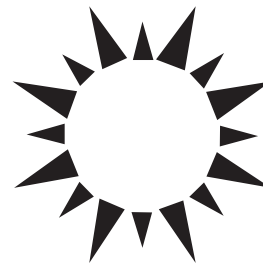


World History and Energy

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Glossary

antiquity The era of ancient (from the Western perspective, mostly the Middle Eastern and Mediterranean) civilizations extant between prehistory and the Middle Ages.

determinism A doctrine claiming that human actions are determined by external factors; its prominent varieties include environmental and geographic determinism.

early modern world The period immediately following the Middle Ages, variously dated as 1493–1800, 1550–1850, or the 16th to 18th centuries.

energy transition A period of passing from one configuration of prime movers and dominant fuels to a new setup.

middle ages The period between antiquity and the modern era, often circumscribed by the years 500–1500 CE.

prehistory The period of human evolution predating recorded history.

A strict thermodynamic perspective must see energy—its overall use, quality, intensity, and conversion efficiency—as the key factor in the history of the human species. Energy flows and conversions sustain and delimit the lives of all organisms and hence also of superorganisms such as societies and civilizations. No action—be it a better crop harvest that ends a famine or the defeat of an aggressive neighbor—can take place without harnessing and transforming energies through management, innovation, or daring. Inevitably, the availability and quality of particular prime movers and sources of heat and the modes of their conversions must have left deep imprints on

history. But no energetic perspective can explain why complex entities such as cultures and civilizations arise and no thermodynamic interpretation can reveal the reasons for either their remarkable history or their astounding diversity of beliefs, habits, and attitudes from which their actions spring. This article examines both of these contrasting views of energy and world history.

1. A DETERMINISTIC VIEW OF HISTORY

Countless energy imperatives—ranging from the solar flux reaching the earth to minimum temperatures required for the functioning of thousands of enzymes—have always shaped life on Earth by controlling the environment and by setting the limits on the performance of organisms. Deterministic interpretations of energy's role in world history seems to be a natural proposition, with history seen as a quest for increased complexity made possible by mastering higher energy flows. Periodization of this quest on the basis of prevailing prime movers and dominant sources of heat is another obvious proposition. This approach divides the evolution of the human species into distinct energy eras and brings out the importance of energy transitions that usher in more powerful, and more flexible, prime movers and more efficient ways of energy conversion. Perhaps the most intriguing conclusion arising from this grand view of history is the shrinking duration of successive energy eras and the accelerating pace of grand energy transitions.

The first energy era started more than 300,000 years ago when the human species, *Homo sapiens*, became differentiated from *Homo erectus*, and the era continued until the beginning of settled societies some 10,000 years ago. Throughout prehistory, all efforts to control greater energy flows were capped

by the limited power of human metabolism and by the inefficient use of fire. Domestication of draft animals and harnessing of fire for producing metals and other durable materials constituted the first great energy transition: reliance on these extrasomatic energies had raised energy throughput of preindustrial societies by more than an order of magnitude. The second transition got under way only several millennia later; it was not as universal as the first one and its effects made a profound, and relatively early, difference only in some places: it came as some traditional societies substituted large shares of their muscular exertions by waterwheels and windmills, simple but ingenious inanimate prime movers that were designed to convert the two common renewable energy flows with increasing power and efficiency.

The third great energy transition—substitution of animate prime movers by engines and of biomass energies by fossil fuels—began only several centuries ago in a few European countries and it was accomplished by all industrialized nations during the 20th century. That transition is yet to run its course in most low-income economies, particularly in Africa. The latest energy transition has been under way since 1882 when the world's first electricity-generating stations were commissioned in London and New York (both Edison's coal-fired plants) and in Appleton, Wisconsin (the first hydroelectric station). Since that time, all modernizing economies have been consuming increasing shares of their fossil fuels indirectly as electricity and introducing new modes of primary electricity generation—nuclear fission starting in the mid-1950s, and later also wind turbines and photovoltaic cells—to boost the overall output of this most flexible and most convenient form of energy. The second key attribute of this transition has been a steady relative retreat of coal mirrored by the rise of hydrocarbons, first crude oil and later natural gas.

Improving the quality of life has been the principal individual benefit of this quest for higher energy use that has brought increased food harvests, greater accumulation of personal possessions, abundance of educational and leisure opportunities, and vastly enhanced personal mobility. The growth of the world's population, the rising economic might of nations, the extension of empires and military capabilities, the expansion of world trade, and the globalization of human affairs have been the key collective consequences of the quest. These advances are discussed in this article and the limits of prime movers and heat sources that were available during the successive eras of energy use and the major

accomplishments that were achieved through ingenuity and better organization are noted.

2. THE EARLIEST ENERGY ERAS

During the long span of prehistory, the human species relied only on its somatic energy, using muscles to secure a basic food supply and then to improve shelters and acquire meager material possessions. Organismic imperatives (above all, the basal metabolism scaling as the body mass raised to 0.75 power) and the mechanical efficiency of muscles (able to convert no more than 20–25% of ingested food to kinetic energy) governed these exertions: healthy adults of smaller statures cannot sustain useful work at rates of more than 50–90 W and can develop power of 10^2 W only during brief spells of concentrated exertion. The former performance sufficed for all but a few extreme forms of food gathering and the latter exertions were called on for some forms of hunting. Simple tools made some foraging and processing tasks more efficient and extended the reach of human muscles.

Energy returns in foraging (energy in food/energy spent in collecting and hunting) ranged from barely positive (particularly for some types of hunting) to seasonally fairly high (up to 40-fold for digging up tubers). The choice of the collected plants was determined above all by their accessibility, nutritional density, and palatability, with grasslands offering generally a better selection of such species than did dense forests. Collective hunting of large mammals brought the highest net energy returns (because of their high fat content) and it also contributed to the emergence of social complexity. Only a few coastal societies collecting and hunting marine species had sufficiently high and secure energy returns (due to seasonal migrations of fish or whales) such that they were able to live in permanent settlements and devote surplus energy to elaborate rituals and impressive artistic creations (for example, the tall ornate wooden totems of the Indian tribes of the Pacific Northwest).

The only extrasomatic energy conversion mastered by prehistoric societies was the use of fire for warmth and cooking, which can be indisputably dated to approximately 250,000 years ago. Eventual shifts from foraging to shifting cultivation and then to sedentary farming were gradual processes driven by a number of energy-related, nutritional, and social factors: there was no short and sharp agricultural revolution. These changes were accompanied by

declining net energy returns in food production, but these declines had a rewarding corollary as the higher investment of metabolic energy in clearing land and in planting, weeding, fertilizing, harvesting, and processing crops, as well as storing grains or tubers, made it possible to support much higher population densities. Whereas the most affluent coastal foraging societies had densities less than 1 person/km² (and most foraging societies had carrying capacities well below 0.1 person/km²), shifting agricultures would easily support 20–30 people/km² and even the earliest extensive forms of settled farming (ancient Mesopotamia, Egypt and China's Huanghe Valley) could feed 100–200 people/km², that is, 1–2 people/ha of cultivated land (Fig. 1).

The increasing size of fields could not be managed by slow and laborious hoeing but plowing is either exceedingly taxing or, in heavy soils, outright impossible without draft animals. Farming intensification thus led to harnessing the first important extrasomatic source of mechanical energy by domesticating draft animals throughout the Old World (the pre-Columbian Americas had only pack animals). Continuous energy investment was then needed for animal breeding and feeding, as well as for producing more complex implements.

Small bovines would rate less than 200 W, stronger animals could sustain more than 300 W, and the best oxen and good early draft horses could surpass 500 W, equal to the labor of 6–8 adult men (Fig. 2). Draft animals thus speeded up field, transportation, and crop processing tasks and boosted agricultural productivity. Their numbers were governed by an obvious energetic imperative: no society could afford to cultivate feed crops where

harvests were barely adequate to provide subsistence diets. Those agroecosystems where grazing land was also limited (the rice regions of Asia) could support only relatively small numbers of draft animals.

Limited unit power of muscles could be overcome by massing people, or draft animals, and the combination of tools and organized deployment of massed labor made it possible to build impressive structures solely with human labor. Massed forces of 20–100 adults could deliver sustained power of 1.5–8 kW and could support brief exertions of up to 100 kW, enough to transport and erect (with the help of simple devices) megaliths and to build impressive stone structures on all continents except Australia. In contrast to this massed deployment of human labor in construction, no Old High culture took steps to a truly large-scale manufacture of goods and the atomization of production remained the norm. In addition, violent conflict powered solely by an individual's muscles could take place only as hand-to-hand combat or by an attack with an arrow launched from less than a couple hundred meters away, a limit ordained by the maximum distance between one extended and one flexed arm when drawing a bow. Eventually catapults, tensioned by many hands, increased the mass of projectiles, but did not substantially lengthen the maximum distance of attack.

Shifting agriculturalists extended the use of fire to the regular removal of vegetation, and early settled societies also adopted fire to produce bricks and containers and to smelt metals, beginning with copper (before 4000 BCE) and progressing to iron (common in some parts of the Old World after 1400 BCE). Charcoaling was used to convert wood to a fuel of higher energy density (29 MJ/kg compared to no more than 20 MJ/kg for wood and less than 15 MJ/kg for crop residues) and superior quality (essentially smokeless and hence suitable for burning indoors in fixed or portable hearths). But open fireplaces and braziers converted less than 10% of the supplied energy into useful heat and traditional charcoaling turned less than one-fifth of the charged wood energy into the smokeless fuel. Primitive furnaces used for metal smelting were also very inefficient, requiring as much as 8–10 units of charcoal for a unit of pig iron. The resulting high demand for wood was a leading cause of extensive deforestation, but a nearly complete disappearance of forests from parts of the Mediterranean (Spain, Cyprus, and Syria) and the Near East (Iran, Afghanistan) was caused by smelting copper rather than iron.

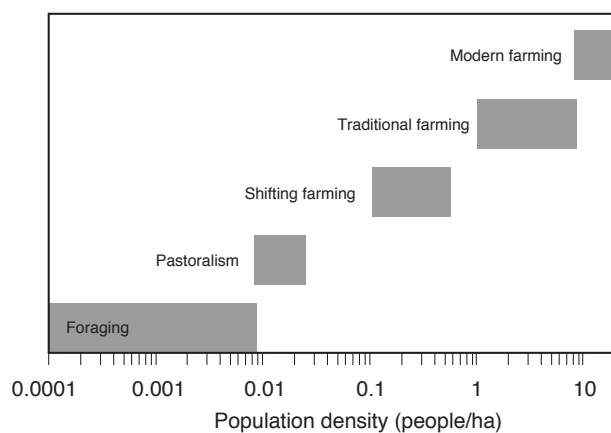


FIGURE 1 Successive stages of sedentary agricultures have required higher energy inputs but have been able to support 10^3 to 10^4 more people per unit of land than did foraging.

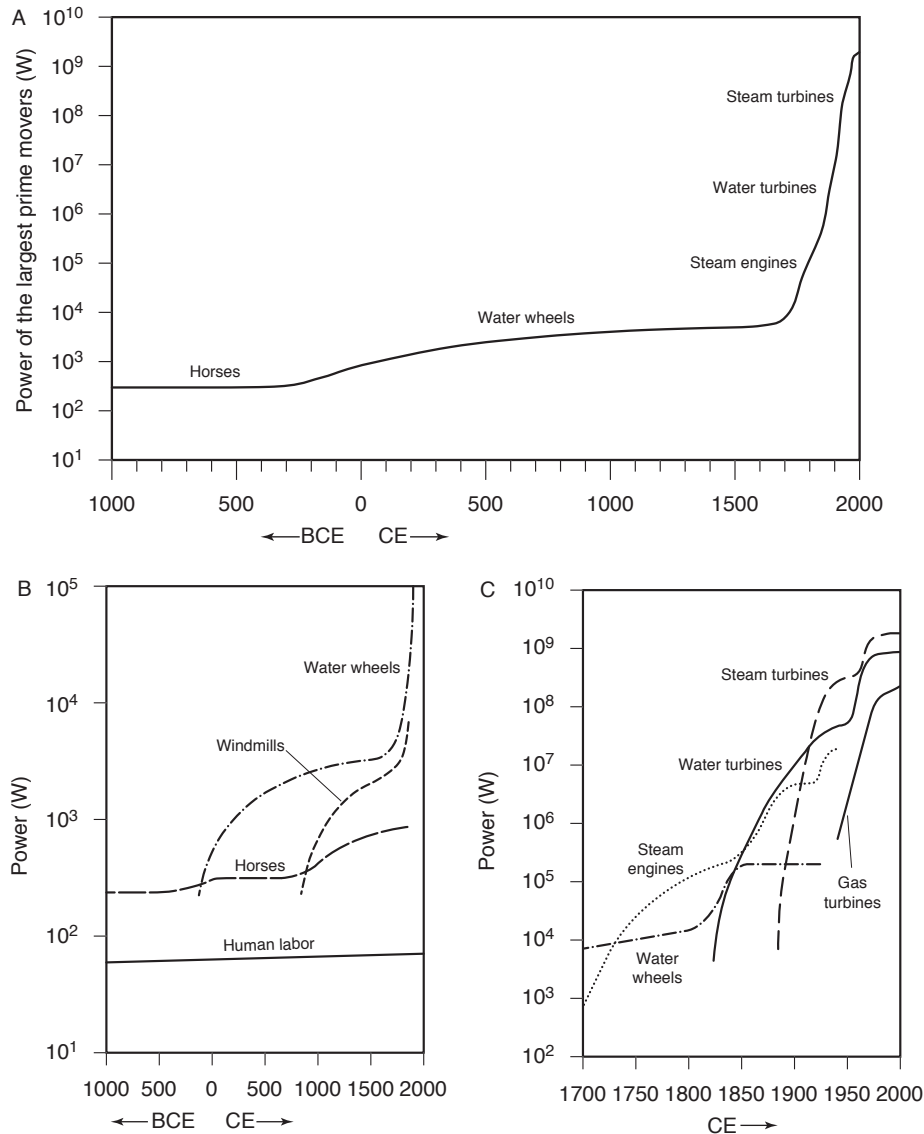


FIGURE 2 The maximum power of prime movers shown as the sequence of the highest capacity converters for the span of the past 3000 years (A) and shown in detail for the periods 1000 BCE to 1700 CE and 1700 CE to 2000 CE (B and C).

Small-scale and highly energy-intensive metallurgy meant that no early societies could smelt enough metal to make it the dominant material in daily use and simple machines, farming implements, and household utensils of the antiquity remained overwhelmingly wooden. This changed radically only when coke-based smelting began producing inexpensive iron after 1750. Similarly, the inherently limited power of oxen, the most affordable draft animals, which were rarely fed any concentrates, meant a ponderous pace of field operations: plowing a hectare of a loamy field with a pair of these animals was easily four times faster than hoeing

the same land, but a pair of well-fed horses would have accomplished the same task in less than one-half the time required by oxen. And the combination of weak animals, inefficient harnessing, and poor (unpaved) roads greatly restricted the size of maximum loads and the greatest distance of daily travel.

European antiquity also saw the first uses of water-driven prime movers. Their origins are obscure, with the first reference to their existence, by Antipater of Thessalonica during the first century BCE, describing their use in grain milling. The earliest wheels were horizontal, with water directed

through a sloping wooden trough onto wooden paddles fitted to a shaft that was directly attached to a millstone above. More efficient vertical water wheels, first mentioned by Vitruvius in 27 BCE, turned the millstones by right-angle gears and operated with overhead, breast, or undershot flows. Although there were some multiple installations of Roman water wheels—perhaps most notably the set of 16 wheels at Barbegal near Arles amounting to over 30 kW of capacity—cheap slave labor clearly limited the adoption of these machines.

3. MEDIEVAL AND EARLY MODERN ADVANCES

The dominance of animate prime movers extended throughout the Middle Ages but their efficiency had improved and they were increasingly joined by gradually more powerful converters of flowing water and wind. Human statures did not show any notable growth during the medieval era but better designs of some man-powered machines were able to harness muscle power more efficiently. Man- and animal-powered tread-wheels were deployed in the construction of tall buildings and in loading and unloading ship cargoes. The combination of breeding, better feeds, more efficient harnessing, and shoeing eventually raised the performance of the best draft animals as much as 50% above the capacities that prevailed during antiquity.

The collar harness, optimizing the deployment of powerful breast and shoulder muscles, had its origins in China of the 5th century of the CE and its improved version became common in Europe five centuries later. Iron horseshoes, preventing excessive wear of hooves and improving traction, became common at approximately the same time. But it took centuries before the intensification of cropping, with more widespread rotation of food and feed (particularly leguminous) species, increased the availability of concentrate feeds and allowed for harder working draft animals. During the 18th century, a good horse was considered to be equivalent to 10 men, or at least 700 W, and the best horses would eventually surpass power equivalent to 1 kW. Whereas a pair of early medieval oxen could sustain no more than 600 W, a pair of good horses in early modern Europe delivered 1.2 kW and large horse teams (up to 40 animals) deployed in the United States after 1870 to pull gang plows or the first grain combines had draft power of at least 8 kW and up to 30 kW.

Some medieval societies began to rely on inanimate prime movers for a number of demanding tasks including grain milling, oil pressing, wood sawing, powering of furnace bellows and forge hammers, and the mechanization of manufacturing processes ranging from wire pulling to tile glazing. Waterwheels were the first machines to spread widely and the famous Domesday Book attests how common they were in England of the late 11th century: it lists 5624 water mills in southern and eastern England, one for every 350 people. A subsequent increase in the highest capacities of waterwheels was slow: it took nearly 800 years to boost the performance by an order of magnitude. Early modern Europe developed some relatively very large water-driven wheels, and although typical unit capacities of these wooden machines remained limited (by 1700 they averaged less than 4 kW), they were the most powerful prime movers of the early modern era (Fig. 2).

Ships with simple square sails were used by the earliest Old World civilizations, but the first written record of wind-driven machines comes only approximately 1000 years after the first mention of water wheels. In 947 CE, al-Masudi's report described their use to raise water for irrigating gardens in what is now eastern Iran, and the first European record dates only from the closing decades of the 12th century. Subsequently, inefficient windmills continued to be used infrequently throughout the Mediterranean and the Middle East, and even less so in India and in East Asia, and they had undergone a great deal of development in only a small number of European regions. The earliest European windmills pivoted on a massive central post that was supported usually by four diagonal quarter-bars, had to be turned to face the wind, and were unstable in high winds and their low height limited their efficiency.

However, they were widely used in grain milling and water pumping (the Dutch drainage mills being the best known example), as well as in some industrial operations. Post mills were gradually replaced by tower mills and smock mills, and during the early 17th century the Dutch millers introduced first relatively efficient blade designs (however, true airfoils, aerodynamically contoured blades with thick leading edges, originated only just before the end of the 19th century), and after 1745 the English invention of using a fantail to power a winding gear turned the sails into the wind automatically. Even with these innovations, the average power of the 18th century windmills remained below 5 kW.

The Late Middle Ages and the early modern era were also the time when wind energy was harnessed

more effectively for Europe's great seafaring voyages. The rise of the West clearly owes a great deal to an unprecedented combination of harnessing two different kinds of energy: better, and larger, sailships equipped with newly developed heavy guns. Once the medieval ships became rigged with a larger number of loftier and better adjustable sails, increased in size, and acquired stern-post rudders and magnetic compasses (both invented in China), they became much more efficient, and much more dirigible, converters of wind energy. These ships carried first the Portuguese and then other European sailors on increasingly more audacious voyages. The equator was crossed in 1472, Columbus led three Spanish ships to the Caribbean in 1492, Vasco da Gama rounded the Cape of Good Hope and crossed the Indian Ocean to India in 1497, and in 1519 Magellan's *Victoria* completed the first circumnavigation of the earth. The inexorable trend of globalization was launched with these sailings.

Gunpowder was another Chinese invention (during the 11th century) that was better exploited by the Europeans. The Chinese cast their first guns before the end of the 13th century, but Europeans were only a few decades behind. Within a century, superior European gun designs transformed the medieval art of war on land and gave an offensive superiority to large sailships. Better gun-making was obviously predicated on major medieval advances in ore-mining and metal-smelting techniques that are exhaustively described in such classics as Biringuccio's and Agricola's volumes from 1540 and 1556, respectively.

These innovations reduced the need for energy inputs, particularly in the iron-making blast furnaces that appeared first in the lower Rhine valley before the end of the 15th century. As these furnaces grew in volume, charcoal's fragility limited their height and the annual volume of individual smelting operations. Larger operations also required the use of water-power (for blasting and subsequent metal forging) and this demand restricted the location to mountainous areas. But the main challenge was to keep them supplied with charcoal, and the English predicament is the best illustration.

By the early 18th century, a typical English furnace produced only approximately 300 tons of pig iron per year, but with at least 8 kg of charcoal per kilogram of iron and 5 kg of wood per kilogram of charcoal, its annual demand was approximately 12,000 tons of wood. With nearly all natural forests gone, the wood was cut in 10- to 20-year rotations from coppicing hardwoods yielding between 5 and 10 tons/ha. This means that approximately 2000 ha

of coppicing hardwoods, a circle with a radius of 2.5 km, were needed for perpetual operation. Nationwide (with nearly 20,000 tons of pig iron produced annually during the 1720s), this translated (together with charcoal needed for forges) to at least 1100 km² of coppiced growth. To produce 1 million tons with the same process would have required putting at least one-quarter of the British Isles under coppiced wood, an obvious impossibility. Yet starting in the mid-1830s, Great Britain began smelting more than 1 million tons of iron per year and yet some the country's forests began regrowing; coke and steam engines made that possible.

4. TRANSITIONS TO MODERNITY

Millennia of dependence on animate power and biomass fuels came to an end only gradually and the great transition to fossil fuels and fuel-consuming engines had highly country-specific onsets and durations. Differences in accessibility and affordability explain why traditional energy sources were used for so long after the introduction of new fuels and prime movers. For example, four kinds of distinct prime movers, in addition to human labor, coexisted in parts of Europe for more than 150 years between the late 18th and the mid-20th centuries before internal combustion engines and electric motors became totally dominant: draft animals (both in agriculture and in city traffic), water wheels (and, since the 1830s, water turbines), windmills, and steam engines. In the wood-rich United States, coal surpassed fuelwood combustion and coke became more important than charcoal only during the 1880s.

Moreover, the epochal energy transition from animate to inanimate prime movers and from biomass to fossil fuels has yet to run its global course. By 1900, several European countries were almost completely energized by coal—but energy use in rural China during the last year of the Qing dynasty (1911) differed little from the state that prevailed in the Chinese countryside 100 or 500 years earlier. Even in the early 1950s, more than one-half of China's total primary energy supply was derived from woody biomass and crop residues. The share of these fuels had been reduced to 15% of China's total energy use by the year 2000, but it remains above 70%, or even 80%, for most of the countries of sub-Saharan Africa (in the year 2000, India's share of traditional biomass fuels was approximately 30% and that of Brazil was approximately 25%), and globally it still accounts for nearly 10%.

Industrialization of the British Isles is, of course, the best known case of an early transition from wood to coal and England was the first country to accomplish the shift from wood to coal during the 16th and 17th centuries. Much less known is the fact that the Dutch Republic completed a transition from wood to peat during its Golden Age of the 17th century when it also replaced a large share of its mechanical energy needs by sailships, which moved goods through inland canals and on the high seas, and by windmills. In England and Wales, the process started as a straightforward fuel substitution in a society where the combined demand for charcoaling, ship- and house-building, heating, and cooking led to extensive deforestation. The use of coal as the fuel for a new mechanical prime mover began only after 1700 with Newcomen's inefficient steam engine. James Watt's separate condenser and other improvements (patented in 1769) transformed the existing engine from a machine of limited utility (mostly water pumping in coal mines) into a prime mover of unprecedented power suitable for many different tasks.

Watt's improved machines still had low conversion efficiency (less than 5%) but his engines averaged approximately 20 kW, more than 5 times that of the typical contemporary watermills, nearly 3 times that of windmills, and 25 times the performance of a good horse. One hundred years later, the largest stationary steam engines were 10 times as efficient as Watt's machines and rated ≈ 1 MW. After the expiration of Watt's patent, the development of high-pressure steam engines progressed rapidly, radically transforming both land and maritime travel. For centuries, horse-drawn carriages averaged less than 10 km/h, but by 1900, trains (the first scheduled services began during the 1830s) could go easily 10 times faster and carry passengers in much greater comfort (Fig. 3). Railways had also drastically lowered the cost of moving voluminous loads in areas where inexpensive canal transport was not possible. Steamships cut the length of intercontinental travel and greatly expanded and speeded long-distance trade. For example, trans-Atlantic crossing, which took more than 1 week with the sailships of the 1830s, was cut to less than 6 days by 1890.

Steam engines will be always seen as the quintessential energizers of the Industrial Revolution, that great divide between the traditional and the modern world. But this notion is far from correct, and so is the very idea of the Industrial Revolution. Coal did power the expansion of iron-making, but the textile industry, the key component of that productive transformation, was commonly energized, both in

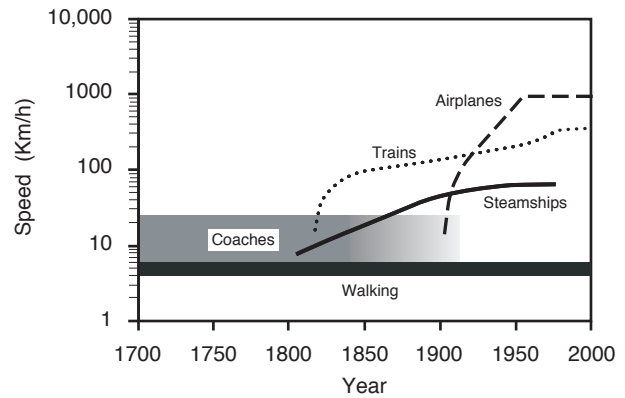


FIGURE 3 Maximum speeds of transportation during the years 1700–2000.

Europe and in North America, by water power rather than by coal combustion. Innovations to meet this demand included Benoit Fourneyron's reaction water turbine (in 1832) and an inward-flow turbine of James B. Francis (in 1847). Before the century's end, Francis' turbines and also Pelton machines (jet-driven turbines introduced in 1889) helped to launch modern water-powered electricity generation (only Viktor Kaplan's axial flow turbines are a 20th century innovation). As for the Industrial Revolution, the author sides with those historians who see it much more as a complex, multifaceted, and protracted process rather than as a clearly definable, intensive transformation powered by coal and coal-generated steam. After all, in 1850, England still had more shoemakers than coal miners and more blacksmiths than ironworkers, and in the United States, coal began providing more energy than wood only during the early 1880s.

Another little appreciated fact is that the harnessing of wind energy reached its peak at the same time that the steam engine did. America's westward territorial progression across the windy Great Plains created a demand for windmills to pump water for steam locomotives, households, and cattle. These machines were made generally of large numbers of fairly narrow slats that were fastened to solid or sectional wheels and usually equipped with either the centrifugal or the side-vane governor and independent rudders. Total sales of these relatively small (less than 1 kW) machines amounted to millions of units after 1860, whereas the capacity of approximately 30,000 larger windmills in countries around the North Sea peaked at approximately 100 MW by the year 1900.

From the vantage point of the early 21st century, it is clear that it was the next energy transition—the

process of electrification and the rising global dependence on hydrocarbons—that has left the greatest mark on individual lives as well as on the fortunes of economies and nations during the 20th century. The invention of a commercially viable system of electricity generation, transmission, and use (beginning only with incandescent lighting) by Thomas A. Edison and his associates was compressed into a remarkably short period during the early 1880s. This was followed by a no less intensive period of innovation with fundamental contributions by George Westinghouse [who correctly insisted on alternate current (AC) for transmission], Charles Parsons (who patented the first steam turbine in 1884), William Stanley (who introduced an efficient transformer in 1885), and Nikola Tesla (who invented the electric motor in 1888).

As a result, by the late 1890s, the entire electric system was basically perfected and standardized in the form that is still relied on today; the challenge ahead was to keep enlarging its unit sizes and improving efficiencies and this challenge has been met in many impressive ways. Since 1900, the maximum sizes of turbogenerators grew from 10 to ≈ 1.5 GW, AC transmission voltages rose from less than 30 kV to more than 700 kV, and in 2003, the best efficiencies of thermal generation surpassed 40% (and with cogeneration 60%), compared to as little as 5% in 1900. An inexpensive and reliable supply of electricity transformed every aspect of everyday activities by bringing bright and affordable light to both interiors and streets, by powering a still-growing array of time-saving and leisure-enhancing gadgets, and by energizing urban and intercity trains.

But the most revolutionary consequence of electrification was in industrial production. The reciprocating motion of steam engines had to be transmitted by rotating shafts and belts, resulting in friction and a great deal of lost time with accidents and allowing only limited control of power at individual workplaces. Inexpensive electric motors of all sizes changed all that: no shafts and belts, no noise and dangerous accidents, only precise and flexible individual power controls. American manufacturing was the first to make the transition in just three decades: by 1929, the capacities of industrial electrical motors accounted for over 80% of all installed mechanical power. Highly productive assembly lines (Ford pioneered them in 1913) were an obvious product of this transformation, as were many new specialized industries. And although the experimental beginnings of radio and television predate World War I, it was only after World War

II that electricity began powering the new computer age with its immense flow of information and entertainment options.

Electricity has been also the principal means of easing the burden of female household labor as a growing variety of machines and gadgets took over common chores. Another great change brought about by inexpensive electricity has been the global spread of air conditioning (first patented by William Carrier in 1902). Its availability opened up the American Sunbelt to mass migration from the Snowbelt, and since the 1980s, room units have also spread rapidly among more affluent households of subtropical and tropical countries.

The age of crude oil was launched during the same decade as that of electricity, and the three key ingredients of a modern automobile—Gottlieb Daimler's gasoline-fueled engine, Karl Benz's electrical ignition, and Wilhelm Maybach's float-feed carburetor—came together during the 1890s when Rudolf Diesel also introduced a different type of internal combustion engine. Subsequent decades have seen a great deal of improvement but no fundamental change of the prime mover's essentials. Only in the United States and Canada did car ownership reach high levels before World War II; Western Europe and Japan became nearly saturated only during the 1980s. By 1904, the Wright brothers built their own four-cylinder engine with an aluminum body and a steel crankshaft to power the first flight of a machine heavier than air, and the first 50 years of commercial and military flight were dominated by airplanes powered by reciprocating engines. Jet engines powered the first warplanes by 1944; the age of commercial jet flights began during the 1950s and was elevated to a new level by the Boeing 747, introduced in 1969.

Transportation has been the principal reason for the higher demand for crude oil, but liquid fuels, and later natural gas, also became very important for heating, and both hydrocarbons are excellent feedstocks for many chemical syntheses. By 1950, crude oil and natural gas claimed approximately 35% of the world's primary energy supply, and by 2000, their combined share was just over 60% compared to coal's approximately 25% (Fig. 4). Fossil fuels thus provided approximately 90% of all commercial primary energy supply, with the rest coming from primary (hydro and nuclear) electricity. Despite a great deal of research and public interest, new renewable conversions (above all, wind turbines and photovoltaics) still have only a negligible role, as do fuel cells whose high conversion efficiencies

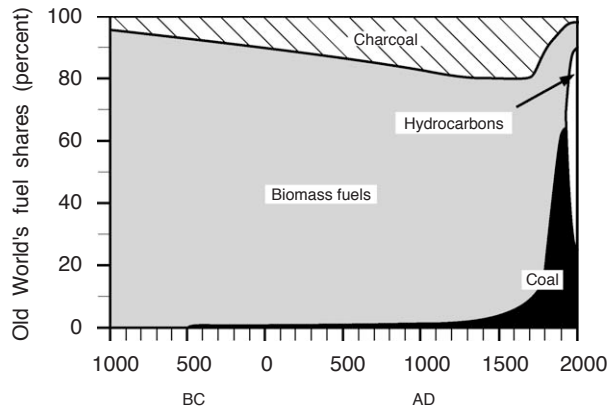


FIGURE 4 Approximate shares of global fuel consumption in the period from 1000 BCE to 2000 CE.

and pollution-free operation offer a much better way of converting gaseous and liquid fossil fuels to kinetic energy than does air-polluting combustion.

5. HIGH-ENERGY CIVILIZATION AND ITS ATTRIBUTES

Fossil fuels and electricity have helped to create the modern world by driving up farm productivity and hence drastically reducing agricultural populations, by mechanizing industrial production and letting the labor force move into the service sector, by making megacities and conurbations a reality, by globalizing trade and culture, and by imposing many structural uniformities onto the diverse world. Inevitably, all of these developments had enormous personal and collective consequences as they released hundreds of millions of people from hard physical labor, improved health and longevity, spread literacy, allowed for rising material affluence, broke traditional social and economic confines, and made the Western ideas of personal freedom and democracy into a powerfully appealing (as well as fanatically resented) global force.

But these benefits are fully, or largely, enjoyed only by a minority (only $\approx 15\%$) of the world's population. The great energy transitions of the past century raised standard of living everywhere but it has not been accompanied by any impressive decline of disparities between rich and poor societies. In the year 2000, the richest 10% of the world's population consumed more than 40% of all commercial primary energy (Fig. 5). In addition to being liberating and constructive, modern high-energy civilization is an enormous source of environmental pollution and degradation

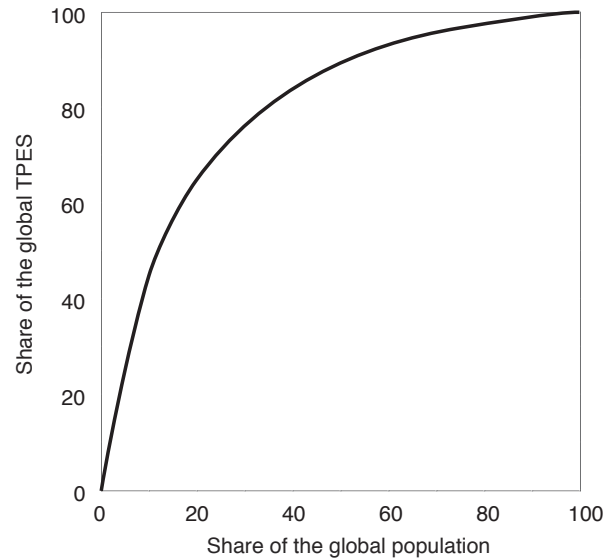


FIGURE 5 Inequality of global commercial energy use in the year 2000 is indicated by a highly convex shape of the Lorenz curve: the richest 10% of the world's population claimed approximately 45% of all energy, whereas the poorest 50% had access to just 10% of the total.

of ecosystems (perhaps even endangering the very maintenance of a habitable biosphere), is prone to many social ills accentuated by urban living, has acquired weapons of mass destruction, and is highly vulnerable to asymmetrical threats of terrorism.

People who live in affluent societies take the levels of energy that individuals and collectives control for granted, but the claims now made on energy resources are still astounding no matter if they are compared across the entire span of human evolution or just across the 20th century. Peak unit capacities of prime movers rose from less than 100 W of sustained human labor for the late Neolithic foragers to approximately 300 W for a draft ox of the early antiquity and to 2 kW for the largest Roman waterwheels. Improved versions of those machines rated approximately 5 kW by the end of the first millennium of the CE and still no more than 8 kW by 1700. A century later, Watt's steam engines pushed the peak ratings to 100 kW, by 1900 the largest steam and water turbines had capacities 100 times higher (10 MW), and steam turbines reached eventually their maximum at 1.5 GW (Fig. 2). Peak unit capacities of prime movers that deliver sustained power thus rose approximately 15 million times in 10,000 years, with more than 99% of the rise taking place during the 20th century. Increases in the destructive discharge of energies have been even more stunning: the largest tested thermonuclear

weapon (the Soviet Union’s 100-megaton bomb in 1961) had power 16 orders of magnitude higher than the kinetic energy of a forager’s arrow.

Because of the rapid growth of the global population, per capita comparisons yield naturally smaller multiples. Despite the near quadrupling of the global population—from 1.6 billion in 1900 to 6.1 billion in 2000—the average gross annual per capita supply of commercial energy more than quadrupled from just 14 GJ to approximately 60 GJ. In the United States, per capita energy use more than tripled to approximately 340 GJ/year, Japan’s more than quadrupled to just over 170 GJ/year, and China’s per capita fossil fuel use, exceptionally low in 1900, rose 13-fold between 1950 and 2000, from just over 2 to ≈ 30 GJ/year. These gains are far more impressive when expressed in more meaningful terms as useful energy services. Conservative calculations indicate that because of better conversion efficiencies, the world in the year 2000 had at its disposal at least 25 times more useful commercial energy than in 1900 and the corresponding multiples exceed 30 in some rapidly industrializing countries.

Perhaps the best way to compare the secular energy gains at a household level is to compare installed electric power. In 1900, a typical urban U.S. household had only a few low-power light bulbs, adding up to less than 500 W. In the year 2000, an all-electric, air-conditioned suburban house with

some 400 m² of living area had more than 80 switches and outlets ready to power every imaginable household appliance and drawing upward of 30 kW, at least a 60-fold jump in one century. Three vehicles owned by that household would boost the total power under the household’s control to close to half a megawatt! Equivalent power—though nothing like the convenience, versatility, flexibility, and reliability of delivered energy services—would have been available only to a Roman *latifundia* owner of ≈ 6000 strong slaves or to a 19th century landlord employing 3000 workers and 400 large draft horses.

Because the adoption of new energy sources and new prime movers needs substantial investment, it is not surprising that this process broadly correlates with the upswings of business cycles. The first wave, well documented by Schumpeter, corresponds to the rising extraction of coal and the introduction of stationary steam engines (1787–1814). The second wave (1843–1869) was stimulated by railroads, steamships, and iron metallurgy, and the third wave (1898–1924) was stimulated by the rise of electricity generation and the replacement of steam-driven machinery by electric motors in manufacturing (Fig. 6).

The initial stages of energy transitions also correlate significantly with the starts of major innovation waves that appear to be triggered by economic depressions. The first innovation cluster, peaking in 1828, was associated mainly with mobile

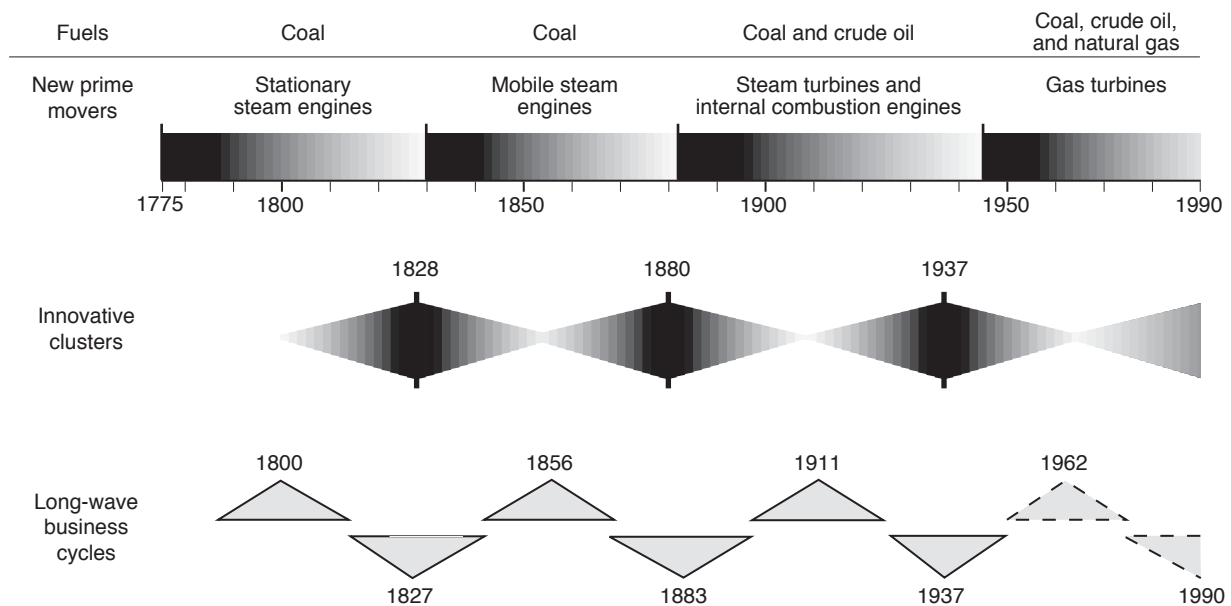


FIGURE 6 Timelines of major energy eras, innovative clusters (according to G. Mensch), and long-wave business cycles (according to J. A. Schumpeter) in the years 1775–1990.

steam engines; the second, peaking in 1880, was associated with the introduction of electricity generation and internal combustion engines, and the third cluster, peaking in 1937, included gas turbines, fluorescent lights, and nuclear energy. Post-World War II extension of these waves would include the global substitution of hydrocarbons for coal and mass car ownership; this wave was checked in 1973 by the sudden increase in the price of oil initiated by the Organization of Petroleum Exporting Countries.

6. LIMITS OF ENERGETIC DETERMINISM

When seen from a strictly biophysical point of view, energy may have an unchallenged primacy among the variables determining the course of history, but when it is considered from broader cultural and social perspectives, it may not even rank as *primus inter pares*. In addition to all of those indisputable energy imperatives, there are a multitude of none-energy factors that initiate, control, shape, and direct human decisions to harness and use energies in a myriad of specific ways. Only if one were to equate the quality of life, or the accomplishments of a civilization, with the mindless accumulation of material possessions, would the rising consumption of energy be an inevitable precondition. But such a primitive perspective excludes the multitude of moral, intellectual, and esthetic values whose inculcation, pursuit, and upholding have no links to any particular level of energy use.

To begin with, timeless artistic expressions show no correlation with levels or kinds of energy consumption: the bison in the famous cave paintings of Altamira are not less elegant than Picasso's bulls drawn nearly 15,000 years later. It should also be noted that all universal and durable ethical precepts, be they of freedom and democracy or compassion and charity, originated in antiquity, when an inadequate and inefficient energy supply was but a small fraction of today's usage. And to cite some more recent examples, the United States adopted a visionary constitution while the country was still a subsistence society running on wood; in contrast, before its collapse, the Soviet Union was the world's largest producer of crude oil and natural gas—yet all that country could offer its citizens was an impoverished life in fear, in a cage they were not allowed to leave. That political freedoms have little to do with energy use can be clearly seen by inspecting the list of the world's least free countries: it includes not only

energy-poor Afghanistan, Vietnam, and Sudan, but also oil-rich Libya and Saudi Arabia.

Long-term trends in population growth are another key historic variable that is hard to relate to changes in the energy base and to levels of energy use. Improved nutrition could be seen as the principal cause of tripling the European population between 1750 and 1900, but such a claim cannot be reconciled with careful reconstructions of average food energy intakes. China's example is even more persuasive: between 1700 and 1900, the Qing dynasty did not see any major change in energy sources and prime movers, and no rise in the average per capita use of wood and straw, but the country's population tripled to approximately 475 million people.

Even the links between economic output and energy use are not that simple. When seen from a physical (thermodynamic) perspective, economies are complex systems that incessantly acquire and transform enormous quantities of fossil fuels and electricity, and some very high correlations between the rate of energy use and the level of economic performance suggest that the latter may be a direct function of the former. There is little doubt that the successive positions of economic preeminence and international influence wielded by the Dutch Republic in the 17th century, Great Britain in the 19th century, and the United States in the 20th century had their material genesis in the early exploitation of fuels that yielded higher net energy returns and allowed for higher conversion efficiencies (peat, coal, and crude oil, respectively).

A closer analysis, however, reveals that the link between energy use and economy cannot be encompassed by any easily quantifiable function as national specificities preclude any normative conclusions and invalidate many intuitive expectations. Possession of abundant energy resources has been no guarantee of national economic success and their virtual absence has been no obstacle to achieving enviable economic prosperity. A long list of energy-rich nations that have nevertheless mismanaged their fortunes must include, to name just the three most prominent cases, the Soviet Union, Iran, and Nigeria. The list of energy-poor nations that have done very well by any global standard must be headed by Japan, South Korea, and Taiwan. And countries do not have to attain specific levels of energy use in order to enjoy a comparably high quality of life.

Although it is obvious that a decent quality of life is predicated on certain minima of energy use, those countries that focus on correct public policies may realize fairly large rewards at levels not far above

such minima, whereas ostentatious overconsumption wastes energy without enhancing the real quality of life. A society concerned about equity and willing to channel its resources into the provision of adequate diets, availability of good health care, and accessibility to basic schooling could guarantee decent physical well-being, high life expectancy, varied nutrition, and fairly good educational opportunities with an annual per capita use of as little as 40–50 GJ of primary energy converted with efficiencies prevailing during the 1990s.

A better performance, pushing infant mortalities below 20/1000, raising female life expectancies above 75 years, and elevating the UNDP's Human Development Index (HDI) above 0.8 appears to require at least 1400–1500 kgoe (kilograms of oil equivalent) of energy per capita, and in the year 2000, the best global rates (infant mortalities below 10/1000, female life expectancies above 80 years, HDI above 0.9) needed no less than approximately 2600 kgoe/capita (Fig. 7). All of the quality-of-life variables relate to average per capita energy use in a nonlinear manner, with clear inflections evident at

between 40 and 70 GJ/capita, with diminishing returns afterward and with basically *no* additional gains accompanying consumption above 110 GJ/capita or ≈ 2.6 metric tons of crude oil equivalent. The United States consumes exactly twice as much primary energy per capita as does Japan or the richest countries of the European Union (340 GJ/year versus 170 GJ/year), but it would be ludicrous to suggest that American lives are twice as good. In reality, the United States falls behind Europe and Japan in a broad range of quality-of-life variables, including higher infant mortality rates, more homicides, lower scientific literacy, and less leisure time.

Finally, energy use is of little help in explaining the demise of the established order. The long decline of the Western Roman Empire cannot be tied to any loss of energy supplies or a drastic weakening of energy conversion capabilities and neither can the fall of the French monarchy during the 1780s, the collapse of the Czarist empire in 1917, or the Nationalist retreat from mainland China during the late 1940s. Conversely, many historically far-reaching consolidations (including the gradual rise of

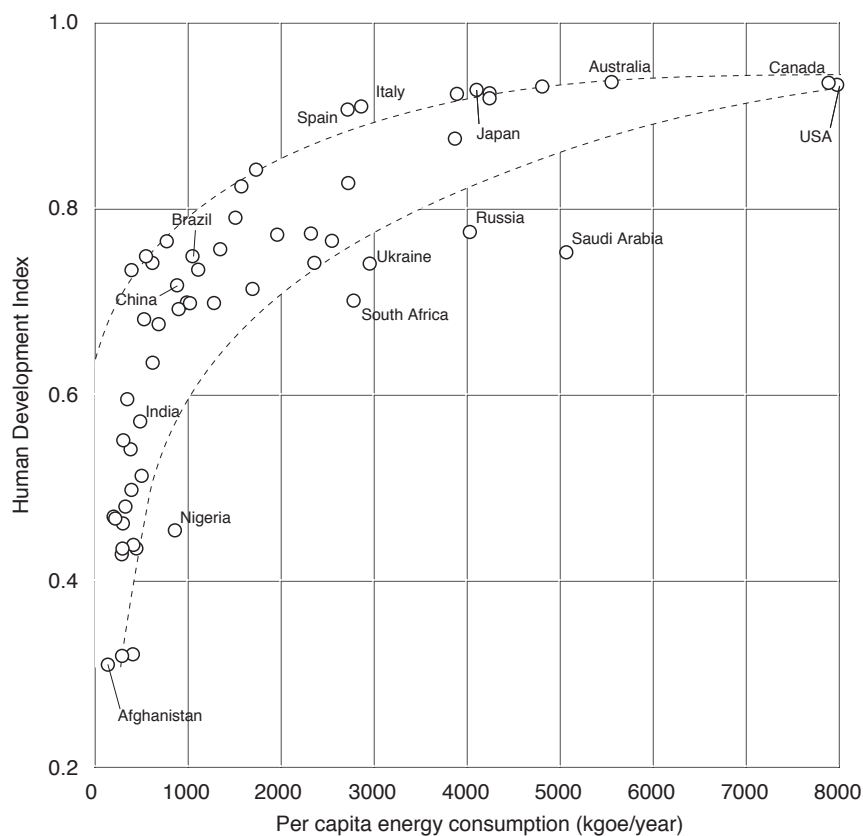


FIGURE 7 Plot of the Human Development Index against the average annual per capita use of commercial energy in the year 2000, which shows that virtually no quality-of-life gains accrue with consumption above 2.6 metric tons of oil equivalent.

Egypt's Old Kingdom, the rise of the Roman Republic, or the rise of the United States) and lightning expansions of power (including the spread of Islam during the 7th and 8th centuries or the Mongolian conquest of the 13th century) cannot be linked to any new prime movers or to better uses of prevailing fuel.

There is clearly an ambivalent link between energy and history. Energy sources and prime movers delimit the options of human history and determine the tempo of life, and, everything else being equal, thermodynamics requires that higher socioeconomic complexity must be supported by more intensive flows of energy. And yet, neither the possession of abundant energy sources nor a high rate of energy consumption guarantees the security of a nation, economic comfort, or personal happiness. Access to energies and the modes of their use constrain the options for human beings' actions but do not explain the sources of people's aspirations and the reasons for the choices they make and do not preordain the success or failure of individual societies at a particular time in history. Indeed, the only guaranteed outcome of higher energy use is greater environmental burdens whose global impacts may imperil the very habitability of the biosphere. To prevent this from happening, humanity's most important future choice may be to limit the use of energy and thus to embark on an entirely new chapter of history.

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