chapter six

energy in the future: trends and unknowns

This closing chapter offers no forecasts; there is no need to add to the large, and growing, volume of that highly perishable commodity. Reviews show that most long range (more than ten to fifteen years ahead) energy forecasts—whether at sectoral, national or global level, and no matter if they were concerned with the progress of individual techniques, the efficiency gains of a particular process, overall energy demand and supply, or the price levels of key commodities—tend to fail in a matter of years, sometimes months. Given the post-World War II penchant for long range forecasting, it is now possible to recite scores of such failures. Perhaps the most tiresomely notorious is the ever-elusive further fifty years that will be needed to achieve commercial nuclear fusion (generating electricity by fusing the nuclei of the lightest elements—the same kind of reactions that power the Sun). Common failures include forecasts of the imminent global peak oil production, and some of the most spectacular misses include the predictions of future crude oil prices (too high or too low, never able to catch the reality of highly erratic fluctuations).

Even if some individual numbers come very close to the actual performance, what is always missing is the entirely new context in which these quantities appear. Imagine that in 1985 (after the collapse of crude oil prices and a sharp drop in global oil production), you accurately forecast global oil production in 2005. Could anybody in 1985 have predicted the great trio of events that changed the post-1990 world: the peaceful collapse of the USSR (first leading to a rapid decline and then to an impressive resurgence of its oil output), the emergence of China as the world's second largest economy (soon to be the world's second largest importer of oil), and September 11, 2001 (with its manifold consequences and implications for the world in general, and the Middle East in particular)?

No forecasts then, only brief reviews of some key factors that will determine the world's future quest for a reliable and affordable energy supply, and the major resource and technical options we can use during the next half-century. During that time, the basic nature of global energy supply will not drastically change, and the world will remain highly dependent on fossil fuels. At the same time, we know our fossil-fueled civilization to be a relatively short-lived phenomenon, and the next fifty years will see an appreciable shift toward non-fossil energy resources. At the beginning of the twentieth century, the world derived about sixty per cent of its energy from coal, crude oil and (a very little) natural gas. A century later, the three kinds of fossil fuels account for about eighty per cent of the world's total primary energy supply; the rest is about equally split between primary electricity (hydro and nuclear) and phytomass fuels.

Even if the recoverable resources of fossil fuels (particularly those of crude oil and natural gas) were much larger than today's best appraisals, it is clear they are not large enough to be the dominant suppliers of energy for an affluent civilization for more than a few centuries. Conversely, the combination of rapidly rising demand and the escalating costs of fuel extraction may limit the fossil fuel era to the past and present centuries—and the rapid progress of pronounced global warming, clearly tied to the combustion of fossil fuels, may force us to accelerate the transition to non-fossil energies. As already stressed in Chapter 1, the overall magnitude of renewable energy flows is not a constraint.

Biomass energies have been with us ever since we mastered the use of fire: wood, charcoal, crop residues, and dung are still used by hundreds of millions of peasants and poor urban residents in Asia, Latin America, and particularly throughout sub-Saharan Africa, mostly for cooking and heating. Our best estimates (there are no reliable statistics, as most of these fuels are collected or cut by the users themselves) put the worldwide energy content, at the beginning of the twenty-first century, of traditional biomass energies at about 45 EJ, roughly ten per cent of the world's aggregate primary energy consumption. But the share is much lower when comparing useful energies, because most of the biomass is burned very inefficiently in primitive stoves. As already noted in Chapter 3, these wasteful uses also have considerable health costs, due to indoor air pollution, and there are also the serious environmental problems of deforestation and the reduced recycling of organic matter. Biomass energies could make a difference only when harnessed by modern, highly efficient techniques without serious environmental and social impacts: achieving this will be an enormous challenge.

Hydroenergy is the only kind of indirect solar energy flow extensively exploited by modern techniques, but, outside Europe, North America and Australia, there is still considerable untapped potential. We have only just begun to harness the other major indirect solar flow, wind, but it is not clear to what extent the recent European enthusiasm for large-scale wind farms will translate into worldwide and sustained contributions. Potentially the most rewarding, and by far the largest, renewable energy resource is the direct solar radiation that brings close to 170 W/m^2 to the Earth—but, so far, its direct conversion to electricity (by photovoltaics) has succeeded only in small niche markets that can tolerate the high cost. There is also the possibility of new designs of inherently safer and more economic nuclear electricity generation. I will review the advantages and drawbacks of all of these major non-fossil options. But before doing so I must stress the magnitude of future energy needs against the background of enormous consumption disparities and long-term energy transitions.

energy needs: disparities, transitions, and constraints

The extent of future global energy needs cannot be understood without realizing the extent of existing consumption disparities. The per caput annual energy consumption in the US and Canada is roughly twice as high as in Europe or Japan, more than ten times as high as in China, nearly twenty times as high as in India, and about fifty times as high as in the poorest countries of sub-Saharan Africa. Because of this highly skewed (hyperbolic) consumption pattern, the global annual average of about 1.4 toe (60 GJ) is largely irrelevant: only three countries (Argentina, Croatia, and Portugal) have consumption rates close to it; the modal (most frequent) national average is below 0.5 toe, and high-income countries average above 3 toe.

UNEQUAL ACCESS TO MODERN ENERGY

The enormous disparity in access to energy is most impressively conveyed by contrasting the national or regional share of the global population with their corresponding share of world-wide primary energy consumption: the poorest quarter of humanity (including most of sub-Saharan Africa, Nepal, Bangladesh, the nations of Indochina, and rural India) consumes less than three per cent of the world's primary energy supply while the thirty or so affluent economies, whose populations add up to a fifth of the global total, consume about seventy per cent of primary energy (Figure 30). The most stunning contrast: the US alone, with less than five per cent of the world's population, claims twenty seven per cent of its primary commercial energy.

No indicator of high quality of life—very low infant mortality, long average life expectancy, plentiful food, good housing, or ready access to all levels of education—shows a substantial gain once the average per caput energy consumption goes above about 2.5 toe/year. Consequently, it would be rational to conclude that the world's affluent nations have no need to increase their already very high averages, ranging from just over 8 toe/caput for the US and Canada, to just over 4 toe for Europe

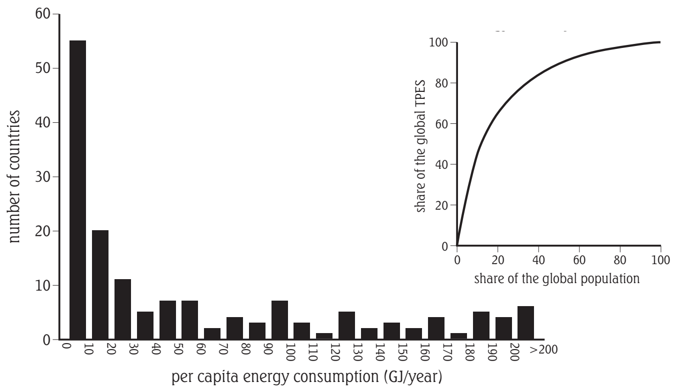

Figure 30 *Distribution of average national per caput energy consumption and a Lorenz curve of global commercial energy consumption*

UNEQUAL ACCESS TO MODERN ENERGY (*cont.*)

and Japan. At the same time, there are still hundreds of millions of people in the poorest countries who do not directly consume any fossil fuels.

Because almost all the world's population growth during the first half of the twenty-first century will take place in low- and medium-income countries (affluent populations, with the exception of the US, will either be stagnant or in decline), most future increases in fossil fuel and electricity consumption will be in Asia, Latin America, and Africa. But there is no easy way to forecast this new demand, as it is a complex function of population growth and economic expansion, the changing composition of the primary energy supply and final energy uses (energy-intensive heavy industries compared to light manufacturing and service industries), and the adoption of new inventions and higher-efficiency innovations (fluorescent rather than incandescent lights, high-efficiency natural gas furnaces rather than coal stores, or subcompacts instead of SUVs).

To achieve a modicum of economic security, the average annual per caput consumption rates should at least triple in sub-Saharan Africa, more than double in India (currently at less than 0.4 toe) and nearly double in China (now at roughly 1 toe). It is clear that future energy use in the world's most populous and rapidly expanding economies will conform (with variations for national characteristics) to the general pattern of energy transitions that has taken place in affluent countries. Their two principal components were noted in Chapter 4: the declining share of coal in total primary consumption (although in China that share will remain relatively high, because it derives about two-thirds of its energy from coal), and a steady rise of oil and natural gas consumption, leading to higher demand for imported liquids and gases.

Another key ingredient of the world-wide transition of commercial energy use has been the rising share of electricity in final consumption. In 1900, less than a generation after the beginning of electricity generation, little more than one per cent of fossil fuels was converted to electricity; by 1950 the global share rose to ten per cent and by 2000 surpassed thirty per cent. The US share is now about thirty-five per cent, and, remarkably and despite a large economic gap between the two countries, China's share, at about thirty per cent, is not far below that. Nearly everywhere, electricity use has been growing at a much faster rate than the consumption of fuels, because during the second half of the twentieth century fossil-fueled generation was extensively augmented by hydroenergy and nuclear fission.

The continued rapid growth of average per caput electricity consumption in low- and medium-income economies will be the only way to narrow the existing disparities. The US annual per caput average is now more than 12 MWh, Japan's is nearly 8 MWh, and Europe averages almost 7 MWh. In contrast, China's annual per caput mean is about 1.1 MWh, India's 0.5 MWh, and in sub-Saharan Africa (excepting South Africa) it remains generally below 0.25 MWh. Despite decades of electrification programmes, nearly two billion people (mainly in India, Southeast Asia and sub-Saharan Africa) still do not have access to electricity. Consequently, the global disparity in average per caput electricity use is greater, and the need for future production increases more acute, than is primary energy consumption. This is perhaps most vividly portrayed by composite night-time satellite images, which starkly contrast brightly-lit affluent countries with the huge areas of darkness, or at best sparse light, over large parts of Asia, Africa, and Latin America.

While the overall efficiency of energy use in low- and medium-income countries is dismally low and should be greatly improved through technical innovation and better management, future higher energy needs cannot be met solely, or even mostly, through higher efficiency. Positive steps in this direction are essential. China's post-1980 achievements (roughly halving the energy use per unit of Gross Domestic Product (GDP)) show their fundamental importance: without them, China would be now consuming about twice as much energy for every unit of its economic product as it now does, as well as burdening its already highly degraded environment with even more pollutants. High-efficiency conversions clearly benefit economies and the environment, but they reduce overall energy use only on an individual or household level, or for a single company, particular industrial process, or entire production sector.

On national and global levels, the record shows the very opposite; there is no doubt that higher efficiencies of energy conversions have led to steadily greater consumption of fuels and electricity. This paradox was noted for the first time by Stanley Jevons (1835–1882), a prominent English economist, in 1865. In his words: "It is wholly a confusion of ideas to suppose that the economical use of fuels is equivalent to a diminished consumption. The very contrary is the truth." Jevons illustrated the phenomenon by contrasting the huge efficiency improvements of eighteenth-century steam engines (from Savery and Newcomen's extremely wasteful machines to Watt's improved design) with the large increases in British coal consumption during the same period.

Two examples illustrate this common phenomenon for modern energy-consuming activities. First, in 2005, the average American passenger vehicle (including SUVs) consumed about forty per cent less fuel per kilometer than in 1960, but more widespread ownership of automobiles (two people per vehicle in 2005, compared to nearly three in 1970) and the higher annual average distance driven (roughly 20,000 km, compared to 15,000 km in 1960) resulted in an average per caput consumption some thirty per cent higher. Second, during the twentieth century, the efficiency of British public street lighting rose about twenty-fold, but the intensity of this illumination (MWh per km of road) rose about twenty-five times, again more than eliminating all efficiency gains.

So higher efficiencies have not resulted in lower overall demand for energy. Its growth has continued, albeit at a slower pace (as expected), even in mature, post-industrial economies. In the 1990s, despite deep economic problems and the stagnation of its GDP, Japan's average per caput energy consumption grew by fifteen per cent; in the same period the already extraordinarily high US and Canadian rates grew by about 2.5%, and France's by nearly ten per cent. Between 1980 and 2000 China, despite the unprecedented achievement of halving the energy intensity of its economy, more than doubled its per caput energy consumption. Replicating similar achievements during the coming decades would be challenging under any circumstances, but we now face the entirely new constraint of possibly rapid global warming.

We have three choices if we wish to keep on increasing energy consumption while minimizing the risks of anthropogenic climate change (due mostly to rising combustion of fossil fuels) and keeping atmospheric levels of greenhouse gases from rising to as much as three times their pre-industrial level: we can continue burning fossil fuels but deploy effective methods of sequestering the generated greenhouse gases, we can revive the nuclear option, or we can turn increasingly to renewable energy. None of these options is yet ready for large-scale commercial adoption, none could be the sole solution, and all have their share of economic, social and environmental problems.

Despite of a great deal of theoretical research, and much interest shown by industries and governments, CO_2 sequestration is only in the very early experimental stages; its eventual contribution to the management of the global warming challenge is uncertain. In contrast, we have half a century of experience of large-scale commercial generation of nuclear electricity, which has shown us what to avoid and what techniques to favor. The general expert consensus is that any development of the nuclear industry cannot be a replica of the first generation; there has been no shortage of new, ingenious designs aimed at minimizing or eliminating the concerns that contributed to the stagnation (and in some countries even retreat) of nuclear electricity generation. Several, so-called, inherently safe nuclear reactor designs provide passive guarantees of fail-proof performance: even operator error could not (as it did in Chornobyl) lead to a core meltdown. Its adoption would be made easier by flexible sizing: a helium-cooled reactor, fuelled by hundreds of thousands of fist-sized graphite spheres filled with tiny particles of uranium oxide, could be built in modules as small as 120 MW. Increased concerns about the possibility of terrorist attacks in the post-9/11 world are a powerful counter-argument to substantial expansion of nuclear generation. But the future of the industry will not depend primarily either on better designs (they have been available since the mid-1980s), or on the fears of a terrorist attack (there are already hundreds of reactors in operation, and many other high-profile targets). What has to change is the public acceptance of this, potentially risky, but very rewarding, form of electricity generation, and I have argued that there is little chance of any substantial worldwide return to nuclear generation unless led by the world's largest economy. But in 2005, US nuclear plans seem no less confused and uncertain than they were in 1995 or in 1985: there is constant talk of the industry's future importance, indeed inevitability, but no practical steps toward making it happen, and no sign that the public distrust of nuclear generation has eased. As the endless wrangling about the location and operation of the country's permanent repository of high-level radioactive wastes shows, the combination of executive intents, legislative delays, and legal appeals makes for decades of irresolution and offers little hope for any determined state-sanctioned nuclear-based solution to the country's future electricity needs.

All that may change, but not because the public finally appreciates the real relative risks of various electricity-generating options, as these have been known for decades. Two developments may bring this shift about: a quicker than expected decline in worldwide crude oil production, and clear signs of exceptionally rapid and highly pronounced global warming. The nuclear option is not greenhouse gas free: we need coke to make the plant's many steel components, and the cement for its massive concrete structures comes from fossil fuel-fired kilns. But in comparison with today's dominant (coal-fired) mode of generation, nuclear plants produce at least ninety-five per cent less CO_2 per unit of electricity. If our civilization were to face a true global warming shock, this would be very appealing. Consequently, the most rational strategy of future energy supply would be to combine improvements in conversion efficiency (particularly in industrialized economies) with reduced rates of overall energy demand (especially in affluent countries), keep the nuclear option open during the development of innovative reactor prototypes, and increase the contributions of non-fossil sources as quickly as economically feasible and environmentally acceptable. Because capital investment considerations and infra-structural inertia mean that it takes several decades for any new energy source or conversion to claim a substantial share of the market, we should not waste any time in aggressively developing and commercializing suitable renewable options.

renewable energies: biomass, water, wind, solar

Biomass energies could only become an important component of future energy supply after the development of large-scale, intensive production of selected crop and tree species convertable, by advanced techniques, into liquid or gaseous fuels or electricity. This strategy has three fundamental drawbacks. First, as explained in Chapter 2, photosynthesis operates with an inherently very low energy density, and hence any large-scale biomass fuel production would claim extensive areas of farmland (and it would have to be farmland, rather than marginal land, to sustain high productivity). Second, humanity already claims a very high share (possibly as much as two-fifths) of the biosphere's net primary productivity

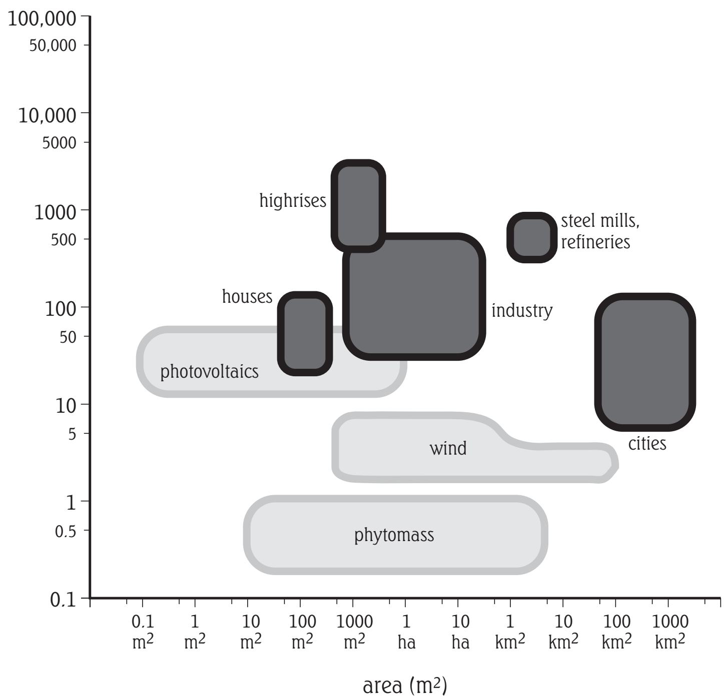

Figure 31 *Comparison of power densities of energy consumption and renewable energy production*

(through harvests of food, feed, wood, grazing, and deliberately set grassland, and forest fires), and adding a further burden through massive fuel production would lead to a further loss of biodiversity and greater environmental degradation. Finally, the overall costs (economic, energetic and environmental) of large-scale biomass energy production are very high.

Low power densities translate into very large land requirements (Figure 31). For example, replacing just a quarter of the world's fossil fuel consumption with cultivated woody biomass would require (even with high average yields of 15 t/ha and high combustion efficiencies) tree plantations larger than the area of total combined forested land in Europe and the US, clearly an impossible option. If all American cars were to run on corn-derived ethanol, the country would have to put all its farmland under that energy crop, another impossible option. Devoting even limited areas to biomass crops would be irrational for the scores of densely populated countries that already have shortages of the arable land needed to secure their basic food supply and so are major food importers. Creating new biomass plantations would lead to further loss of natural grasslands, wetlands, and lowland tropical forests. Only a few countries (Brazil and US above all), could spare significant shares of their farmland for large-scale fuel production.

Moreover, a number of energy analyses show that ethanol production from US corn entails a net loss of energy (due to the combined energy cost of machinery, fertilizers, irrigation, and the grain's fermentation to alcohol). Other studies show a small net energy gain, but efficient and inexpensive enzymatic conversion of cellulose and hemicellulose (making it possible to use corn stalks and leaves) rather than just starches (that is, fermenting only grain corn) would radically improve the overall energy balance. In contrast Brazilian ethanol, made from sugar cane, has a positive energy return, because the fermentation process can be fuelled by *bagasse*, the fibrous residue remaining after the expressing of the sweet juice from the cane stalks. But even when biomass crops and their processing produce a net energy gain, their cultivation would still have undesirable environmental impacts, above all increased soil erosion, soil compaction, and contamination of aquifers and surface waters by nitrogen and phosphorus lost from fertilizers, causing aquatic eutrophication (that is, the enhanced growth of algae, which disrupt the existing ecosystem).

Until we have bioengineered micro-organisms, able to convert non-starch phytomass into reasonably priced liquid fuels, we should continue to use efficiently all biomass wastes (logging and lumber mill residues, and crop residues not needed for protecting soils against excessive erosion and recycling nutrients), and limit the production of liquids from biomass to tropical sugar cane grown in countries with abundant farmland. Expanding fuelwood groves for household use and planting fast-growing species for commercial wood deliveries is desirable in areas with good growing conditions, or regions with plenty of available barren slopeland, where afforestation may not only improve regional fuel supply but also reduce soil erosion. But any dreams of a modern urbanized civilization fuelled by biomass should remain, for the sake of a reliable food supply and limited environmental impacts, just that.

Hydrolectricity is the largest modern non-fossil source of primary energy; the combination of relatively low cost, high suitability to cover peak demand, and the multi-purpose nature of most large reservoirs (they serve as sources of irrigation and drinking water, a protection against downstream flooding, recreation sites, and, increasingly, places for aquacultural production) should make it one of the most desirable choices in a world moving away from fossil fuels. This conclusion seems to be strengthened by the fact that on the global scale most of this clean renewable energy resource remains untapped: the International Commission on Large Dams put the global potential of economically feasible projects at just over 8 PWh, roughly three times the current rate of annual generation. As expected, the remaining potential is unevenly distributed. Europe, North America, Australia, and Japan have already developed as much of their large-scale hydrogenerating capacity as they can (there is always the potential for microstations), but Latin America has so far tapped less than a quarter, Asia less than a seventh, and Africa not even a twentieth, of their respective potentials.

This untapped potential would seem especially welcome, as it is precisely those continents where future demand will be highest, but it now appears that the development of hydrogeneration in those regions will not proceed either as rapidly or as exhaustively as was assumed two decades ago. In an important shift of perception, hydroenergy has changed, from a clean, renewable, and environmentally benign resource, to a much more controversial cause of socially and environmentally disruptive, and economically questionable, developments. As a result, there has been a spreading international and internal opposition to megaprojects (plants with multigigawatt capacities), and a marked decline in the willingness of governments and international lending agencies to finance such developments. Sweden has banned further hydrostations on most of its rivers, Norway has set aside all existing plans, in the US, since 1998, the decommissioning rate for large dams has overtaken the construction rate, and many countries in Asia (most notably in India) and Latin America have seen vigorous public protests against new projects.

CONCERNS ABOUT LARGE DAMS

In 2000, the World Commission on Dams published a report which stressed that all future projects should consider social and environmental effects to be as important as the, traditionally dominant, economic benefits of electricity generation (or of irrigation or

CONCERNS ABOUT LARGE DAMS (*cont.*)

water supply). While some recent criticism has been ideologically motivated and clearly overwrought, there is no doubt that large hydroprojects bring a number of serious social and environmental changes. In Chapter 4 I noted the major concerns: the large numbers of people displaced by the creation of major reservoirs, the excessive silting of many storages, the aging of average river runoff and the fact that water reservoirs are (much like fossil fuels) sources of greenhouse gas emissions, as they release CO_2 and CH_4 from submerged and decaying trees and shrubs.

A new concern has emerged, as we see more indications of the inevitable deterioration of aging dams and contemplate the costs of their eventual decommissioning: these matters were given no, or insufficient, attention when they were built. We can only speculate about the ultimate life expectation of such massive structures, and have no good strategies to deal with the excessive silting and premature filling of reservoirs, which reduces their useful life span (in parts of monsoonal Asia affected by severe deforestation the process has already cut the expected duration of some reservoirs by as much as half). All this makes it much more unlikely that the remaining hydrogeneration potential will be developed as aggressively as it was in the twentieth century.

But even without any obstacles to their construction, new hydrogeneration capacities could supply only a part of the expected demand, and then only by claiming large expanses of river valleys, forests, grasslands, settlements, and agricultural land. The average power density of existing hydrostations (actual generation rather than installed capacity: this adjustment is necessary because dry years curtail generation at many dams) equates to about 1.7 W/m^2 and they claim some 175,000 km^2 of land. If all of the remaining potential were to be realized during the first half of the twenty-first century, new reservoirs would claim roughly 500,000 km^2, an area as large as Spain. But hydroenergy can be also harnessed on a smaller scale, and many Asian, African, and Latin American countries have excellent potential for developing stations, with capacities less than 10–15 MW, which would not make much of a dent in a nationwide supply of a populous country, but could suffice to electrify a remote region or an island.

Wind energy, harnessed by large and efficient turbines, has emerged in the 1990s (less than a decade after a failed mini-boom during the 1980s) as the leading renewable energy choice, thanks largely to aggressive promotion and adoption in a number of Western European countries. Better designs, and larger sizes, of wind machines made a big difference: ratings rose from 40–50 kW during the early 1980s to 500–750 kW by the late 1990s, when the first turbines with capacities of more than 1 MW went on line. Danish designs have led the way, and the country also leads in per caput wind capacity, but Germany (thanks to a guaranteed high fixed price for wind-generated electricity) has become the country with the highest aggregate capacity, followed by Spain. More than seventy per cent of installed wind turbine capacity is in Europe, Denmark gets about twenty per cent and Germany and Spain more than five per cent of their electricity from wind. But there is a long way to go before wind power becomes a substantial player on the global scale: by the end of 2004 it generated just over one per cent of the world's electricity.

To avoid conflict, much future wind power will be in large offshore wind farms (some already operate in Denmark, Sweden, Holland and the UK), or re-powering of old sites with larger turbines. Wind power will remain the fastest growing segment of renewable electricity generation for years to come, but its ultimate extent is uncertain. It is an immense resource, and even a restrictive appraisal (taking into account suitable wind speeds and siting restrictions) shows a global potential of about 6 TW, or about fifty per cent larger than the world-wide electricity-generating capacity in 2005. But this grand total is largely irrelevant, because the wind power cannot be relied on either to cover the high base-load demanded by modern societies or meet spiking peak loads.

This inability is due to the high, poorly predictable, variability in wind speeds (on time scales from daily to annual), and to the fact that optimum wind flows do not correlate well with periods of the highest electricity demand. Strong winds are as undesirable as protracted calm, because to avoid structural damage, modern wind turbines cut out at speeds greater than 25 m/s (90 km/h). European studies show that wind capacities of up to twenty per cent of installed power can be successfully integrated into a national supply, especially when a relatively small nation is well connected to neighboring countries (as in Denmark)—but there is no realistic way to make wind power, even in regions where the resource greatly surpasses actual electricity demand, the sole provider of the base load supply.

Other factors that complicate large-scale reliance on wind-driven turbines range from the sudden, substantial (10–20%), loss of power due to the soiling of leading blade edges by swarms of summer insects, to the damage that could be inflicted on towers and blades by hurricane- and tornado-strength winds. Environmental concerns range from the well-documented risks to migrating birds, to esthetic objections, both to turbines massed in large onshore wind farms and the size of the largest machines (nearly twice as high as the Statue of Liberty). As with any major engineered system, it is far too early to appraise the overall reliability of the technique. We have to accumulate operating experience with a very large number of units to be able accurately to assess the long-term availability and reliability of wind turbines: how will offshore wind farms fare in hurricanes, how will the machines be affected by heavy icing, or to what extent will the smooth blades surfaces be pitted by abrasive airborne particulate matter?

Compared to wind-powered electricity generation—with recent worldwide annual increments of the order of 5–8 GW and aggregate installed capacity in 2005 of over 50 GW—photovoltaics (PV) is still a minor affair: its worldwide capacity was below 3 GW in 2005, with just three countries (Japan, Germany, and the US) accounting for more than eighty per cent of the total. Moreover, the power ratings of PV units are not directly comparable with other modes of electricity generation, because they are expressed in peak watts measured under high irradiance (1,000 W/m^2, the equivalent of mid-day, clear-sky insolation) rather as an average performance. Three fundamental reasons make the PV conversion of solar radiation into electricity the most appealing of all renewable sources: the unparalleled magnitude of the resource, its relatively high power density, and the inherent advantages of the conversion technique (no moving parts, silent operation at ambient temperature and pressure, and easy modularity of units), but the two key reasons for its rather limited commercial penetration are the relatively low conversion efficiency and the high unit cost. Efficiencies have risen from less than five per cent during the early 1960s, when the first PV cells were deployed on satellites, to almost twenty-five per cent for high-purity silicon crystals in the laboratory, but the best field efficiencies are still below fifteen per cent, which eventually deteriorate to less than ten per cent. PV films, made of amorphous silicon (or gallium arsenide, cadmium telluride, or copper indium diselenide), have reached as much as seventeen per cent in the laboratory, but deliver much less than ten per cent in field applications. Although these advances have lowered the unit cost of PV cells, the modules are still too expensive to compete, price-wise, with fossil-fueled generation. But their marketing has finally moved beyond specialized, low-power applications to larger, grid-connected capacities, and sales are rising worldwide, from less than 50 MW (peak capacity) a year in 1990 to more than 700 MW in 2003.

Competitive and reliable PV would be a most welcome breakthrough, because of its relatively high power densities: efficiencies close to twenty per cent would translate to electricity generation rates between 20–40 W/m^2, two orders of magnitude better than biomass conversion, and one better than most hydro and wind projects. Problems with the natural randomness of the resource, outside the predictably sunny subtropical desert regions, cannot be easily overcome: converting diffuse radiation in cloudy regions is much less efficient than using direct sunlight; and there are no techniques for large-scale storage of electricity on the commercial horizon. Consequently, grid-connected PV could work very well in providing a sizeable share of overall electricity demand, while reducing the need for fossil-fueled generation, during sunny hours, but not (until a number of technical breakthroughs become commercial) as the dominant means of base-load supply.

innovations and inventions: impossible forecasts

The most welcome advance would be a large-scale affordable means of electricity storage: without this even a combination of affordable wind-driven and PV electricity generation could not provide a reliable base-load supply. But no imminent breakthroughs are expected, and pumped storage remains the only effective way of storing surplus electricity on a large scale. This uses two water reservoirs at least several hundred meters apart in height; electricity not needed by the grid is used to pump water from the lower to the upper storage, where it is kept until released for generation during periods of peak demand. The world-wide capacity of pumped storage is close to 100 GW; the largest units surpass 2 GW. But pumped storages are expensive, and the requirement for reservoirs in high relative elevations makes them inconceivable in densely populated lowlands. Batteries cannot store energy on such a large scale, because they are too expensive, their energy density is too low, they are difficult to charge, and have very short life cycles. This is why large-scale electricity generation based on variable flows of renewable energies would benefit from using hydrogen as a major energy carrier.

HYDROGEN AS ENERGY CARRIER

Hydrogen cannot, contrary to what so many popular writings repeatedly imply, be a significant source of energy. Unlike methane, it is not present in huge reservoirs in the Earth's crust, and energy is needed to produce it, from either methane or water. But some of its properties make it an outstanding energy carrier. Its key advantages are superior energy density (liquid hydrogen contains 120 MJ/kg compared to 44.5 MJ/kg for gasoline), a combustion that yields only water, and the possibility of using it in fuel cells.

The key advantages of fuels cells (electrochemical devices that combine hydrogen and oxygen to produce electricity) are the absence of moving parts, a quiet and highly efficient (commonly in excess of sixty per cent) operation, and their modularity (they can be made small enough to power a laptop or large enough to generate electricity in multi-megawatt plants). An enormous amount of research interest in fuel cells has recently led to exaggerated expectations of their early commercialization, but their cost (except for a few relatively small niche markets) is still prohibitive, and many innovations are needed to make them affordable and reliable converters. There are also major problems in setting up a distribution system for hydrogen—and unless this is in place, carmakers will be reluctant to mass-produce hydrogen-powered cars. Niche conversions (fleet vehicles such as buses, taxis, and delivery trucks, which can be fuelled at just a few points in a city), might be better than pushing hydrogen for passenger cars.

The transition to hydrogen-powered vehicles will also be complicated by the need for energy-dense storage and safe handling. Uncompressed hydrogen occupies 11,250 l/kg; pressurizing it into a high pressure (hence dangerous) steel tank reduces this to 56 l/kg, but this is equivalent to less than three liters of gasoline, or enough fuel to move an efficient compact car less than fifty kilometers.

HYDROGEN AS ENERGY CARRIER (*cont.*)

Liquefied hydrogen occupies only 14.1 l/kg but needs to be kept below −241 °C—an immense engineering challenge in a small vehicle. Adsorption on special solids with large surface areas, or absorption by metal hydrides seem to be the most promising options.

The safety of hydrogen distribution is no smaller challenge. While the highly buoyant gas leaks quickly and it is non-toxic (making its spills more tolerable than those of gasoline) its ignition energy is only one-tenth that of gasoline, its limit of flammability is lower, and its range of flammability much higher. These will mean much stricter precautions at hydrogen stations than those now in place at gasoline filling stations.

Moving toward a system dominated by hydrogen is clearly consistent with the long-term decarbonization of the modern energy supply, but the progress will be gradual and we should not expect any large-scale transition to a hydrogen economy during the coming generation (Figure 32). The hydrogen:carbon (H:C) ratio of dominant fuels has moved from around 0.1 in wood, to about 1.0 in coal,

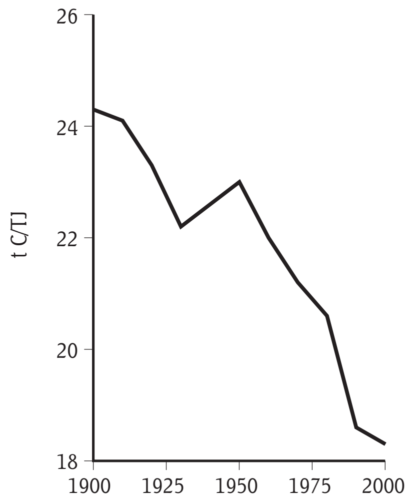

Figure 32 *Decarbonization of the world's energy supply*

and 2.0 in crude oil. The continuation of this trend points first to the emergence of natural gas (with H:C of 4) as the leading source of global primary energy, and eventually (but almost certainly not during the first half of the twenty-first century) to a hydrogen-dominated world. But trends can be derailed or accelerated by social or political upheavals, or enter frustrating culs-de-sac, and only those that are strongly entrenched and rely on mature techniques have a high probability of continued adoption, accompanied by further innovation. Neither hydrogen nor a strong revival of the nuclear option belong to this category, and hence any forecasts of future milestones or diffusion rates of these techniques are just guesses.

In contrast, there is no doubt that the combustion of fossil fuels—gradually becoming more efficient, cleaner and less carbon-intensive—will dominate the global energy supply during the next two generations. As electricity will be supplying a steadily higher share of the world's final use of energy, its already generally highly-efficient conversions will become even better. The greatest room for improvement is in lighting, and light emitting diodes are a most promising innovation. They have been around for many years as the little red or green indicator lights in electronic devices, and (although you may think you have a light bulb there) are now common in car brake lights, tail-lights, and turn signals, and also in traffic lights. But they will make the greatest impact once their full-spectrum prototypes (producing daylight-like light) become commercial. So our grandchildren will use lights that may be, on average, at least fifty per cent more efficient than ours.

There is also little doubt that our continued reliance on fossil fuels will be first augmented and then progressively supplanted by renewable energies: major hydroenergy projects in Asia and Africa and by wind-powered electricity generation and PV conversions on all continents (Figure 33). And history makes it clear that the train of human ingenuity is not about to stop. Although major inventions tend to come in irregularly spaced clusters rather than an orderly progression, half a century is long enough to see the emergence, and even substantial diffusion, of several new inventions whose universal adoption could transform the energy foundations of late-twenty-first century civilization. Such developments are highly probable, but their nature and their timing are entirely unpredictable: remember the two major late twentieth century examples; the emergence of mass air travel thanks to the invention of the gas turbine and its much improved turbofan designs, and the

Figure 33 *Albany wind farm*

invention of solid state electronic devices (transistors, integrated circuits, and microprocessors).

The transition to an energy system based predominantly on non-fossil resources is in only its earliest phase. In some ways this appears to be a greater technical and social challenge than the last epochal shift (from animate energies and biomass fuels to coal, hydrocarbons, engines, and electricity). But, given the knowledge and resources at our command, this challenge should be manageable. After all, we now have much more powerful scientific and technical means to come up with new solutions, and we also have the benefits of unprecedented information sharing and international co-operation, and can take advantage of various administrative, economic, and legal tools aimed at promoting the necessary adjustments, from more realistic pricing to the sensible subsidies required to kick-start new and promising techniques or help them to achieve a critical market mass more quickly.

The task ahead is daunting, because the expectations for energy futures are high. They combine the anticipation of continued supply improvements (in access, reliability, and affordability) in already affluent (or at least fairly well-off) countries (whose populations total about one billion), not only with the necessity of substantial increases in average per caput energy consumption among the world's (roughly five billion) less fortunate people, but also with the need to harness, distribute, and convert these massive energy flows in ways compatible with long-term maintenance (and in many cases major enhancement) of local and global environmental quality. Such challenging, fundamental transformations offer the best opportunities for creative solutions and effective adaptations. The evolutionary and historical evidence shows that humans are uniquely adapted to deal with change. While our past record of ingenuity, invention, and innovation is no guarantee that another fairly smooth epochal energy transition will take place during the next few generations—it is a good foundation for betting that our chances are far better than even.