ENERGY FUTURES
FOUR COMMANDMENTS WITH EXAMPLES

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A lifetime of systems studies has given me enough material to formulate more than ten energy commandments but the brevity of this presentation leaves room for just four key exhortations, each illustrated with three apposite examples and finished with two warnings concerning the present perceptions and goals.

The first commandment is observed by most energy experts only in its breach: **You shall not make any long-range quantitative forecasts**. No matter if you try to pin down production, consumption or trade rates, capacities of individual techniques or timing of commercial penetrations — you are bound to be wrong. But even should you, accidentally, get a particular number right, you will not capture that all-important context. My two examples of spectacular failures are chosen from the opposite ends of the energy supply spectrum, one symbolizing the centralized, hard, nuclear, path, the other one soft, decentralized, energy production.

In 1971, Glenn Seaborg, a Nobelian in chemistry and at that time the Chairman of the US Atomic Energy Commission, predicted that by the year 2000 nuclear energy will bring "unimagined benefits" that will directly improve the quality of life for most of the world's population. In such a world fission reactors were to be just the magic for the beginners, merely a temporary fix before being supplanted by fast breeders. In 1970 the Nixon administration scheduled the completion of the US prototype Liquid Metal Fast Breeder Reactor (LMFBR) for 1980. When outlining long-range possibilities of the global energy supply Weinberg captured the hopes many invested into the technique by concluding that there is not "much doubt that a nuclear breeder will be successful" and that it is "rather likely that breeders will be man's ultimate energy source."

Not surprisingly, Westinghouse Electric, the company contracted to build the US breeder, was confident that "the world can reap tremendous benefits in terms of greatly increased energy resources". General Electric expected that commercial fast breeders will be introduced by 1982, and that they will claim half of all new large thermal generation market in the US by the year 2000. And in 1977 a consortium of European utilities decided to build Superphénix, a full-scale breeder reactor at Creys-Malville as the prototype of the continent's future nuclear plants. In reality, this inevitable, ultimate technique collapsed long before the century's end.

The US breeder program amounted to a string of failed promises. In 1967 the first 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. The entire project was abandoned in 1983, and the country's only small experimental breeder reactor was shut down in 1994. As Superphénix was nearing its completion Vendryes 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. Both the US and French forecasts of breedersustained energy future thus proved to be complete failure mere 13 years after they were made and the world does not derive a single kWh from breeders.

In 1992 Amory Lovins looked back at his “soft path” prediction of aggregate energy consumption in the US which was published in 1976 and concluded that 15 years later his scenario stood the test of time far better than the conventional wisdom. True, his forecast is much closer to reality than all those simplistically exponential governmental predictions published during the 1970s. But it is a curious interpretation of reality when Lovins says that “the hard path hasn’t happened and won’t”. True, we do not have giant nuclear islands sheltering breeder reactors –- but neither do we have a new economy that is significantly dependent on renewable commercial energies, nor a one that is poised to swing sharply in that direction.

In his famous Foreign Affairs article in 1976 Lovins anticipated that the US will derive about a third of its energy (around 750 Mtoe) from soft techniques by the year 2000 –- but the actual total for renewables, including all hydro, biomass and solar, in that year was about 175 Mtoe. After subtracting conventional large-scale hydrogeneration (clearly a kind of energy conversion that is neither small nor soft) renewables contributed just over 75 Mtoe, no more than about 10% of the share projected a generation ago by Lovins. But more than half of that total was accounted by using woody waste in large saw and paper mills and by subsidized gasohol production which means that the real soft energy output amounted to less than 5% of Lovins’s forecast. Missing the target by about 95% over a period of 24 years is hardly a noteworthy forecasting accomplishment.

At least Lovins called for “just” around 30% of the US total energy consumption to be delivered by renewables in the year 2000. In contrast, Sørensen forecast an American energy future where 49% of the country’s energy use by the year 2005 were to originate from renewables, with biogas and wind supplying each 5%, and photovoltaics 11% of the total. As the actual US consumption shares in the year 2000 were practically zero for biogas, 0.04% for wind and 0.08% for all forms of direct solar conversions, Sørensen’s forecasts are off by anywhere between two orders of magnitude and infinity. Final example in this category is one of my own forecasts (yes, more than 25 years ago I was imprudent enough to make quantitative forecasts). Median values of China’s primary commercial energy consumption for the years 1985 an 1990 that I made in my first book on the country’s energy written in 1975 turned out to have errors of, respectively, a mere 2% and 10%. I was certain that major changes will follow Mao’s death (in 1976) -- but I could not have predicted either the speed or the extent of China’s post-1979 modernization with all of its complex implications for energy demand, economic expansion and environmental degradation which I traced ten and twenty years later.

Between 1980 and 2000 the GNP of China’s rapidly modernizing economy increased roughly sixfold, or almost twice as fast as I anticipated in the mid-1970s –- but the country has been also dramatically reducing its relative need for energy. During the last six years of Mao’s rule energy intensity of China’s economy actually rose by 34%. But then Deng Xiaoping’s modernization resulted in closing of the most inefficient enterprises, large-scale modernization of energy-intensive processes and gradual restructuring of industrial output in favor of higher-value added manufactures. Between 1980 and 1990 the average energy intensity of China's economic product fell by about 40%. Consequently, my excellent forecast of China's total energy needs in 1985 and 1990 was the result of **being doubly wrong** as the real economic growth was nearly twice as high as I anticipated but as its energy intensity was almost halved.

The second commandment, one that goes beyond the confines of energy, also seems to exist only in order to be disregarded by assorted techno-enthusiasts who push, uncritically and dogmatically, their favorite schemes: **Do not prejudge any energy conversion technique**. In order to judge the efficacy, acceptability and persistence of any engineering system you should wait at least one generation, that is the minimum of 20-25 years. Only then you should look back and judge. One of the best classical examples I am aware of is the early history of automobile, and perhaps the best modern case is the enormous misjudgment of nuclear fission.

Karl Benz built his first reliable, high-rpm gasoline-fueled engine in 1883, mounted it on a simple three-wheel chassis in 1886 and began (small) serial production of his cars in 1888. But a decade later gasoline cars were generally seen as temporary oddities as electric cars were preferred by both public and many leading experts of the day, including Thomas A. Edison who spent a great deal of time and money to make their batteries more energy dense. Late 1890s and the first years of a new century looked particularly promising for electric vehicles. In 1896 at the first US track race a Riker electric car decisively defeated Dureya's gasoline vehicle, and three years later in France another electric car broke the100 km/h barrier. And, of course, the electrics were clean and quiet and they did not require any dangerous cranking to start them (a necessity that eliminated most of the female drivers) and did not need any refills with smelly and flammable gasoline.

Their commercial introduction began in 1897 with a dozen of Electric Carriage & Wagon Company's taxicabs in New York. In 1899 the US production of electric cars surpassed 1,500 vehicles, compared to 936 gasoline-powered cars. Two years later Pope's Electric Vehicle Company was both the largest maker and the largest owner and operator of motor vehicles in the US. At that time it was possible to take an electric car from New York to Philadelphia thanks to six charging stations that were built in New Jersey. Ever-optimistic, and still stubbornly searching for a high power-density car battery, Edison kept predicting that electric cars will eventually cost less to run than the gasoline-fueled ones even as the Electric Vehicle Company's operations were reduced to just occasional rides in and around the Central Park, as the enterprise went bankrupt (in 1907), and as Ford launched his Model T in 1908. Consequently, it took exactly a quarter century to go from Benz's first reliable high-rpm gasoline engine to the first mass-produced and affordable car. As for the electrics, a century later they are still rather firmly in the category of Edisonian dreams rather than quotidian engineering realities.

The story of America's PWRs is well known to the participants in this meeting: their economies, their speed of construction, their reliability and their requirements for long-term waste disposal were badly prejudged during the 1960s. The resulting large-scale construction program produced a system that generates about 20% of the country's electricity –- but that cannot serve as the foundation for the expansion of fission and that remains haunted by the unfinished business of waste disposal. Canadian example is much less known but it is, relatively, a much more spectacular case of prejudgment. When American PWRs began showing the signs of age and creeping safety concerns, heavy-water, natural uranium CANDUs were touted as the most reliable nuclear assemblies and their generation constituted the bulk of electricity supply in Ontario, Canada's most populous and most productive province.

But during the early 1990s fuel rods in Ontario's CANDUs began to crack and their failure rate eventually became so high that individual reactors and entire stations had to be shut down and the utility, suddenly short of several GW of capacity, began a long and extremely costly process of reconstructing and repowering the failed units. Prejudging the performance of CANDU reactors will have cost the Ontario taxpayers tens of billions of dollars and more than a decade of uncertain, and expensive, electricity supply.

The veracity of the third commandment was convincingly proved more than a century ago by Stanley Jevons, one of the early, and highly perceptive, writers on energy matters: **Do not think that higher energy conversion efficiencies will be the key to a better energy future**. Needless to say, lower intensity of energy use is one of the most desirable goals for any rational society, and it is both absolutely necessary and technically doable. There is no doubt that relying on devices and machines that convert fuels and electricity with higher efficiency leads to lower energy use and to savings of money at microeconomic level, that is for individual consumers, households and companies and even at mesoeconomic level, for entire industries. But what happens at the national, that is macroeconomic, level? Historical evidence shows unequivocally that secular advances in energy efficiency have not lead to any declines of aggregate energy consumption.

Stanley Jevons was the first economist to address, in 1865, the potential of higher efficiency for "completely neutralising the evils of scarce and costly fuel". He was well aware that good engines and furnaces of his day converted only a small part of the consumed coal into useful work but he concluded that

> It is wholly a confusion of ideas to suppose that the economical use of fuels is equivalent to a diminished consumption. The very contrary is the truth. As a rule, new modes of economy will lead to an increase of consumption according to a principle recognised in many parallel instances (emphasis is in the original).

Jevons cited the example of Watt's low-pressure steam engine and later high-pressure engines whose efficiencies were eventually more than 17 times higher than that of Savery's atmospheric machine but whose diffusion was accompanied by a huge increase in coal consumption. His conclusions have been shared, and elaborated, by virtually all economists who have studied the macroeconomic impacts of increased energy efficiency — and they have been disputed by many environmentalists and efficiency advocates. Herring provides excellent surveys of these debates. The most resolute counterarguments claim that the future elimination of large existing conversion inefficiencies and the shift toward increasingly service-based, or supposedly more dematerialized, economies can lead to no less than stunning reductions of energy use at the national level.

A more measured assessment concluded the improvement in efficiency is, per se, only a small part of the reason why total energy consumption may have gone up, and that the overall growth of energy use is more related to increasing population, household formation and rising incomes. How small is not easy to determine. To begin with, there are disputes about the relative magnitude of the rebound effect whereby savings accruing from more efficient use of energy lead to lower prices and hence eventually to increased consumption, either in the very same category (direct rebound) or for other goods and service (indirect rebound effect). Lovins argued that at the consumer's level the overall rebound is minimal, a position rejected by Khazzoom. Some studies have shown direct rebound on the order of 20%.

The fact is that improved energy conversion efficiencies are almost uniformly accompanied by rising energy use. Examples abound. Power density of energy use in new houses is now lower, but the houses have grown larger, with average size of new US house is up by more than 50% since the early 1970s and in 2001 it topped 200 m^2. Moreover, in the country's Sunbelt inhabitants of these houses may buy superefficient air conditioners to maintain indoor summer temperatures they would consider too cold in winter. In view of these recent consumption trends we should not to be impressed by the stress that the contemporary American energy policy puts on energy efficiency: such emphasis overlooks the human actions that tend to increase energy consumption in the long-run and may not necessarily save anything even in the short run.

Herring offers another excellent example of greatly improved efficiency negated by an even faster growing demand. Efficacy of lights rose impressively during the 20th century, and the improvement in British street lighting since the 1920s was about 20-fold, from 10 lumen/W for incandescent bulbs to about 200 lumen/W for low-pressure sodium lamps. However, more roads (less than 50% increase) and a huge rise in the average light intensity (when measured in lumens per km of road it rose more than 400 times) meant that during the same period electricity consumption per average km of British roads has increased 25-fold, entirely negating the enormous advances in efficiency.

And it is easy to perform a revealing exercise on a national level. Average energy intensity of the US economy fell by 34% between the years 1980 and 2000, while the country's population increased by about 22%. If the average per capita GDP remained at the 1980 level then the US TPES in the year 2000 would have been 20% below the 1980 level. Even if the average had grown by a third the TPES in the year 2000 would have been only about 7% ahead of the 1980 total. In reality, average per capita GDP rose by more than 55% and so in spite of that impressive decline in the energy intensity of the US economy the country's TPES in the year 2000 was about 26% higher!

Historical evidence is thus replete with examples demonstrating that substantial gains in conversion (or material use) efficiencies stimulated increases of fuel and electricity (or additional material) use that were far higher than the savings brought by these innovations. Indeed, the entire history of Western modernization can be seen as a continuing quest for higher efficiencies as generations of engineers have tried wringing additional returns from their contraptions and as entire nations, guided by that famously invisible hand, have been relentlessly following the path of reduced waste and higher productivity. But the outcome is indisputable: global energy consumption far higher than the rate of population growth and than the need to satisfy not just basic existential needs but also a modicum of comfort and affluence.

Given the fact that efficiency has become a mantra of modern, globally-competitive business whose key goal is to make and sell more, the quest for better performance can be then seen, in Rudin's disdainful view, as a justification "to consume our resources efficiently without limit." And he points out the distinction between relative and absolute savings by noting that "our environment does not respond to miles per gallon; it responds to gallons". So if we are to see any actual reductions in overall energy use we need to go beyond increased efficiency of energy conversions. One way to preserve these cuts in energy use would be to tax away the savings accruing from higher efficiency and reinvest them in projects whose low energy-intensity would be combined with demonstrably positive impacts on public welfare and the integrity of the biosphere. Planting of trees and many other activities aimed at restoring natural habitats and preserving biodiversity would be the most obvious choices.

A more realistic goal is to promote energy conservation. Of course, in strict scientific sense the term 'energy conservation' should be avoided because there is no need to perpetuate yet another erroneous usage akin to the already noted interchangeable and incorrect use of terms energy and power. Energy is always conserved: such is the universal physical imperative summed up in the first law of thermodynamics. But the term is too ingrained to ignore it, and it entails any measures aimed at reducing energy use by either voluntary or mandated cuts in quality or rate of energy services.

One of the most iconic entries of the concept of energy conservation into the public consciousness was thanks to cardigan-clad Jimmy Carter imploring the US citizens to lower thermostats and don sweaters during the somber years of 'energy crisis' of the late 1970s. But it was the speed limit imposed on the US Interstate highways during the same time (the famous double-nickel, 55 mph) that was the most obvious everyday reminder of regulated energy conservation for millions of American drivers. Given the complexity of modern societies regulation would always have a role in energy conservation but the bulk of such savings should be preferably delivered by enlightened public that chooses to change its behavior and modify its lifestyle. Appeals for this shift have been made by many devoted conservationists. The fact that "improved efficiency coincides with increased use of resources should be enough to make us think in non-business terms… Using less energy is a matter of discipline, not fundable political correctness."

Finally, a bold exhortation of the fourth commandment: **Think at least something impossible, it will happen sooner than you might think**. As in the case of the previous commandment, the historical evidence is undeniable: fortunes of societies and civilizations are determined primarily by epoch-making discontinuities rather than by gradual shifts. Gradual, and hence to some extent fathomable, evolution of technical capabilities furnishes the societies with the means to act, grow, manage and expand –- but it does not determine the uses to which these capacities are put, their goals and their outcomes. All of these have their primary origins in sudden and inherently unpredictable changes.

Again, suitable examples of these realities abound, and the following one is among the most interesting cases of this fascinating genre. CO_2 remains the single largest contributor to the anthropogenic warming of the troposphere, and its emissions are greatly affected by socio-economic discontinuities that are, inevitably, translated into changed energy demand. Neither of the two events that had the greatest effect on global CO_2 emissions of the last 20 years of the 20th century –- the precipitous but nonviolent collapse of the Soviet empire and the rise of surprisingly more efficient China integrated into the world economy -- could have been considered by even the most astute climate modeller in 1980. After all, they came as total surprises even to the people who have spent decades studying the two countries in question.

During the 1990s energy consumption in the successor states of the USSR and in the nations of the former Soviet empire fell by about a third, and as a result those countries released at least 2.5Gt C less than if they would have consumed fossil fuels at the late-1980s level, and about 3 Gt less than if their growth of energy demand would have continued at the same rate as it did during the 1980s. And because during the 1990s energy needed per unit of GDP by China's fast-growing economy was cut by half, the country's aggregate carbon emissions for the decade were about 3.3 Gt C lower. Consequently, the demise of the Soviet empire and unexpectedly strong efficiency gains in China prevented the release of nearly 6.5 Gt C during the 1990s, an equivalent of the world's average annual carbon production from fossil fuels during the decade's last two years. Who among the forecasters of global CO_2 generation (they are mostly atmospheric physicists) would have even dreamt about including these massive energy consumption shifts in global climate models they were building during the early 1980s?

I will close by asking you to think about something that is **never** mentioned in discussions of long-term energy futures: about restricting per capita energy consumption. Rationale for this challenge is clear. All energy conversions undertaken by humans share the same raison d'etre: they are just means toward a multitude of ends. All of the commonly used measures of energy use –- be it conversion efficiencies, energy costs, per capita utilization levels, growth rates, consumption elasticities, output ratios -- are just helpful indicators of the performance and the dynamics of processes whose aim should not be merely to secure basic existential needs or to satisfy assorted consumerist urges but also to enrich intellectual lives and to make us more successful as a social and caring species. And, given the fundamental necessity to preserve the integrity of the one and only biosphere we inhabit, all of those aims should be accomplished in ways that are least disruptive to the maintenance of irreplaceable environmental services. High quality of life, physical and mental, is the goal, rational energy use is the means of its achievement.

If the energy requirements of good life were to be quantified on the basis of health alone then the two most sensitive indicators, infant mortality and life expectancy at birth, point to annual maxima of about 110 GJ of total primary energy supply per capita: virtually no gains accrue beyond that level, and only marginal gains are to be had once the consumption passes 70-80 GJ/capita. Correlation between higher education and energy consumption is very similar: no more than 100 GJ/capita is needed to assure easy access to postsecondary schooling, while primary and secondary requirements are well satisfied at less than 80 GJ/capita.

Let me remind you at this point that most of the rewarding enrichments of human life –-be it personal freedoms and artistic opportunities, or pastimes of physical or mental nature — do not claim large amounts of additional fuels or electricity. Of course, as far as pastimes go there are those high-powered, noisy, polluting and body-maiming worlds of car racing, speedboating or snowmobiling but most of the leisure activities and hobbies cost only a modest amount of energy embodied in books, music recordings or table games. Other pastimes require just a small additional food input to provide kinetic energy for scores of sports and outdoor activities. And the activity that is most beneficial in preventing cardiovascular disease, by far the most important cause of death in Western populations, is a brisk walk for 30-60 minutes a day most days of the week -- and it requires moderate energy expenditure of only 4.2 MJ/week, or the food energy equal to a single good dinner.

Consequently, this rich evidence leads to the conclusion that the average consumption of between 50-70 GJ/capita provides enough commercial energy to secure general satisfaction of essential physical needs in combination with fairly widespread opportunities for intellectual advancement and with respect for individual freedoms. Moreover, convincing historical evidence demonstrates that the only outcome guaranteed by the increasingly more ostentatious energy use above that level (and particularly in excess of 150 GJ/capita) is a higher intensity of environmental degradation. Remarkably, the global mean of per capita energy consumption at the beginning of the 21st century, 58 GJ/year, is almost exactly in the middle of the 50-70 GJ range. This means that equitable sharing of the world’s fuels and electricity would supply every inhabitant of this planet with enough energy to lead fairly healthy, long and active life enriched by more than a basic level of education and made more meaningful by opportunities for the exercise of individual liberties. Naturally, all of the desirable minima of per capita consumption refer to the now prevailing energy conversion efficiencies and hence they should be substantially lowered in the future as all common energy uses leave much room for additional gains.

I must also note the notable absence of correlation between the average economic well-being and energy use on one hand and the feelings of personal and economic security, optimism about the future, and general satisfaction with life on the other. In 1999 annual average per capita energy use in Germany (175 GJ) was only half, and in Thailand (40 GJ) mere 1/8, of the US rate (340 GJ), and the American PPP-adjusted GDP was 34% above the German mean and 5.2 times the Thai average. But the Gallup poll done in 1995 found that 74% of Germans and Thais were satisfied with their personal life -- compared to 72% of Americans. Such findings should not be surprising as a personal assessment of the quality of life involves strong individual emotions and perceptions that may be largely unrelated to objectively measured realities. In fact, many studies have shown little connection between subjective appraisals of quality of life and personal satisfaction on one hand and the objective socio-economic indicators on the other. The quest for ever-higher energy use thus has no justification either in objective evaluations reviewed in this section, or in subjective self-assessments.

Working toward reduced energy consumption seems unthinkable in the continent of 14 mpg SUVs, palatial custom-built houses and transcontinental flights to gambling tables of Las Vegas. But the perpetuation of our existing patterns may lead, more rapidly than anyone thinks today, to different unthinkable outcomes: to the collapse of the American Empire, or to an unmanageable concatenation of economic, environmental and social problems on continental, or even global, scale.

These musings are taken mostly from my forthcoming book <u>Energy at the Crossroads: Global Perspectives and Uncertainties</u> (to be published by the MIT Press in November 2003) where the reader will also find all the references.