

MEETING ENERGY CHALLENGES: TECHNOLOGY AND POLICY

In characterizing the years 2000–01, many energy analysts recalled the “Perfect Storm”—the confluence of climatic events that took the *Andrea Gail* and its crew in 1991. The energy events that invited this comparison included volatile prices for oil, gasoline, and natural gas; heating oil shortages; environmental issues; the California electricity crisis; and increased energy demand associated with the robust economic growth of the late 1990s. The September 11th attacks on the World Trade Center and the subsequent war on terrorism put a spotlight back on Middle East instability and its implications for the global energy picture.

Against this backdrop, oil dependence, energy conservation, and the environmental impacts of energy use have reemerged in public discourse at a level not seen since the oil shocks of the 1970s. The public debate has placed a renewed focus on the role of energy technology and policy in meeting several energy challenges. Preeminent among these challenges are energy security, provision of adequate and reliable electricity, and reduction of harmful emissions in the face of increasing energy demands associated with economic growth.

Energy security refers primarily to the geopolitical issues associated with ensuring adequate supplies of oil, on which the world’s transportation sector is almost totally dependent. Increased oil consumption exacerbates an ever-shifting century-old web of alliance and conflict between the world’s major oil suppliers and its major oil consumers. In the near future, geopolitical issues are likely to emerge in connection with natural gas supplies as well.

Adequate electricity supplies are central to economic growth and quality of life. Two billion people in the developing world are currently without access to electricity, and the environmental performance of existing plants is often poor. In the industrialized world, capacity needs to be increased in a manner consistent with the strict reliability requirements of the digital economy. In addition, out-

Effectively addressing today’s energy challenges requires advanced technologies along with policies that influence economic markets while advancing the public good.

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dated infrastructures need to be modernized, and suitable mechanisms for market deregulation need to be developed.

Major environmental concerns such as urban smog, acid rain, and greenhouse gas emissions with their potential for global warming and climate impact, arise principally as a consequence of energy use.

The development of clean, efficient, and economical technologies is necessary. However, technology development is not enough. Timely technology deployment often depends on having shaped the marketplace by policies designed to benefit the public.

A variety of fiscal, tax, security, regulatory, environmental, and educational instruments are policy tools used to advance the public good. The corporate average fuel-economy (CAFE) standards for vehicle fuel efficiency have reduced the nation’s reliance on oil and have improved the environment. Investments in unconventional natural gas production technology have led to a coal-bed methane resource that did not exist in 1982 but that now supplies more than 5% of our domestic natural gas consumption. Tax credits have helped stimulate the rapid growth of wind power, and industrial and automotive emissions caps have dramatically improved urban and regional air quality. A public education and outreach program reduced California’s electricity use by 10% last year.

Incentives or market mechanisms such as trade in carbon-emission credits, in theory, help move new technologies into the marketplace. Other policies, however, impede technology deployment or have unintended consequences. The following discussion of energy challenges highlights the links between technology and policy.

Global energy in perspective

Anticipated worldwide economic growth will lead to concomitant increases in energy demand and carbon emissions. This is evident in the following table, which provides key economic, energy use, and emissions data for 1999 and projections for 2020.¹ (The “quad” of energy cited in the table is a quadrillion Btu or 1.06×10^{18} joules.) In the developing world, the global tendencies are particularly pronounced.

The same factors that make it difficult to meet energy challenges, however, also highlight opportunities for new

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Key Indicators in 1999 and Projections for 2020				
Indicator	World	Industrialized countries	Eastern Europe/ former Soviet Union	Developing countries
Gross domestic product (trillions US\$)				
Total (1999/2020)	30.5/59.1	23.8/40.3	0.94/2.3	5.6/16.5
% increase/year	3.2	2.6	4.3	5.3
Energy consumption (quads)				
Total (1999/2020)	382/607	210/270	51/72	122/264
% increase/year	2.2	1.2	1.7	3.8
Electricity use/year (trillions kW hours)				
Total (1999/2020)	12.8/22.2	7.5/10.9	1.5/2.1	3.9/9.2
% increase/year	2.7	1.8	1.9	4.2
Carbon emissions (billion tonnes)				
Total (1999/2020)	6.1/9.8	3.1/4.0	0.81/1.1	2.2/4.6
% increase/year	2.3	1.2	1.4	3.7
Data adapted from ref. 1.				

technologies. For example, efficiency technologies applied in Eastern Europe, the former Soviet Union, and the developing world can, in the near term, substantially slow demand growth, ease competition for scarce resources, decrease carbon emissions, and increase energy export opportunities for energy-producing regions such as Russia.

The energy-consumption data presented in the table tell a compelling story. Over the next two decades, total world energy consumption is expected to increase by more than 50%. By 2020, energy demand in the developing world will more than double, and will roughly equal that of industrialized nations.

Electricity consumption forecasts, considered separately, tell an even more dramatic story. Global demand for electricity is predicted to grow by three-quarters from 1999 to 2020. In developing Asia, electricity consumption is forecast to increase by 150% over the same period. As with total energy, electricity consumption in the developing world will nearly equal that of the industrialized world by 2020.

Figure 1 shows, with an important qualification, that fossil fuels (oil, gas, and coal) will continue to provide more than 85% of the world's energy for the foreseeable future.¹ The data used to prepare the figure do not include energy generated by biomass fuels such as wood, charcoal, crop wastes, and manures. Such fuels, used especially in the developing world, may account for as much as 50 additional quads of energy each year.²

Transportation is the primary driver of increased oil demand, while increased natural gas consumption will be largely for power generation and greater industrial requirements. US consumption represents roughly half of that for the industrialized world and US fuel source consumption closely mirrors world patterns. Developing Asia, Central America, and South America will see the greatest increase in requirements for natural gas; they are each expected to triple their demand over the next twenty years.

Oil dependence and national security

World oil consumption is expected to grow by 60% over the period 1999–2020, from 75 million to 120 million barrels per day (1 barrel = 159 liters). Much of this increased consumption will be in transportation. In the developing world, people will own more cars and trucks—China alone expects a five-fold increase in vehicles by 2020. In the US, vehicle fleet efficiency is expected to remain flat for several years.

Large increases in oil and gas consumption raise significant geopolitical issues that could intensify as compe-

tition for supplies increases, market power is accumulated in fewer places, and more product is moved over longer distances. As figure 2 shows, oil supply and demand are not geographically well correlated. Despite the diversification of oil-producing regions in the past 20 years, global dependence on the Persian Gulf—which holds two-thirds of the world's proven oil reserves—will increase over the next two decades. The oil wealth of the Persian Gulf gives the region substantial geopolitical influence and constrains the ability of the US to fully exercise its strategic interests.

These effects are magnified by the concentration of excess production capacity (unused capacity that can be quickly produced when demand is high) in the Gulf. OPEC cohesion contributed to extreme oil price volatility since 1999; the high oil prices of 1999 and 2000 likely cost the US as much as 0.7 percentage points in gross domestic product (GDP).³

The most significant increases in oil demand will be in Asia, further enhancing the Gulf's influence. Earlier in this article we referred to the shifting web of alliance and conflict connected to oil production and consumption. The evolving reliance on Gulf oil has the potential to dramatically redefine that web.

A number of policies can be initiated or expanded whose objectives address oil and national security issues. Some of those objectives depend on investment, financial, or diplomatic actions for their realization. Examples include increasing protection against supply disruptions

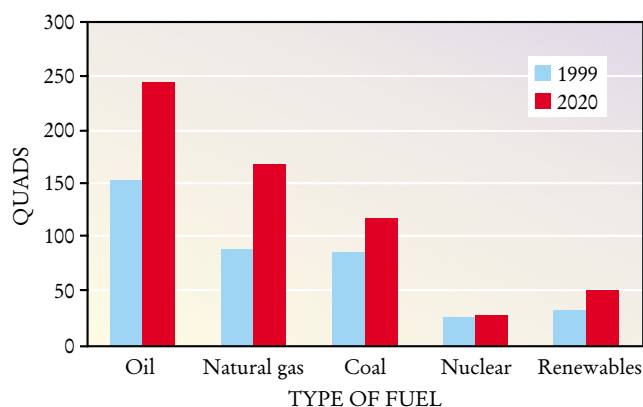
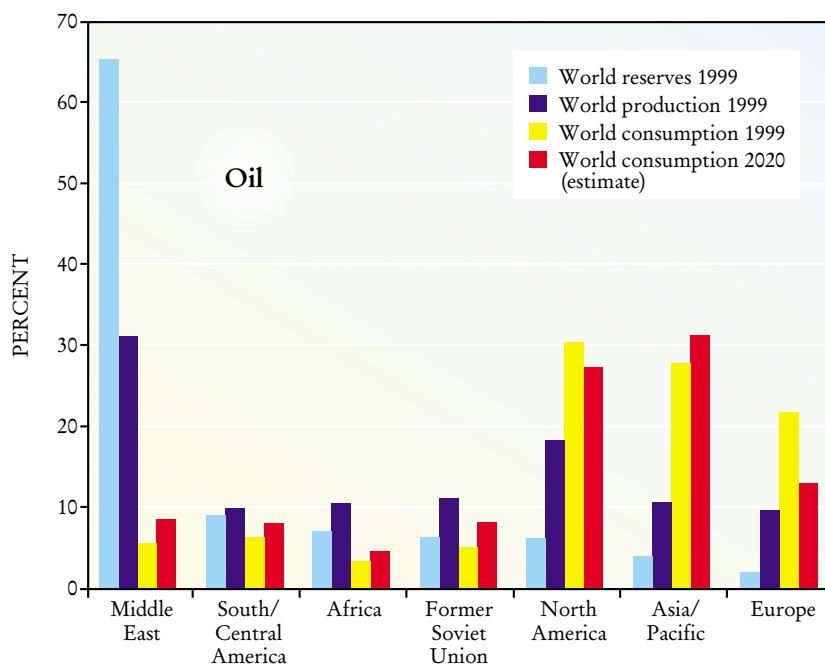


FIGURE 1. ENERGY CONSUMPTION by fuel source. The graph indicates world energy consumption in quads (1 quad = 1.06×10^{18} joules) for the years 1999 and 2020 (estimate) for various fuel sources. (Data adapted from ref. 1.)

FIGURE 2. OIL PRODUCTION, consumption, and reserves by region, as a percentage of the world total.
(Data adapted from ref. 1.)



by expanding strategic stocks, more effectively managing oil price volatility, and encouraging expanded international production capacity. Other objectives, such as developing unconventional oil resources or affordable alternatives to oil, and using oil more efficiently are largely driven by technology.

Figure 3 shows projections made by the President's Committee [now Council] of Advisors on Science and Technology (PCAST) of how aggressive technology deployment will affect US oil dependence.² Reducing oil imports by 6–7 million barrels per day before 2030 hinges on the highly uncertain prospect of strong policy actions in the next few years.

Policy support for R&D investments in the development of unconventional oil resources is critical to US domestic production, and to the expansion of production capacity in countries like Venezuela, which has vast reserves of ultraheavy oil that currently cannot be produced profitably. Oilfield production will also benefit from technological advances: Enhanced recovery techniques are essential for improving the 20–30% efficiency typical of traditional oil wells. (See the article "Physics in Oil Exploration," by Brian Clark and Robert Kleinberg, on page 48.) Given the time scale of technology development, R&D investments must be made in the near future to help meet mid-term demand.

Rising oil demand will also bring new requirements for R&D in transportation infrastructure (tankers and pipelines), and for affordable alternatives to refined oil products. Such alternatives include products derived from gas-to-liquid conversion, gasification of coal, and biomass. Corn-based ethanol has a small share of the vehicle fuel market, thanks mainly to a substantial federal subsidy; other biofuels, such as cellulose-based ethanol, may have growing significance in a decade or so.

Improved fuel economy provides the greatest opportunity for the US to reduce its oil dependence in the near to intermediate term. The current CAFE standards set average fuel-efficiency requirements of 27.5 miles per gallon (8.55 liters per hundred kilometers) and 20.6 mpg (11.4 L per 100 km) for new cars and light trucks (including sport utility vehicles), respectively. Technologies available now, some of them developed through a government–industry Partnership for a New Generation of Vehicles (PNGV), can greatly increase efficiency levels.⁴ Commercially available hybrid cars can approximately double the CAFE standard, and PNGV concept cars reached 80 mpg (2.94 L per 100 km) in 2000.

In January of this year, the Bush administration announced its intention to discontinue the PNGV program in favor of a greatly increased focus on one technology—hydrogen fuel cells. (See the article "Hydrogen: The Fuel of the Future?" by Joan M. Ogden, on page 69.) Hydrogen shows promise as a technology that could free transporta-

tion from its dependence on oil. Few, however, believe that the results of fuel-cell research will be seen on the highways for at least the next two decades. Conducting business as usual until fuel-cell vehicles are widely introduced is likely to greatly reduce the benefits of the advanced automotive technologies shown in figure 3, and will leave the US correspondingly more oil-dependent. The time scales for reaping the benefits of the PNGV and fuel-cell programs are significantly different. The nation needs to commit to both hydrogen R&D and to policies designed to accelerate the market penetration of technologies advanced by the PNGV program.

Developing natural gas resources

We noted earlier that geopolitical issues related to energy security are likely to emerge in connection with natural gas supply. Global demand for natural gas is growing as unevenly as it is dramatically, and the most significant increases are in those regions of the world with the fewest indigenous resources. Natural gas markets are limited by the inflexibility and expense of gas (versus liquid) transportation. Over half of the world's natural gas reserves are very far from users and it is currently not profitable to transport such "stranded" gas from these reserves to customers.

Figure 4 illustrates the geographic disparities between natural gas production and consumption.^{1,5} These disparities highlight the need to address key technical challenges concerning natural gas: developing resources; accessing stranded resources through gas-to-liquid conversion, liquefied natural gas process improvements, and new transportation and processing infrastructures; extending the resource base using alternative fuels such as biomass or, in the long term, methane hydrates; and using gas more efficiently in, for example, advanced turbine systems and smart buildings.

Both conventional and unconventional resources need to be developed. The National Petroleum Council emphasized the importance of major technology R&D efforts to access new domestic supplies within 15 years.⁶ In particular, the Council called attention to unconventional onshore reservoirs (low-permeability coal-bed methane,

tight gas sands, and shale) and ultra-deep (deeper than 5000 feet) offshore reservoirs.

Reliable power for a new age

Electrification was hailed by the US National Academy of Engineering as the greatest engineering achievement of the 20th century. In the century of lasers, computers, and space travel, that remarkable distinction reflects how electricity has transformed the quality of life: A flick of a switch now brings clean energy to virtually every household in the industrialized world. (See the cover of this issue.) One of the challenges of the 21st century will be to provide electricity to the developing world without significantly damaging the environment. A second challenge will be to improve power quality to meet the stringent requirements of the digital economy.

Today's dominant power architecture consists of large plants that provide power over long distances via high-voltage alternating-current transmission lines. This aged architecture is a product of technology from the first half of the 20th century. Nowadays, it is confronted with major bottlenecks that translate into outages and is ill-equipped to handle the complex transactions of the 21st-century marketplace. Transmission infrastructure expansions and upgrades face substantial local and regional opposition.

Advanced transmission technologies can help overcome infrastructure bottlenecks. In the near term, high-power solid-state electronics, integrated with modern sensors and communications, can provide much faster responses than those provided by electromechanical devices. As a consequence, solid-state devices are better able to manage system flows and disturbances. Even now, solid-state systems are relieving supply constraints to New York City. For the longer term, superconducting transmission lines offer many benefits, such as several-fold increases in the capacity of congested urban distribution lines, and will ultimately be used for long distance transmission. (See the article by Gloria B. Lubkin, "Power Applications of High-Temperature Superconductors," *PHYSICS TODAY*, March 1996, page 48.) To open up the needed technology investments, answers must be found for policy questions such as who owns and operates regional transmission systems in a deregulated electricity sector.

Widespread distributed generation—an architecture in which smaller, modular, grid-connected power sources are close to the customer—could relieve transmission demands, reduce transmission losses, and yield enhanced power quality.⁷ In addition, distributed sources can use fuel much more efficiently by exploiting the heat created as a byproduct of electricity generation, and they offer the possibility of bundling a range of consumer services. Many technologies, such as microturbines, fuel cells, advanced combustion engines, and those technologies associated with renewables can be hooked up to the electricity grid and are already economic for numerous applications. Off-grid applications of these technologies are particularly important in developing countries. In the US, regulatory and business barriers associated with the traditional monopoly utility system inhibit the development of 21st century distributed architectures. For example, a national grid interconnection standard would be important for the economics of small projects, but none exists, nor are there "rules of the road" for sharing transmission and distribution system benefits with the owners of the power sources.

Meeting the electricity demands of developing economies without major environmental degradation is a formidable challenge. China and India, the most populous nations on the planet, have substantial coal resources but

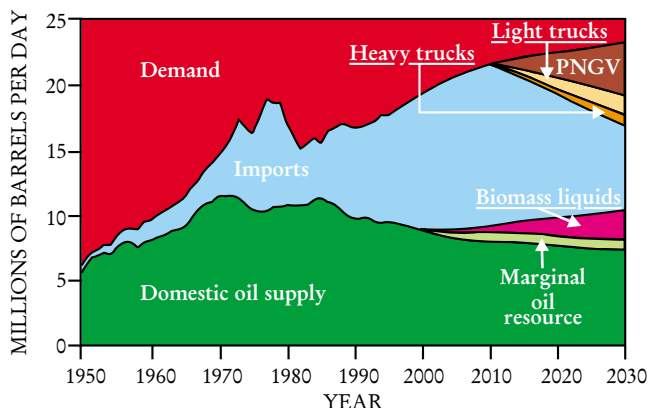


FIGURE 3. ADVANCED TECHNOLOGY and US oil imports.

This projection, formulated in 1997 by the President's Committee [now Council] of Advisors on Science and Technology (PCAST), shows the potential impact of aggressively introducing new technologies. Fuels generated from biomass have the greatest potential for increasing supply. Improvements in the fuel efficiency of automobiles and light trucks have the greatest potential effect on demand. In formulating its projections, PCAST assumed ethanol use in gasoline would grow from its current level of about 100 000 barrels per day from corn to about 2 million barrels per day from cellulosic biomass (1 barrel = 159 liters). They also assumed that cars with fuel efficiencies of 80 miles per gallon (2.94 liters per 100 kilometers) and light trucks that get 60 mpg (3.92 L per 100 km) would enter the market in 2010 and that market share would grow linearly to 100% in 2030. Absent major oil shocks, the PCAST assumptions are unlikely to be met without major policy initiatives. Such initiatives could take the form of higher corporate average fuel-economy (CAFE) standards, for example. (Adapted from ref. 2.)

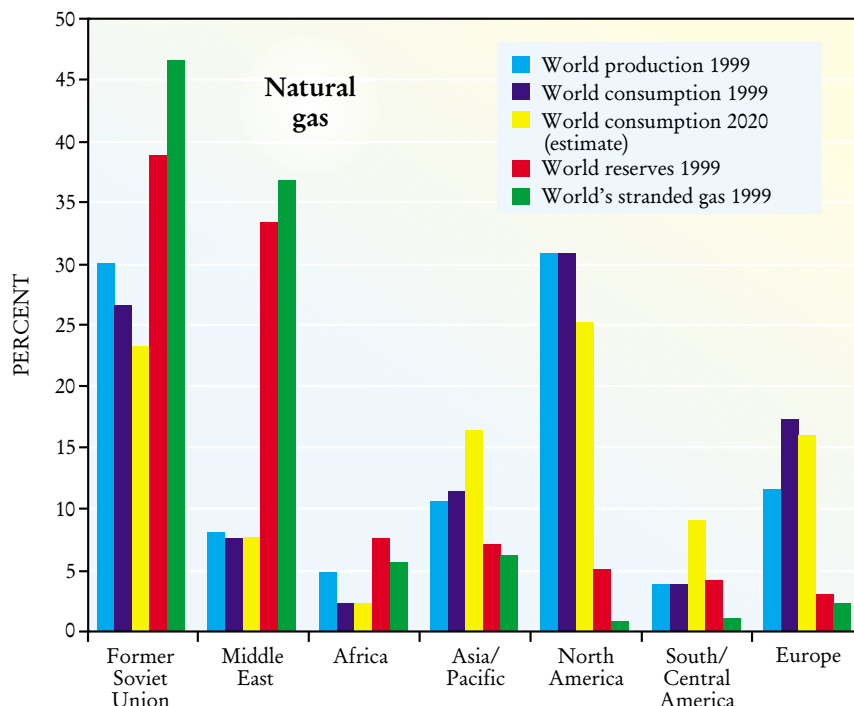
little natural gas. Advanced coal technologies are in the early stages of deployment in several countries and are much less polluting than traditional technologies. An example of such technologies is the integrated gasification combined-cycle turbine in which the exhaust heat from a gas-driven turbine is used to drive a steam turbine. Coal-based polygeneration, in which electricity, heat, and liquid fuels are produced simultaneously, can be economically attractive if the electricity can be sold at competitive prices. An additional attraction is that the efficiency of polygeneration reduces carbon emissions.

Environmental stewardship and climate change

Harmful atmospheric emissions from energy production and use are principally responsible for numerous environmental problems. Figure 5 shows the recent history of economic growth and emissions from electricity generation.⁸

The past 15 years have provided a model of sustained economic growth coupled with stabilization in nitrogen oxide emissions and reductions in emissions of sulfur dioxide. Policy-derived constraints on emissions of NO_x and SO_2 , which are largely responsible for smog and acid rain, and on other emissions have pushed environmental technologies into the marketplace. Carbon emissions, however, have not been subject to such constraints. A federal requirement for dramatic reductions of greenhouse gas emissions, in particular for carbon dioxide, over the next decades would greatly accelerate the next major transformation of world energy systems: a shift away from carbon-based energy sources that would be as profound as the

FIGURE 4. NATURAL GAS production, consumption, and reserves by region, as a percentage of the world total. (Data adapted from refs. 1 and 5.)



transformation that ushered in the age of fossil fuels.

The science of climate change has advanced considerably in the past few years.⁹ Scientists who model climate generally agree that a serious risk of disrupting the climate system could result if the atmospheric concentration of CO₂ were to rise to double its preindustrial level. Concentrations of CO₂ have already increased by one third. If carbon emissions are sustained at current global levels, CO₂ concentrations will probably meet the doubling mark in about a century. In fact, as figure 1 shows, global emissions levels are expected to increase well beyond current levels, shortening the doubling time commensurately. The typical time scales associated with energy-sector capital investment (15 years for automobiles, 40 years for power plants, 80 years for buildings) and with CO₂ persistence in the atmosphere (centuries) demand a prudent and timely public policy response. Each year of delay will bring a round of investments that will make it more difficult to reduce future carbon emissions.

One should not underestimate the policy or technology difficulties involved in reducing carbon emissions. The effects of climate change may be profound in the years or decades ahead, but political realities tend to focus on here-and-now health and ecological concerns. This short-term focus is problematic, since actions to head off long-term damage from greenhouse gases can have the greatest impact if taken early. Another problem is that the inherently global nature of climate change requires that policy be made internationally, a process that introduces a multitude of complicating political components.

The Kyoto Protocol calls for US carbon emissions by 2012 to be reduced by about 20% from today's levels. A more modest, but illustrative target would be that global carbon emissions at mid-21st-century equal today's levels. Fossil fuels now supply about 320 quads of energy globally and total energy is projected at more than 1000 quads in 2050, if one assumes an annual growth in fuel consumption of about 2%. If the projected growth is to be met while carbon emissions are maintained at current levels, the use of economic non-carbon-emitting energy sources will have to increase by more than an order of magnitude. That's a 5% annual increase maintained for 50 years.

Deconstructing carbon emission

Several factors that affect carbon emission can be presented together with the help of the often used notional equation:

$$\text{net carbon emissions} = \text{GDP} \times (\text{energy/GDP}) \times (\text{carbon emissions/energy}) - \text{carbon sequestered}.$$

The challenge to reduce carbon emissions can be analyzed by considering the individual terms in this equation.

The gross domestic product (GDP) is an indicator of economic development and energy use. Anticipated GDP growth, especially in the developing world, will lead to increased energy demand and intensify the need to mitigate environmental impacts of energy use. The global economic slowdown of the past year has temporarily flattened energy demand and masked the serious shortcomings of transportation and processing infrastructures—for example, tankers, pipes and wires, storage, and refineries. These shortcomings will resurface when the economy recovers.

Energy intensity (energy/GDP) measures efficiency in energy use. Technologies that use energy efficiently are environmentally attractive and often make good economic sense, allowing businesses to become more competitive by saving money over time. Policy changes to promote efficiency represent the most effective near-term opportunity for advancing energy and environmental goals, and may be exploited in the transportation, building, and industrial sectors of the economy. Decreasing global energy use by an additional 1% per year would reduce energy needs in 2050 by almost 40%.

Carbon intensity (carbon emissions/energy) describes the amount of carbon emitted per unit of energy used. Improving efficiency is important, but it will not be enough: Significantly increased use of “decarbonizing” technologies will also be necessary to meet ambitious long-term targets for emissions reduction. (See the article “Renewable Energy: Progress and Prospects,” by Samuel F. Baldwin, on page 62.)

For the near to intermediate term, use of less carbon-intensive fossil fuels—for example, natural gas instead of coal for electricity generation—is a technologically straightforward and economical way to reduce carbon intensity and meet growing demand.

To meet the long-term emissions-level target previously mentioned would require more than an order of magnitude increase in energy from non-carbon-emitting

sources as well as a different way of thinking about renewable and nuclear options. Suppose, for example, that current light-water reactor technologies were to provide an order of magnitude more energy than they supply today. The resulting worldwide deployment of thousands of gigawatts of nuclear power would likely be unacceptable for a combination of safety, waste, and proliferation concerns. Implementing fusion or advanced fission fuel cycles economically represents a formidable R&D challenge that requires international collaboration. (See the article, “New Designs for the Nuclear Renaissance,” by Gail H. Marcus and Alan E. Levin, on page 54.)

The Bush administration’s climate-change policy is based on a different definition of carbon intensity than what we use in this article: The administration uses carbon emissions per unit of GDP. The table shows that the intensity we defined is essentially constant, while the intensity defined by the administration drops 1.4% annually because of ongoing energy efficiency gains. Thus, the administration’s projected 18% reduction in carbon intensity over 12 years is equivalent to the scenario reflected in the table.

Large-scale, long-term carbon sequestration could, in principle, occur postcombustion (which is appropriate for stationary sources such as power plants) or after carbon removal from fuels (for example, if hydrogen is produced from natural gas). The challenge of geologically storing massive amounts of CO₂ while ensuring long-term stability and environmental safety involves technological issues and questions of fundamental science. (For a specific sequestration example, see the box on page 51 of this issue.) Meeting the challenge would enable the world’s huge coal reserves to be exploited even if greenhouse gas emissions were regulated.

No silver bullet

There is clearly no magical solution to solve the energy challenges we have discussed, but a host of approaches can help meet energy and environmental imperatives. Some require more R&D; others are poised for near- to intermediate-term impacts but would need supporting policies or the removal of policy barriers. In many ways, the core issue of energy policy in a market economy is the manner in which the political system influences the market so as to affect behavior and stimulate technology deployment for the public good. Our recommendations follow.

▷ Oil and natural gas are global commodities. Both price volatility and supply concerns can be addressed by a refined international strategy that supports more distributed reserve production capacity (for example, the former Soviet Union has the capacity to significantly increase reserve production) and a more robust international oil reserve system. New exploration and production technologies for difficult oil and gas reservoirs could significantly expand the areas (including in the US) where valuable energy commodities can be produced, as could natural gas-to-liquids technologies for stranded gas.

▷ Efficiency improvements represent the most effective opportunity for meeting energy and environmental goals in the near to intermediate term. Policies requiring efficiency standards for new energy-related capital investments, particularly in buildings and transportation, would undoubtedly accelerate the evolution of commercially

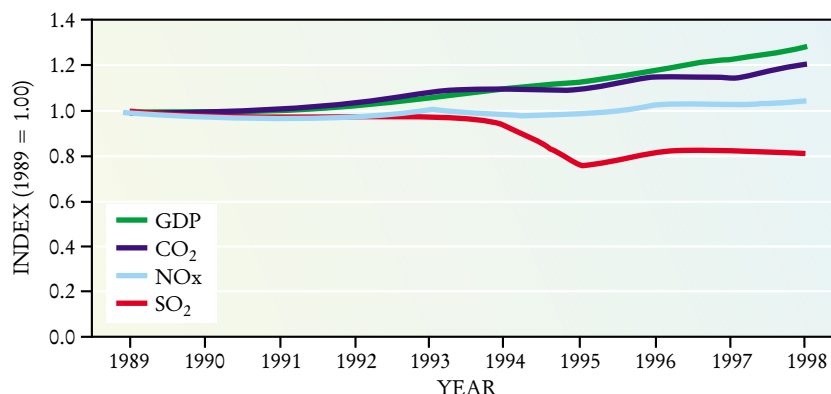


FIGURE 5. HARMFUL GAS EMISSIONS and economic growth, tracked over the period 1989–98. Economic growth is indexed by the gross domestic product (GDP) while gas emissions are indexed by mass. (Adapted from ref. 8.)

available efficiency technologies. The Energy Information Administration recently estimated that distributed, highly efficient combined heat and power systems could displace 75 gigawatts of electric power, as well as provide heating and cooling to US commercial and institutional buildings alone.¹⁰ Some commercially available central air conditioners are 30% more efficient than efficiency standards mandate; today’s efficiency achievement should, at a minimum, serve as the baseline for tomorrow’s efficiency standards. Substantial efficiency improvements in the automobile and light truck fleet are desirable and achievable, and would be accelerated through stricter fuel-efficiency standards. A 50% improvement in fuel economy over the next 10–15 years is certainly possible.

▷ Critical US energy infrastructure improvements require both policy change and policy certainty. Stresses on the electricity delivery system are likely to be relieved only when federal policies are in place to stimulate competitive returns on infrastructure investments and to enable development of a 21st-century distributed architecture. Such an architecture would deliver new consumer products and services through an “intergrid”—a convergence of electricity, gas, telecommunications, and perhaps other networked delivery systems. The opportunity for networked delivery may be especially great in certain developing countries.

▷ The global oil infrastructure is stretched very thin. A proliferation of fuel specifications has been imposed on an inflexible distribution system, reducing the global and regional fungibility of refined oil products. Bottlenecks could be eliminated through international fuel standards coupled with policy changes supportive of private industry efforts.

▷ Responsible environmental stewardship has already placed significant emissions requirements on energy production and use, with tangible public health and ecological benefits. However, the greenhouse gas challenge remains largely untouched at the federal level. Arguments to delay action are misplaced. Aggressive R&D programs for decarbonizing technologies are essential today to enable reasonable policy choices tomorrow. Also, today’s policies should stimulate the introduction of available clean energy technologies. The Bush administration’s initiative to move toward the “hydrogen economy” is welcome, but should not come at the expense of higher environmental standards achievable with available technologies,

for example, combustion engine–battery hybrids for automobiles or advanced building and appliance technologies. > The US and the rest of the industrialized world must engage the developing world through “clean development mechanisms” that lead to high-efficiency and decarbonizing technology deployment. Indeed, timely introduction of advanced technologies can have maximal impact in developing countries because of those countries’ current limited technology base and substantial expected economic growth.

Each year that passes without progress toward solving the challenges we have discussed adds to the mortgage on our collective future. There’s a story told of a French military figure Lyautey who, on returning to France following a long campaign, directed his gardener to plant a particular tree next to his residence. The gardener protested that such a tree would take 100 years to mature. Lyautey is reported to have responded that the tree should then be planted that very afternoon. There was no time to lose.

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