ENERGY AT THE CROSSROADS

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Bernard Frois asked me to make some unorthodox, even controversial, remarks. I am eager to comply with his request because acting as an intellectual agent provocateur has been always one of my preferred modes of public action. Some of my conclusions, and hence my convictions, run against a number of expectations, promises and forecasts that you will hear during the next two days: as an incorrigible skeptic I have yet to be convinced about the bright prospects, eventual scales and timelines of many techniques and advances that will be extolled in the coming presentations. I want to impress you with half a dozen basic realities, all resting on the first principles, all avoiding any wishful thinking, all eschewing any advocacy of preferred solutions. And in every case I offer at least one or two simple, and I hope memorable, quantifications to stress the key points.

Speaking first as a historian of technical advances, I must stress that it is extremely unlikely that any long-term plans, technical and price forecast and global visions, be they offered by extraordinary minds or by iterative expert consensus, will come anywhere near the always unpredictable realities. Long-term historical perspectives also show that energy transitions are deliberate, protracted affairs: large-scale energy conversions are still dominated by prime movers and processes invented during the 1880s (steam turbines, internal combustion engines, thermal and hydro electricity generation) or during the 1930s (gas turbines, nuclear fission) and no techniques currently under development can rival any of these conversions during the coming two or three decades.

Speaking as a scientist relying on the first principles I must stress the extraordinary scale of the coming transition: the shift to non-fossil energies is an order of magnitude larger task than was the transition from phytomass to fossil fuel, and its qualitative peculiarities will also make it more, rather than less, demanding; consequently, its pace may have to be much slower than is commonly assumed. At the same time, only one of the many renewable energy resources has a natural flux far surpassing any prospective needs, and the remaining palette of available choices is not at all as bright as seen through the eyes of true believers, biased proponents and omnipresent instant energy experts. Moreover, nuclear fission remains a flawed and a highly uncertain choice, and I am hardly alone in arguing that nuclear fusion should not be even included among realistic options. And, finally, if the key energy issue of coming generations is not the abundance of fossil resources but rather an unacceptably high probability of pronounced and rapid global warming, then the solution should not include any massive hiding of the emissions.

HISTORICAL PERSPECTIVES

1. Energy, and other, forecasts. Energy forecasts are not worth even the cost of the cheapest acid paper on which they get printed: even that poor paper will get embrittled only after decades, while most energy forecasts are obsolete in a matter of years, sometimes in just a few months. This conclusion applies equally to technical predictions, price projection or demand aggregates. Thirty five years ago this kind of meeting would have heard a confident presentation by one of the world's leading scientists, a Nobelian and a Chairman of the US Atomic Energy Commission (USAEC) who would have assured us that by the year

2000 nuclear fission would not only dominate global electricity generation (with an increasing share coming from fast breeder reactors) but that we will also rely on commercial fusion and nuclear-propelled spaceships ferrying men to Mars (Seaborg 1972). Other brilliant minds would have added a common use of nuclear explosives in mining and in blasting new harbors and canals (Kirsch 2005). And the USAEC's 1974 forecast had 1.2 TW of nuclear capacity installed in the US in the year 2000: the actual 2000 total was 81.5 GW, less than 7% of the original forecast, an order of magnitude forecasting miss. And fusion, as already noted, remains an ever advancing mirage.

And 25 years ago this kind of meeting might have heard from Amory Lovins, an anti-nuclear guru of renewable futures who, nevertheless, adopted the same lack of critical thinking and indiscriminate zeal as did the nuclear advocates in order to extol small-scale distributed renewable energies as inexhaustible, nonpolluting and exceedingly inexpensive. Lovins (1976) anticipated that in the US these energies will cover 30% of the TPES (about 32 EJ) by the year 2000 -- but after subtracting large-scale hydrogenation, new renewables contributed just 3.2 EJ, 10% of the original claim. Once more, this is an order of magnitude forecasting miss over the course of a single generation (inexplicably, Lovins retains his guru aura no matter how wrong he is). Sørensen (1980) trumped even Lovins' delusions as he put the share of US renewables at 49% by the year 2005, with biogas and wind supplying each 5%, and photovoltaics 11% of the total: actual shares were 0% for biogas, 0.04% for wind and 0.08% for PV, so his forecasts are off by anywhere between two orders of magnitude and infinity.

These realities have no effect on today's forecasters as they busily offer their laughable predictions. I stopped collecting these delusions long time ago, but two recent ones are pretty irresistible. The IPCC (2006) sequestration report assures us that in 2095 it will cost US$ 130 to get rid of 1 t of CO_2: you can best appraise the chances of this being anywhere near the real cost by imagining that it is the year 1917 and you are forecasting a cost of a large-scale commercial technique in the year 2006 on the basis of a purely conceptual outline. And OPEC published its crude oil price forecast for the next two decades -- a steady decline to US$ 20/bbl by the year 2025 -- just a few months before the prices took off on their climb past US$ 70/bbl (OPEC 2004).

2. Dominance of pre-1940 conversions and the slow pace of energy transitions. Technical progress has two distinct modes as gradual, ever-working improvements of established techniques that boost efficiencies, increase reliability and lower costs are repeatedly (but irregularly, unpredictably and often inexplicably) interspersed with great saltations, periods of astonishing progress that overturn old paradigms and install new ways that may last not only for generations but for centuries. The greatest technical watershed in modern history took place between 1867 and 1914 when the concatenation of electricity, steam and water turbines, internal combustion engines, inexpensive steel, aluminum, explosives, synthetic fertilizers and electronic components laid the lasting technical foundations of high-energy civilization (Smil 2005). A second remarkable saltation (smaller but still hugely important) took place during the 1930s and 1940s with the introduction of gas turbines, nuclear fission, electronic computing, semiconductors, key plastics, insecticides and herbicides.

All those overenthusiastic, uncritical promoters of new energy techniques would do well to consider: 1/ that steam turbine, the most important continuously working high-load prime mover of the modern world, was invented by Charles Parsons 120 years ago, and it remains fundamentally unchanged: gradual advances in metallurgy made it simply larger and more efficient; 2/ that gasoline-fueled internal combustion engine, the most important transportation prime mover of the modern world, was first deployed (based on older stationary models) during the same decade as Parsons machine, and that it reached a remarkable maturity in a single generation after its introduction: more than 80% of its 1885-2006 performance evolution was complete by 1910 with commercially available engines of low mass/power ratio, high speed, and great reliability; 3/ that Diesel's inherently more efficient machine followed shortly after the Benz-Daimler-Maybach design and that it matured almost as rapidly; and 4/ that gas turbine, the most important prime mover of modern flight, is now entering the fourth generation of service after a remarkably fast progression from Frank Whittle's and Pabst von Ohain's conceptual designs to high-bypass turbofans.

Since the end of WWII we have introduced a large number of new energy converters but no new prime movers and, with the exception of a hurried and flawed design of the first generation of fission reactors, we have not tapped any new energy sources on scales large enough to make a global difference. No matter how many stunning wind capacity forecasts are released by Danish or German enthusiasts, the fact remains that wind turbines make such an excellent addition to large, interconnected electricity-generating systems precisely because they can be never thought of as suppliers of guaranteed mass base-load: Parsons' turbines (and in some countries large hydro -- Francis, Pelton and Kaplan turbines -- of equally venerable provenience) are still the only machines able to do so. Similarly, no matter how many city mayors drink water exhaust from experimental hydrogen-fueled buses or how many pop-science articles predict the world overrun by fuel cell cars by 2010, it is a pretty safe bet that Otto- and Diesel-cycle engines will dominate the automotive market for decades to come.

Appraisals of long-term prospects of technical and economic developments have become increasingly devoid of appropriate historical perspectives. But this blindness of progressively more amnesic civilization will not force a different outcome: future technical developments will not conform to simplistic notions of accelerated development and exponentially declining costs of new conversions. Recent costs of many renewable techniques have been actually increasing (Makower, Pernick and Wilder 2006). PV silicon prices have more than doubled, cost of structural steel, aluminum and plastics for wind turbines has been rising as has been the cost ethanol fermentation from corn because all of these techniques depend on large inputs of more costly fossil energies. And replacing Si by Cu, Ga, In or Se is hardly a solution: copper prices are reaching historic highs and the world does not have enough indium to run a civilization on thousands of square kilometers of panels made from that rare metal.

Historical evidence is irrefutable: modern primary energy systems are remarkably (and, considering the infrastructural investment, inherently) inertial and hence the fundamental energy transitions are protracted affairs and many decades, rather than years, are always needed to diffuse large-scale harnessing of new energy sources and to develop new primary energy converters to the point where they could be significant players (with shares > 15-20% of their respective markets) or where they become the single largest providers of a particular energy service. Energy transitions span generations and not, microprocessor-like, years or even months: there is no Moore's law for energy systems. Keep this in mind when you read yet another of the casually tossed-off claims about a continent to be electrified by wind or fueled by crop-derived ethanol by 2020 or 2025.

CONSTRAINTS DERIVED GROM THE FIRST PRINCIPLES

3. Scale and qualities of the coming energy transition. The best retrospective statistical studies indicate that the global consumption of fossil fuels surpassed that of phytomass sometime during the 1890s (Smil 1994). By the late 1890s, when phytomass slipped below 50% of the world's total primary energy supply (TPES), coal (and a small amount of oil) were consumed at the rate of 600 GW while in 2005 the world used fossil energies at a rate of 12 TW, a 20-fold difference. Complete displacement of phytomass would have thus required additional 20 EJ a year during the late 1890s, today the complete replacement of fossil fuels calls for almost 400 EJ/year of new supply. Of course, phytomass was never totally displaced: during the 20th century its use roughly doubled and even now wood, charcoal and crop residues provide about 10% of the global TPES.

Scaling magnitudes can be illustrated by a tedious series of comparisons: the following example should go some way to tone down some of the misplaced enthusiasm. More rational proponents of grain-derived ethanol concede that that conversion is not the most rational use of an edible photosynthate but maintain that everything will change with cellulose-based ethanol fermented from sugars hydrolyzed by bioengineered enzymes. In 2005 the leading enzymatic innovator, Ottawa's Iogen, was producing 40 t of ethanol a day in its demonstration plant (using wheat straw and poplar tree pulp) -- while 10% of Canada' daily liquid fuel need amounted to 28,000 t, a 700-fold difference, and 10% of the global daily liquid fuel requirements added up to just over 1 Mt, a nearly 26,000-fold difference: obviously it will take a while for cellulosic ethanol (regardless of the fermentation cost) to make any meaningful mark.

But it would be misleading to think that the coming energy transition is only a matter of magnitude, calling for an order of magnitude larger displacement of dominant resources than during the last major energy transition. That transition also introduced fuels with superior energy densities: even low-quality bituminous coal contains 50% more energy than air-dry wood, best hard coals are twice as energy-dense as wood, and liquid fuels refined from crude oil have nearly three times higher energy density. Moreover, these fuels could be produced with power densities of three orders of magnitude higher than wood, charcoal or straw. Inherently low efficiency of photosynthesis means that phytomass harvests do not surpass 1 W/m^2 while most of the fossil fuel extraction proceeds at rates above 1 kW/m^2. With this transition we are facing the reverse challenge: replacing crude oil-derived fuels by less energy-dense biofuels would also require commonly 1000-fold and often 10,000-fold larger areas under crops than the land claimed by oil field infrastructures, and shifting from coal-fired to wind-generated electricity would require at best 10 times and often 100 times more space.

In order to energize the existing residential, industrial and transportation infrastructures inherited from the fossil-fueled era, a solar-based society would have to concentrate diffuse flows to bridge power density gaps of 2-3 orders of magnitude (Smil 2003). Mismatch between the inherently low power densities of renewable energy flows and relatively high power densities of modern final energy uses means that a solar-based system will require a profound spatial restructuring with major environmental and socio-economic consequences. Most notably, there would be vastly increased fixed land requirements for primary conversions, especially with all conversions relying on inherently inefficient photosynthesis whose power densities of are minuscule: the mean is about 450 mW/m^2 of ice-free land, and even the most productive fuel crops or tree plantations have gross yields of less than 1 W/m^2 and subsequent conversions to electricity and liquid fuels prorate to less than 0.5 W/m^2.

During the first years of the 21st century global consumption of gasoline and diesel fuel in land and marine transport and kerosene in flying was about 75 EJ. Even if the most productive solar alternative (Brazilian ethanol from sugar cane at 0.45 W/m^2) could be replicated throughout the tropics the aggregate land requirements for producing transportation ethanol would reach about 550 Mha, slightly more than a third of the world's cultivated land or nearly all agricultural land in the tropics. Consequently, global transportation fuel demand cannot be filled by even the most productive alcohol production. Corn ethanol's power density of 0.22 W/m^2 means that about 390 Mha (slightly more than twice the country's entire cultivated area) would be needed to satisfy the US demand for liquid transportation fuel. Power densities of a fully solar operation (fuelling the machinery with ethanol, distilling with heat derived by the combustion of crop residues) would drop, even with the highest claimed energy return on energy investment, to about 0.07 W/m^2.

The US would then require 1.2 Gha, more than 6 times its entire arable area and about 75% of the world's cultivated land, planted to corn destined for fermentation. The prospect does not change radically by using crop residues to produce cellulosic ethanol: only a part of these residues could be removed from fields in order to maintain key ecosystemic services of recycling organic mater and nitrogen, retaining moisture and preventing soil erosion (Smil 1999). Moreover, even large efficiency improvements in alcohol fermentation or car performance will not make up for inherently low power densities of cropping: the US transportation sector 3 times more efficient than it was during in 2000 would still claim some 75% of the country's farmland if it were to run solely on ethanol produced at rates prevailing in 2005.

Nor it will be easy to supplant the most important metallurgic use of fossil fuels in iron and steel production. Return to charcoal would be the only practical choice. Using the best Brazilian smelting practices (0.725 t of charcoal/t of pig iron) and yields of 10 t/year for tropical eucalyptus (Ferreira 2000) would require (for nearly 600 Mt of pig iron smelted annually in the early 2000s) about 250 Mha of tree plantations: half of the Brazil's total forested area in the year 2000 would have to be devoted to growing wood for the world's metallurgical charcoal, a most unlikely proposition. And it would be even more difficult to solarize the production of nitrogenous fertilizer. Haber-Bosch synthesis uses mostly natural gas both as a source of hydrogen and as a fuel (oil and coal are more cumbersome choices) and no large-scale non-fossil alternatives to this technique are commercially available (Smil 2001).

4. Renewable fluxes: magnitudes and complications. Insolation (at 122 PW) is the only renewable flux that is nearly 4 orders of magnitude greater than the world's TPES of nearly 13 TW in the year 2005. No less importantly, direct solar radiation is the only renewable energy flux available with power densities of 10^2 W/m^2 (global mean of about 170 W/m^2) which means that increasing efficiencies of its conversion (above all better PV) could harness it with effective densities of several 10^1W/m^2 (the best all-day rates in 2005 were on the order of 30 W/m^2). But direct solar conversions would share two key drawbacks with other renewables: loss of location flexibility of electricity generating plants and inherent stochasticity of energy flows. The second reality poses a particularly great challenge to any conversion system aiming at a steady, and highly reliable, supply of energy required by modern industrial, commercial and residential infrastructures.

Terrestrial net primary productivity (NPP) of 55-60 TW is nearly 5 times as large as was the global TPES in 2005 but proposals of massive biomass energy schemes are among the most regrettable examples of wishful thinking and ignorance of ecosystemic realities and necessities. Their proponents are either unaware of (or deliberately ignore) three fundamental findings of modern biospheric studies. First, as the Millennium Ecosystem Assessment (2005) demonstrated, essential ecosystemic services (without which there can be no viable economies) have been already modified, reduced and compromised to a worrisome degree and any massive, intensive monocultural plantings of energy crops could only accelerate their decline.

Second, humans already appropriate 30-40% of all NPP as food, feed, fibre and fuel, with wood and crop residues supplying about 10% of the TPES (Rojstaczer, Sterling and Moore 2001). Moreover, highly unequal distribution of the human use of NPP means that the phytomass appropriation ratios are more than 60% in East Asia and more than 70% in Western Europe (Imhoff et al. 2004). Claims that simple and cost effective biomass could provide 50% of the world's TPES by 2050 or that 1-2 Gt of crop residues can be burned every year (Breeze 2004) would put the human appropriation of phytomass close to or above 50% of terrestrial photosynthesis. This would further reduce phytomass available for microbes and wild heterotrophs, eliminate or irreparably weaken many ecosystemic services and reduce the recycling of organic matter in agriculture: only an utterly biologically illiterate mind could recommend such an action.

Finally, nitrogen is almost always the critical growth-limiting macronutrient in intensively cultivated agroecosystems as well as in silviculture and mass production of phytomass for conversion to liquid fuels, gases or electricity would necessitate a substantial increase in continuous applications of this element. Proponents of massive bioenergy schemes appear to be unaware of the fact that the human interference in global nitrogen cycle has already vastly surpassed the anthropogenic changes in carbon cycle, and that the surfeit of reactive nitrogen -- dissolved in precipitation, dry deposited, causing spreading contamination and eutrophication of fresh and coastal waters, escaping as N_2O via denitrification, and changing the specific composition of sensitive ecosystems -- is already the cause of an undesirable biosphere-wide change (Smil 2002). Minimizing any further interference in global nitrogen cycle is thus highly desirable and this wise choice would inevitably restrict any future energy contributions of large-scale cultivation of phytomass for energy.

But instead of counselling only careful utilization of surplus crop residues and the expansion of tree plantations on deforested and marginal land, bioenergy promoters are advancing preposterous claims about phytomass as the solution the world's energy problems, and are moving beyond phytomass to advocate the use of animal lipids. There is now actually a proposal to use biofuel from salmon oil (Reyes and Sepúlveda 2006). For the benefit of those who know nothing about salmonid fishes I should explain that a/ wild salmons have been largely decimated by overfishing and hence any additional salmon catch for fuel oil would spell the final death toll for the precariously suriving species; and b/ the farmed salmon requires roughly 3.1-3.9 units of fishmeal and fishoil (which must be obtained by catching massive amounts of such wild species as sardines, anchovies and shrimp) in order to produce a unit of edible tissue (Tacon 2004). Consequently, one could not think about more insane way to either completely destroy once super-abundant marine species or to produce a hugely negative energy outcome than producing salmon oil fuel.

Regrettably, these kinds of delusions are publicly funded, some to the tune of hundreds of millions of dollars a year. Among the most bizarre ideas is (this is not a joke) an IEA program that evaluates "the risk of using animal tallow derived from specified risk materials, dead stock, and downer animals as feedstock for the production of biodiesel" (IEA 2005:39). Just imagine: relying on biofuel from “risk material”: read BSE (mad) cows! How far would that go? And there is also a proposal (thankfully a non-EIA) to “link a biodiesel plant with the cosmetic surgeons.” Says a New Zealander Peter Bethune, the founder of Earthrace project aiming to set a new round-the-world powerboat speed record in a boat to be powered by biodiesel fuel partly manufactured from human fat: “In Auckland we produce about 330 pounds of fat per week from liposuction, which would make about 40 gallons of fuel” (Schouten 2005).

Except for direct solar radiation and a cripplingly high harvest of planetary NPP, no other renewable energy resource can provide more than 10 TW: generous estimates of technically feasible maxima are less than 10 TW for wind, less than 5 TW for ocean waves, less than 2 TW for hydroelectricity and less than 1 TW for geothermal and tidal energy and for ocean currents. All of these estimates are maxima of uncertain import and actual economically and environmentally acceptable rates may be only small fractions of the technically feasible totals. Rational allocation of research monies should take the magnitudes of these flows, as well as the typical power densities of these resources, into account: direct conversions of solar radiation, into both low- and high-temperature heat and into electricity would then become unrivaled beneficiaries of aggressive R&D whose commercial success could supply a lasting, planet-wide foundation to non-fossil economies.

5. Nuclear fission and fusion. Nuclear fission keeps paying the price for its rushed post-1945 development. No other mode of primary electricity production was commercialized as rapidly as the first generation of water reactors: only some 25 years elapsed between the first sustained chain reaction that took place at the University of Chicago on December 2, 1942 and the exponential rise in orders of new nuclear power plant after 1965. This rush led the expert consensus of the early 1970s to envisage the worldwide electricity generation in the year 2000 dominated by inexpensive fission. Instead, the industry has experienced stagnation and retreat. In retrospect, it is clear that commercial development of nuclear generation was far too rushed and that too little weight was given to the public acceptability of fission (Cowan 1990). Economics of fission generation has been always arguable as the published numbers do not include either the enormous government subsidies for nuclear R&D or the costs of decommissioning the plants and safe permanent storage of highly radioactive wastes.

Weinberg (1994:21) conceded that “had safety been the primary design criterion [rather than compactness and simplicity that guided the design of submarine PWR], I suspect we might have hit upon what we now call inherently safe reactors at the beginning of the first nuclear era . . .” Moreover, promoters of nuclear energy ignored Enrico Fermi’s warning that the public may not accept an energy source that generates large amounts of radioactivity as well as fissile materials that might fall into the hands of terrorists. Accidental core meltdown and the release of radioactivity during the Chornobyl disaster in Ukraine in May 1986 made the matters even worse. Although the Western PWRs with their containment vessels and tighter operating procedures could not experience such a massive release of radiation as did the unshielded Soviet reactor that accident only reinforced the widely shared public perception of all nuclear power being inherently unsafe.

To this must be added the serial failure of fast breeder reactors: during the 1970s they were seen as miraculous workhorses of fission-powered world of the year 2000 and hence they were boldly promoted in several countries, but the three major programs were soon abruptly shut down, first in the US, then in France and finally in Japan. In 1967 the US demonstration reactor was proposed for 1975 completion at a cost $ 100 million; by 1972 the completion date advanced to 1982, and cost estimates reached $ 675 million (Olds 1972). The entire project was abandoned in 1983. As the French Superphénix was nearing its completion Vendryes (1984:279) thought that the age of LMFBR "is now at hand, with all necessary safety guarantees," but it was precisely because of safety concerns that the reactor was shut down in 1990.

And Japan's nuclear history is particularly telling given the country's otherwise enviable technical accomplishments. In 1991 there was a radioactive leak at Mihama; in 1995 the country's experimental liquid metal fast breeder reactor ad to be closed after 640 kg of liquid sodium leaked from its secondary coolant loop; in 1997 fire and explosion released radioactivity into the atmosphere at Tokaimura; an on August 9, 2004 four workers were killed and seven were injured by super-heated steam from a burst pipe at Mihama plant. And the country's largest utility, Tokyo Electric Power Company, had to shut down temporarily all of its 17 reactors after it was discovered that it falsified its safety inspection records.

Prospects for new, more efficient, fission designs remains highly uncertain: public acceptance of nuclear generation and final disposal of radioactive wastes remain the key obstacles to massive expansion. And it is also extremely unlikely that nuclear fusion can be a part of an early (before 2050) or of any solution. Engineering challenges of a viable plant design (heat removal, size and radiation damage to the containment vessel, maintenance of vacuum integrity) mean that the technique has virtually no chance to make any substantial contribution to the global TPES of the next 50 years (Parkins 2006). And yet this fata morgana of energy techniques keeps receiving enormous amount of taxpayer monies: US spending on fusion has averaged about a quarter-billion dollars a year for the past 50 years with nothing practical to show for it. Undoubtedly, things would have been different if more biologists, rather than nuclear physicists, were in charge of R&D portfolios.

Excessive research spending has been bestowed on all forms of nuclear generation: the US nuclear industry received more than 96% of $(1998)145 billion disbursed by the Congress between 1947 and 1998 (NIRS 1999). Moreover, in 1954 the Price-Anderson Act reduced private liability by guaranteeing public compensation in the event of a catastrophic accident in commercial nuclear generation (DOE 2001). No other industry has enjoyed such a sweeping state protection. And the US is not alone in favoring nuclear energy: of the roughly $ 9.4 billion spent in the year 2004 on energy R&D by all IEA countries, $ 3.1 billion went for fission and even fusion (at $ 700 million) received nearly twice as much as PV (IEA 2006), an inexcusable disparity given the magnitude and the power density of insolation and its lasting potential for solving the global energy challenge in thermally invariant and carbon-free way.

A miracle of a new generation of inexpensive, safe and reliable fission reactors would provide an essential foundation for a transition to a hydrogen-based energy system but even then its realization would be a protracted affair. Undeniably, energy transitions have been steadily decarbonising the global supply as average atomic H/C ratios rose from 0.1 for wood, to 1 for coal, 2 for crude oil and, obviously, 4 for methane. As a result, logistic growth process points to a methane-dominated global economy after 2030 but hydrogen-dominated economy, requiring production of large volumes of the gas without fossil energy, could take shape only during the closing decades of the 21st century (Ausubel 1996).

As a diligent student of the history of energy systems I agree with those who argue that hopes for an early reliance on hydrogen are just that (Mazza and Hammerschlag 2004). There is no inexpensive way to produce this high-energy density carrier and no realistic prospects for the over-hyped 'hydrogen economy' to materialize for decades (Service 2004). In any case, a methanol economy may be a better, although also very uncertain, alternative (Olah, Goeppert and Prakash 2006). And there will be also no rapid and massive adoption of fuel cell vehicles as they do not offer any significant efficiency advantage over hybrid cars in city driving (Demirdöven and Deutch 2004).

6. Undesirability of underground carbon sequestration. Underground sequestration of carbon -- now routinely sold as both a feasible and an effective solution to avoid global warming (Socolow 2005; IPCC 2006) -- is a prime example of what I call the GM approach to engineering a desirable change. In the early 1970s, when faced with the legislative fiat to cut automotive emissions of CO, NO_x and VOC the world's largest company chose not to lower them at all but to install costly and resource-intensive three-way catalytic converters. In contrast, Soichirō Honda, the founder of the eponymous and now legendary engineering corporation, approached the challenge as an ecologist and asked:

“What would happen if catalytic converters were installed in a large number of automobiles, emitting platinum, palladium, and other heavy metals that would then enter human bodies? There are too many unknowns.” (Sakiya 1982:181). Honda’s engineers thus concentrated on developing their extraordinary compound vortex controlled combustion (CVCC hence Honda Civic) and theirs was the first engine to meet US EPA’s strict automotive emissions requirements.

Honda’s way -- minimizing the production of undesirable outputs rather than controlling them as an after-thought -- should be always the guiding principle of any intelligent, far-sighted, rational design. I do not have to belabor the wider lesson taught by these two companies. Three decades after it surprised with its innovative engine design Honda is the world’s leading, and a highly profitable, automotive innovator whose two dominant vehicles, Accord and Civic, rate, set the standard for car-making in compact and sedan class while GM is a virtually bankrupt outfit (losing thousands of dollars on every car sale) whose products include such ridiculous monsters as Yukon (24 L/100 km) and H1, a military assault vehicle weighing 4,700 kg. We know that anorexia nervosa correlates highly with high incomes and so in affluent neighborhoods of US cities we can see nearly 5,000-kg cars driven by anorexic 50-kg females to buy a 500 g carton of a slimming concoction. In these situations I am always trying to imagine what would be the verdict of a truly sapient extraterrestrial informed about this behavior of affluent Earthlings.

I must hasten to add that underground CO_2 sequestration in the service of secondary oil recovery is most desirable, as is any form of plant-bound sequestration, ranging from a gradual build-up of soil organic matter to massive planting of trees. But beyond these highly desirable actions the stress must be on reducing the emissions, not hiding them in an uncertain and costly manner. There are simply too many unknowns to commit enormous investments to an undertaking whose results could be obtained in many more preferable ways. But ignoring the avoidance principle that should guide any sound engineering and environmental action does not turn sequestration into a more practical proposition: even if we were to embrace this second-rate option the magnitude of the enterprise needed to make a real difference will defeat us.

A key comparison illustrates the daunting scale of the challenge. In 2005 worldwide CO_2 emissions amounted to nearly 28 Gt; even if were to set out only a modest goal of sequestering just 10% of this volume we would have to put away annually about 6 Gm^3 (assuming that all of the gas is compressed at least to its critical point where its density is 0.47 g/mL). The current extraction of crude oil (nearly 4 Gt in 2005) translates to less than 5 Gm^3. Sequestering a mere 1/10 of today's global CO_2 emissions (< 3 Gt CO_2) would thus call for putting in place an industry that would have to force underground every year the volume of compressed gas larger than or (with higher compression) equal to the volume of crude oil extracted globally by petroleum industry whose infrastructures and capacities have been put in place over a century of development. Needless to say, such a technical feat could not be accomplished within a single generation.

The obvious question is why it should be even attempted given the fact that a 10% reduction in CO_2 emissions could be achieved by several more rational, mature and readily available adjustments. The most radical of these steps would be the reduction of the average annual US per capita energy (about 330 GJ/year, or roughly twice the affluent EU level) by about 40%: this transformation alone would reduce the global carbon emissions by at least 2.5 GT CO_2. Of course, this suggestion is always met with derision and the chances of such a shift are judged to be utterly impossible. But before you rush to join that dismissive howl recall that when empires unravel their energy use shrinks. The last perfect example was the demise of the Soviet Empire: between 1989 and 1997 the primary energy use in the successor states of the USSR fell by a third. Then consider the current US trajectory of enormous accumulated budget and trade deficits, more than twice as large unfunded health and social security liabilities, absence of any new domestic savings, gutting of the country's manufacturing, dismal state of its education, acute strategic overstretch and a crippling dependence on energy imports (as of 2005 even its net food imports!) -- and you do not need a great deal of imagination to construct scenarios of a major economic (choose one: crisis, pull-back, collapse) to be accompanied by significantly reduced energy consumption.

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Basic lessons are simple: forecasts are the mirrors of our ignorance not the embodiments of our understanding; long-term historical perspectives are truly invaluable; energy transitions are protracted, generations-long affairs; dubious claims made on behalf of small-scale, experimental and demonstration-size techniques are no substitutes for mercilessly critical appraisals based on the first principles; biased promotions of grand theoretical solutions rarely survive brutal encounters with scaling up for large-scale, reliable operations in the real world.

And above all: innovations and technical fixes cannot provide a lasting resolution. History shows that energy demand keeps growing even in the most energy-saturated affluent societies: encouraging worldwide diffusion of this trend (new China, and then India, aspiring to replicate the US) and trying to fill the supply through scientific and engineering ingenuity is not a formula compatible with maintaining a viable biosphere. Obviously, poor countries need more energy; but the rich ones should, sooner, rather than later, think about engineering rational reductions in energy use. All economies are just subsystems of the biosphere and the first law of ecology is that no trees grow to heaven. If we are not going to engineer thoughtful, gradual reductions, we run a considerable risk that the biosphere may do the scaling-down for us in a much less desirable (if not catastrophic) manner.

Georgescu-Roegen (1975:379) summed this choice perfectly: "Will mankind listen to any program that implies a constriction of its addiction to exosomatic comfort? Perhaps, the destiny of man is to have a short, but fiery, exciting and extravagant life . . ." The choice is still ours, but we do not have the comfort of postponing it for many generations.

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