> "Any realistic appraisal of global energy futures must begin with a comprehensive and balanced understanding of resources and their uses. What are the kinds and magnitudes of energy stores and flows available to supply the world's still-growing needs for fuels and electricity? And what is the intensity and pattern of their use?"

Energy Resources and Uses: A Global Primer for the Twenty-First Century

VACLAV SMIL

Most discussions of the earth's energy resources and their use by modern societies betray a widespread lack of scientific literacy and abound in misinformation, biases, and proffers of dubious solutions driven by various special-interest agendas. Any realistic appraisal of global energy futures must begin with a comprehensive and balanced understanding of resources and their uses. What are the kinds and magnitudes of energy stores and flows available to supply the world's still-growing needs for fuels and electricity? And what is the intensity and pattern of their use?

FOSSIL FUELS: WHAT AND WHERE

The earth is well endowed with two kinds of energy resources: enormous stores of fossil fuels, and huge renewable flows of energies originating in the sun's thermonuclear reactions and in the planet's internal heat generation. As their name makes clear, all fossil fuels were traditionally considered the products of ancient conversions of solar radiation into biomass, which, through fossilization, yielded different types of solids, liquids, and gases. (Recently, and controversially, a group of geologists has come to believe that some oils and gases have abiotic origins in the earth's crust.)

Coals, dominated by carbon adulterated with incombustible ash and water, became the world's most important solid fuels during the 1890s, when their energy content surpassed that of the biomass fuels (mainly wood and crop residues). Subsequent increase in output has been accompanied by a steady decline in relative importance: coal now provides less than 25 percent of the world's total primary energy supply (TPES: all commercial fuels and primary electricity, including hydro, nuclear, wind, solar, and geothermal generation). A tonne (metric ton) of bituminous coals, whose extraction dominates world coal output, has an energy equivalent to about 0.5 tonnes of crude oil.

Hydrocarbons—crude oils and natural gases—are mixtures of organic molecules. Liquid hydrocarbons are made up of longer-chained organic molecules, and their number determines the fuel's specific density. Refining of the lightest crude oils (especially those from Algeria and Nigeria), which are more than 25 percent lighter than water, yields a high percentage of gasolines, while many crude oils from the Middle East are nearly as heavy as water and require expensive catalytic cracking to produce fuels that can be used by vehicles and planes. Despite different densities, the energy content of all crude oils and liquids produced by their refining is very similar: about twice as large as that of bituminous coal and nearly three times as large as that of air-dried wood. Crude oil became the world's most important primary fuel during the 1970s and now it provides about 40 percent of the world's TPES.

Natural gases are usually mixtures of the lightest methane (CH_4) and heavier molecules of the alkane series, mostly ethane and propane. Their energy density under normal atmospheric pressure is only 1/1000 that of crude oil and hence their use as a portable transportation fuel is limited. Compared to oils, they are also more expensive to transport in continental pipelines and even more so by liquefied natural gas tankers. But the cleanliness of their com-

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bustion has made them the best choice for space heating and recently also for electricity generation; they now claim nearly 25 percent of the world's TPES.

Because of their origin in plant and animal biomass, fossil fuels contain traces of sulfur—generally around 2 percent in coals, usually less in oils and gases. Combustion releases this sulfur as sulfur dioxide, whose oxidation produces sulfates, the largest contributors to acid precipitation, the environmental effects of which are especially pronounced in eastern North America, Western Europe, and East Asia. The oxidation of fossil carbon, however, is of the greatest environmental concern. Emitted carbon dioxide is the most important anthropogenic greenhouse gas and its rising atmospheric concentrations—from 280 parts per million (ppm) 150 years ago to 370 ppm in 2000—have already begun changing the global climate. The carbon content of coals is as much as 85 percent, in crude oils it ranges between 84 and 87 percent, and the CH_4 found in natural gases has only 75 percent carbon (and hence its combustion generates the least amount of carbon dioxide per unit of released energy).

RESERVES AND RESOURCES

Assessments of fossil-fuel endowment work with two principal categories, reserves and resources. Resources represent the totality of a particular mineral in the earth's crust. Reserves are those well-explored shares of total resources that can be extracted with available techniques at an acceptable cost; advances in exploration and extraction constantly transfer minerals from the broader, poorly known resource category to the reserve pool. Resources are, reserves become. Rising costs of extraction and its unacceptable environmental and social consequences have led us repeatedly to stop the transfer between the two categories long before any mineral resource could be exhausted on the global scale (exhaustion of local deposits is, of course, common).

Resource substitutions—the copper-iron-steel-aluminum-plastics-composites sequence, for example, or the wood-coal-oil-natural gas sequence—have been a key feature of human evolution for the past five millennia, and there is no reason to assume that this process has ended. Increased efficiencies of resource use have been another critical factor as everyday energy conversions now provide two or three times as much useful energy (be it space heat, light, or motion) from a unit of fossil fuels than they did in 1900. Again, this process is nowhere near its end. Seen from these perspectives, sensationalized claims about an early exhaustion of a mineral resource can be discounted. Long before any resource can be physically exhausted it will be replaced by a combination of new inputs and higher efficiencies.

Available estimates of global coal resources are at least 6 trillion and as much as 11 trillion tonnes. Even a perfect knowledge of global coal resources would be irrelevant, since most of the fuel in the ground will always remain undisturbed, too costly to mine, and too polluting to burn if it were mined. Coal reserves are about 1 trillion tonnes, and the global reserve/production ratio (r/p, calculated by dividing the reserve total by annual output) is about 230 years, more than three times as high as the rate for natural gas and more than four times larger than the global r/p for crude oil. And while coal deposits are more widely distributed than hydrocarbon reservoirs, reserves of good-quality coal are actually more concentrated. The five nations with the largest coal reserves—the United States, Russia, China, Australia, and Germany—account for about 69 percent of the world's total.

The global natural gas r/p ratio is above 60 years, with the largest gas reserves found in Russia (about one-third of the total), Iran (about 15 percent), Qatar (over 7 percent), and Saudi Arabia and the United Arab Emirates (4 percent each). The Middle East claims about 35 percent of all known natural gas reserves, a share much smaller than the 64 percent of crude oil resources it holds. Renewed predictions of an early peak in global oil extraction have refocused attention on the world's crude oil resources and reserves.[1]

Because a complete course of extracting a finite resource should follow a fairly symmetrical bell curve, global oil extraction would begin to fall once the cumulated production passes the midpoint of ultimately recoverable resources; Colin Campbell and Jean Laherrère assert this will happen before 2010. Many petroleum geologists concur with this conclusion, and some forecast world oil shortages and even mass unemployment, breadlines, homelessness, and the end of industrial civilization.

These Cassandras are just the latest contributors to the venerable tradition of forecasting the end of

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[1] Most prominently, Colin Campbell and Jean Laherrère claim that with 850 billion barrels in existing reserves, and with just 150 billion barrels of oil to be discovered, we have no more than 1 trillion barrels to produce in the future, or only about 20 percent more than we have burned already. Campbell's and Laherrère's publications and other writings about the oil era are available at <http://www.hubbertpeak.com>.

the oil era. One example is especially priceless. In 1979 the United States Central Intelligence Agency concluded that global oil "output must fall within a decade ahead" and that the world "does not have years in which to make a smooth transition to alternative energy sources." In essence, the CIA experts were arguing that the world's primary energy supply needed to be converted to a different source within months, an utter impossibility. A generation later, oil output is more than 10 percent higher than it was in 1979.

The latest global evaluation by the United States Geological Survey has concluded, much more realistically, that the mean grand total of undiscovered conventional oil, reserve growth in discovered fields, and cumulative production up to the year 2000 is just over 3 trillion barrels, or 20 percent higher than its previous assessment, and 72 percent above the Campbell and Laherrère total. And in 1996 Laherrère himself conceded that adding the median reserve estimates of natural gas liquids and nonconventional oil would result in up to 1.9 trillion barrels of oil that has yet to be produced, twice the amount of his conservative estimate for conventional crude oil alone. Moreover, nonconventional oil is also locked in tar sands and oil shales. The former resource is already commercially exploited in Canada and Venezuela. And we cannot exclude the possibility that the combination of efficiency and substitution may outpace the rate of oil depletion and that crude oil, like most of today's coal or uranium, could become uncompetitive; the peak of its global production may have little to do with resources in the ground but with the demand above it.

Whatever the actual course of future oil extraction, there is no reason—historical, economic, or technical—to interpret the eventual demise of today's cheap oil as a harbinger of unmanageable civilizational difficulties. Energy transitions have always stimulated human inventiveness, shaped modern industrial and postindustrial civilization, and left deep imprints on the structure and productivity of economies as well as on the organization and welfare of societies. Of course, these transitions inevitably produce enormous problems for the providers of the energies that are being replaced, and they require the scrapping or reorganization of many old infrastructures and the introduction of entirely new links, procedures, and practices.

Sectoral and regional socioeconomic dislocations are thus common; the infrastructural transformations are often costly and protracted, and their diffusion may be very uneven; societies also take generations to adjust to new sources of energy and to new modes of its conversion. But historical perspectives show that every transition—from biomass fuels to coal, from coal to oil, from oil to natural gas—has brought tremendous benefits for society as a whole by elevating economies and societies to new levels of productivity and affluence, and by improving environmental quality. Thus, even if we were to experience an early global decline of conventional oil production, we should see it as an opportunity rather than as a catastrophe.

RENEWABLE ENERGIES: PROSPECTS AND LIMITS

Given the time needed to improve new extraction and conversion techniques and to make their cost competitive with dominant means of energy supply, energy transitions are always gradual and protracted affairs. Moreover, expensive infrastructures associated with a particular energy resource (ranging from coal-fired power plants to supertankers) cannot be rapidly discarded. During the 1950s and 1960s, there were great hopes that nuclear-generated electricity—first from fission, later from fast breeder reactors, and eventually from fusion—would surpass fossil-fueled generation before the year 2000 and that it would dominate global energy supply during the first half of the twenty-first century. Economic realities and concerns about catastrophic accidents and nuclear weapons proliferation combined to abort these bold plans. Nuclear energy did become important (it supplies nearly 20 percent of the world's electricity) but chances for its future vigorous expansion appear modest at best.

Consequently, the transition from coal and conventional oil will rely not only on increased consumption of nonconventional liquids and vigorous expansion of natural gas extraction but on steadily rising contributions of renewable energies. These sources fall into two basic categories, solar and terrestrial. Solar energy can be harnessed directly by converting radiation to heat and electricity, and indirectly by tapping solar-powered energy flows, especially those of water and wind, and using biomass fuels. Geothermal energy, radiating from the earth's core and mantle, is the only nonsolar renewable flow that has a significant commercial potential, but less than 0.5 percent of the world's electricity-generating capacity has been installed in geothermal power plants, mostly in California, the Philippines, Mexico, and Italy.

The solar radiation reaching the earth every year is equivalent to nearly 14,000 times the current global TPES. If only 1 percent of all wind energy were converted to electricity, global capacity would be more than 10 times the total that was installed in all fossil, nuclear, and hydro stations in 2000. And every year, photosynthesis stores in plants energy equal approximately five times the world's TPES. Costs obviously matter, and many renewable conversions are still years or decades from being truly competitive with established fossil fuel–based techniques. However, even if production costs were of little concern, only a small fraction of these huge totals could be harnessed, since it is obviously impossible to convert all winds or all river flows into electricity (atmospheric circulation and free-flowing rivers would cease) or to use the entire increment of forest biomass for energy (lumber and paper would disappear, biodiversity would plummet, nutrients would not be recycled).

Hydroelectric generation is the only renewable conversion that has played a major commercial role for over a century. Hydrostations produce almost 20 percent of the world's electricity, with Canada, the United States, Brazil, China, and Russia accounting for more than half the total. Eventual development of all economically feasible projects could triple today's generation. The largest untapped potential remains in Africa (less than 5 percent harnessed) and Asia (less than 15 percent of potential used). Europe and North America have already captured nearly half of the economically feasible total, or about as much as is practical to allow for necessary stream flows and other water uses.

There is no reason to interpret the eventual demise of today's cheap oil as a harbinger of unmanageable civilizational difficulties.

Hydrogeneration will most likely maintain its current share of global electricity production during the next two decades, but new projects will have to be much better designed and more carefully built to avoid the repetition of many problems for which the industry has been recently criticized. These negatives include the disruptive and poorly conceived mass relocations of people to make way for new reservoirs (exemplified by India's Narmada River projects and by China's giant Three Gorges dam, the world's largest hydrostation, whose reservoir will displace at least 1.2 million people), and a variety of environmental impacts created by building large dams and impounding voluminous reservoirs (these range from reductions of biodiversity to greenhouse gas emissions from decaying submerged vegetation).

BLOWIN' IN THE WIND

Wind-driven electricity generation remains the most successfully commercialized renewable energy conversion. Improved designs have resulted in larger, more reliable, more efficient, and less expensive wind turbines. The best of these machines can produce electricity whose price is already competitive with fossil-fueled generation. Because of the environmental advantages of wind energy (above all, no emissions of acidifying or greenhouse gases), several countries have begun to promote its use through incentives and subsidies. Less than 1 percent of all electricity was generated worldwide by wind turbines during 2000, with Germany, Denmark, and the United States accounting for nearly two-thirds of the total. But falling costs mean that a period of rapid expansion lies ahead: 10 percent of the world's electricity may be coming from wind by 2020.

An even greater promise is held by photovoltaic (PV) cells that convert solar radiation directly into electricity, offering no moving parts, no air pollutants, and more flexible locations (sunny places are much more abundant than windy spots). The PV phenomenon has been known since 1839, but the key scientific breakthrough came only in 1954 when Bell Laboratories researchers produced silicon solar cells that converted 4.5 percent of sunlight absorbed to electricity. Today's commercial crystalline silicon cells are about 15 percent efficient. Worldwide, PV cells have capacity equal to less than 0.1 percent of the total available in fossil-fueled generators. Clearly, the costs of PV generation must fall before the technique can be used as widely by households and industries as it has been successfully used in space and in specialized terrestrial applications.

Biomass energies—especially fuel wood (and charcoal made from it) and crop residues (mainly cereal straws)—dominated the world's fuel consumption until the 1890s. Today's biomass fuels, burned mostly by households and some industries in low-income countries, contribute about 8 percent of global TPES. This consumption should be significantly reduced or eliminated, since it comes from excessive woodcutting; moreover, arable lands would benefit from more intensive recycling, rather than burning, of crop residues. Nor is the intensive cultivation of energy crops a desirable option. Efficiencies of photosynthesis are low (typically less than 1 percent of incident solar energy is converted into new biomass), and the use of land for energy plantations would compete with its use for food and fiber. Intensive cultivation of trees or annual energy crops could also lead to further declines of biodiversity and to excessive use of water and fertilizers.

The much-misunderstood place of hydrogen in the world's future energy supply should be mentioned here. Hydrogen is not, as countless uninformed accounts have it, a new source of energy—indeed, it is not an energy source at all but, like electricity, an energy carrier. Energy must be used to produce it, either through electrolysis of water or the steam reforming of coal or natural gas. Once the gas is available, its combustion releases more energy per mass than any fossil fuel while producing only water; it could thus be used in fuel cells to produce electricity. Steady advances of renewable conversions and hydrogen-based techniques will continue, but no energy revolutions lie ahead. The global energy system in 2010 or 2025 will not be dominated by fuel cells, wind turbines, and photovoltaics, but all these conversions will claim increasing shares of the TPES as we will continue to rely on fossil fuels used with increasingly higher efficiency.

Even if we were to experience an early global decline of conventional oil production, we should see it as an opportunity rather than as a catastrophe.

THE INTOLERABLE GAP—AND HOW TO NARROW IT

All energy conversions undertaken by humans are just means toward a multitude of ends. We convert energies not only to secure basic existential needs but also to satisfy assorted consumerist urges, to enrich our intellectual lives, and to make us more successful as a social and caring species or more brutal as an aggressive and belligerent one. And we have come to realize that, given the fundamental necessity to preserve the integrity of the biosphere we inhabit, all these conversions should be accomplished in ways that are the least disruptive to the maintenance of irreplaceable environmental services.

No extraordinary knowledge of history is needed to conclude that our record has been very mixed, with energy conversions that serve desirable and life-enriching goals occurring alongside a multitude of wasteful and destructive practices. But the most remarkable attribute of the global use of energy is that it proceeds on two different planes—in two different worlds even. The first still relies heavily on traditional biomass, and most of its citizens convert only enough wood, coal, or kerosene to ensure basic subsistence—about 2 billion of them still do not have access to electricity. Average energy use in the affluent countries is five, ten, or even twenty times higher, and it assures a surfeit of food, lengthy schooling, unprecedented material wealth, and a high degree of personal mobility.

Although the gap has been narrowing, it remains wide. At the beginning of the twentieth century, industrializing countries in Europe and North America consumed about 98 percent of the world's commercial energy (excluding biomass). At that time most of the world's inhabitants were subsistence farmers in Asia, Africa, and Latin America who did not use any modern energies directly. Very little had changed by the first half of the twentieth century: in 1950 industrialized countries consumed about 93 percent of the world's TPES. Subsequent economic development in Asia and Latin America finally began to reduce this share, but by 2000 affluent countries, containing just one-fifth of the world's population, claimed no less than about 70 percent of all primary energy.

The United States alone, with less than 5 percent of humanity, consumed about 27 percent of the world's TPES in 2000; the seven largest economies of the world (commonly known as the Group of Seven—the United States, Canada, Japan, Germany, France, Britain, and Italy), whose population adds up to just about 10 percent of the world's total, claimed about 45 percent of the global TPES. In contrast, the poorest quarter of mankind—some 15 sub-Saharan African countries, Nepal, Bangladesh, the nations of Indochina, and most of rural India—consumed a mere 2.5 percent of global TPES. Moreover, the poorest people in the poorest countries—which consist of several hundred million adults and children, and include subsistence farmers, landless rural workers, and destitute and homeless people in expanding megacities—still do not consume *any* commercial fuels or electricity directly. National per capita means range from less than 20 kg of oil equivalent in the poorest countries of sub-Saharan Africa to more than 7 tonnes of oil equivalent (toe) in the United States and Canada.

How much is needed to support a healthy, productive, and intellectually rewarding life? Correlations between average per capita energy consumption and numerous indicators of quality of life—including infant mortality, life expectancy, food supply, literacy, educational opportunities, and political freedoms—make for some fascinating conclusions. A society willing to channel its resources into the provision of adequate diets, the availability of good health care, and the accessibility to basic schooling could guarantee decent physical well-being, high life expectancy, varied nutrition, and fairly good educational opportunities with as little as 1 toe per capita. Pushing infant mortalities below 20 per 1,000 live births, raising female life expectancies above 75 years, and elevating the United Nation's Human Development Index above 0.8 (the HDI's maximum, most closely approached by Canada, Japan, and Norway, is 1.0) appear to require at least 1.5 toe per capita.

The best global rates (infant mortalities below 10, female life expectancies above 80 years, HDI above 0.9) need no less than about 2.6 toe per capita. All the quality-of-life variables relate to average per capita energy use in a nonlinear manner, with diminishing returns becoming obvious at between 1 and 1.6 toe per capita, and with basically no additional gains accompanying consumption above 2.6 toe. Prospects for a nation's political freedoms have little to do with any increases in energy use above the existential minima (contrast, for example, energy-rich autocratic Saudi Arabia bereft of most of the basic personal freedoms with India's vibrant exercise of democratic rights).

Public opinion polls show a remarkable absence of correlation between average economic well-being and energy use, and feelings of personal and economic security, optimism about the future, and general satisfaction with life. Our quest for ever-higher energy use thus has no objective or subjective justification. If there is no good reason why average per capita energy use in affluent countries should be increasing (it did during the 1990s), numerous environmental and social reasons show why it should be declining. And because of a large untapped potential to derive more useful energy from a steadily declining amount of primary supply, this could be done without compromising quality of life.

Opportunities for efficiency gains remain abundant even in the most advanced economies, and individual actions, multiplied by many millions, would make an enormous difference. The car I drive (a Honda Civic) needs 60 percent less gasoline to take me to work than does a 4x4 Range

Rover; the compact fluorescent light in my lamp consumes 65 percent less electricity than does an incandescent bulb; the high-efficiency furnace in my basement converts 94 percent of the natural gas it uses as fuel into warmth inside my house (compared to the 50 percent efficiency for an older oil furnace and the 10 percent efficiency for seemingly "green" but actually heat-wasting wood-burning fireplaces whose multiple installations are de rigueur in the megahouses of nouveaux riches). And large opportunities for efficiency gains in modernizing countries have been impressively illustrated by China, which needs less than half as much energy per unit of its GDP than it did in 1980.

Annual per capita energy consumption of between 1.2 and 1.6 toe appears to be the minimum for any society where a general satisfaction of essential physical needs is combined with fairly widespread opportunities for intellectual advancement and with respect for basic individual rights. Remarkably, the global mean of per capita energy consumption is now about 1.4 toe per year, almost exactly in the middle of this range. Egalitarian sharing would thus provide everybody with enough energy to lead a fairly healthy, long, and active life enriched by more than a basic education. Obviously, that will not happen, as it would require halving today's per capita consumption rate in Europe and cutting it by 80 percent in North America. And it should not happen: egalitarianism does not generate the innovation needed for the world's technical and social advances.

What should happen is the greatest possible reduction of excess: undoubtedly, a combination of doable and affordable technical and social fixes could cut the affluent world's per capita energy use by 25 to 35 percent within a generation, and do so without lowering the standard of living. When combined with expanded supply of conventional and nonconventional hydrocarbons, with higher conversion efficiencies in Asia, Africa, and Latin America, and with effective and steady commitments to the diffusion of improved renewable energy techniques everywhere, this gradual reduction would shift the global energy system in the right direction—and the world's inexcusably huge energy gap could be narrowed impressively well before 2050. ■