FEATURE ARTICLES

Global Energy: The Latest Infatuations

In energy matters, what goes around, comes around —but perhaps should go away

Vaclav Smil

To follow global energy affairs is to have a never-ending encounter with new infatuations. Fifty years ago media ignored crude oil (a barrel went for little more than a dollar). Instead the western utilities were preoccupied with the annual double-digit growth of electricity demand that was to last indefinitely, and many of them decided that only large-scale development of nuclear fission, to be eventually transformed into a widespread adoption of fast breeder reactors, could secure electricity's future. Two decades later, in the midst of the second energy "crisis" (1979–1981, precipitated by Khomeini's takeover of Iran), rising crude oil prices became the world's prime existential concern, growth of electricity demand had slumped to low single digits, France was the only nation that was seriously pursuing a nuclear future, and small cars were in vogue.

After world crude oil prices collapsed in 1985 (temporarily below $5 per barrel), American SUVs began their rapid diffusion that culminated in using the Hummer H1, a civilian version of a U.S. military assault vehicle weighing nearly 3.5 tonnes, for trips to grocery stores—and the multinational oil companies were the worst performing class of stocks of the 1990s. The first decade of the 21st century changed all that, with constant fears of an imminent peak of global oil extraction (in some versions amounting to nothing less than lights out for western civilization), catastrophic consequences of fossil fuel-induced global warming and a grand unraveling of the post-WW II world order.

All of this has prompted incessant calls for the world to innovate its way into a brighter energy future, a quest that has engendered serial infatuations with new, supposedly perfect solutions: Driving was to be transformed first by biofuels, then by fuel cells and hydrogen, then by hybrid cars, and now it is the electrics (Volt, Tesla, Nissan) and their promoters (Shai Agassi, Elon Musk, Carlos Ghosn) that command media attention; electricity generation was to be decarbonized either by a nuclear renaissance or by ubiquitous wind turbines (even Boone Pickens, a veteran Texas oilman, succumbed to that call of the wind), while others foresaw a comfortable future for fossil fuels once their visions of mass carbon capture and sequestration (CCS) were put in practice. And if everything fails, then geoengineering—manipulating the Earth's climate with shades in space, mist-spewing ships or high-altitude flights disgorging sulfur compounds—will save us by cooling the warming planet.

This all brings to mind Lemuel Gulliver's visit to the grand academy of Lagado: No fewer than 500 projects were going on there at once, always with anticipation of an imminent success, much as the inventor who "has been eight years upon a project for extracting sunbeams out of cucumbers" believed that "in eight years more, he should be able to supply the governor's gardens with sunshine, at a reasonable rate"—but also always with complaints about stock being low and entreaties to "give … something as an encouragement to ingenuity." Admittedly, ideas for new energy salvations do not currently top 500, but their spatial extent puts Lagado's inventors to shame: Passionately advocated solutions range from extracting work from that meager 20-Kelvin difference between the surface and deep waters in tropical seas (OTEC: ocean thermal energy conversion) to Moon-based solar photovoltaics with electricity beamed to the Earth by microwaves and received by giant antennas.

And continuous hopes for success (at a low price) in eight more years are as fervent now as they were in the fictional 18th century Lagado. There has been an endless procession of such claims on behalf of inexpensive, market-conquering solutions, be they fuel cells or cellulosic ethanol, fast breeder reactors or tethered wind turbines. And

Figure 1. In *Gulliver's Travels* Lemuel visits the grand academy of Lagado, where more than 500 research projects were ongoing, always with expectations of an early payoff. The inventor here, as shown in an illustration by Milo Winter in the 1930 edition, is soon to extract sunbeams from cucumbers. The author sees an analogy with the current attitude toward energy in the United States and Canada. Instead of facing the fact that these two countries use twice as much energy per capita as other wealthy nations with similar indicators of human development and instead of learning to do as much with much less, these countries continue to search for technical fixes to maintain, even to increase, their use of energy.

Vaclav Smil is a Distinguished Professor at the University of Manitoba. His interdisciplinary research deals with interactions of energy, environment, food, economy, population and technical advances. He is the author of 30 books on these topics; the latest ones (in 2010) include Energy Myths and Realities, Energy Transitions *and* Two Prime Movers of Globalization. *E-mail: vsmil@cc.umanitoba.ca Website: http://www.vaclavsmil.com*


EXT
CUC
MILO WINTER

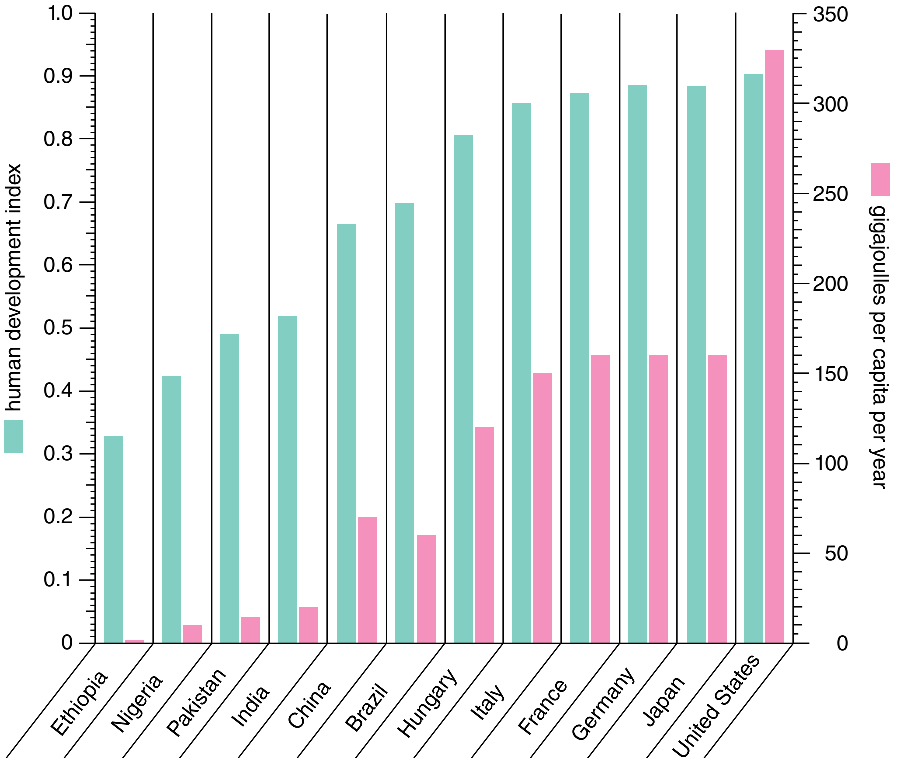


Figure 2. At very low and low per capita consumption levels, higher use of energy is clearly tied to rising index of human development, but once energy per capita reaches about 150 gigajoules per year, the correlation breaks down. More is not better.

energy research can never get enough money to satisfy its promoters: In 2010 the U.S. President's council of advisors recommended raising the total for U.S. energy research to $16 billion a year; that is actually too little considering the magnitude of the challenge—but too much when taking into account the astonishing unwillingness to adopt many readily available and highly effective existing fixes in the first place.

Enough to Go Around?

Although all this might be dismissed as an inevitable result of the desirably far-flung (and hence inherently inefficient) search for solutions, as an expected bias of promoters devoted to their singular ideas and unavoidably jockeying for limited funds, I see more fundamental, and hence much more worrisome, problems. Global energy perspective makes two things clear: Most of humanity needs to consume a great deal more energy in order to experience reasonably healthy lives and to enjoy at least a modicum of prosperity; in contrast, affluent nations in general, and the United States and Canada in particular, should reduce their excessive energy use. While the first conclusion seems obvious, many find the second one wrong or outright objectionable.

In 2009 I wrote that, in order to retain its global role and its economic stature, the United States should

> provide a globally appealing example of a policy that would simultaneously promote its capacity to innovate, strengthen its economy by putting it on sounder fiscal foundations, and help to improve Earth's environment. Its excessively high per-capita energy use has done the very opposite, and it has been a bad bargain because its consumption overindulgence has created an enormous economic drain on the country's increasingly limited financial resources without making the nation more safe and without delivering a quality of life superior to that of other affluent nations.

I knew that this would be considered a nonstarter in the U.S. energy policy debate: Any calls for restraint or reduction of North American energy use are still met with rejection (if not derision)—but I see that quest to be more desirable than ever. The United States and Canada are the only two major economies whose average annual per capita energy use surpasses 300 gigajoules (an equivalent of nearly 8 tonnes, or more than 50 barrels, of crude oil). This is twice the average in the richest European Union (E.U.) economies (as well as in Japan)—but, obviously, Pittsburghers or Angelenos are not twice as rich, twice as healthy, twice as educated, twice as secure or twice as happy as inhabitants of Bordeaux or Berlin. And even a multiple adjustment of national per capita rates for differences in climate, typical travel distances and economic structure leaves most of the U.S.–E.U. gap intact: This is not surprising once it is realized that Berlin has more degree heating days than Washington D.C., that red peppers travel the same distance in refrigerated trucks from Andalusia to Helsinki as they do from California's Central Valley to Illinois, and that German exports of energy-intensive machinery and transport-equipment products surpass, even in absolute terms, U.S. sales.

Moreover, those who insist on the necessity and desirability of further growth of America's per capita energy use perhaps do not realize that, for a variety of reasons, a plateau has been reached already and that (again for many reasons) any upward departures

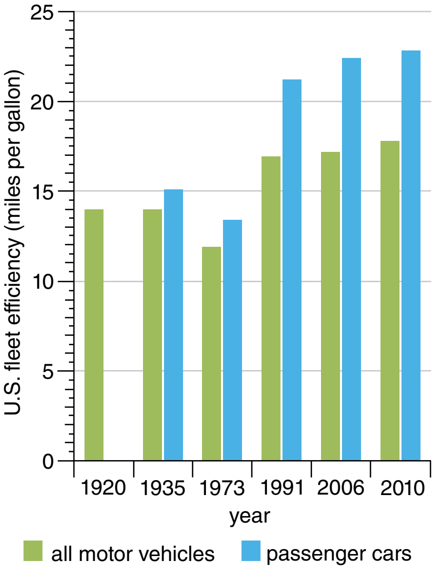


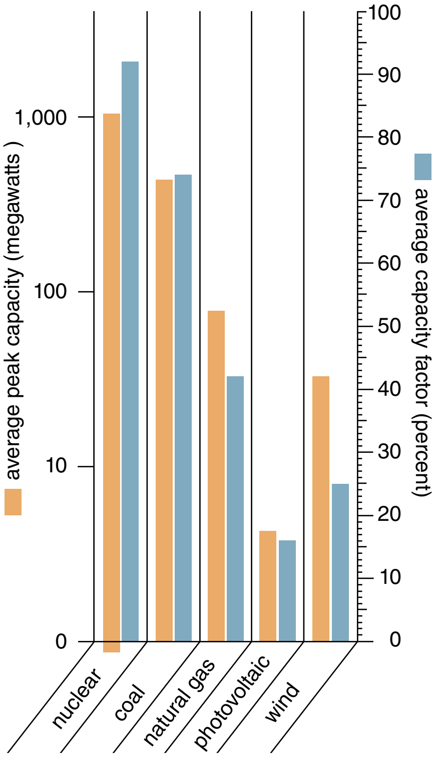
Figure 3. Although the efficiency of internal combustion engines has increased substantially in the past 90 years (particularly when the adoption of diesel-powered cars is taken into account), the average performance of motor vehicles in the Unites States has improved only from about 14 miles per gallon to about 18 mpg.

are highly unlikely. In 2010 U.S. energy consumption averaged about 330 gigajoules per capita, nearly 4 percent lower than in 1970, and even the 2007 (pre-crisis) rate of 355 gigajoules (GJ) per capita was below the 1980 mean of 359 GJ. This means that the U.S. per capita consumption of primary energy has remained essentially flat for more than one generation (as has British energy use). How much lower it could have been can be illustrated by focusing on a key consumption sector, passenger transport.

Planes, Trains and Automobiles

After 1985 the United States froze any further improvements in its corporate automobile fuel efficiency (CAFE), encouraged a massive diffusion of exceptionally inefficient SUVs and, at the same time, failed to follow the rest of modernizing world in building fast train links. For 40 years the average performance of the U.S. car fleet ran against the universal trend of improving efficiencies: By 1974 it was lower (at 13.4 miles per gallon [mpg]) than during the mid-1930s! Then the CAFE standards had doubled the efficiency of new passenger cars by 1985, but with those standards subsequently frozen and with the influx of SUVs, vans and light trucks, the average performance of the entire (two-axle, four-wheel) car fleet was less than 26 mpg in 2006 or no better than in 1986—while a combination of continued CAFE upgrades, diffusion of new ultra low-emission diesels (inherently at least 25–30 percent more efficient than gasoline-powered cars) and an early introduction of hybrid drives could have raised it easily to more than 35 or even 40 mpg, massively cutting the U.S. crude oil imports for which the country paid $1.5 trillion during the first decade of the 21st century.

Figure 4. Generation of electricity by wind turbines and photovoltaic (PV) cells differs in two fundamental ways from thermal electricity production. First, as shown in the left column, average capacities of photovoltaic and wind farms are smaller than those of nuclear, coal and even natural gas-powered generators. (Note the logarithmic scale.) Second, the percentage of time that the generators can work at full capacity (load factor) is much lower. (The capacity factor of gas-fired generators is constrained not by their ability to stay online but by their frequent use as intermittent sources to meet demand peaks.) Moreover, differences in capacity factors will always remain large. In 2009 the load factor averaged 74 percent for U.S. coal-fired stations, and the nuclear ones reached 92 percent, whereas wind turbines managed only about 25 percent. (All plots show the U.S. averages in 2009.)



And the argument that its large territory and low population density prevents the United States from joining a growing list of countries with rapid trains (traveling 250–300 kilometers per hour or more) is wrong. The northeastern megalopolis (Boston-Washington) contains more than 50 million people with average population density of about 360 per square kilometer and with nearly a dozen major cities arrayed along a relatively narrow and less than 700-kilometer long coastal corridor. Why is that region less suited to a rapid rail link than France, the pioneer of European rapid rail transport, with a population of 65 million and nationwide density of only about 120 people per square kilometer whose *trains à grande vitesse* must radiate from its capital in order to reach the farthest domestic destinations more than 900 kilometers away? Apparently, Americans prefer painful trips to airports, TSA searches and delayed shuttle flights to going from downtown to downtown at 300 kilometers per hour.

In a rational world animated by rewarding long-term policies, not only the United States and Canada but also the European Union should be boasting about gradual reductions in per capita energy use. In contrast, modernizing countries of Asia, Latin America and, most of all, Africa lag so far behind that even if they were to rely on the most advanced conversions they

Figure 5. Canada's Sarnia Photovoltaic Power Plant became the world's largest PV plant at 80 megawatts of peak power when it was completed in September 2010. It consists of about 1.3 million thin-film PV panels covering about 966,000 square meters, but its capacity factor is expected to be only about 17 percent. (Photo courtesy of First Solar.)

would still need to at least quadruple (in India's case, starting from about 20 GJ per capita in 2010) their per capita supply of primary energy or increase their use by more than an order of magnitude—Ethiopia now consumes modern energies at a rate of less than 2 GJ per capita—before getting to the threshold of a decent living standard for most of their people and before reducing their huge internal economic disparities.

China has traveled further, and faster, along this road than any other modernizing nation. In 1976 (the year of Mao Zedong's death) its average per capita energy consumption was less than 20 GJ per capita, in 1990 (after the first decade of Deng Xiaoping's modernization) it was still below 25 GJ, and a decade later it had just surpassed 30 GJ per capita. By 2005 the rate had approached 55 GJ and in 2010 it reached 70 or as much as some poorer E.U. countries were consuming during the 1970s. Although China has become a major importer of crude oil (now the world's second largest, surpassed only by the United States) and it will soon be importing large volumes of liquefied natural gas and has pursued a large-scale program of developing its huge hydrogenation potential, most of its consumption gains have come from an unprecedented expansion of coal extraction. While the U.S. annual coal output is yet to reach one billion tonnes, China's raw coal extraction rose by one billion tonnes in just four years between 2001 and 2005 and by nearly another billion tonnes by 2010 to reach the annual output of 3 billion tonnes.

China's (and, to a lesser degree, India's) coal surge and a strong overall energy demand in Asia and the Middle East have been the main reason for recent rises of CO_2 emissions: China became the world's largest emitter in 2006, and (after a small, economic crisis-induced, decline of 1.3 percent in 2009) the global total of fossil fuel-derived CO_2 emissions set another record in 2010, surpassing 32 billion tonnes a year (with China responsible for about 24 percent). When potential energy consumption increases needed by low-income countries are considered together with an obvious lack of any meaningful progress in reducing the emissions through internationally binding agreements (see the sequential failures of Kyōtō, Bali, Copenhagen and Cancún gatherings), it is hardly surprising that technical fixes appear to be, more than ever, the best solution to minimize future rise of tropospheric temperatures.

Renewable Renaissance?

Unfortunately, this has led to exaggerated expectations rather than to realistic appraisals. This is true even after excluding what might be termed zealous sectarian infatuations with those renewable conversions whose

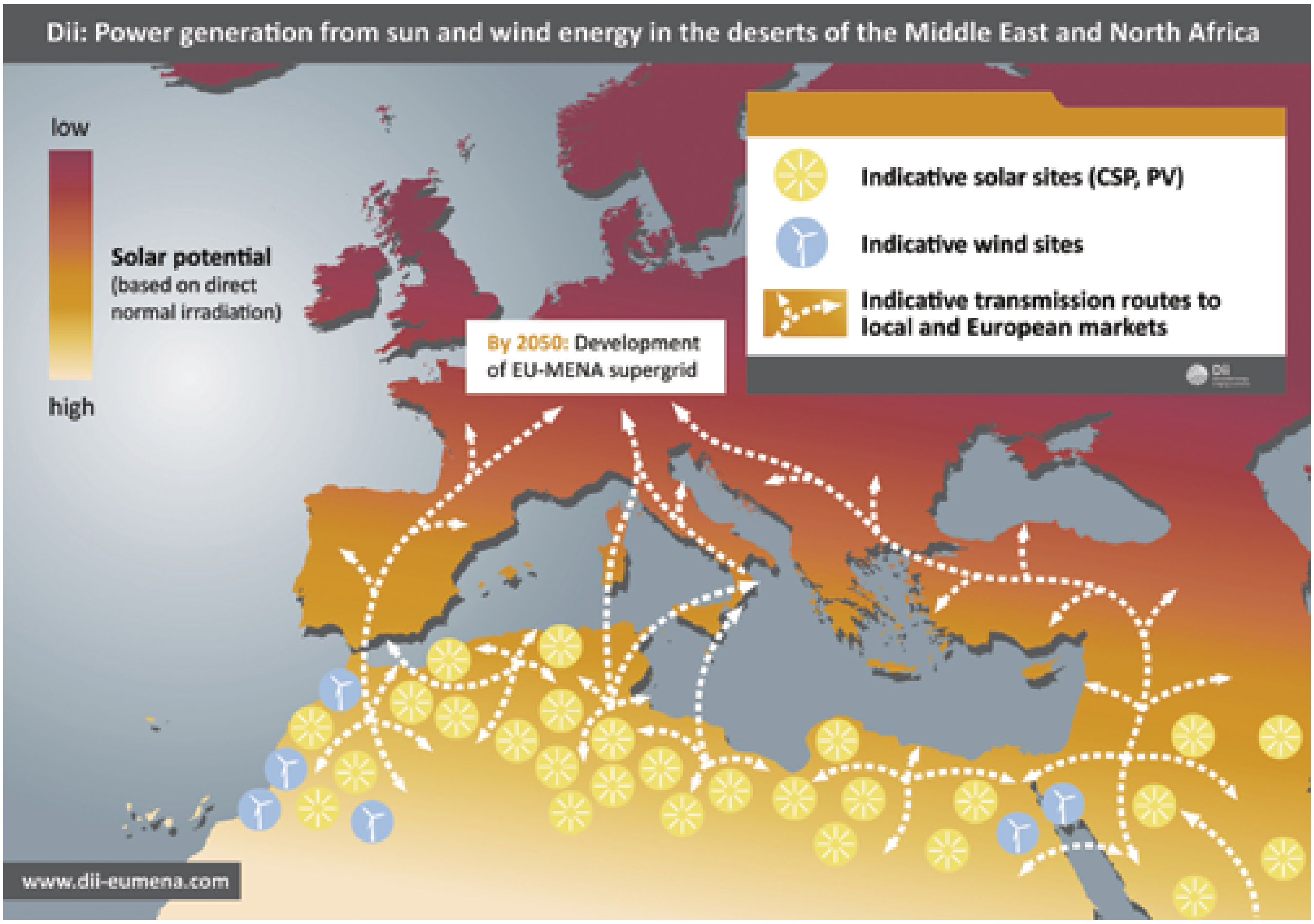


Figure 6. Desertec is perhaps the most ambitious renewable energy plan yet conceived. Most of its electricity would come from concentrating solar thermal power plants in desert regions of northern Africa and the Middle East and would be transmitted by intercontinental high-voltage direct-current lines. The scale of the challenge is obvious, and recent political upheavals across the entire region where these conversions were to take place are not encouraging. (Map courtesy Desertec: http://www.dii-eumena.com/home.html)

limited, exceedingly diffuse or hard-to-capture resources (be they jet stream winds or ocean waves) prevent them from becoming meaningful economic players during the next few decades. Promoters of new renewable energy conversions that now appear to have the best prospects to make significant near-term contributions—modern biofuels (ethanol and biodiesel) and wind and solar electricity generation—do not give sufficient weight to important physical realities concerning the global shift away from fossil fuels: to the scale of the required transformation, to its likely duration, to the unit capacities of new convertors, and to enormous infrastructural requirements resulting from the inherently low power densities with which we can harvest renewable energy flows and to their immutable stochasticity.

The scale of the required transition is immense. Ours remains an overwhelmingly fossil-fueled civilization: In 2009 it derived 88 percent of its modern energies (leaving traditional biomass fuels, wood and crop residues aside) from oil, coal and natural gas whose global market shares are now surprisingly close at, respectively, 35, 29 and 24 percent. Annual combustion of these fuels has now reached 10 billion tonnes of oil equivalent or about 420 exajoules (420 × 10^{18} joules). This is an annual fossil fuel flux nearly 20 times larger than at the beginning of the 20th century, when the epochal transition from biomass fuels had just passed its pivotal point (coal and oil began to account for more than half of the global energy supply sometime during the late 1890s).

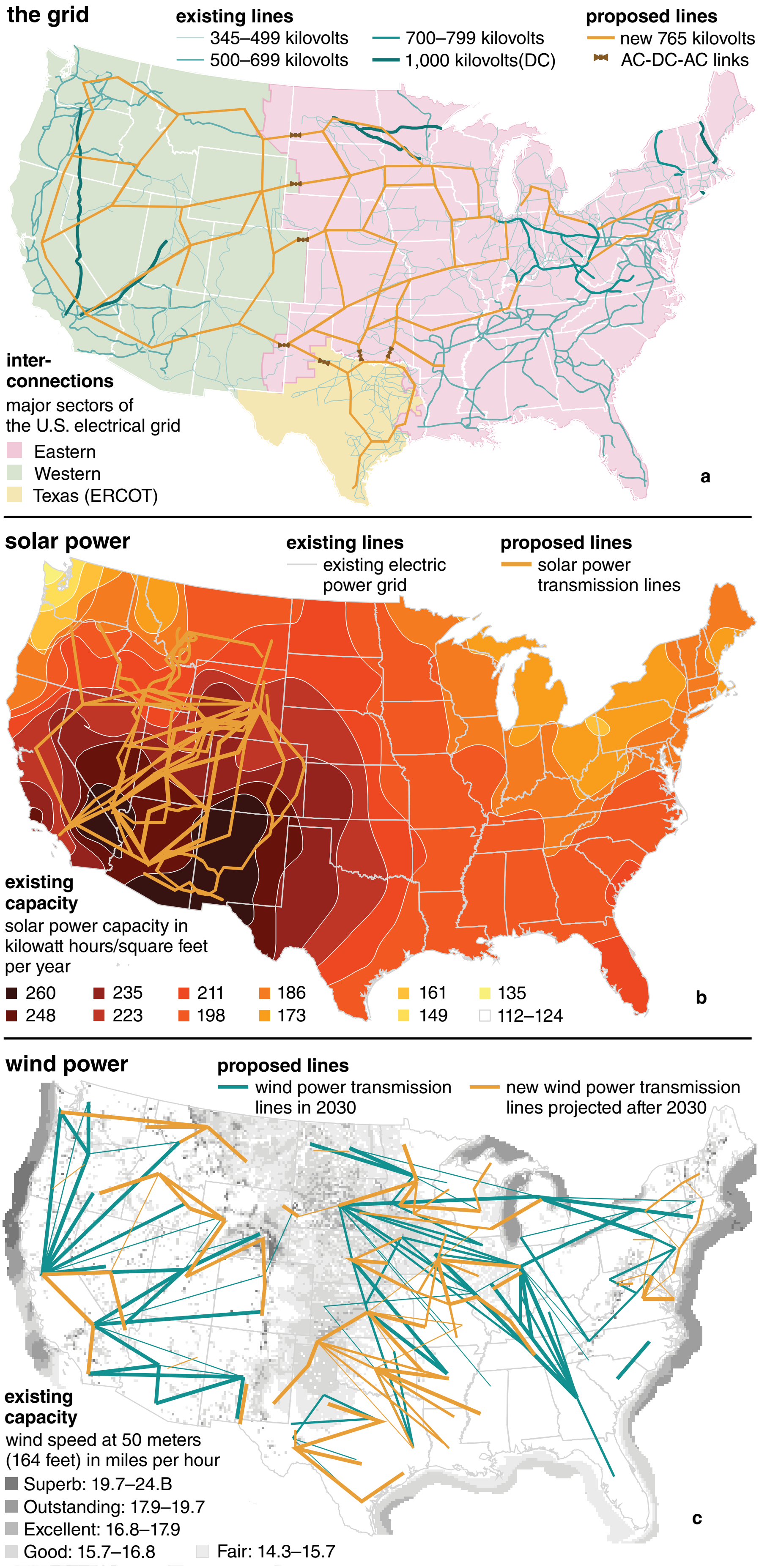


Figure 7. In the United States the foremost problem in replacing much conventional electrical production with renewables is to get power from where it is most efficiently produced to where it is most needed. The existing U.S. grid is divided into zones *(a)*, which do not normally share power on a large scale, and a new nationwide grid would be needed to connect them. The availability of solar power is concentrated in the southwestern United States *(b)*. Even there, many new transmission lines would be required to transfer PV electricity from production to demand. Challenges of delivering wind-generated electricity from the Great Plains and other windy regions to the coastal concentrations of heaviest demand are even greater *(c)*. (Maps adapted from National Public Radio: http://www.npr.org/templates/story/story.php?storyId=110997398)

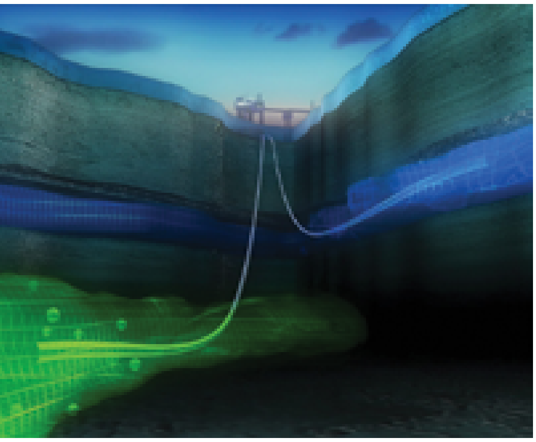


Figure 8. Since 1996 Statoil, the Norwegian state oil company, has been capturing annually one million tonnes of carbon dioxide from natural gas production at Sleipner West field (250 kilometers offshore in the North Sea) and sequestering it in an aquifer more than 800 meters below the seabed. But the global challenge is three to four orders of magnitude greater: If sequestration were to slow down the rise of atmospheric CO_2 it would have to proceed at an annual rate of many billions of tonnes. (Image cuourtesy of Statoil.)

Energy transitions—shifts from a dominant source (or a combination of sources) of energy to a new supply arrangement, or from a dominant prime mover to a new converter—are inherently prolonged affairs whose duration is measured in decades or generations, not in years. The latest shift of worldwide energy supply, from coal and oil to natural gas, illustrates how the gradual pace of transitions is dictated by the necessity to secure sufficient resources, to develop requisite infrastructures and to achieve competitive costs: It took natural gas about 60 years since the beginning of its commercial extraction (in the early 1870s) to reach 5 percent of the global energy market, and then another 55 years to account for 25 percent of all primary energy supply. Time spans for the United States, the pioneer of natural gas use, were shorter but still considerable: 53 years to reach 5 percent, another 31 years to get to 25 percent.

Displacing even just a third of today's fossil fuel consumption by renewable energy conversions will be an immensely challenging task; how far it has to go is attested by the most recent shares claimed by modern biofuels and by wind and photovoltaic electricity generation. In 2010 ethanol and biodiesel supplied only about 0.5 percent of the world's primary energy, wind generated about 2 percent of global electricity and photovoltaics (PV) produced less than 0.05 percent. Contrast this with assorted mandated or wished-for targets: 18 percent of Germany's total energy and 35 percent of electricity from renewable flows by 2020, 10 percent of U.S. electricity from PV by 2025 and 30 percent from wind by 2030 and 15 percent, perhaps even 20 percent, of China's energy from renewables by 2020.

Unit sizes of new converters will not make the transition any easier. Ratings of 500–800 megawatts (MW) are the norm for coal-fired turbogenerators and large gas turbines have capacities of 200–300 MW, whereas typical ratings of large wind turbines are two orders of magnitude smaller, between 2 and 4 MW, and the world's largest PV plant needed more than a million panels for its 80 MW of peak capacity. Moreover, differences in capacity factors will always remain large. In 2009 the load factor averaged 74 percent for U.S. coal-fired stations and the nuclear ones reached 92 percent, whereas wind turbines managed only about 25 percent—and in the European Union their mean load factor was less than 21 percent between 2003 and 2007, while the largest PV plant in sunny Spain has an annual capacity factor of only 16 percent.

As I write this a pronounced high pressure cell brings deep freeze, and calm lasting for days, to the usually windy heart of North America: If Manitoba or North Dakota relied heavily on wind generation (fortunately, Manitoba gets all electricity from flowing water and exports it south), either would need many days of large imports—yet the mid-continent has no high-capacity east-west transmission lines. Rising shares of both wind and PV generation will thus need considerable construction of new long-distance high-voltage lines, both to connect the windiest and the sunniest places to major consumption centers and also to assure uninterrupted supply when relying on only partially predictable energy flows. As the distances involved are on truly continental scales—be they from the windy Great Plains to the East Coast or, as the European plans call for, from the reliably sunny Sahara to cloudy Germany (Desertec plan)—those expensive new supergrids cannot be completed in a matter of years. And the people who fantasize about imminent benefits of new smart grids should remember that the 2009 report card on the American infrastructure gives the existing U.S. grid a near failing grade of D+.

And no substantial contribution can be expected from the only well-tested non-fossil electricity generation technique that has achieved significant market penetration: Nuclear fission now generates about 13 percent of global electricity, with national shares at 75 percent in France and about 20 percent in the United States. Nuclear engineers have been searching for superior (efficient, safe and inexpensive) reactor designs ever since it became clear that the first generation of reactors was not the best choice for the second, larger, wave of nuclear expansion. Alvin Weinberg published a paper on inherently safe reactors of the second nuclear era already in 1984, at the time of his death (in 2003) Edward Teller worked on a design of a thorium-fueled underground power plant, and Lowell Wood argues the benefits of his traveling-wave breeder reactor fueled with depleted uranium whose huge U.S. stockpile now amounts to about 700,000 tonnes.

But since 2005, construction began annually on only about a dozen new reactors worldwide, most of them in China where nuclear generation supplies only about 2 percent of all electricity, and in early 2011 there were no signs of any western nuclear renaissance. Except for the completion of the Tennessee Valley Authority's Watts Bar Unit 2 (abandoned in 1988, scheduled to go on line in 2012), there was no construction underway in the United States, and the completion and cost overruns of Europe's supposed new showcase units, Finnish Olkiluoto and French Flamanville, were resembling the U.S. nuclear industry horror stories of the 1980s. Then, in March 2011, an earthquake and tsunami struck Japan, leading to Fukushima's loss of coolant, destruction of reactor buildings in explosions and radiation leaks; regardless of the eventual outcome of this catastrophe, these events will cast a long suppressing shadow on the future of nuclear electricity.

Technical Fixes to the Rescue?

New energy conversions are thus highly unlikely to reduce CO_2 emissions fast enough to prevent the rise of atmospheric concentrations above 450 parts per million (ppm). (They were nearly 390 ppm by the end of 2010). This realization has led to enthusiastic exploration of many possibilities available for carbon capture and sequestration—and to claims that would guarantee, even if they were only half true, futures free of any carbon worries. For example, a soil scientist claims that by 2100 biochar sequestration (essentially converting the world's crop residues, mainly cereal straws, into charcoal incorporated into soils) could store more carbon than the world emits from the combustion of all fossil fuels.

Most of these suggestions have been in the realm of theoretical musings: Notable examples include hiding CO_2 within and below the basalt layers of India's Deccan (no matter that those rocks are already much weathered and fractured), or in permeable undersea basalts of the Juan de Fuca tectonic plate off Seattle (but first we would have to pipe the emissions from Pennsylvania, Ohio and Tennessee coal-fired power plants to the Pacific Northwest)—or using exposed peridotites in the Omani desert to absorb CO_2 by accelerated carbonization (just imagine all those CO_2-laden megatankers from China and Europe converging on Oman with their refrigerated cargo).

One of these unorthodox ideas has been actually tried on a small scale. During the (so far) largest experiment with iron enrichment of the surface ocean (intended to stimulate phytoplankton growth and sequester carbon in the cells sinking to the abyss) an Indo-German expedition fertilized of 300 square kilometers of the southwestern Atlantic in March and April 2009—but the resulting phytoplankton bloom was devoured by amphipods (tiny shrimp-like zooplankton). That is why the best chances for CCS are in a combination of well-established engineering practices: Scrubbing CO_2 with aqueous amine has been done commercially since the 1930s, piping the gas and using it in enhanced oil recovery is done routinely in many U.S. oilfields, and a pipeline construction effort matching the extension of U.S. natural gas pipelines during the 1960s or 1970s could put in place plenty of links between large stationary CO_2 sources and the best sedimentary formations used to sequester the gas.

But the scale of the effort needed for any substantial reduction of emissions, its safety considerations, public acceptance of permanent underground storage that might leak a gas toxic in high concentrations, and capital and operation costs of the continuous removal and burial of billions of tonnes of compressed gas combine to guarantee very slow progress. In order to explain the extent of the requisite effort I have been using a revealing comparison. Let us assume that we commit initially to sequestering just 20 percent of all CO_2 emitted from fossil fuel combustion in 2010, or about a third of all releases from large stationary sources. After compressing the gas to a density similar to that of crude oil (800 kilograms per cubic meter) it would occupy about 8 billion cubic meters—meanwhile, global crude oil extraction in 2010 amounted to about 4 billion tonnes or (with average density of 850 kilograms per cubic meter) roughly 4.7 billion cubic meters.

This means that in order to sequester just a fifth of current CO_2 emissions we would have to create an entirely new worldwide absorption-gathering-compression-transportation- storage industry whose annual throughput would have to be about 70 percent larger than the annual volume now handled by the global crude oil industry whose immense infrastructure of wells, pipelines, compressor stations and storages took generations to build. Technically possible—but not within a timeframe that would prevent CO_2 from rising above 450 ppm. And remember not only that this would contain just 20 percent of today's CO_2 emissions but also this crucial difference: The oil industry has invested in its enormous infrastructure in order to make a profit, to sell its product on an energy-hungry market (at around $100 per barrel and 7.2 barrels per tonne that comes to about $700 per tonne)—but (one way or another) the taxpayers of rich countries would have to pay for huge capital costs and significant operating burdens of any massive CCS.

And if CCS will not scale up fast enough or it will be too expensive we are now offered the ultimate counterweapon by resorting to geoengineering schemes. One would assume that a favorite intervention—a deliberate and prolonged (decades? centuries?) dispensation of millions of tonnes of sulfur gases into the upper atmosphere in order to create temperature-reducing aerosols—would raise many concerns at any time, but I would add just one obvious question: How would the Muslim radicals view the fleets of American stratotankers constantly spraying sulfuric droplets on their lands and on their mosques?

These are uncertain times, economically, politically and socially. The need for new departures seems obvious, but effective actions have failed to keep pace with the urgency of needed changes—particularly so in affluent democracies of North America, Europe and Japan as they contemplate their overdrawn accounts, faltering economies, aging populations and ebbing global influence. In this sense the search for new energy modalities is part of a much broader change whose outcome will determine the fortunes of the world's leading economies and of the entire global civilization for generations to come. None of us can foresee the eventual contours of new energy arrangements—but could the world's richest countries go wrong by striving for moderation of their energy use?

Bibliography

British Petroleum. 2010. BP Statistical Review of World Energy. http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2010_downloads/statistical_review_of_world_energy_full_report_2010.pdf

International Energy Agency. 2010. *Key World Energy Statistics.*

http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf

Jackson, R. B., and J. Salzman. 2010. Pursuing geoengineering for atmospheric restoration. *Issues in Science and Technology* 26:67-76.

Metz, B., et al., eds. 2005. *Carbon Dioxide Capture and Storage*. Cambridge: Cambridge University Press.

Sivak, M., and O. Tsimhoni. 2009. Fuel efficiency of vehicles on US roads: 1923-2006. *Energy Policy* 37:3168-3170.

Smil, V. 2008. *Energy in Nature and Society: General Energetics of Complex Systems*. Cambridge, MA: The MIT Press.

Smil, V. 2009. U.S. energy policy: The need for radical departures. *Issues in Science and Technology* 25:47-50.

Smil, V. 2010. *Energy Transitions: History, Requirements, Prospects.* Santa Barbara, CA: Praeger.

Smil, V. 2010. *Energy Myths and Realities: Bringing Science to the Energy Policy Debate.* Washington, DC: American Enterprise Institute.

U.S. Energy Information Administration. 2010. International Energy Outlook 2010. http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2010).pdf

For relevant Web links, consult this issue of *American Scientist Online:*

http://www.americanscientist.org/issues/id.90/past.aspx