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The Prospects for Affordable Renewable Energy

Robert H. Williams

Recent advances in energy technologies have made it possible to project scenarios in which renewables satisfy more than half of global primary energy demand by the middle of the next century. One reason these studies are bullish about renewables is that it appears that many key technologies can be brought to market at relatively modest costs.

Among renewable energy technologies, wind power has benefitted the most from commercialization. In the 1980s a variety of government incentives helped to launch an international wind energy industry. Since then, most technical problems have been solved, and costs have fallen dramatically in California from an average of 16 cents/kWh in 1985 to 5 cents/kWh today. Costs are expected to drop further as a result of gains in the economies of mass production and prospective innovations (Cavallo et al., 1993)*.

Compared to the global electricity generation rate of 11,600 TWh/year in 1990, the gross potential for global wind electric power generation is enormous – some 500,000 TWh/year. However, most of this can not be exploited practically. From the gross potential, Grubb and Meyer (1993) subtract cities, forests, unreachable mountain areas, etc., to get a "first-order potential"; from this they estimate a "second-order potential" of 53,000 TWh/year that also takes into account a wide range of social, environmental, and land-use constraints, including aesthetic concerns about visual impacts. Somewhat more conservatively, the World Energy Council (1994) has estimated the practical potential to be 20,000 TWh/year.

Often, good wind resources are concentrated in sparsely settled regions. For example, the total electric generation potential from relatively good wind resources (average power densities > 400 Watts/m² at 50 m hub height) in the U.S. alone is 7,900 TWh/year. This compares with a total 1990 U.S. electricity demand of 2,700 TWh. Approximately 98% of that wind power is, however, in the 12 states of the sparsely populated Great Plains.

The combination of long-distance transmission lines with "overbuilt" wind farms is a promising way to exploit this resource (Cavallo, 1995). Figure 1a shows the cost of electricity in California delivered 2000 kilometers via a 2 GWe direct current transmission line from a hypothetical wind farm in Kansas, as a function of the number of wind turbines on the farm. The first bar represents an installed turbine capacity of 2 GWe and a transmission line capacity factor equal to that of the wind farm (36%). As more turbines are added to the farm, the transmission line capacity factor increases because high-speed winds are much less frequent than winds of modest speeds. The cost of delivered electricity declines until the turbine capacity reaches about 3.4 GWe and the corresponding transmission line capacity factor reaches 55%. This occurs because the reduction in the cost per kWh of transmission that arises from improved transmission line capacity utilization more than offsets the cost from spillage (the electricity that cannot be utilized whenever line capacity is exceeded). As still more turbines are added to the farm, the cost of delivered electricity begins to rise, because the cost from spillage exceeds the further gains from improved transmission capacity utilization.

These rising costs can be contained by adding compressed air energy storage at the wind farm, as shown in Figure 1b. With storage,

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* All references are available upon request from the author..

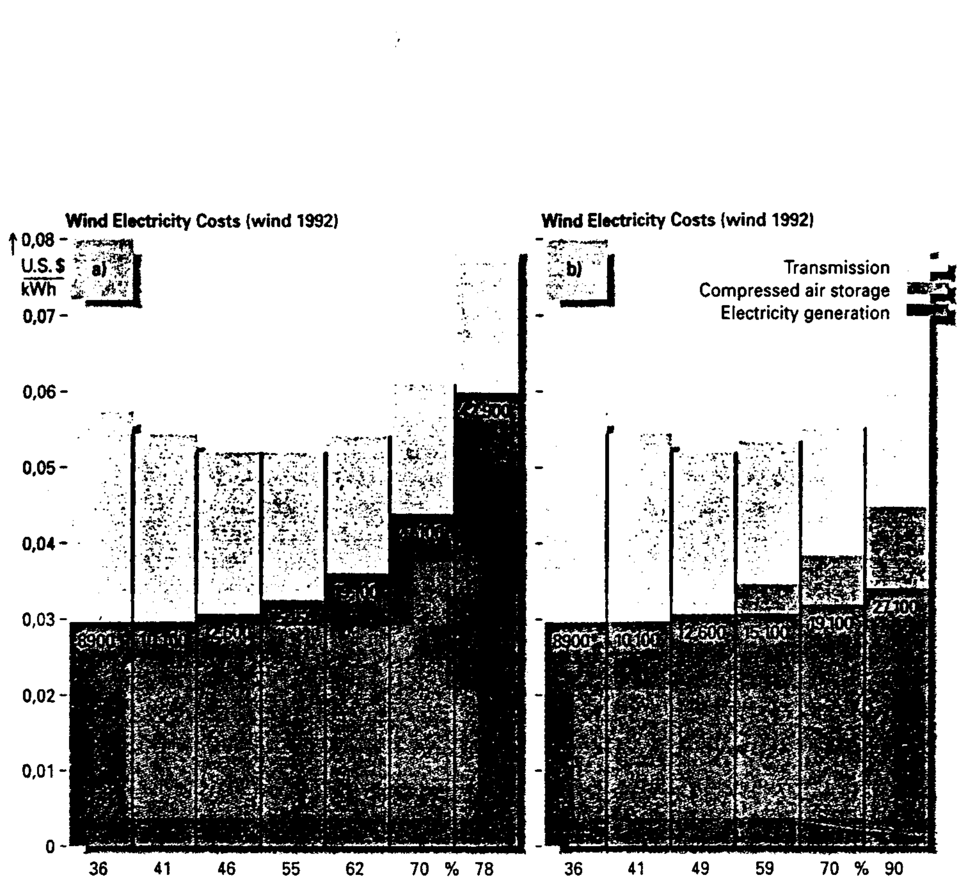

Fig. 1
Costs for wind electricity delivered 2000 km to southern California via a hypothetical 2 GWe direct-current transmission line, from an overbuilt wind-farm in Kansas established ca. 2010, with compressed air energy storage (right) and without (left).
The wind turbines are assumed to be rated @ 225 kWe and have an installed cost of $700 per kWe.
Source: (Cavallo, 1995).

the transmission line capacity factor for this system can be increased to 90% and the wind farm capacity to 6 GWe without exceeding the delivered cost of electricity from a 2 GWe wind farm. In effect, this strategy allows wind power to be converted to non-dispatchable base-load power.

Coming Up: Photovoltaic Power

Today, photovoltaic (pv) electricity is far more costly than wind power. However, costs of pv modules have fallen (in 1993 dollars) from more than $50 per peak Watt in 1976 to $5 per peak Watt in 1994. For large modules sold in quantity, prices are currently below $4 per peak Watt.

There are two basic types of pv devices: (i) flat-plate systems that convert both direct and diffuse radiation and (ii) concentrators (usually used in combination with sun-tracking devices) that convert primarily direct radiation and use mirrors or lenses to focus the incident light onto small solar cells. The prospects for major cost reductions are especially good for thin-film pv modules used in flat-plate devices, and for tracking, concentrating systems. Concentrating devices are well-suited for areas with good direct radiation. Here, the focus is on thin-film devices, as these have a much larger potential market.

The leading thin-film technologies involve amorphous silicon and two polycrystalline materials: cadmium telluride, and copper indium diselenide. Thin-film devices are characterized by layers of active pv material that are typically one or two microns thick (compared to 100 microns or more for crystalline silicon) and that can be deposited with relative ease on large areas (e.g. modules of 1 m^2 or more) of appropriate substrate materials (e.g. glass). While the achievable efficiencies of thin film systems are less than for the more conventional crystalline and polycrystalline pv devices, the relative ease of mass production and the fact that only small quantities of active materials are required implies a potential for achieving very low costs at acceptable efficiencies.

The long-term (2010) goals for thin-film pv are stable efficiencies of 15% for modules 1 m^2 in area and module costs of $0.5/Wp or less. If these goals can be achieved, pv technology would be widely competitive in grid-connected electrical markets.

Laboratory achievements with small cells suggest that there are good prospects for meeting the 15% efficiency target with cadmium telluride and copper indium diselenide (Zweibel et al., 1993). For amorphous silicon, the thin-film technology closest to being commercialized, stable efficiencies of 10% have been achieved for submodules (area 0.1 m^2). It is generally expected that such efficiencies will be achievable with further development for full sized modules. But it is uncertain whether 15% module efficiencies will be achievable for amorphous silicon using the present glow discharge module manufacturing technique. However, a new "hot-wire" manufacturing technique under investigation indicates that cells with substantially enhanced stability may be on the horizon; if the promise of this technique is borne out, amorphous silicon efficiencies could continue to increase in the future.

For flat-plate pv technology, the largest potential market is likely to be in distributed grid-connected applications with installations near users rather than at central station power plants. The reasons for this are the absence of significant scale economies all the way down to multiple kilowatt system sizes, the fact that operating personnel are not needed on-site, the absence of pollution or noticeable noise levels, low maintenance requirements, and the greater value of electricity generated near the user.

Biopower: Breakthroughs Based on Turbine Technology

A renewable energy option scarcely considered a few years ago is electricity from biomass, i.e., photosynthetically derived materials. Emerging "biopower" technology offers the potential for being competitive with both coal and nuclear power in a wide range of circumstances. This prospect arises not from developments relating to biopower per se but rather as a result of remarkable advances that have been made in gas turbine technology, intensive efforts aimed at usi coal with gas turbines, and the relative ease and low incremental cost of adapting these advances to biomass.

Biomass, mainly industrial and agricultural residues and municipal solid waste, is presently used to generate electricity with conventional steam turbine power systems. The U.S. has an installed biomass electric generating capacity of more than 8,000 MWe. The plants can provide cost-competitive power where low-cost biomass is available, especially in combined heat and power applications. The use of this technology will not expand much in the future, however, because low-cost biomass supplies are limited. Technologies that are less capital-intensive and more energy-efficient are needed to make the more abundant but more costly biomass sources (e.g. biomass grown on plantations dedicated to energy crops) competitive, particularly for power-only applications.

Higher efficiency and lower unit capital costs can be realized with cycles involving gas turbines. Present developmental efforts are focussed on biomass integrated gasifier/gas turbine (BIG/GT) cycles (Williams and Larson, 1993). The optimal scale for this technology when plantation biomass is used varies with the site, but is generally in the range of 100 to 300 MWe (Marrison and Larson, 1995) much larger than the scales for biomass residue-fueled steam plants, but smaller than the scales typical for coal plants. Because biomass feedstocks generally contain very little sulfur, the gases exiting the gasifier can be cleaned at higher temperatures than is presently feasible for coal (hot-gas sulfur removal technology is not yet commercially proven). This makes air-blown gasifiers attractive alternatives to the oxygen-blown gasifiers used in commercial coal integrated gasifier/gas turbine cycles. Air-blown gasifiers tend to be less costly than oxygen-blown gasifiers and their costs are less scale-sensitive, so that smaller scale installations can be economically attractive. With various advanced gas turbine cycles, efficiencies in the range 40 to 45% (double the efficiency of commercial biomass plants) are expected to be achievable at competitive costs. Several BIG/GT projects are underway. A 6 MWe pilot plant is being tested at Varnamo, Sweden, and a 30 MWe commercial demonstration plant is being planned for the northeast of Brazil with support from the Global Environment Facility. Additional BIG/GT demonstration projects are being planned in Finland, Belgium, Italy, The Netherlands, and the U.S.

Potentially, BIG/GT systems can provide electricity competitively compared with coal-based power produced in plants designed to meet tough air quality regulations, even if biomass is somewhat more costly than coal (on a $/GJ basis). The low sulfur content of biomass makes it possible to avoid the costly capital equipment and operating cost penalties associated with sulfur removal.

Managing Renewables on the Grid

Utilities are accustomed to managing power supplies that can be varied in response to changing demand (load-following and peaking plants) or that provide continuous power (baseload plants). This will change as intermittent renewable electric sources come onto grid systems.

Figure 2 presents the results of a modeling exercise aimed at understanding the economics of power

Fig. 2
The average cost
relative CO_2 emis
for meeting annu
tricity needs (top
fraction of electri
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Tan segments rep
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The net cost is gi
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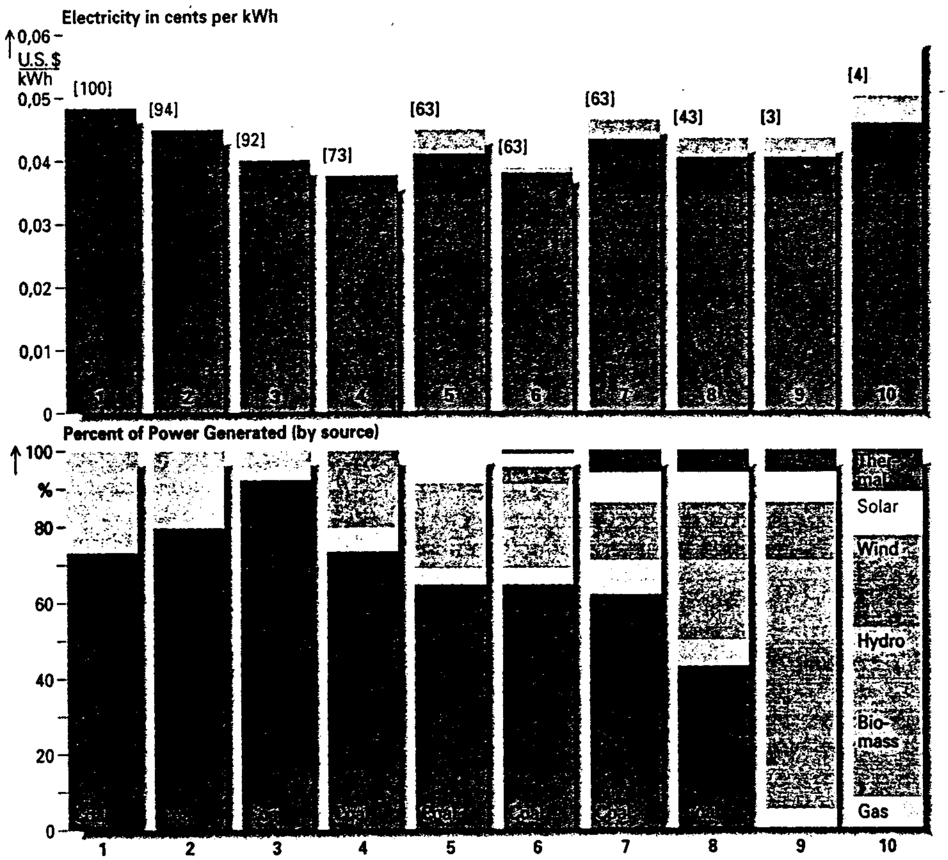
bars.
Source: Kelly
and Weinberg, 19



[ ] CO_2 emissions (relative to base case = 100)

1 Conventional fossil-fired plant
2 Best new fossil-fired plant
3 Advanced fossil-fired plant
4 Advanced fossil-fired with 21% hydro
5 Advanced fossil-fired with 10% PV and 21% hydro
6 Advanced fossil-fired with 10% intermittents and 21% hydro
7 Advanced fossil-fired with 30% mixed intermittents
8 Advanced fossil-fired with 30% mixed intermittents (three wind sites) and 21% hydro
9 Advanced biomass and gas with 30% mixed intermittents (three wind sites) and 21% hydro
10 Advanced biomass and gas with 50% mixed intermittents (three wind sites) and 21% hydro

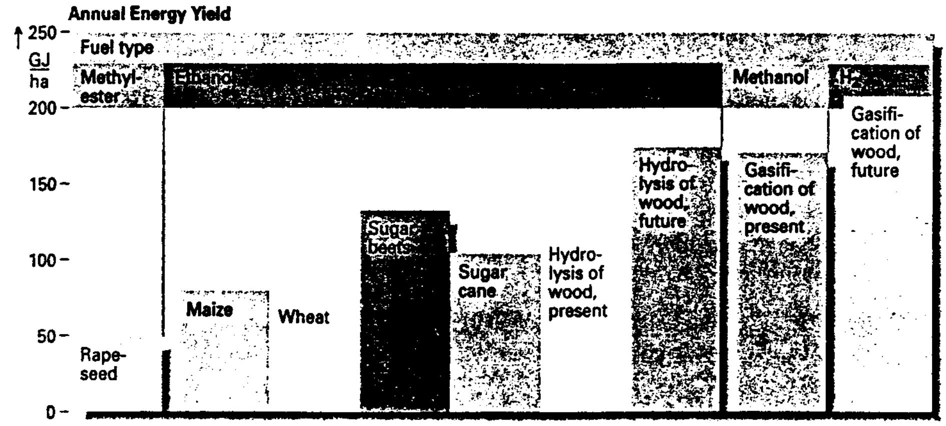


Fig. 3
Transport fuels derived from thermochemical gasification of wood chips can provide much more useful energy per hectare than the production of ethanol from grain and sugar beets or rape methyl ester from rape seed. Source: (Williams et al. 1995).

generation with varying amounts of intermittent and other renewable sources on an electric utility grid (Kelly and Weinberg, 1993). The modeling involved simulating the Pacific Gas & Electric (PG&E) system in northern California for alternative portfolios of generating equipment that could come on line by 2010. The model takes into account prospective costs and both wind and direct solar resource availability in relation to the utility load, on an hour-by-hour basis, with the same degree of system reliability in each case.

Figure 2 has several noteworthy features: (i) All but option 10 have a lower cost than conventional fossil fuel generating technologies. (ii) All renewables-intensive options are more costly than the advanced fossil fuel generation option. (iii) The economic penalty for shifting to the renewables-intensive options is small and could vanish if externalities were taken into account (e.g. via a modest carbon tax). (iv) The fraction of electric energy provided by intermittents can rise to about 30% before costs start rising rapidly. The high level penetration of intermittent renewables on the system without substantial cost increases arises from the assumption that the optimal mix of thermal technologies is used to back up the intermittent renewables. If the backup capacity were baseload units (e.g. nuclear, super-critical fossil steam-electric plants), only a relatively low intermittent renewable penetration could be realized, because it is b technically difficult and costly vary the output of baseload pla to accommodate relatively ra changes in the output of the in mittent renewable equipment.] for a given level of intermittents the system, what is modeled in] ure 2 is the optimum combinatio thermal back-up capacity and fu At higher penetrations, less b load and more load-following peaking capacity are needed – pacity that is characterized by unit capital cost and the ability tc spond quickly to changes in the (put of the intermittent renew supplies. This exercise shows the ongoing shift to gas turbines combined cycles in new genera equipment purchases around world is consistent with subseq additions of intermittent ren ables.

Greater levels of penetratio intermittent renewables could b commodated on the system witl substantial increases in cost if storage (e.g. compressed air en storage) were taken into acco For this modeling exercise the electrical storage considered wa dropower. The buffering capaci hydropower was found to be helpful in making higher pen tions of intermittent renew economically attractive. This gests a new planning strategy fo dropower: to add extra turbin pacity at existing hydropower where feasible, so as to give hy larger role in buffering intermi renewables. The modeling exe also underscores the importan taking a systems approach in w thermal, intermittent renewabl dro, and biomass power are co nated so that the actual capacit is close to optimal over time.

On the Road to the Right Fuel

Most of the effort committe making transport fuels from re able energy sources has focuse making ethanol from grain and ar beets and rape methyl ester rape seed. These fuels have prospects of ever becoming con itive. Moreover, useful energy y (in GJ per hectare per year) a

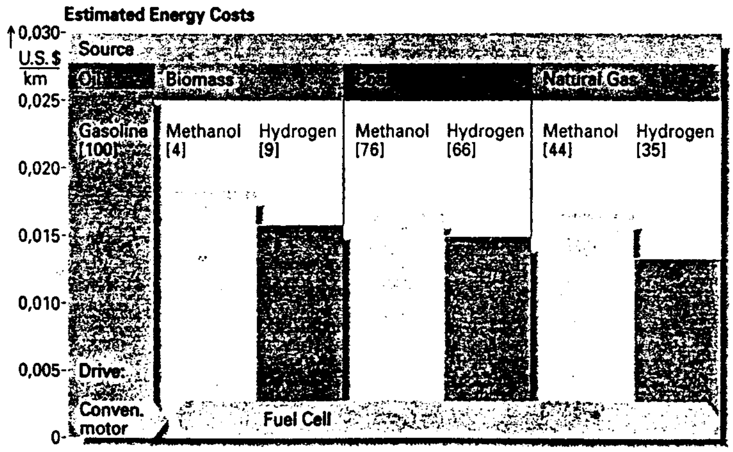


Fig. 4
Fuel costs to the consumer and relative lifecycle CO_2 emissions for alternative fuels (2010-2020) per unit of service (dollars and CO_2 emissions per km of driving) for methanol or hydrogen derived from alternative feedstocks and used in fuel cell cars, compared to gasoline used in cars with internal combustion engines. Source: (Williams et al. 1995).

small (see Figure 3) that such fuels would not be able to make major contributions to transport fuel supplies.

The production of methanol or hydrogen from woody biomass feedstocks (e.g. woodchips made from fast-growing trees) by processes that begin with thermochemical gasification can provide much more useful energy per hectare (Fig. 3). But methanol and hydrogen derived from biomass are likely to be much more costly, in dollars per GJ, than conventional hydrocarbon fuels unless oil prices rise to levels that are far higher than expected. Thus, if used to displace a hydrocarbon fuel in internal combustion engine (ICE) vehicles, these biofuels are not likely to be cost-competitive.

On the other hand, methanol and hydrogen are well-suited for use in fuel cell vehicles. Such vehicles can either use hydrogen directly (e.g. stored onboard the vehicle in compressed gas canisters or as a metal hydride) or methanol, which can be reacted with steam to form a gaseous mixture of hydrogen and CO_2. Because fuel cell cars would be 2 1/3 to 3 times as energy-efficient as ICE cars of comparable performance, the yield of energy services (measured in km of travel per hectare per year) would be 5 to 9 times as large as for ethanol or rape methyl ester used in ICE cars. Fuel cell cars would have zero local air pollution emissions if operated on hydrogen and near zero emissions if operated on methanol. Lifecycle CO_2 emissions would be less than 1/10 as much per km of driving a fuel cell car powered with these biofuels as for a gasoline ICE car (see Figure 4, top). Moreover, used in fuel cell cars, these biofuels would have good prospects of offering lower fuel costs per km (Fig. 4) and competitive lifecycle costs (Williams et al., 1995).

At costs expected to be achievable for plantation biomass in many developing countries and in the U.S. in the period 2010-2020, these biomass-derived fuels have good prospects for being comparably priced to fuels derived from coal. Biomass-based fuels are particularly attractive because of their low sulfur content, and because biomass is much more reactive than coal. In fuel production coal is first gasified in oxygen; partially burning some of the coal in the gasifier provides the high temperature heat needed for gasification. Biomass, on the other hand, can be gasified at a lower temperature, in steam, with heat provided through a heat exchanger from an external combustor. The capital costs for these indirectly heated biomass gasifiers would be lower than for oxygen-blown coal gasifiers, in large part because of the high cost of the air separation plant needed to produce oxygen.

If fuel cell cars become a commercial reality, they will probably run initially on gasoline or diesel fuel converted onboard into a hydrogen-rich gas by a process known as partial oxidation. Later, the fuel will probably be methanol or hydrogen derived from natural gas. But at some point in the future, natural gas prices will be high enough to make it worthwhile, on the basis of direct cost considerations only, to shift to methanol or hydrogen derived from coal or biomass (Fig. 4). Since costs to the consumer would be about the same for coal and biomass while CO_2 emissions would be much lower for biomass (Fig. 4), society could choose the biomass alternative with little or no cost penalty if the greenhouse problem were regarded seriously.

How Much Land is Needed?

If biomass were developed on a large scale most supplies would come from dedicated energy plantations. Good candidates for this are excess agricultural lands in industrialized countries and deforested or otherwise degraded lands that are suitable for revegetation in developing regions (Johansson et al, 1993).

Would there be enough land in these categories to enable biomass to play major roles in the energy economy? Consider, for illustrative purposes, the land area required to displace all coal-fired power generation at the 1985 global level with BIG/GT power plants and to provide hydrogen fuel for 1 billion cars (the number projected for the world in 2020) powered by fuel cells. Assuming biomass plantations having an average yield of 15 dry tonnes per hectare per year (corresponding to an annual average efficiency of 0.5% for converting solar energy into harvestable biomass energy), which is generally thought to be achievable on average on lands where plantations might be established, the global land area required would be less than 200 million hectares. This corresponds to about 13% and 6% of land in food crops and permanent pasture, respectively). The amount of land potentially available for such purposes is probably considerably larger than this, even taking into account future land requirements for food production in developing countries (Johansson et al., 1993; Larson et al., 1995).

Adding It Up

There are good prospects that, during the early decades of the next century, renewable energy will become available at costs comparable to those of fossil fuels. Where low-priced natural gas is abundantly available, the shift to renewables will be slower than if the major fossil fuel competition were from coal. But there are many regions where natural gas supplies are relatively limited, which could become theaters for introducing renewables. Moreover, natural gas-based turbines and combined cycles are the ideal thermal power complements for intermittent renewables on electric utility grids. Considering this, it is auspicious that these gas-based technologies are now being widely adopted. Likewise, in the transport area, a shift to fuel cell vehicles operated on biomass-derived fuels will be facilitated by the earlier use of natural gas-derived fuels in fuel cell vehicles.

If, during the era of low-cost natural gas, we make the needed investments in renewable energy R&D and provide the incentives needed to launch new renewable energy industries, then, as gas prices eventually rise, we will be prepared to shift to new energy sources. Such a strategy would limit energy price increases in the long term, improve energy security, and substantially reduce the burden on our environment. •