terms of dollars per ton of avoided carbon. Such "costs" are negative in the case of the buildings, transportation, and industrial sectors, meaning that the carbon-reduction measures more than pay for themselves; that is, the net present value of the energy savings exceeds the cost of implementing the measures. In the utility sector, however, the costs of carbon-reduction measures are estimated to be positive: Utilities will have to make a net investment under this scenario, in the five-labs study. But if, to meet its Kyoto goals, the US needs to purchase carbon "credits" from nations that currently use less than their quota, then a premium may become attached to efforts to save on carbon emissions. In the five-labs study, we assumed that these carbon emission credits might fall in the range of

\$25 per tonne to \$50 per tonne. In figure 3, the cumulative carbon savings is the decrease in 1998–2010 carbon emissions predicted if carbon credits are \$50 per tonne⁵ compared to the emissions expected in the same period if no additional energy-efficiency measures are introduced.¹⁰

The energy reductions shown in figure 3 for the building, industrial, and transportation sectors stem, in the five-labs study, primarily from improvements in end-use technology. In the utility sector, most of the savings come on the supply side, from fuel substitutions such as retrofitting, or "repowering," power plants to burn natural gas rather than coal (which generates almost twice as much carbon per kWh generated), or from adapting a procedure known as "carbon-based electricity dispatch," in which plants with lower carbon fuels are preferentially operated over those powered by cheaper, higher carbon fuels.

We now survey some of the existing and emerging technologies that made possible the savings predicted by the five-labs study for the three energy end-use sectors: buildings, industry, and transportation. We have chosen not to discuss the utility sector explicitly. That sector is changing rapidly and becoming increasingly intertwined with the end-use sector through the introduction of distributed power generation, such as combined heat and power systems (see the box on page 32). The utility sector is also turning toward greater use of noncarbon sources, such as renewables.

The buildings sector

Energy is used in buildings to provide lighting, space conditioning, refrigeration, and hot water, and to power electrical equipment. In the US, energy consumption by both commercial and residential buildings accounts for a little more than one-third of total primary energy consumption and related carbon emissions.¹¹

A sterling example of the possible gains in energy efficiency is the story of US refrigerators, which in 1973 accounted for 20% of the energy used in residences. Thanks to a combination of regulations, namely federal labeling and standards for energy efficiency of appliances, and technological innovations such as blown-in foam insulation, the rate of annual energy use for refrigerators changed from a 7% per year growth before 1974 to a 5%

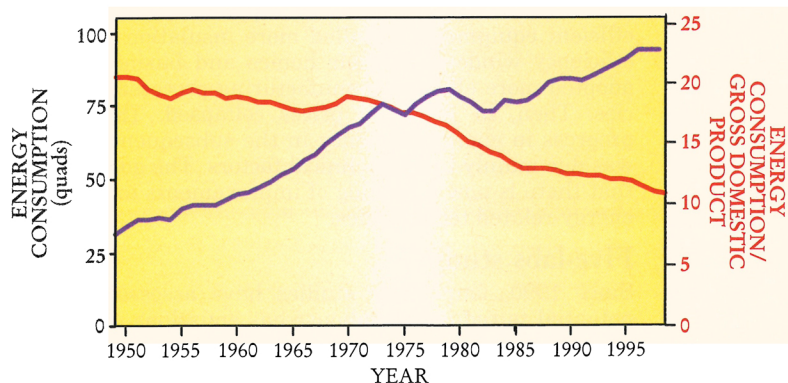


FIGURE 2. ENERGY USE AND ITS RATIO TO GDP in the US* from 1949 to 1999. Energy demand remained flat from 1973 to 1986, but has begun to rise in recent years. The decrease in energy per dollar of GDP (in 1996 dollars) shows that our economy continues to become more efficient.

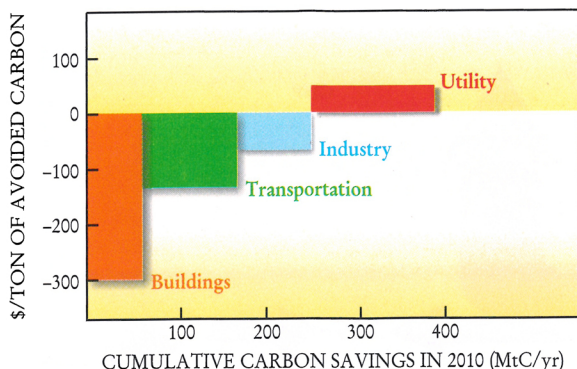


FIGURE 3. ESTIMATES OF CARBON SAVINGS AND COSTS predicted to be achievable by different sectors of the US economy.⁵ Negative costs indicate that the introduction of energy-efficient, low-carbon technologies costs less than the energy they save.

drop every year for the past 25 years. As the average US refrigerator has evolved from one that guzzled 1800 kWh/yr in 1974 toward the 2001 federal standard of 450 kWh/yr, refrigerator energy use has dropped to one-quarter of its former use, even as the average volume has grown from 18 to 20 cubic feet. As for economic savings, by the time 150 million refrigerators and freezers have

reached year-2001 efficiency, compared to 1974, they will use 200 billion kWh less per year, saving consumers \$16 billion per year. That's also the wholesale value (at the bus bar) of all nuclear energy sold in the US last year. The lesson is that conservation deserves as much of our research attention as new sources of fuel, if not more.

Similar opportunities to save energy exist in the buildings sector. Here's just a sampling of the technologies that could be developed by 2010, in the estimate of the five-labs study, given sufficient R&D support:

- ▷ sensors and controls that facilitate better management of building energy use, allowing building settings (such as temperature) to respond to energy prices in real time
- ▷ self-powered buildings¹²
- ▷ modular construction, with computer-assisted design

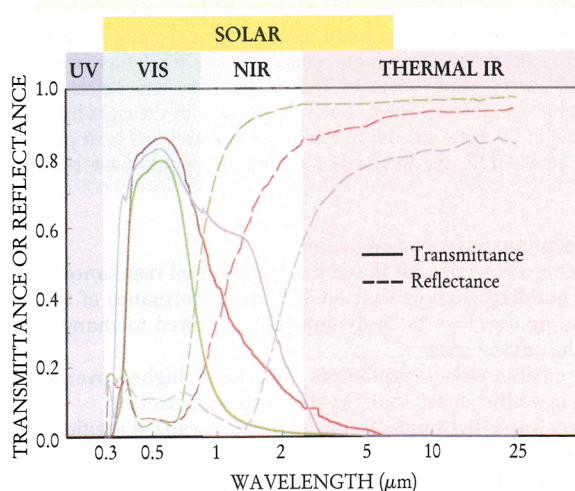
Low-Emissivity Window Coatings

Before 1973, nearly 5% of the national energy consumption was attributed to windows—that is, to the heating, cooling, and lighting required to compensate for the effect of windows. Advances in window technology have substantially reduced those losses and have the potential to make windows net sources rather than sinks of energy, especially in cold climates.¹³ Unlike insulated walls, which at their best prevent the outward flow of heat, optimal windows can accept solar gain and hence provide net heating.

Great advances have come from research on coatings for windows. Although many kinds of coatings have been developed, such as solar control coatings seen on high-rise office buildings, which reflect across the whole spectral range to reduce glare or overheating from the sun, the most effective coatings for reducing energy consumption are those with low emissivity (e). Such coatings can greatly reduce the radiative heat losses, which account for two-thirds of heat transfer through a double-glazed window. The coatings have a high reflectance, hence low e , in the thermal infrared (IR) and a high transmittance (T) in the visible. Additionally, some coatings are designed either to admit solar near IR (NIR) to help heat a building in a cold climate or reflect the NIR back in a warm climate. Since their introduction in 1981, windows with low- e coatings have captured 35% of the sales and generated gas savings that are equivalent in energy to one-half the output of oil in Prudhoe Bay. But the windows will long outlast that dwindling northern reserve.

To engineer these optical properties of a coating, researchers can either select a material with the right intrinsic properties or combine several materials to achieve the desired performance. One class of high- T , low- e materials consists of doped oxides of tin or indium, which are wide bandgap semiconductors. Adjusting the dopant level can tune the wavelength cutoff between transmittance and reflectance.

Another class of materials comprises very thin films of noble metals, especially silver. Although thick films of silver are highly reflective, the reflectance of very thin films (10–20 nm) can be suppressed by thin-film interference effects. Adding dielectric layers to the front and back of the metal layer thus reduces the reflectance of the thin film for a limited range of wavelengths. These coatings can be made highly transparent to



visible radiation, but remain reflective in the NIR.

The figure above shows the transmittance (solid curves) and reflectance (dotted curves) of three actual window coatings. The single-layer conducting oxide coating (gray) has a high T throughout the IR, and the other two, both thin metal coatings, have reduced T in the NIR. The double metal layer (green) cuts out more of the NIR and has a sharper transition between transmittance and reflectance than does the single metal layer (red).

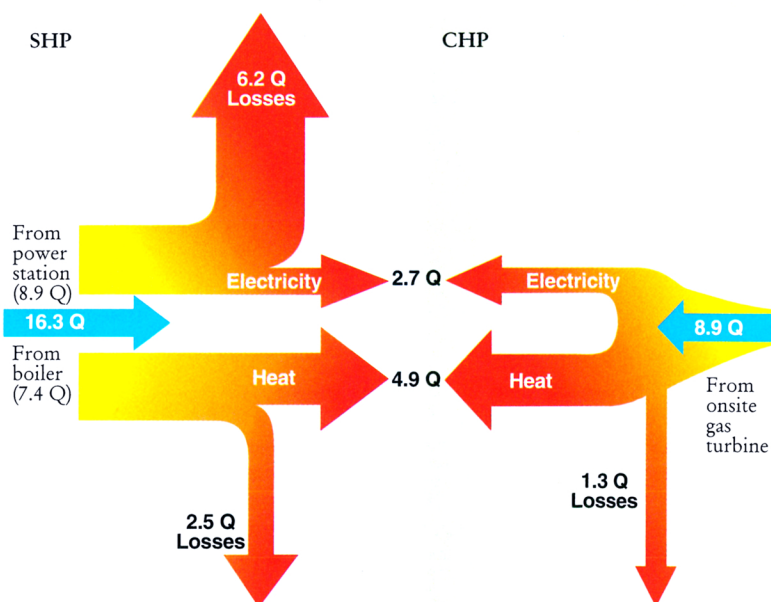
Low- e coatings insulate best when combined with features such as multiple panes with low-conductance-gas fills that minimize convection, and with insulated window frames that minimize conductive heat transfer. Researchers are now trying to design windows whose properties can be switched either actively or passively as ambient conditions change. For example, electrochromic windows can be electrically switched to give greater or less transmittance. The key to these more complex devices is better understanding of materials properties. Another thrust is to make coatings that are easier and cheaper to manufacture. (The cover of this issue shows a chamber used to deposit experimental low- e coatings on windows for research.)

Combined Heat and Power Systems

Many industries currently receive their electricity from a central power station and their process heat from a separate onsite boiler. However, increasing numbers are opting to produce both electricity and heat onsite with a combined-heat-and-power (CHP) system, also called cogeneration. CHP, largely in the industrial sector, now accounts for nearly 10% of US electricity generation.¹⁴

Conventional power plants typically have efficiencies of just 30% and thus discard 70% of the input energy as waste heat. By contrast, the natural-gas-fired combustion turbines used in the industrial sector have efficiencies that have risen from less than 20% in the mid-1970s to more than 40% today. Their system efficiencies are above 85% when the waste heat is used for industrial processes or for plant heating and cooling.

Considerable savings in energy could result from wider deployment of CHP systems,^{15,16} as illustrated in the figure at right. As seen for the separate heat and power (SHP) system in the left-hand panel, US manufacturers in 1994 used 2.7 Q in electricity supplied from power stations and 4.9 Q of process heat produced in an onsite boiler. Associated losses were 6.2 Q at the power plant and in the transmission lines, and 2.5 Q for the boiler, for a total energy requirement of 16.3 Q and a system efficiency (usable energy/total energy) of 47%. As seen in the right-hand panel, if the same amount of electricity and heat had been produced as CHP, the total fuel requirements would have been



only 8.9 Q, giving a system efficiency of 85%. Much larger penetration of CHP into the industrial sector is possible by 2010 because more than three quarters of the thermal capacity installed in industries today is likely to be retired by that date.¹⁶ The main barriers to greater adoption of CHP are nontechnical, such as the numerous and sometimes conflicting state and local electricity and environmental regulations.

to facilitate mass customization

▷ new materials that maximize the thermal resistance of the building shell or that enable the performance of the building envelope to be dynamically adjusted to changes in the environment

▷ multifunctional appliances that have higher overall thermal efficiencies than smaller, separate units

▷ advanced lighting systems mixing centralized artificial light sources with tracking sunlight concentrators and light distribution systems

The box on page 31 details one of the building-energy technologies that has benefited from materials research: low-emissivity windows.

The industrial sector

Energy use is extraordinarily complex and heterogeneous in the industrial sector, which encompasses not only manufacturing but also agriculture, mining, and construction. In the US, industrial energy consumption (including non-utility electric generators) accounts for slightly more than one-third of total primary energy consumption and about one-third of related carbon emissions.⁴ Manufacturing accounts for about 70% of industrial-sector energy consumption. About half of that comes from the most energy-intensive manufacturers such as producers of iron and steel, pulp and paper, and petroleum refining.

Compared with the building and transportation sectors, the industrial sector has shown the greatest energy efficiency improvements. In looking at ways to reduce carbon generation by the industrial sector, the five-labs study examined supply-side technologies that reduce emissions without necessarily reducing the end-use demand. These

technologies include using by-product fuels more efficiently and retrofitting boilers for combined generation of heat and power, as described in the box above. On the demand side, savings might come from high-efficiency motors and advanced motor system drives and controls that have applications in many different types of industry.

Many other low-carbon, energy-efficient technologies vary with the particular industry. Take the steel industry, for example. A new cokeless steel-making process could cut energy use by 30% relative to the use of blast furnaces by going directly from solid ore to steel. This “smelt reduction” technique could also increase the industry’s productivity because its investment costs and operating costs (including environmental compliance) are much lower than for the traditional process.

In the aluminum industry, deployment of a carbonless anode as part of an advanced aluminum production cell could result in a 50% (or 2 MtC/yr) reduction in the emissions of carbon or its equivalents by 2010. In the manufacture of cement, the calcination of limestone is now the largest single source of process carbon emissions. By substituting waste products such as fly ash and blast-furnace slag for a portion of the calcined cement clinker (an intermediate product in cement production), emissions could be reduced 1–2 MtC/yr by 2010.

The transportation sector

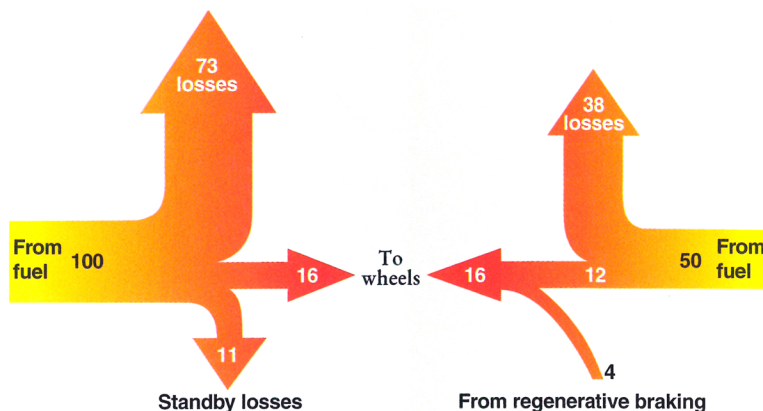
Transportation accounts for about one-quarter of total US primary energy consumption and one-third of carbon emissions. Although it currently has the fastest growth in carbon emissions, at 2.1% per year, it also has the highest potential carbon reductions. Technologies to double vehi-

A Doubly Efficient Electric Hybrid

The efficiency of an internal combustion engine can be increased if the engine is combined with an electric motor that enables it to reduce the standby energy lost while the engine is idling or running below full power. The flow chart in the figure at right compares the 100 units of fuel needed in a typical internal combustion engine (left) to 50 units needed by a "2X electric hybrid" (right) to produce the same amount of drive power in a car with twice the efficiency. Such efficient hybrids are now commercially available. As seen in the figure, even today's relatively efficient gasoline spark-ignition internal combustion engine loses 84 units of power per 100 units of input fuel, primarily to the exhaust, radiator, engine friction, and accessories. The most easily reduced of these losses are the standby losses, which eat up roughly 11% of the fuel; they are high in part because the engine is oversized to allow for acceleration. The 16 units of power delivered to the drive train are eventually all dissipated in braking and in overcoming rolling and wind resistance.

The 2X electric hybrid suffers no standby engine losses because it features a less powerful, more fuel-efficient engine-generator that is either on at full load or off. The hybrid uses a battery-powered electric motor to boost acceleration, so that the internal combustion engine is not oversized. When the engine is off, the battery powers these motors. When the engine is on, the batteries are either being recharged or boosting acceleration. The hybrid configuration shown in the figure also uses regenerative braking rather than friction braking: The electric motor is run as a generator during braking to recapture energy and charge the battery.

Prototypes of 2X vehicles have been produced by three US automakers—DaimlerChrysler, Ford, and General Motors—in



conjunction with the Department of Energy. In 1993, these three companies joined with DOE in a government-industry venture called the Partnership for a New Generation of Vehicles (PNGV) whose long-term goal is to come up with a 3X car that can triple the fuel efficiency of a 1993 car while preserving safety, performance, amenities, and the potential for recycling—all while holding down costs.¹⁸ Meeting this challenge will require continued intensive R&D. A major obstacle to reaching the PNGV affordability goal is the high cost of advanced lightweight body and tire materials.

The PNGV is also investigating other paths besides the hybrid to eliminate standby losses; these include advanced diesels, direct-injection stratified-charge gasoline engines, and fuel cells. As a result of PNGV, federal government R&D in advanced automotive technologies has been reorganized and redirected toward this ambitious goal.

cle miles per gallon are available today (see the box above). The automobile companies spend a large amount of money on R&D and have demonstrated their capacity for innovation by enormous improvements in vehicle performance. After the US government introduced the Corporate Average Fuel Economy (CAFE) standards, which set goals for the fuel efficiency of new vehicles sold in the US, the industry realized a gain for new passenger cars from 14 miles per gallon (mpg) in 1975 to 28.3 mpg in 1999.¹⁷ Recently, however, the average efficiency for new passenger cars has barely changed, going from 28.2 mpg in 1986 to 28.3 mpg today. (CAFE standards have been frozen since 1990 at 27.5 mpg.) The fuel economy of the entire fleet (passenger cars plus light trucks) has decreased in this period by 5%, due largely to a growth from about 29% to 44% in the percentage of light trucks—notably including today's popular minivans and sport utility vehicles. These trends are evident in figure 4.

In recent years, carmakers have focused their technical improvements on roomier, more powerful vehicles: The average new car horsepower has increased by nearly 40%, the weight by 9%, and the power per weight by 27%. To keep the fuel economy about the same while making heavier, more powerful cars, the automotive industry has had to introduce some fuel-saving features.

What fuel economy would the fleet have today if the R&D had focused on reducing fuel use rather than increasing power and weight? To answer that, we very roughly scale the fuel economy by the inverse of a vehicle's weight

and by inverse of the square root of the power. Using such an empirical formula, we estimate that today's cars might be getting 34 mpg if they hadn't gained weight and power since 1986. If, in addition, the percentage of less-efficient (20.7 mpg) light trucks in the fleet had remained constant at the 1986 value of 26%, the average fleet fuel economy would be 30.5 mpg rather than today's value of 24.5 mpg.

In its estimate of carbon reductions in the transportation sector, the five-labs study included a myriad of proven technologies deemed likely to enter the market by 2010 because of ongoing R&D: reduced aerodynamic drag, lower rolling resistance of tires, decreased engine friction, leaner burning engines, and variable valve timing. The study also stressed additional technologies that can raise fleet fuel economy by 2010 given the appropriate incentives. These technologies included direct-injection stratified charge gasoline engines, direct-injection diesel engines, and proton-exchange-membrane fuel-cell power trains, all of which give more control of the combustion process and hence greater efficiency than in a traditional internal combustion engine.

Commitment is required

It's clear that there are still many opportunities to reap gains in energy efficiency. Some technologies are already in the works and will be adopted in the due course of time. Other technologies will require R&D and may not come to pass unless a significant commitment is made to the required research. The challenge is to develop ways to pro-

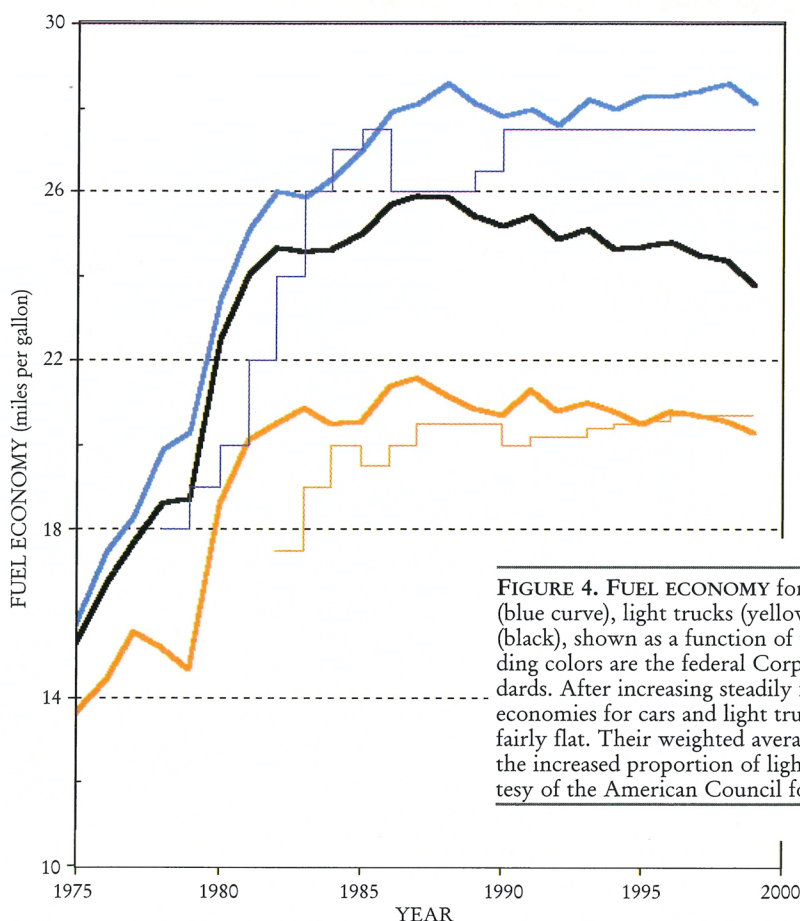


FIGURE 4. FUEL ECONOMY for the fleet of new US passenger cars (blue curve), light trucks (yellow) and the overall average of the two (black), shown as a function of time. The lighter lines in corresponding colors are the federal Corporate Average Fuel Economy standards. After increasing steadily for about ten years, the fuel economies for cars and light trucks sold in the US have remained fairly flat. Their weighted average has fallen, however, because of the increased proportion of light trucks sold in the US. (Figure courtesy of the American Council for an Energy-Efficient Economy.)

vide the same services at little or no increase in cost and with no sacrifice in performance. Even with adequate performance, some technologies will face nontechnical barriers to adoption. Thus, meeting the Kyoto accords will also require a significant commitment to governmental policies that stimulate adoption of higher efficiency and low-carbon technologies, such as those discussed in this article.

References

1. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, K. Maskell, eds., *Climate Change 1995: The Science of Climate Change* (contribution of Working Group I to the second assessment report of the Intergovernmental Panel on Climate Change), Cambridge U. Press, Cambridge, England (1996).
2. P. D. Jones, M. New, D. E. Parker, S. Martin, I. G. Rigor, *Rev. Geophys.* **37**, 173 (1999). J. Hanson, R. Ruedy, J. Glascoe, M. Sato, *J. Geophys. Res.* **104**, 30997 (1999).
3. *Annual Energy Outlook 1999*, (DOE/EIA-0383), Energy Information Administration, Department of Energy, Washington, DC (1998), Table 8.
4. *Annual Energy Review 1998* (DOE/EIA-0384), Energy Information Administration, Department of Energy, Washington, DC (1999). <http://www.eia.doe.gov>.
5. "Scenarios of US Carbon Reductions: Potential Impacts of Energy Technologies by 2010 and Beyond," (ORNL/CON-444), Oak Ridge National Laboratory, Oak Ridge, TN (1997). http://www.ornl.gov/ORNL/Energy_Eff/PDF/CON444/Summary.pdf
6. National Academy of Sciences, *Policy Implications of Greenhouse Warming*, National Academy Press, Washington, DC (1991).
7. US Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases* (OTA-O-482) US Government Printing Office, Washington, DC (1991).
8. Tellus Institute, <http://www.tellus.org>.
9. For a summary of the methodology and results of the four studies, see M. A. Brown, M. D. Levine, J. P. Romm, A. H. Rosenfeld, J. G. Koomey, *Annu. Rev. Energy and Environ.* **23**, 287 (1998).
10. *Annual Energy Outlook 1997* (DOE/EIA-0383), Energy Information Administration, Department of Energy, Washington, DC (1996).
11. *Annual Energy Outlook 2000* (DOE/EIA-0383), Energy Information Administration, Department of Energy, Washington, DC (1999).
12. T. Kaarsberg, R. Fiskum, J. Romm, A. Rosenfeld, J. Koomey, W. P. Teagan, *Combined Heat and Power of Saving Energy and Carbon in Buildings*, http://www.nemw.org/ACE_98.htm.
13. See <http://windows.lbl.gov> and <http://www.efficientwindows.org>
14. T. Kaarsberg, R. N. Elliott, M. Spurr, in *Proc. ACEEE 1999 Industrial Summer Study*, American Council for an Energy-Efficient Economy, Washington, DC (1999). See also <http://www.nemw.org/uschpa>.
15. *Manufacturing Energy Consumption Survey*, Energy Information Administration, Department of Energy, Washington, DC (1996). <http://www.eia.doe.gov/emeu/mecs>.
16. T. M. Kaarsberg, J. M. Roop, *IEEE Aerosp. and Electron. Syst. Mag.*, Jan. 1999, p. 7.
17. <http://www.nhtsa.dot.gov/cars/problems/studies/fuelecon>.
18. See <http://www.ott.doe.gov/oaat/pngv.html> and <http://www.ott.doe.gov/hev>.