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Science, energy, ethics, and civilization

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The laser is a perfect example of doing more with less – and of doing it more precisely and more affordably yet with reduced undesirable impacts. As such, it belongs to that remarkable class of inventions that have transformed our civilization in countless unforeseen ways. At the same time, all of these scientific innovations have also reinforced and accelerated the fundamental historic trend toward higher per capita use of energy. This quest can be seen as perhaps the most imperative dynamic of humanity. In this chapter, I take a closer look at this trend of increased energy use and consider its problematic social, economic, and environmental consequences. In conclusion, I outline the need to end it before it compromises the habitability of the biosphere.

35.1 Human energy use: an evolutionary trend with a unique outcome

In 1922 Alfred Lotka (1880–1949) formulated his law of maximized energy flows:

> In every instance considered, natural selection will so operate as to increase the total mass of the organic system, to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system so long as there is present and unutilized residue of matter and available energy (Lotka, 1922, p. 148).

The greatest possible flux of useful energy, the maximum power output (rather than the highest conversion efficiency) thus governs the growth, reproduction, maintenance, and radiation of species and complexification of ecosystems. The physical expression of this tendency is, for example, the successional progression of vegetation communities toward climax ecosystems that maximize their biomass within the given environmental constraints – although many environmental disturbances may prevent an ecosystem from reaching that ideal goal. In the eastern United States, an unusually powerful hurricane may uproot most of the trees before an old-growth forest can maximize its biomass. Human societies are, fundamentally, complex subsystems of the biosphere and hence their evolution also tends to maximize their biomass, their rate of circulation of matter, and hence the total energy flux through the system (Smil, 2007).

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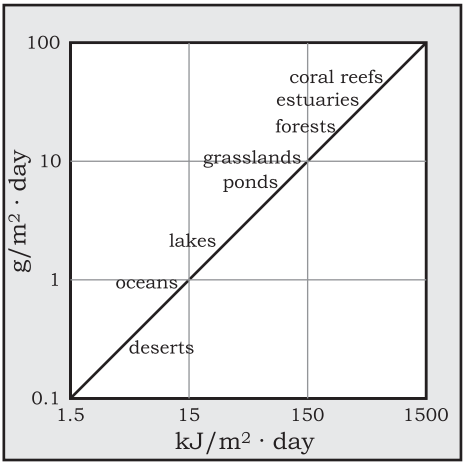


Fig. 35.1. Approximate mass and energy flows through ecosystems.

Some climax ecosystems are naturally limited by energy flows, including inadequate or excessive temperature. Limits imposed by precipitation and by the availability of nutrients, however, are more common. The latter limit is most commonly encountered as a shortage of nitrogen, the most important macronutrient needed in order to produce new phytomass. Plants symbiotic with leguminous bacteria can overcome this restriction insofar as they supply the nitrogen fixers with carbohydrates in exchange for ammonia, whose enzymatic synthesis requires at least one atom of Mo per molecule of nitrogenase. The limit may thus come down to trace amounts of a rare element. Where non-energy variables have no, or marginal, effect, productivities and standing biomass of ecosystems and their complexity (number of species and trophic levels) correlate with the incoming solar radiation. Tropical rain forests and coral reefs have the highest energy flux through their intricate webs (Fig. 35.1).

Human societies have always been limited by the rates at which they have been able to harness solar radiation and its terrestrial transformations. Food and fuel production were limited by inherently low efficiencies of photosynthesis, as well as by inadequate supply of plant nutrients. As a result, average crop yields remained low for millennia, producing recurrent famines and chronic malnutrition. Even modest urbanization and energy-intensive artisanal manufacturing led to large-scale deforestation. Energy storage was limited by the low energy density of biomass (dry straw at 15 $\mathrm{MJ\,kg^{-1}}$, air-dry wood at 15–17 $\mathrm{MJ\,kg^{-1}}$), and the specific power of dominant prime movers was restricted to less than 100 W of sustained labor for humans and typically less than 500 W for draft animals. Even so, traditional societies had gradually increased their overall use of energies by tapping water and wind power and by deploying more working animals. However, unit capacities of inanimate energy converters and their typical efficiencies remained low even during the early modern era (Smil, 1994).

A fundamental shift in the kind and intensity of energy uses took place only with large-scale extraction and combustion of fossil fuels. Traditional societies drew their food, feed, heat, and mechanical power from sources that were almost immediate transformations of

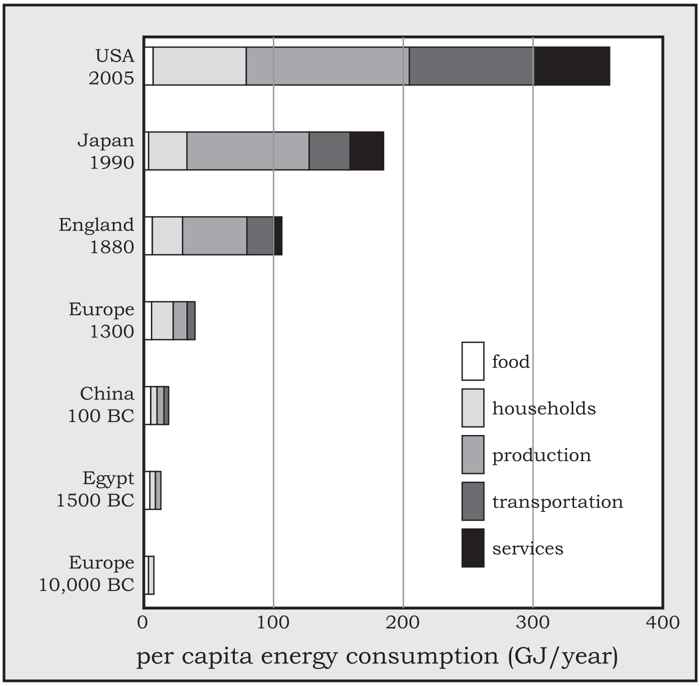


Fig. 35.2. Typical per capita energy consumption rates during the past 12,000 years.

solar radiation (flowing water and wind) or that harnessed it in the form of biomass and metabolic conversions that took just a few months (crops harvested for food and fuel), a few years (draft animals, human muscles, shrubs, young trees), or a few decades (mature trees) to grow before becoming usable. In contrast, fossil fuels were formed through slow but profound changes of accumulated biomass under pressure; except for young peat, they range in age from 10^6 to 10^8 years. A useful analogy is to see traditional societies as relying on instantaneous or minimally delayed and constantly replenished solar income. By contrast, the modern civilization is withdrawing accumulated solar capital at rates that will exhaust it in a tiny fraction of the time needed to create it.

Traditional societies were thus, at least in theory, energetically sustainable on a civilizational timescale of 10^3 years, though in practice many of them caused excessive deforestation and soil erosion and overtaxed their labor. In contrast, modern civilization rests on indubitably unsustainable harnessing of a unique solar inheritance that cannot be replenished on the civilizational timescale. This dependence has given us access to energy resources that, unlike solar radiation, are both highly concentrated and easy to store and that can be used at steadily higher average rates. Reliance on fossil fuels has removed the limit that the inherently low photosynthetic efficiency and low-level conversions of animate, water, and wind energies imposed on human energy consumption. As a result, the total energy flux through civilization has risen steadily to unprecedented levels (Fig. 35.2).

Preagricultural societies consumed only around 10 GJ/year, roughly divided between food and phytomass for open fires. By the time of Egypt's New Kingdom (1500 BCE), the

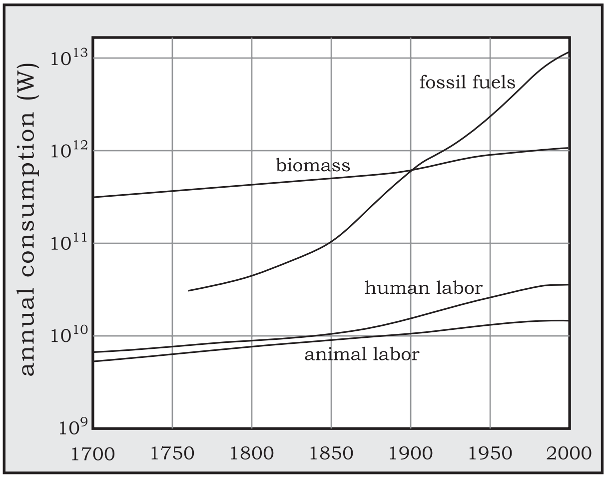


Fig. 35.3. Global consumption of primary energy, 1750–2000.

rate had increased by half because of the wood used in artisanal manufactures (smelting of copper and gold, making of glass). During the rule of the Han dynasty in China (206 BCE–220 CE), where wood and charcoal dominated the supply, and where coal was used only for some metallurgical processes, the rate approached 20 GJ per capita. It was double that rate in the richest parts of medieval Europe, which began to use small quantities of coal and peat for heating and in manufacturing. Industrial England of the late nineteenth century boosted the rate to around 100 GJ per capita. Virtually all of this energy came from coal, with most of it going into metallurgical and textile industries and to steam-driven transport.

A century later, the major economies of the European Union, as well as Japan, averaged around 170 GJ per capita, as production and transportation uses remained dominant and the supply included significant shares of all three fossil fuels: coal, crude oil, and natural gas. By 2005, the energy supply of the world's largest economy was similarly diversified, with 40% of the total primary energy supply (TPES) coming from oil, roughly 25% each from natural gas and coal, and the rest from hydro and nuclear electricity. Thus the average annual consumption prorated to more than 330 GJ per capita, with transportation needs nearly matching the industrial use and with household needs about as large as the energy requirements of services. Therefore, the late-nineteenth-century per capita energy use in the most advanced industrializing societies was an order of magnitude above the levels common in antiquity, and by the beginning of the twenty-first century the US rate was about fifty times as large as the energy commanded annually by a Neolithic hunter (Fig. 35.2).

Approximate reconstruction of the world's TPES (including all biomass and fossil fuels and primary, that is water- and fission-generated, electricity) shows it rising from just over 10 EJ in 1750 to nearly 20 EJ a century later, then to 45 EJ by 1900, nearly 100 EJ by 1950, and about 400 EJ by the year 2000 (Fig. 35.3). Despite the nearly quadrupled population (from 1.6 to 6.1 billion people), the twentieth century saw the average global per capita rate of TPES more than double, from 28 to 65 GJ, while the average annual per capita supply of fossil fuels more than quadrupled. This secular ascent has been even more impressive when expressed in terms of useful energy. Continuing technical advances have improved typical efficiencies of all principal commercial energy conversions, many of them by an order of magnitude. Actually delivered energy services (heat, light, motion) thus give a truer impression of the rising energy flux than do gross primary energy inputs.

Space heating illustrates well these efficiency gains. Traditional hearths and fireplaces had efficiencies below 5%. Wood stoves were usually less than 20% efficient. Coal stoves doubled that rate, and fuel-oil furnaces brought it to nearly 50%. Efficiencies of natural-gas furnaces were initially below 60%, but by the 1990s there was a large selection of furnaces rated at about 95%.

Lighting provides an even better illustration of the rise of useful energies (Fig. 35.4). Ancient sources of illumination (oil lamps, candles) were the only option available until the early nineteenth century, when the first coal-gas lights were introduced. Candles and oil lamps had conversion efficiencies (chemical to electromagnetic energy) of the order of 0.01%. The first coal-gas lights were about 0.04% efficient. By contrast, today's common sources of illumination have efficiencies of up to 15% (for fluorescent lights), with a maximum of 25% for high-pressure sodium lamps.

In affluent countries, the overall efficiencies of primary energy use nearly tripled during the twentieth century. As they moved from primitive hearths and clay stoves to natural gas, and from steam engines to gas turbines, poor industrializing countries saw their overall energy-conversion efficiencies easily quadrupled during the twentieth century. Even with a conservative assumption of tripled conversion efficiency, average global per capita flow of useful energies has increased at least sevenfold since 1900 and of the order of twentyfold since 1800.

Another way to illustrate the increased energy use in modern societies is to contrast the flows controlled directly by individuals in the course of their daily activities, as described below.

In 1800, a New England farmer using two oxen to plow his stony field controlled about 500 W of animate energy. In 1900, a prosperous Great Plains farmer controlled 5 kW of sustained animate power as he held the reins of six large horses when plowing his fields. In 2000, his great-grandson performed the same task in the air-conditioned comfort of the insulated cabin on a huge tractor capable of 300 kW.

In 1800, a coach driver controlled about 2.5 kW of horse power on an intercity route. In 1900, an engineer operated a steam locomotive along the same route, commanding about 1 MW of steam power. In 2000, a captain of a Boeing 737 flying between the same two cities could leave it to onboard microprocessors to control two jet engines whose aggregate cruise power added up to about 10 MW.

A sweep across the entire history of civilization shows that the peak unit capacities of prime movers rose about 15 million times in 3,000 years – from 100 W of sustained human labor to 1.5 GW for the largest steam turbogenerators – with more than 99% of the rise taking place during the twentieth century (Figs. 35.5(a) and (b)). A comparison of energy costs makes it clear that the race to the top also applies to energies embodied in commonly

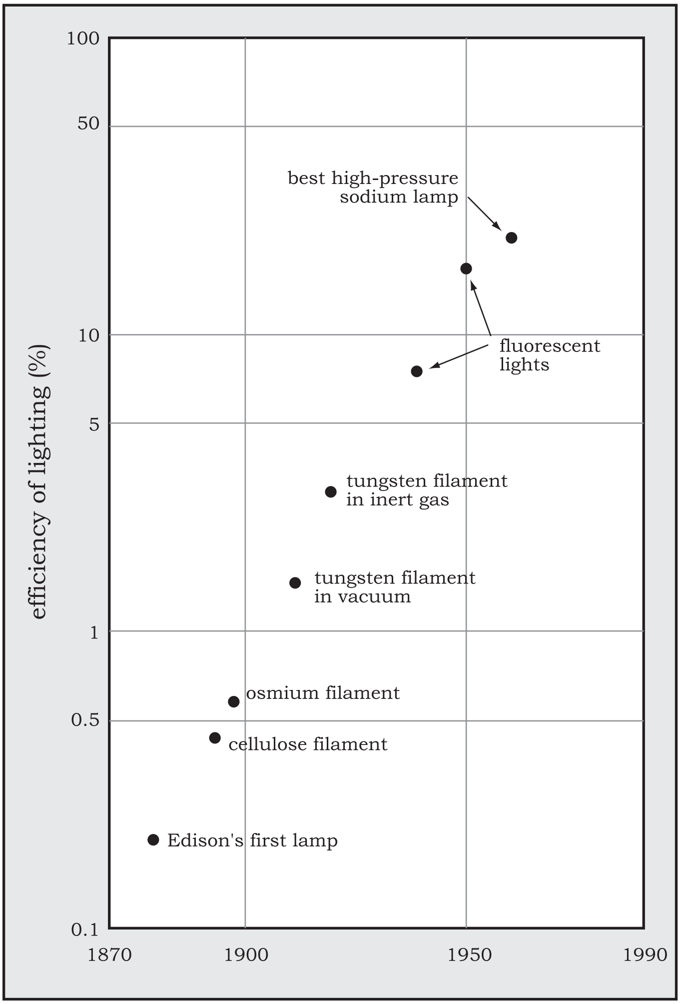
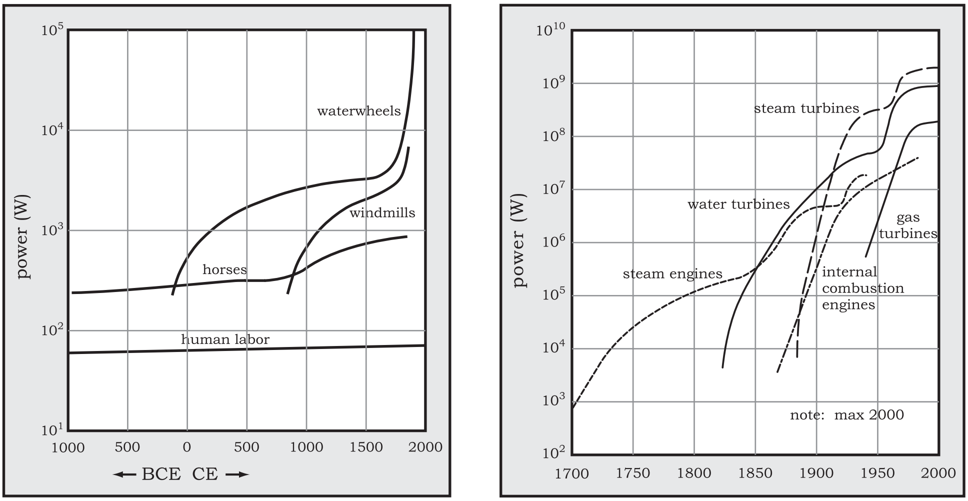


Fig. 35.4. Lighting efficiency: from candles to high-pressure sodium lamps.

used materials. Hand-sawn lumber and quarried stone cost less than 1 MJ kg^{-1}, as did Roman concrete. In contrast, specialty steels commonly used for modern machines need up to 50 MJ kg^{-1}. Most plastics cost in excess of 100 MJ kg^{-1}. Primary aluminum requires around 200 MJ kg^{-1}. Composite materials are even more costly, and semiconductor-grade silicon has an energy cost exceeding 1 GJ kg^{-1}. Naturally, similar multiples apply to the cost of finished products. A wooden house using hand-sawn lumber embodied less than 10 MJ kg^{-1} of its mass, whereas a modern car rates close to 100 MJ kg^{-1}, and both airplanes and computers embody at least 300 MJ kg^{-1}.

A closer look at data disaggregated by income indicates that this Lotkian race to maximize energy throughputs is not approaching an unbreachable asymptote. The latest survey of energy use in US households shows that those earning more than $100,000 per year (in



(a) (b)

Fig. 35.5. Maximum power of prime movers during the past 3,000 years.

2001 \$) consumed nearly 40% more energy for heating, air conditioning, and appliances than those with annual incomes below \$15,000 (US Energy Information Administration, 2001). But direct household use is only a small part of overall energy consumption. Millions of America's high-income families (there are nearly 10 million households with annual incomes of more than \$100,000) now have several cars, whose most powerful versions exceed 500 kW, compared with a Honda Civic at 104 kW. The energy cost of their extensive air travel alone may prorate to more refined fuel per month than most families use in their cars per year.

35.2 Consumption inequities and their implications

The trend toward higher energy throughputs has been universal, but the process has been proceeding at a very uneven pace, with affluent countries claiming disproportionate shares of modern energies. In 1900, their share of the global consumption of commercial energies (fossil fuels and primary electricity) was about 98%. At that time most people in Asia, Africa, and Latin America did not use directly any modern energies. Very little had changed during the first half of the twentieth century – by 1950, industrialized countries still consumed about 93% of the world's commercial energy. Subsequent economic development in Asia and Latin America finally began reducing this share. However, in 2000 affluent countries, containing just 20% of the global population, claimed no less than about 70% of commercial TPES.

The United States, with less than 5% of the world population, consumed about 27% of the world's commercial TPES in 2000, and G7 countries (the United States, Japan, Germany, France, the UK, Italy, and Canada), whose population adds up to just about 10% of the world's total, claimed about 45% (Fig. 35.6). In contrast, the poorest quarter of

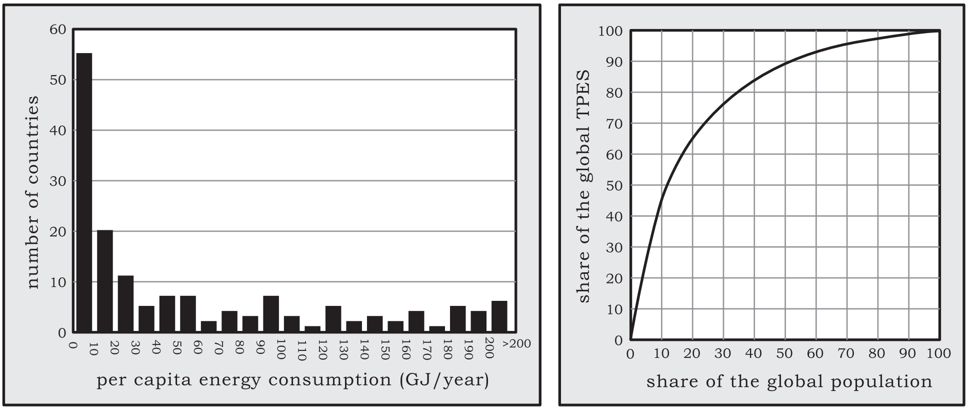


Fig. 35.6. Pronounced inequities of global energy consumption.

mankind – the populations of some fifteen sub-Saharan African countries, Nepal, Bangladesh, the nations of Indochina, and most of rural India – consumed a mere 2.5%, and the poorest people in the poorest countries (several hundred million adults and children including subsistence farmers, landless rural workers, and destitute and homeless people in expanding megacities) still do not consume directly any commercial fuels or electricity at all.

National averages show that at the beginning of the twenty-first century annual consumption rates of commercial energy ranged from less than 0.5 GJ per capita in the poorest countries of sub-Saharan Africa (Chad, Niger) to more than 330 GJ per capita in the United States and Canada. The global mean was about 65 GJ per capita, but only three countries – Argentina, Croatia, and Portugal – had national averages close to it. Persistent consumption disparities result in a hyperbolic distribution of average per capita energy use, with the modal value (including a third of all countries) of less than 10 GJ per capita (Fig. 35.6). With less than a sixth of all humanity enjoying the benefits of the high-energy civilization, a third of it is now engaged in a frantic race to join that minority, and more than half of the world's population has yet to begin this ascent. The potential need for more energy is thus enormous. However, as the following calculation indicates, the probability of closing the gap during the coming one or two generations is nil.

The utterly impossible option is to extend the benefits of two North American high-energy societies (about 330 million people consuming annually some 330 GJ per capita) to the rest of the world (about 6.5 billion people in 2005). This would require nearly 2.3 ZJ of primary energy, or slightly more than five times the current global supply. Neither the known resources of fossil fuels nor the available and prospective extraction and conversion techniques could supply such an energy flux by 2030 or 2050. The Japanese mean of about 170 GJ per capita is the same as that of the richest economies of the EU. Its extension to 6.5 billion people would require about 1.1 ZJ, or 2.5 times the current level.

This level is more realistic to contemplate, but its eventual achievement would, without a radical change of the primary energy composition, lead to unacceptably high levels of CO_2 emissions. In order to keep the future global warming within acceptable limits, concentrations of atmospheric CO_2 should be kept below 500 ppm (they had surpassed

380 ppm by 2005). That, of course, implies a necessity of limiting the future rate of fossil-fuel combustion. Two much-discussed strategies commonly seen as effective solutions are energy conservation and massive harnessing of renewable sources of energy. Unfortunately, neither of these strategies offers a real solution.

35.3 No solution through higher conversion efficiencies

Contrary to a widely shared conviction that increased efficiencies hold the key to a rational energy future, rising energy use cannot be arrested, much less reversed, by being less wasteful. This myth was exposed as early as in 1865 when William Stanley Jevons (1835–1882), a leading Victorian economist, asked about the potential of higher efficiency for "completely neutralizing the evils of scarce and costly fuel." He rightly concluded that

> *It is wholly a confusion of ideas to suppose that the economical use of fuel 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 (Jevons, 1865, p. 140; the emphasis is in the original).

Jevons used the example of steam engines whose efficiencies were, at the time of his writing, nearly twenty times higher for the best high-pressure machines than those of Savery's pioneering atmospheric engines – but whose growing numbers were consuming increasing amounts of coal. (British coal consumption grew by an order of magnitude between 1815 and 1865.) Many modern examples reinforce the validity of this universal combination of falling **specific** consumption and higher **overall** use of fuel or electricity that has been saved by the more efficient converters. Two prominent examples involving household energy use and private automobiles illustrate these trends, as described below.

Specific energy use in new houses ($\mathrm{W\,m^{-2}}$) has been falling with better insulation and with more efficient appliances – but the houses have grown larger, interior temperatures are kept to higher standards of desired comfort, and more appliances are plugged in. The average size of a new US house has increased by more than 50% since the early 1970s and now has topped 200 $\mathrm{m^2}$ (US Energy Information Administration, 2001). Also, the average size of a custom-built house now exceeds 400 $\mathrm{m^2}$, and houses in excess of 600 $\mathrm{m^2}$ are becoming more common. Furthermore, while new homes may have super-efficient air conditioners, these units are used to maintain indoor summer temperatures at levels typically considered too cold in winter. Typical American comfort levels are now 20 °C (68 °F) in summer, but 25 °C (77 °F) in winter.

Car performance stagnated for nearly half a century, but since the early 1970s passenger vehicles have become more efficient thanks to better engines, better aerodynamics, and a more common use of lighter materials (aluminum engine blocks replacing iron; plastics and composite materials replacing steel and glass in bodies). Yet decreasing specific fuel use and a lower mass/power ratio of passenger cars would have translated into considerable fuel savings only if cars of the early twenty-first century had matched or showed reductions in weight, power, number of energy-consuming accessories, and distance driven

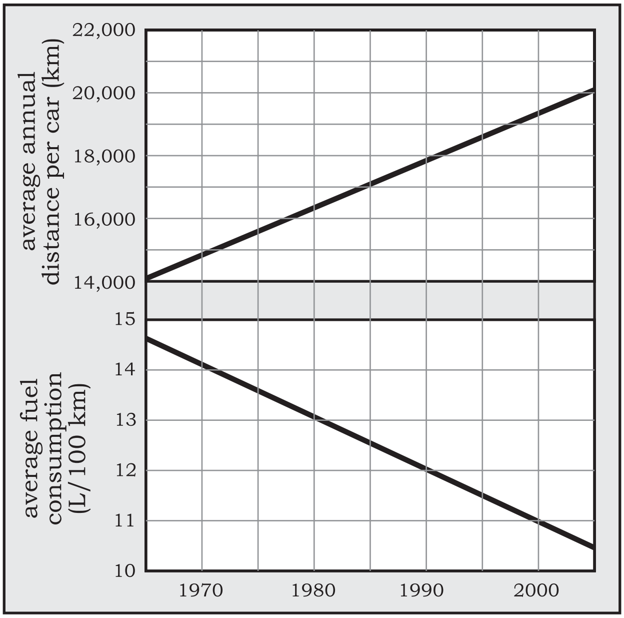


Fig. 35.7. Average fuel consumption and average distance driven per US car, 1965–2005.

compared with the vehicles of the mid 1970s. In reality, the trends have been in the opposite direction.

As for the mass, nearly half of the passenger vehicles of choice are not even cars, since SUVs and pick-ups are classified in the "light truck" category. These vehicles commonly weigh between 2 and 2.5 t, with the largest ones topping 4 t, compared with 0.9–1.3 t for compact cars. Fuel consumption in city driving (where they are mostly used) commonly surpasses 15 L per 100 km (20 L per 100 km for some vehicles); for comparison, efficient subcompacts need less than 8 L/km, and compacts average around 10 L/km. But these cars, too, have become heavier and more powerful than a generation ago. My 2006 Honda Civic is more powerful and heavier than my Honda Accord of 20 years ago.

Moreover, the average distance driven per year keeps increasing (Fig. 35.7). In the US, it is now around 20,000 km per motor vehicle, up by about 30% between 1980 and 2000 (Bureau of Transportation Statistics, 2007), as commutes have lengthened and as more touring trips to remote destinations are taken. The net outcome of all of this is that America's motor vehicles consumed 35% more energy in 2000 per licensed driver than they did in 1980.

In aggregate, these efficiency gains have translated into continuing declines in the energy intensity of national economies, the amount of primary energy consumed to generate a unit of GDP (Fig. 35.8). Despite this trend, however, the average per capita consumption of energy has been rising everywhere – not only in such rapidly industrializing nations as China, but also in countries where these rates are already very high, as illustrated by the US and Japanese examples in Fig. 35.9.

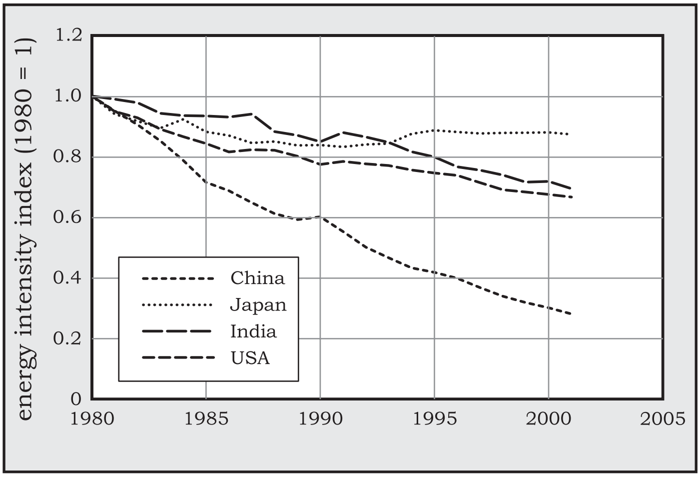


Fig. 35.8. Declining energy intensities of national economies, 1980–2002.

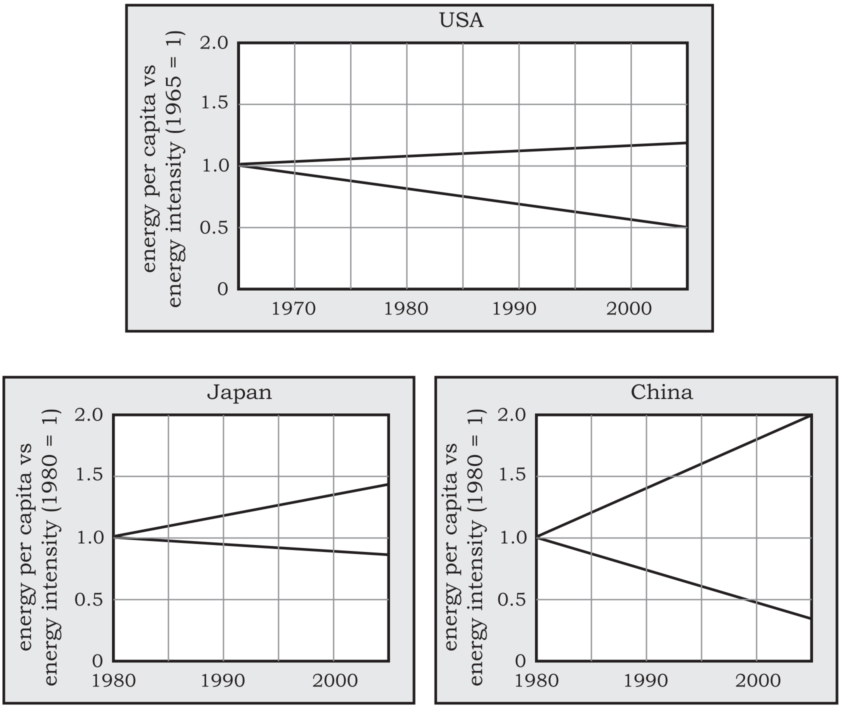


Fig. 35.9. Average per capita energy use keeps rising despite the continuously falling energy intensities of national economies.

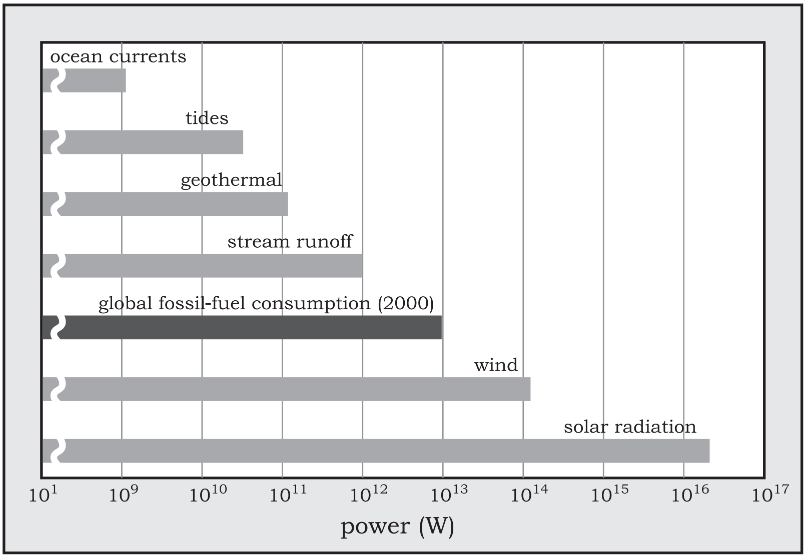


Fig. 35.10. Global flux of renewable energies compared with global fossil-fuel consumption.

35.4 Renewable energies: problems of scale and power density

Insolation (at 122 PW) is the only renewable flux; it is nearly four orders of magnitude greater than the world's TPES of nearly 13 TW in the year 2000 (Fig. 35.10). 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 photovoltaics) could harness it with effective densities of 10^1 W m^{-2}; the best all-day rates in 2005 were of the order of 30 W m^{-2}. All other renewable flows are harnessed with power densities that are one to three orders of magnitude lower than the typical power densities of energy consumption in modern societies (Fig. 35.11). 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 as is required by modern industrial, commercial, and residential infrastructures.

Terrestrial net primary productivity (NPP) of 55–60 TW is nearly five 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 already been modified, reduced, and compromised to a worrisome degree. Massive, intensive monocultural plantings of energy crops could only accelerate their decline.

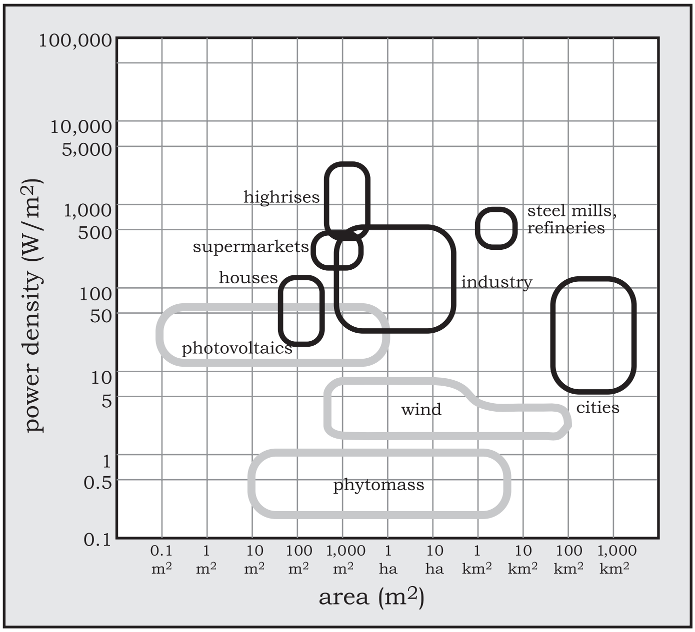


Fig. 35.11. Mismatch between power densities of energy consumption and renewable energy production.

Second, humans already appropriate 30%–40% of all NPP as food, feed, fiber, and fuel, with wood and crop residues supplying about 10% of the TPES (Rojstaczer *et al.*, 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 approaches could provide 50% of the world's TPES by 2050 or that 1–2 Gt of crop residues can be burned every year would put the human appropriation of phytomass close to or above 50% of terrestrial photosynthesis. This would further reduce the 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 action.

Finally, nitrogen is almost always the critical growth-limiting macronutrient in intensively cultivated agroecosystems as well as in silviculture. Mass production of phytomass for conversion to liquid fuels, gases, or electricity would necessitate a substantial increase in continuous application of this element. Proponents of massive bioenergy schemes appear to be unaware of the fact that the human interference in the global nitrogen cycle has already vastly surpassed the proportional anthropogenic change in carbon cycle. 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 the 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.

Except for direct solar radiation and a cripplingly high harvest of planetary NPP, no other renewable energy resource can provide more than 10 TW (Fig. 35.10). 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.

The conclusions are thus clear. Efficiency fixes (i.e., scientific and technical innovations) will not solve the present civilization's energy problem. Less wasteful and more affordable solutions will only stimulate future demand. Until we create engineered organisms capable of superior enzymatic conversion or photosynthetic efficiencies, or at least until we have affordable, efficient direct photovoltaic solar-energy conversion, there are two fundamental reasons why we cannot substitute for fossil fuels by harnessing renewable energy flows. First, except for prospects to tap direct insolation, global aggregates of all proposed renewable energy sources are smaller than current global energy use. Second, none are available at suitably high power densities sufficient to deliver the high energy throughputs required by the existing global civilization.

There is yet another strategy worth considering, an anti-Lotkian quest for limited energy consumption. Unfortunately, we cannot rely on market forces, which have been so useful for promoting consumption, to give us any clear signals to pursue this opposite course. This becomes obvious on considering relations between energy use and quality of life. An examination demonstrates that the quest for ever higher energy throughputs has entered a decidedly counterproductive stage, insofar as further increases of per capita energy use are not associated with any important gains in physical quality of life or with greater security, probity, freedom, or happiness. We had plenty to gain earlier as we were moving along the energy escalator – but now the affluent world is within the realm of limited to grossly diminished returns.

35.5 Energy use and the quality of life

While higher energy flows correlate highly with greater economic outputs, all of the **physical** quality-of-life variables relate to average per capita energy use in a distinctly nonlinear manner (Smil, 2003). There are some remarkably uniform inflection bands beyond which the rate of gains declines sharply, and some clear saturation levels beyond which further increases of fuel and electricity consumption produce hardly any additional gains. These surprisingly regular patterns are illustrated here with three key variables:

- infant mortality, perhaps the most sensitive indicator of overall physical quality of life, since it directly reflects many health, nutritional, and economic circumstances (Fig. 35.12);
- female life expectancy, which is perhaps the best indicator of the ultimate outcome of the quest for good quality of life (Fig. 35.13); and

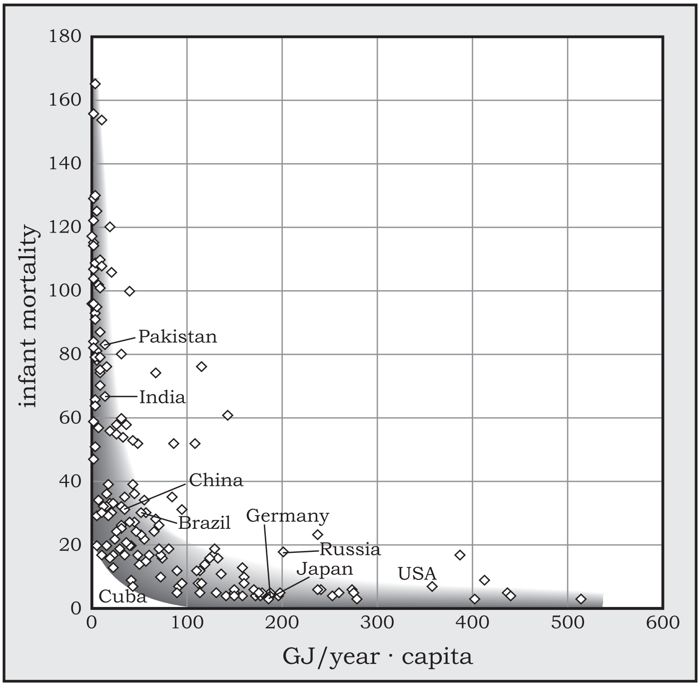


Fig. 35.12. Per capita energy use and infant mortality.

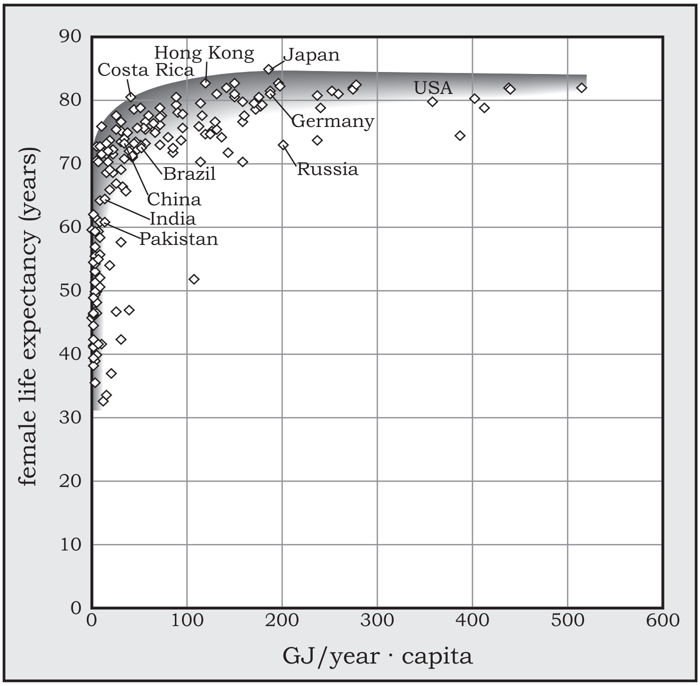


Fig. 35.13. Per capita energy use and female life expectancy at birth.

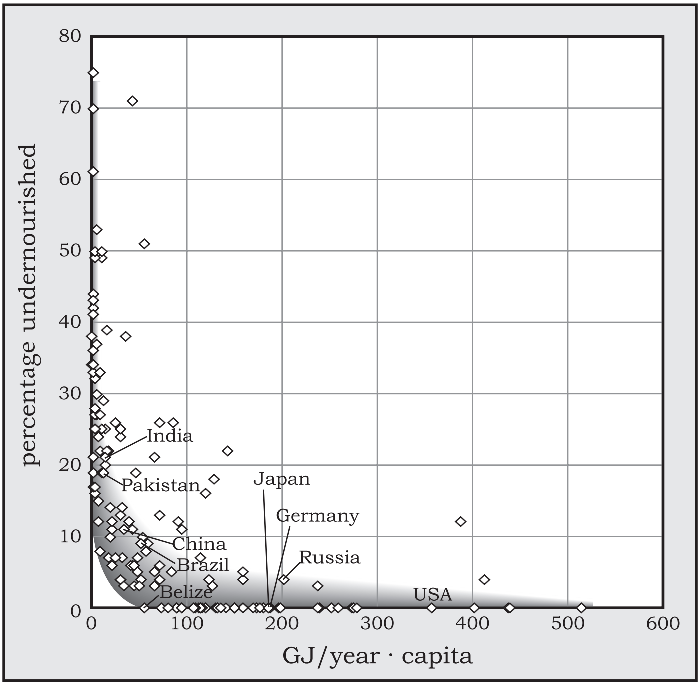


Fig. 35.14. Per capita energy use and malnutrition.

- the proportion of undernourished people, an indicator that captures the progress beyond the minimum existential requirements (Fig. 35.14).

In all of these (and numerous other) cases, there are pronounced gains as commercial energy use increases toward 30 and 40 GJ per capita, and clear inflections are evident at annual consumption levels of 50–60 GJ per capita; these inflections are followed by rapidly diminishing returns and finally by a zone of no additional gains accompanying primary commercial energy consumption above 100–110 GJ per capita. The pattern changes only a little when the plot is done for an aggregate Human Development Index (HDI) favored by the United Nations Development Programme and composed of three indices for life expectancy, education, and GDP (Fig. 35.15).

These realities make it clear that a society concerned about equity, determined to extend a good quality of life to the largest possible number of its citizens and hence willing to channel its resources into the provision of adequate diets, good health care, and basic schooling could guarantee decent physical well-being with an annual per capita use (converted with today's prevailing efficiencies) of as little as 50 GJ. A more satisfactory combination of infant mortalities below 20, female life expectancies above 75 years, and HDI above 0.8 requires annually about 60 GJ. But, once the physical quality of life reaches a satisfactory level, other concerns that contribute to the overall well-being of populations become prominent:

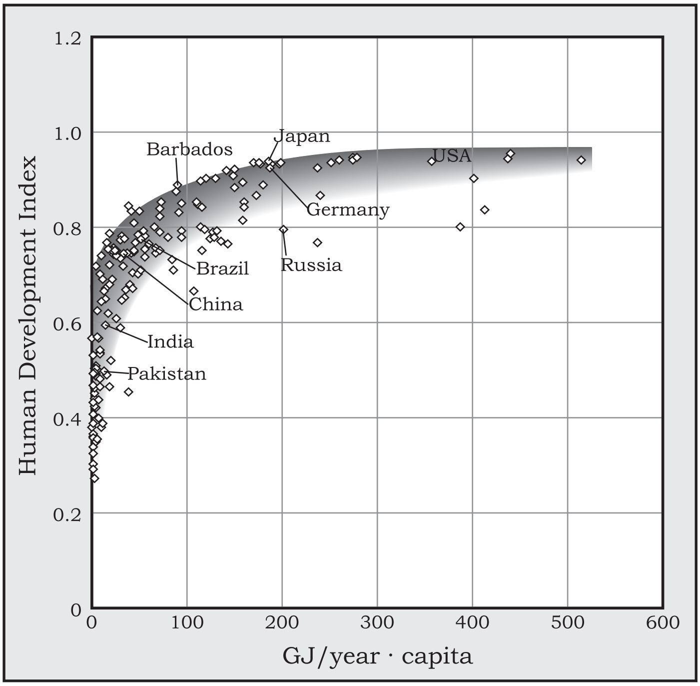


Fig. 35.15. Per capita energy use and HDI.

economic status, intellectual advancement (particularly good post-secondary education opportunities), and individual and political freedoms.

Surprisingly, even this combination is achievable without exorbitant energy consumption. Physical conditions that now prevail in affluent Western societies – infant mortalities below 10, female life expectancies above 80 years, and, needless to say, a surfeit of food – can be combined with high rates of house ownership (more than half of households), good access to post-secondary education, and HDI above 0.9 at energy consumption levels as low as 110 GJ per capita. Insofar as political freedoms are concerned, they have little to do with any increases of energy use above the existential minima; indeed, some of the world's most repressive societies have high, or even very high, energy consumption (Fig. 35.16).

Actual US and Canadian per capita energy use is thus more than three times the high-level minimum of 110 GJ, and almost exactly twice as much as in Japan or the richest countries of the EU – yet it would be ludicrous to suggest that the American quality of life is twice as high. In fact, the US falls behind Europe and Japan in a number of important quality-of-life indicators, including much higher rates of obesity and homicide, relatively even higher rates of incarceration, lower levels of scientific literacy and numeracy, and less leisure time. Among the obvious signs of economic underperformance are the decay of America's inner cities and the loss of economic competitiveness reflected by an enormous trade deficit.

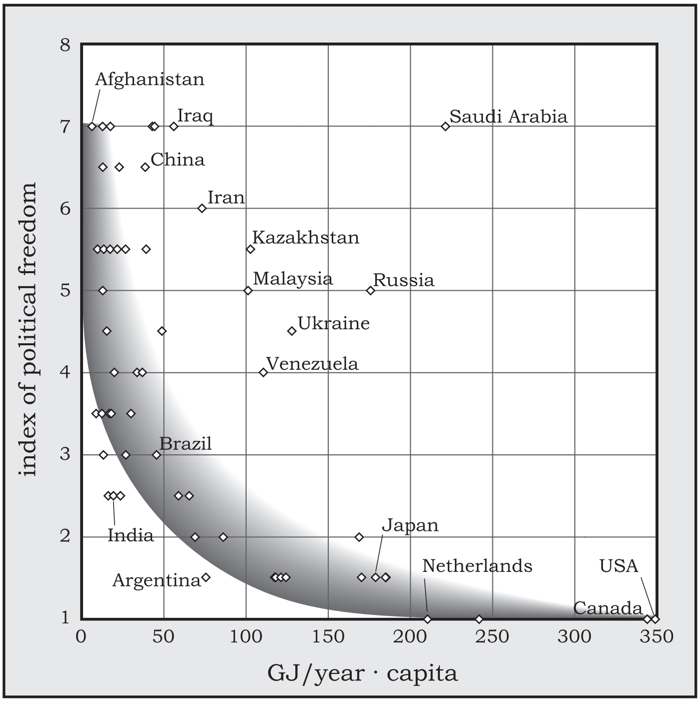


Fig. 35.16. Per capita energy use and the Political Freedom Index.

Pushing beyond 110 GJ per capita has not brought many fundamental quality-of-life gains. I would argue that pushing beyond 200 GJ per capita has been, on the whole, counterproductive. The only unmistakable outcome is further environmental degradation. These considerations become even more intriguing once these rational limits on average energy use are considered together with potentially large gains from further improvements of typical energy-conversion efficiencies. Given the annual 1%–1.5% efficiency gain (a rate well supported by historical experience), within a generation today's level of useful energy services could be supported with initial energy inputs 25% lower. This means that, in 2020, a good quality of life that now requires around 110 GJ per capita could be supported with primary inputs of just around 80 GJ per capita, a rate that is only marginally higher than today's global mean of 75 GJ per capita. The UN's medium variant of its global population forecast sees 25% more people by 2030 compared with the population in 2005, which means that during the next generation we would need to increase global energy use by only 25%–30% in order to provide every one of the 8.1 billion people in the year 2030 with a decent quality of life.

35.6 Choices ahead

Truly long-range forecasts are impossible, albeit increasingly common. Two prominent physicists, Martin Rees and Stephen Hawking, have recently joined the catastrophist school.

They believe there is a high probability of civilization's demise before 2050. I have consistently argued against such speculations and in favor of effective action. The global energy challenge is simply stated: how to guarantee a decent worldwide quality of life without the need to multiply the current TPES, in order to prevent rapid global warming. I have argued that it would be fatuous to think that this dual goal can be reached through increased conversion efficiencies. Undoubtedly, they are badly needed, and the opportunities for further major gains are far from being exhausted – but it is clear that without concurrent limits on consumption they become a part of the problem rather than an effective solution because they stimulate rather than reduce the overall energy use.

Besides the already noted problems with renewable energies, three additional factors will constrain the contributions made by new energy sources and new conversions. Their combination will make it highly unlikely that by 2025 or 2040 the world's primary energy supplies and its dominant prime movers will be drastically different from what they are today. The first factor is the well-documented slow rates of energy transitions. At least two generations are needed before a new energy source captures a major share of the market. The second is the longevity of established prime movers. All three of the quintessential machines of the modern world – steam turbines, internal combustion engines, and electrical motors – were introduced during the 1880s, and it is highly likely that they will be with us during the 2080s (Smil, 2006). The third is the persistence of expensive energy infrastructures (mines, oil and gas fields, refineries, power plants, transmission lines, ports, pipelines) that represent collectively the single largest industrial investment made by modern civilization.

But precisely because of these realities we should make a commitment to accelerate the development of alternatives to fossil fuels and create economic and social conditions for their rapid diffusion. Fundamental physical realities dictate that direct solar-energy conversions, particularly more efficient and more durable photovoltaics, should receive the highest possible priority. At the same time, we must begin to think seriously about the modalities of restrained energy use and its more equitable global distribution. I am well aware that these prescriptions run contrary to the dominant infatuation with continuously expanding supply and with the insistence that innovative technical fixes will solve the challenge. Yet nobody has produced a convincing proof that the rest of the world can replicate the North American level of average per capita energy consumption and that, even if there were resources to support such a feat, this would not result in intolerable global environmental change. Engineers at the Swiss Institute of Technology came to the same conclusion. Their project for a sustainable-energy society (Jochem *et al.*, 2002) pitches the rational average level at 2000 W per capita, a goal that is close to my analysis (2000 W per capita = 63.4 GJ per year).

Objections to visions of a 75 GJ per capita or 63 GJ per capita world are obvious – this situation would be welcome in Sudan, India, and China, but it would require massive energy cuts in the average use by Europeans and even more so for Americans and Canadians, and these populations will never agree to the drastic reductions of their living standards that such cuts in energy consumption would imply.

Rebuttals of these objections are equally obvious. To begin with, per capita consumption of around 75 GJ per year should be viewed as a desirable modal value rather than as an actual mean with tight deviations, and one to be achieved by a gradual process spanning at least several generations. More importantly, life-cycle assessments of products and processes and studies in environmental economics show that a great deal of current energy use in affluent countries is wasted on environmentally damaging activities whose elimination could only improve, rather than reduce, the overall standard of living.

Most fundamentally – unless one posits such improbable solutions as the imminent availability of inexpensive fusion or commercial harnessing of an entirely new source of energy – there is no other more efficacious alternative. The benefits of high energy use that are enjoyed by affluent countries, that is by less than one-sixth of humanity consuming >150 GJ per capita, cannot be extended to the rest of the world during the next one or two generations because fossil fuels cannot be produced at that rate even if their resources were not an issue, and, in any case, the environmental consequences of this expansion would be quite unacceptable. Are not these realities sufficiently compelling to start us thinking about what too many people believe to be unthinkable, about approaching the global energy problem as an ethical challenge, as a moral dilemma?

Its solution would then consist of determined moves to end the historic quest for ever higher energy throughputs, to put in place rational limits that guarantee a decent quality of life for an increasing proportion of humanity while preserving the integrity of the only biosphere our species will ever inhabit. Extraction and conversion of fossil fuels removed the key limit that had historically been imposed on energy flux through human societies through the inefficient use of current solar-energy income. This allowed the affluent nations to push the quest for maximized energy throughputs far beyond the levels compatible with tolerable global inequities and, because of the inevitable by-products of the combustion of fossil fuel, also beyond the levels compatible with the long-term integrity of the biosphere. We have the technical and economic means to move gradually away from the pursuit of maximized energy throughputs and thus reverse perhaps the greatest imperative of human evolution.

The modalities of this fundamental evolutionary shift cannot be specified *a priori* in any grandiose global or intergovernmental plan. As with any ultimately successful evolutionary trend, they will have to emerge from an unruly, complex, and protracted process whose progress will be marked by wrong choices, cul-de-sacs, and unproductive errors. The most important first step is to agree that an ever-rising energy and material throughput is not a viable option on a planet that has a naturally limited capacity to absorb the environmental by-products of this ratcheting process. To invert Lotka's dictum, we must so operate as to stabilize the total mass of the organic system, to limit the rate of circulation of matter through it, and to leave an unutilized residue of matter and available energy in order to ensure the integrity of the biosphere.

Acknowledgments

Ideas, technical details, and statistics in this chapter are drawn from the sources cited in the list below, as well as from the *Review of World Energy* (2006) published by British Petroleum (http://www.bp.com/worldenergy).

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