A new world of energy

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By the 1750s a few small regions of Western Europe (most notably parts of England, Wales, Scotland, Belgium, and Germany) were in the early stages of energy transition from plant fuels to fossil fuels and from animate prime movers to machines powered by combustion. This remarkably rapid epochal shift created the modern world, which is marked by unprecedented magnitudes and efficiencies of energy uses, enormous technical advances, rapid population and economic growth, and new social arrangements. Eventually the entire world was transformed by this grand transition, but until after the middle of the twentieth century surprisingly little was added to its progress outside North Atlantic Europe (where the process began) and the United States (where it reached new heights and maturity between 1870 and 1950).

Great powers of the past that continued to rely on traditional energy sources and on animate prime movers were swiftly left far behind: although in aggregate terms China, with its large population, remained the world's largest economy until the 1880s, in per capita terms its economic product had stagnated for many generations and by 1913 it was less than a tenth of the British rate, which had quadrupled in less than a century. Similarly, the US economy, whose aggregate size was only about a tenth of India's value in 1820, was 2.5 times as large in 1913, and roughly eight times as rich in per capita terms.

In fundamental energetic terms the path of all late modernizers was thus preordained: in all cases the subsequent economic development had to follow the new Euro-American pattern of energy uses. This first became evident in the case of two new economic and military rivals to the Atlantic dominance – imperial Japan (starting in the 1870s) and Soviet Russia (starting in the 1920s). Both of these had to base their quest for influence on copying, adopting, and adapting Western techniques, resting on a mastery of new energy sources, such as coal, oil, and hydroenergy, and new energy converters, including internal combustion engines and electric motors and lights.

They intensified this quest after the Second World War when they were joined by the world's most populous economies, China and India. China's epochal energy transition began only during the 1950s; it was marked initially by some tragic choices, including the Great Leap Forward and the ensuing famine of 1959–1961, and entered an accelerated stage only during the 1980s. India's transition took off only during the 1990s.

Historians have not ignored energy as a subject of their studies but it is undeniable that the production, transport, and conversion of fuels and electricity and multitudes of their final uses have been, at least in explicit terms, relatively neglected as a leading topic of modern historical inquiries. Of course, dealing with energy cannot be avoided. After all, as any physicist would point out, every action (from shining stars to marching armies) requires a conversion of one form of energy into another – and a thermo-dynamicist would add that all those conversions entail a loss of entropy, that is a decrease in energy's utility: no energy ever gets lost but every conversion degrades its quality, so say the two most fundamental physical laws.

So all historians are unwitting illustrators of the universal dictates of thermodynamic laws. In addition, although they rarely use the term power in their writings in its correct physical meaning, that is, as energy flow per unit of time (rather than as a common descriptor of might or military capacity), many historians have contributed detailed insights into the evolu-tion of prime movers (humans, draft animals, waterwheels, windmills, steam engines, internal combustion, rockets), energy sources (wood and charcoal, coal, oil and natural gas, thermal and hydroelectricity generation), and their uses. And the minority of historians dealing explicitly with the complex phenomena of energy has been joined by assorted interdisciplinarians con-tributing their knowledge and insight from other fields.

Consequently, we have been fairly well served with many detailed histor-ical studies of particular energy sectors. The history of coal is particularly well covered, as is that of electricity generation and use. The evolution of prime movers ranging from horses and sailing ships to internal combustion engines has been well studied, as have the vehicles, ships, and airplanes these engines have powered.

Measuring energy advances

The breadth and quality of existing studies allows me not to recapitulate their findings, many of which provide fascinating but highly time- and place-specific details. Instead I will concentrate on just six universal measures, the

understanding of which offers convenient keys to unlocking the meaning and import of past energy developments that have created the modern world through an unprecedented (and perhaps unrepeatable?) combination of advances. These are: energy density, power density, the maximum power of prime movers, the efficiency of energy conversions, the per capita consumption of useful energy, and, given the role of violent conflicts in history, the maximum energies of weapons.

Before 1750 most of these indicators had either remained (quantitatively and qualitatively) entirely unchanged or had shown only very slow, hesitant, and uneven advances during the millennia of recorded history. As a result, in 1700 Chinese peasants plowing grain fields, Indian builders erecting tall structures, Turkish merchants trading with distant places, Italian messengers carrying urgent news, English laborers smelting metals, and Inca families cooking their meals relied overwhelmingly on the same energy sources (low-energy-density plant fuels) and on the same prime movers (their own muscles or the exertions of often inadequately fed domesticated animals) that their predecessors used one or two millennia earlier.

There were some notable improvements but they took place very slowly: their use was largely restricted to only a few regions and did not amount to a fundamental qualitative change. By 1700 the best-built English waterwheels, whose origins go back to antiquity, became fairly efficient, as did (after nearly a millennium of evolution) the best windmill designs, but in many regions both devices did not greatly differ from their ancient prototypes. For example, simple "Cretan" windmills with four to twelve triangular cloth sails were used around the Mediterranean in an unchanged form from medieval to modern times, while in other regions (most notably in parts of China and Japan) any mechanical prime movers were a rarity.

By contrast to the unchanging, stagnating, or very slowly improving measures concerning the quality of energy sources and the performance of prime movers before 1750, the centuries after this brought great changes, introducing not only impressive quantitative gains but also fundamentally superior qualities. When seen from physical thermodynamic perspectives, the magnitude of those stunning, concatenated post-1750 changes can be traced by following the (rising or declining) trajectories of the fundamental measures and by comparing their outcomes at the end of the twentieth century with the performances that prevailed in the middle of the eighteenth century. Doing so requires, as energy studies invariably do, plenty of numbers, but I will deploy them in a user-friendly way, explaining the quantities and key assumptions in order to allow an interested reader to

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verify and replicate the calculations as a means toward a deeper understanding of fundamental energy realities that help to explain much of post-1750 world history.

Energy density

The first of my six universal measures is the fundamental matter of energy density, that is, the quantity of energy in a unit mass of matter: in modern scientific parlance this is joules (J) per gram (g) or (because both of those are such tiny units), megajoules (MJ) per kilogram (kg) or gigajoules (GJ) per tonne (t), and because both of those units go up three orders of magnitude in each step the number itself does not change. At a basic existential level, the importance of this variable is best grasped by comparing the energy densities of different types of food, because acquiring food determined much of the behavior of our species during the first 95 percent of its existence. Active lives of adult gatherers and hunters demanded easily more than 13 MJ of food energy a day. Getting them from leaves or stems (as many primates, including gorillas, do) would require eating more than 15 kg of such plant mass a day and spending most days just gathering that amount, leaving little time for evolving more intelligent existence.

Getting that amount from fruits (as do chimpanzees, our closest primate relatives) would require finding 5 kg of them a day, an equivalent of more than thirty apples, sweet but with no fat and with only a low share of the protein needed for growth; not surprisingly, in their quest for protein chimpanzees also hunt colobus monkeys and "fish" for termites with blades of grass. And securing 13 MJ a day by foraging for nutritious underground biomass required digging 5 kg of tubers by hand or with simple digging sticks, and would still lead to deficiencies in protein and fat. And, obviously, fruits and tubers could be had in temperate and boreal regions only seasonally, restricting the extent of human habitation.

In contrast, killing of megaherbivores (mammoth, bison, giant elk) provided hundreds of kilograms of fatty meat and internal organs whose high energy density made it possible to survive in boreal environments. Eating just 1.5–2 kg of this food supplied not only all the needed energy but also plenty of the best-quality protein and fat. No wonder our ancestors were willing to take their chances by hunting animals whose body mass was ten or even fifty times greater than their own. These quests left them well fed and with enough free time to create admirable paintings of animals on the cave walls of Altamira, Lascaux, or Chauvet.

Advantages of higher energy density are no less discernible in the quest for fuels. Although some fossil fuels were used millennia ago, such as outcropping coal in Han China and bitumen pools in ancient Mesopotamia, the only fuels used by most societies since antiquity were a few varieties of phytomass: wood (usually burned after a period of air-drying), charcoal derived from it, crop residues (mostly cereal straws), roots, leaves, and grasses. A few minor exceptions aside, since their emergence as a distinct species humans had thus lived only by tapping solar energy recently transformed into food and fuel, that is, by relying on almost instant flows (a financial equivalent would be to stay on a steady income) of renewable energy. Large-scale coal mining began the epochal switch of the energy basis of our society to living on ancient accumulations of solar flows, on products of photosynthesis transformed after millions of years of underground processing into carbonaceous fuels: we began to draw on a finite store of accumulated energy capital.

Between 1750 and 1900 there was an exponential expansion of coal mining in Europe and the United States (as well as the beginning of modern coal industries in Russia, China, and India), and during the last decade of the nineteenth century the energy content of extracted coal had surpassed the aggregate energy content of phytomass fuels burned worldwide to generate household and industrial heat. And by that time coal was not the only fossil fuel that was extracted on a commercial scale: new industries tapping crude oil emerged in the United States, Russia, Burma, and Indonesia and the United States pioneered the use of natural gas. Comparison of energy densities of these fuels makes it clear why modern civilization is so fundamentally different from its predecessors.

All phytomass fuels are products of photosynthesis, with cellulose and lignin dominating their chemical composition and their energy density. As a result, their energy density is around 15 MJ per kg of air-dry matter. There was an option of using pyrolysis (slow heating in the absence of oxygen) to produce charcoal from wood (and sometimes from other biomass): every Old World civilization used it, from antiquity into the twentieth century. But while charcoal (a nearly pure carbon) has energy density of 29 MJ/kg (nearly twice that of air-dry wood), its traditional production required at least five units of wood per unit of charcoal, resulting in 60 percent loss of initially charged energy and making charcoal much more expensive than wood and beyond the reach of most people.

Anthracite, the best variety of coal, has pretty much the same high energy density as charcoal (29–30 MJ/kg), and that is why its accessible reserves

were the first ones to be exhausted: its extraction peaked in Pennsylvania in 1917 (at about 90 megatonnes (Mt)/year) and by 1970 it was less than 10 percent of that peak. Most bituminous coals (used to generate electricity or to produce metallurgical coke) have densities 1.5 times that of air-dry wood (22–23 MJ/kg), while a kilogram of refined oil products (be it gasoline, kerosene, or diesel fuel) packs about 42 MJ, nearly three times the energy density of air-dried wood. Moreover, crude oil (petroleum) and liquid fuels produced from it by the refining of crude oil (gasoline, kerosene, diesel fuel, heavy oil) are particularly convenient: easy to transport (by pipelines, ships, barges, trucks), easy to store (underground or in aboveground tanks), flexible to use (for any stationary application and for land, water, and air transport). As a result, economies relying on liquid fuels are far more efficient and flexible than those dependent on coal or wood.

Many limits and possibilities of everyday options and historical developments can be explained by comparing energy densities: the more concentrated sources of energy offer many great advantages in terms of their extraction, transportation, and storage costs, flexibility of use and conversion options. An excellent historical example of economic (and hence social) constraints due to energy density concerns the efficiency of transatlantic crossings. For a single crossing in 1907, the ill-fated *Lusitania* (launched in that year as the biggest passenger ship ever and torpedoed by a German U-boat in May 1915) displacing 45,000 t, had to carry about 5,500 t of coal taking up 10,000 m³ of bunker space (assuming 23 GJ/t, 0.6 t/m³ of pulverized coal); if it were fueled by wood chips (15 GJ/t; 0.3 t/m³ of wood chips) its fuel load would have been more than 50 percent heavier and it would have taken up three times as much space – while an oil-fueled vessel of the same displacement would have needed only 3,000 t of fuel oil (42 GJ/t; 0.85 t/m³) in tanks taking up only a third of coal storage's space.

Actual mass and volume differences would be even larger because of higher combustion efficiencies of coal versus wood and, even more so, of oil versus coal; but even this simplified comparison makes it clear why there could never be affordable wood-fueled transatlantic crossings that would have transported more than 40 million European emigrants to North and South America, and why the shipping companies switched from coal to fuel oil as soon as the latter high-energy density liquid became reliably available: as with so many technical innovations, that switch was led by the military, as the British Navy, prodded by Winston Churchill, began converting its ships to oil just before the First World War.

Power density

Many developments can be best explained by examining combinations of energy density and power density. The latter ratio has a number of meanings in different science and engineering disciplines, but I favor its use as a universal measure of energy flow (that is power) per unit of horizontal surface area (W/m^2). The main advantage of this measure is its suitability for comparing virtually all natural or anthropogenic energy flows, and it is particularly revealing for highlighting the differences between traditional renewable energy flows (characterized by low to very low power densities) and modern fossil fuel uses (proceeding at medium to very high power densities). I will illustrate this by using two revealing examples. The first one demonstrates why mass-scale urbanization, a key attribute of modernization, could not have been fueled by wood, even less so by charcoal, because those phytomass fuels have inherently low power density. The second one calculates the demand that the smelting of civilization's most important metal would have made on the world's forests in the absence of coke made from metallurgical bituminous coal.

During the first decade of the nineteenth century, London's population surpassed 1 million people and its annual energy demand was equivalent to about 4 t of wood per capita used for heating, lighting, and a multitude of small and large manufacturing enterprises. Photosynthesis converts solar radiation into new chemical bonds in wood with inherently low efficiency, and hence all phytomass fuels are produced with very low power densities. Even if London were surrounded by highly productive forests (good beech and oak stands) whose annual wood production averaged 5 t/ha, their cutting would produce fuel with average power density of only about 0.25 W/m^2 and the city would have needed a reserve of about 800,000 ha (or a forested circle around the city with a radius of just over 50 km) of which it would have to clear-cut, and promptly replant, some 50,000 ha of mature trees (containing 100 t/ha) every year.

Cutting and transporting that much wood would have been costly and inconvenient; burning it within the city would have been very polluting: polycyclic organic matter released by wood combustion is highly carcinogenic. Replacing all that wood by charcoal would have needed at least 4 tonnes of wood (15 GJ/t) to produce a tonne of charcoal (29 GJ/t), that is, a 50 percent loss of energy due to charcoaling resulting in a power density rate of just 0.12 W/m^2 in order to produce convenient, light, sulfur-free, and nearly smokeless fuel. Such low power densities of energy production would have

required very large areas to secure the fuel: with minimized transport, forests would have to encircle the city with a radius of 80 km – and that was for only 1 million people. Not surprisingly, by the early nineteenth century all but a very small share of London's energy came from coal.

Similarly sized contemporaneous Beijing managed with much less coal (extracted in small mines just west of the capital since the tenth century) because its per capita energy use was considerably lower, due to minimal heating in winter (hence cotton-padded clothes worn inside) and to the absence of energy-intensive manufacturing enterprises within the city. Obviously, even in 1810, energizing a rapidly growing and industrializing London-like city solely with wood or charcoal would have been a most impractical and exceedingly costly proposition, and large cities and conurbations of the late nineteenth century and megalopoli of the twentieth century became direct expressions of high-energy-density fossil fuels produced with high power densities: both coal and crude oil could be extracted with power densities commonly 1,000 and often 10,000 times higher ($>100 - >1,000$ W/m^2) than the harvests of phytomass fuels.

Similar constraints apply to smelting iron, the metal (now mostly converted to a wide variety of steels) that was and remains the signature material of the modern world: its global annual output is larger than that of the next four most important metals (aluminum, copper, zinc, and lead) combined. For nearly three millennia iron was smelted from its ores by using charcoal. By 1800, global production of 1 Mt of iron would have required (with mass ratios of 8/1 for charcoal/metal and 1/5 for charcoal/wood) about 40 Mt of wood, or the cutting down of 4,000 km^2 of high-density virgin forest a year. If widely spread it would have been a negligible burden at a time when the world still had large areas of intact virgin forests. By the year 2000, efficiencies had improved (charcoal/metal ratio at 0.75/1, charcoal/wood at 1/4) but the global iron output rose to 580 Mt and it would have required about 1.75 gigatonne (Gt)/year of wood.

Even if all of it came from high-yielding tropical plantations (power density of roughly 0.5 W/m^2) it would still mean cutting down annually at least 1.75 million km^2 of trees, an area equal to slightly more than all forests in the European Union. In contrast, when all surface structures needed for coal mining and coking are accounted for, the power density of coke production will be at least 1,000 W/m^2 (compared to 0.012 W/m^2 for charcoal). Global output of coke thus occupied less than 10,000 km^2 of land, a difference of four orders of magnitude. This is certainly one of the best examples illustrating the consequences of using energies produced with low power density in modern

high-energy civilization. Moreover, besides obvious cost advantages, coke has an added structural superiority as it can support much heavier charges of ore and limestone than the friable and easily crushable charcoal, making larger and cheaper blast furnaces possible.

Maximum power of prime movers

Maximum power of individual prime movers matters because it determines the maximum magnitude of many tasks. Mass deployment of smaller power units is often impractical or outright impossible: we would not use ten low-power steam locomotives to pull a heavy train; there is no way to harness one hundred horses to pull in a single direction under a driver's command (the maximum in California's grain fields of the 1890s was more than thirty draft animals harnessed to the earliest combines) and passenger aircrafts with a range of just 200 km cannot be used in a staggered manner to accomplish transoceanic flights.

The post-1750 increase in the maximum power of prime movers controlled by a single person during the performance of quotidian tasks has been enormous. The greatest exercise of concentrated power performed daily by millions of people in 1750 was leading draft animals as they plowed or harrowed crop fields or pulled wagons and coaches on roads. A peasant walking behind his weak ox harrowing a field commanded less than 200 W of draft power (or less than a third of mechanical horsepower of 745.6 watts). During the last decades of the nineteenth century, many farmers plowing the Great Plains wheat fields guided six powerful horses (at least 4 kW), and with the first grain combines pulled by thirty-two animals more than 20 kW of draft power was under a single command at the beginning of the twentieth century.

Another hundred years later and many Great Plains farmers drive 300-horsepower (224 kW) tractors sitting in air-conditioned cabins, while anybody with a driver's licence can be behind the wheel of an even more powerful SUV (the most powerful one on the market in 2011, the BMW X6, rated 407 hp or 303 kW). This means that since 1750 the maximum power of prime movers commonly controlled by millions of individuals in the course of their daily life rose 1,000-fold (three orders of magnitude), from about 200 W to more than 200 kW.

Gains in prime movers commonly used for public transport on land have been even more stunning. In 1750 a driver of a fast four-horse coach held reins of about 2,600 W (2.6 kW). By 1850 an engineer of a steam locomotive

Table 6.1 Maximum power of prime movers in field work

Date and prime mover	W
1750 Chinese peasant hoeing a cabbage field	50
1750 Italian peasant harrowing with an old, weak ox	200
1800 English farmer plowing with two small horses	1,000
1870 North Dakota farmer plowing with six powerful horses	4,000
1900 California farmer using thirty-two horses to pull a combine	22,000
1950 French farmer harvesting with a small tractor	50,000
2000 Manitoba farmer plowing with a large diesel tractor	224,000

Table 6.2 Maximum power of prime movers in land transportation

Date and prime mover	W
1750 French coach-and-four	2,500
1850 English steam locomotive	200,000
1900 The fastest American steam locomotive	1,000,000
1950 Powerful German diesel locomotive	2,000,000
2000 Electric motors of Japan's Shinkansen (high-velocity "Bullet" train)	13,000,000

controlled more than 200 kW; by 1900 his grandson in control of a transcontinental train traveling 100 km/h had at his disposal about one megawatt (MW) of steam power. Manually stoked locomotives could do about 120 km/h, while trains in Japan (Shinkansen) or France (trains à grande vitesse) have at their command electric motors with power rating approaching or even exceeding 10 MW. And another order of magnitude has to be added for air travel: pilots of the Boeing 747 (first flown commercially in 1969) or Airbus 380 (in commercial service since 2007) cruising 11 km above sea level have computerized control of more than 100 MW developed by four gas turbines mounted under the planes' wings.

Above are two comparative ladders of maximum power ratings (all numbers are in watts) for 250 years between 1750 and the year 2000, the first one (Table 6.1) for those prime movers that are commonly used in field work (starting with a value for sustained human labor; peak exertions lasting a few minutes can be an order of magnitude higher), the second one (Table 6.2) for prime movers used in land transportation of passengers (starting with a value for a horse-drawn carriage, the best means of overland travel before the emergence of mechanical prime movers).

Efficiency of energy conversions

In this respect historians have not been nearly as guilty as the modern media, whose idea of dealing with technical advances is to personalize them by focusing on the lives of great inventors (preferably those of a heroic, or at least highly charismatic, cast such as Edison or Tesla) or innovators (Gates, Jobs) and to ignore the process of diffusing those inventions, turning them into acceptable commercial choices, and, most of all, relentlessly improving their often initially poor performance. Without the latter advances most modern energy conversions would play surprisingly marginal roles because they would be too expensive or too inconvenient to use.

If intercontinental flights were still powered by the first generation of commercial gas turbines introduced before 1958 they would consume 50 percent more kerosene. And if the owners of a new house built in California who installed, as is now common, more than fifty lights were to pay their electric bill in pre-1910 electricity prices, this would be at least forty times higher than today, due to the low efficiency of the thermal power plants that provided electric power a century ago. Actually, there is no better example to illustrate the long-term conversion efficiency gains than lighting, as no other common use of energy has seen such gains since 1750. Only a few technical improvements have had such a profound effect on human affairs as extending the day at will (and thus reading, writing, travel, and work in factories), banishing the night and making stairways, houses, and cities safer.

In 1750 candles remained the most convenient source of relatively clean but expensive indoor light. They came in a variety of sizes, qualities, and costs and their production eventually became a major manufacturing endeavor – but their wax-to-light efficiency remained dismal: in 1750 an inexpensive (and smelly) tallow candle converted just 0.01 percent of chemical energy in that animal lipid to light. Banishing the darkness thus remained nearly as inefficient during the time of the first encyclopaedists as it was more than one-and-a-half millennia before their time, when Marcus Aurelius wrote down his meditations among the Quadi on the Granua. The first improvement came with lights that used flammable gas made from coal, commercially produced since 1812, which multiplied those dismal efficiencies, with early lamps reaching about 0.04 per cent. In 1881, Edison's earliest carbon filaments converted only 0.15 percent of electricity to light.

By 1900 efficiencies of incandescent lights reached 0.5 percent with metal filaments and by 1950 lights with coiled tungsten filaments were closing on

Table 6.3 Efficiency of lights for indoor illumination

Date and type of light	Percent
1800 tallow candle	0.01
1850 coal gas light	0.04
1900 incandescent light bulb	0.50
1950 fluorescent light	10.00
2000 metal halide light	16.00

2 percent efficiency. But by that time the fluorescent lights, commercially available since the 1930s, were on the top, with efficiencies as high as 12 percent. This performance was eventually surpassed by low-pressure sodium lights that convert close to 30 percent of electricity to visible radiation (they have been used almost exclusively for outdoor city illumination and they impart characteristic yellowish hue to cityscapes at night) while the best indoor options (linear fluorescents and screw-in metal halide light bulbs) convert electricity to visible radiation with more than 15 percent efficiency (Table 6.3).

Even a small new American house will now have at least thirty lights (or no less than 2.4 kW of installed power) that can be turned on and off by a simple flip or push of a switch. Assuming a mixture of incandescent and fluorescent lights, the overall luminous efficiency will be close to 10 percent and providing the same amount of light (but, obviously, not with the same flexibility and convenience) would require about 10,000 standard paraffin candles. Logistics (and fire hazards) of lighting and extinguishing them aside, it would also be a very costly operation. As for the cost, William Nordhaus calculated that by the end of the twentieth century the true price (in constant monies) of illumination (the cost of the service rather than of the good, in this case a source of light) was four orders of magnitude lower (the actual ratio was about 0.0003) than it was in 1800. Similarly, Roger Fouquet's detailed calculation for the United Kingdom showed that, again in constant monies, light was roughly 6,000 times more expensive in 1750 than it was in 2000.

Perhaps the second most impressive illustration of improved conversion efficiencies is the performance of prime movers powered by combustion of fossil fuels. The first commercial models of such a machine, Thomas Newcomen's atmospheric steam engine, were extraordinarily inefficient, converting no more than half a percent of charged coal into reciprocating motion, and hence suited only for installation at coal mines where there was

Table 6.4 Top efficiency of internal combustion engines

Date and type of engine	Percent
1750 Smeaton's (improved Newcomen) steam engine	1.4
1800 Watt's improved steam engine	4.0
1850 Best high-pressure locomotive steam engine	6.0
1900 American triple-expansion steam engine	15.0
1950 Best low-speed marine diesel	45.0
2000 Large German diesel engine	51.0

no need for transporting the fuel. In 1750, John Smeaton managed to raise the efficiency above 1 percent and James Watt's subsequent famous improvements (patent of 1769) were only relatively impressive because the absolute efficiency of his machines remained pitiful, no better than 4 percent during the 1780s. But the gain was sufficient to site them more flexibly away from mines, particularly where the fuel could be brought by vessels. Only high-pressure steam engines did considerably better, surpassing 10 percent by 1850, and by the century's end the most efficient triple-expansion designs converted more than 15 percent of coal's thermal energy into useful mechanical energy.

That was a performance superior to new internal combustion engines, but those lighter and much more flexible machines were improved rapidly, particularly as Rudolf Diesel's inherently efficient high-compression engines began to conquer first shipping and then heavy land transport. In 1897 the final prototype of Diesel's new engine had thermal efficiency of almost 35 percent; before the Second World War the best machines surpassed 40 percent and by the year 2000 the massive diesels powering the world's largest container ships and oil tankers were the world's most efficient engines, converting just over 50 percent of energy in heavy fuel oil into propulsion (Table 6.4).

Their closest competitors in terms of efficiency are large gas turbines (jet engines) that have been powering modern long-distance commercial aviation since the late 1950s: in 1940 the first British and German prototypes converted less than 10 percent of kerosene into useful thrust. By the mid-1960s the first generation of jetliners had engines operating with 25 percent efficiency, and by the century's end gas turbines had thermal efficiencies of about 40 percent. These gains have made mass-scale air travel affordable: in 1950, at the beginning of the last decade of air travel powered by reciprocating

engines, the world's airlines logged 30 billion passenger-kilometers; in 2000 the total reached 2.8 trillion.

Per capita consumption of useful energy

Supply of phytomass fuels and mechanical power (human and animal muscles, waterwheels and windmills – relatively common in some regions, rare or absent in others) remained low and stagnating for millennia. My reconstruction of fuel supply in Rome during the first two centuries of the Common Era came up with at least 10 GJ and possibly 15 GJ/capita. Estimates for average annual wood consumption in London of 1300 put this at 1.5 t or just over 20 GJ/capita, which means that the national average had to be below 20 GJ, not that different from the Roman energy consumption. Peasants on the deforested North China Plain burned annually no more than 10 to 15 GJ/capita of straw, roots, leaves, and grasses even during the early decades of the twentieth century.

Extraction of fossil fuels had multiplied the average supply, often in just one or two generations. Historical comparisons of energy use per capita rates are calculated after converting different fuels and other forms of primary energy (hydro, nuclear, geothermal, wind, and solar electricity) into a common energy denominator. The joule should be the preferred choice, but international statistics used to convert to a tonne of coal equivalent (tce, equal to 29 GJ, because it took the highest quality coal as the standard); but since the 1980s all of the most often cited sources (United Nations, OECD, the annual survey of world energy by British Petroleum) use a tonne of oil equivalent (toe, equal to 42 GJ or 1.45 tce).

British data show the average per capita use of primary energy rising from about 30 GJ in 1750 to just over 150 GJ in the year 2000, a relatively small (five-fold) multiple because the country already had a fairly high per capita use by 1750; the French use, reliably traceable since 1850, went from 20 GJ to 180 GJ in 2000, a nine-fold increase in 150 years. The multiple for Japan, a latecomer to modernization (begun only after the Meiji Restoration of 1868) was nearly eighteen-fold during the twentieth century (from about 10 GJ to just over 170 GJ/capita), and China's belated modernization was energized by going from just 1.5 GJ/capita (fossil fuels and hydroelectricity, excluding phytomass fuels) in 1950 to 35 GJ in 2000, a twenty-three-fold gain in just five decades (Table 6.5).

Impressive as these multiples may be, they obscure the real gains in the consumption of modern energy: because of the just-reviewed gains in typical

Table 6.5 Average annual consumption of primary energy (rounded to the nearest 5 GJ/capita and including all phytomass and fossil fuels and primary electricity)

	1750	1800	1850	1900	1950	2000
China	10	10	10	<15	<20	40
UK	30	60	80	115	100	150
France	<20	20	25	55	65	180
Japan	10	10	10	10	25	170
USA	<80	<100	105	135	245	345
World	<20	20	25	35	40	65

efficiencies of all common energy conversions, modern increases in per capita consumption of useful energy (that is, energy services including heat, light, and motion) have been far higher. Average US phytomass energy use in 1850 was very high, about 100 GJ/capita, compared to about 350 GJ/capita for all fossil and biomass fuels in the year 2000. But with typical mid-nineteenth-century combustion efficiencies at only about 10 percent, the useful energy in 1850 was just 10 GJ/capita while the overall energy conversion efficiency in the US economy reached 40 percent by the year 2000, delivering roughly 150 GJ/year of useful energy services, a rate nearly fifteen-fold higher than in 1850.

Fouquet's British data disaggregate the useful gains: for all industrial power (in 1750 it was delivered by human and animal labor, waterwheels, windmills, and a few steam engines; in 2000 it was mostly produced by electric motors and internal combustion engines) the multiple was thirteen-fold in 250 years; for heating (in 1750 a mixture of wood, charcoal, and coal; by 2000 mostly natural gas) it was fourteen-fold; for all passenger transport (in 1750 horses, carts, coaches, barges, ships; in 2000 cars, buses, trains, ships, and airplanes) it was nearly 900-fold; and lighting gains take the top place, as the trajectory from candles and oil lamps in 1750 to an assortment of electric lights in the year 2000 ended up with about 11,000 times more light per capita.

For China my best estimates are an increase from no more than 0.3 GJ/capita of useful energies in 1950 to about 15 GJ in 2000, a fifty-fold increase in just two generations. These multiples are the proper metric that reveals the achievements of modern civilization; they are behind large gains in productive capacity, they created comfortable interiors, they brought previously unimaginable mobility (of materials, goods, and people) and they generated so much light that the night-time satellite images show most of Western

Europe, eastern North America, and Japan as nothing but large continuous patches of brilliance.

Maximum energies of weapons

Winning armed conflicts has not always required superior weapons: superior planning could decide the outcome even before a conflict began; nimble combat tactics could reverse an apparent rout into a sudden victory; well-timed betrayal could open the gates of fortified cities; coastal blockade could weaken and demoralize entire populations; epidemic disease and inclement weather could stop marching armies, and uncooperative winds could divert attacking fleets of sailing ships. But in most conflicts weapons made the difference. The damage they inflict is due to a sudden release of kinetic or thermal energy or their combined impact, and discharge of these energies is determined by the maximum capability of the prime movers that set them into action. When seen from this vantage point, all armed conflicts can be classified into four distinct periods: those powered by animate prime movers; those dominated by low-energy explosives; those relying on high-energy explosives; and those that deploy nuclear weapons.

All warfare from prehistory until the late Middle Ages used weapons powered solely by animate prime movers, overwhelmingly by human muscles. In close combat warriors used cutting (axes, swords) or piercing (daggers, lances) weapons, while injuring and killing from a distance relied on the piercing powers of spears and arrows launched by using bows or more powerful crossbows. The invention of gunpowder, with the explosive mixture first solidly documented before the end of the twelfth century in China, and its use reaching Europe just before the end of the thirteenth century, introduced a new powerful prime mover.

Although it is now classed as a low-velocity explosive, gunpowder's detonation speed was (depending on the composition of the powder, always dominated by KNO_3, usually about 75 percent of the mass, and always containing charcoal, but not always with added sulfur) at least 400 and up to 1,300 metres per second (m/s) while sword cuts had usual velocities less than 50 m/s. Gunpowder-propelled projectiles from field cannons and soon afterwards from ship guns raised the destructive power of weapons by an order of magnitude for personal weapons (1,000 J or 1 kJ for the best muskets), and by three orders of magnitude when launching projectiles from field or ship guns: in medieval cannons it imparted 50 kJ to

stone balls, in eighteenth-century cannons it gave iron balls kinetic energy of 300 kJ.

The destructive energy of weapons was greatly raised by the introduction of new, high-energy explosives (made by the nitration of cellulose, glycerine, phenol, and toluene) and by using those explosives to fill gun cartridges, and later bombs and rockets, that detonated on impact, with their explosive energy far surpassing the impact of their kinetic energy. Detonation velocity of new high-energy explosives kept on rising, from about 5,000 m/s for dynamite (Alfred Nobel patented his detonator in 1863) to 6,900 m/s for TNT (synthesized first in 1863) to 8,800 m/s for RDX (Royal Demolition eXplosive, made first by Georg Friedrich Henning in 1899), and to just over 10,000 m/s for ONC (octanitrocubane). Again, as with the escalation of destructive kinetic energy from arrows to cannon balls, there were destructive gains of explosive energies spanning orders of magnitude.

The first modern field gun, the French Canon 75 mm modèle 1897 (commonly known as "Le Soixante-Quinze") fired shells filled with nearly 700 g of picric acid whose explosive energy reached 2.6 MJ. Perhaps the best-known gun of the Second World War was the German anti-aircraft Flak (Flugzeugabwehrkanone) 18, whose variant was also used in Tiger tanks; it fired shrapnel shells whose explosive energy was 4 MJ. But the most powerful explosives of the Second World War were the massive bombs which were dropped on cities. The most powerful bomb carried by the Flying Fortress (Boeing B-17) had explosive energy of 3.8 GJ. And during the last month of the Second World War, the United States dropped two bombs, at Hiroshima on August 6, 1945 and at Nagasaki three days later, that introduced the fourth category of weapons powered by nuclear fission, and later (since 1952) also by fusion.

Yet again, the multiplication of destructive energies took place, this time in record time. The Hiroshima bomb released 63 trillion joules (TJ) of energy, and in 1961 the Soviets tested above Novaya Zemlya their most powerful fusion bomb (Tsar Bomba) that released 209 quadrillion joules (PJ) of energy. The two superpowers had eventually amassed roughly 5,000 strategic nuclear warheads with the aggregate destructive energy of about 20 exajoules (EJ, 10^{18}), a sum so incredibly large that that lunacy actually served us well, preventing a global thermonuclear war that, all too obviously, nobody could win. The truly staggering progression of maximum destructive energy of explosive weapons during the twentieth century is shown in Table 6.6.

Table 6.6 Maximum energy of explosive weapons, 1900–2000

Date and type of weapon	J
1900 Picrite-filled shell from French 75 mm modèle 1897 gun	2,600,000
1940 Amatol/TNT-filled shrapnel from German 88 mm Flak	4,000,000
1944 The largest bomb carried by Boeing B-17	3,800,000,000
1945 Hiroshima bomb	63,000,000,000,000
1961 Soviet Tsar Bomba tested in 1961	209,000,000,000,000,000

Energy in world history

These brief recapitulations of half a dozen key trends in the history of modern energy use make it clear why and how the combustion of fossil fuels and massive deployment of more efficient prime movers created a world in which material comforts, private consumption, mobility, and the overall quality of life are so fundamentally different from the pre-1750 era. Put another way, the epochal energy transition created what Nordhaus rightly called "tectonic shifts in output and consumption." But if many fundamental whys and hows of modern history cannot be properly understood without appreciating the quantities and qualities of modern energy uses, arraying those accomplishments alone is no substitute for more complex perspectives: energetic determinism, as any other kind of reductionist explanation, is bound to mislead.

Many examples could be cited in order to illustrate the limits of energy-based determinism. With its enormous fossil fuel, nuclear, and hydroenergy resources, the USSR was a true energy superpower but it squandered that enviable patrimony, mostly because of its chronic economic mismanagement and a terribly inefficient quest for global hegemony. In contrast, post-Second World War Japan was not prevented by its lack of energy resources from becoming a great economic power, and, moreover, one with perhaps the world's most efficient use of energy – but that was not enough to prevent the country's protracted post-1990 economic and social decline. Another revealing contrast illustrating the limits of energy-based explanations is to note that for many decades the US per capita energy use has been twice as high as in the richest countries of the European Union, yet most of America's quality-of-life indicators lag behind the European averages.

A third and final contrast, from yet another perspective, is the fact that the timeless intellectual accomplishments of the last quarter millennium – be they Mozart's absorbing operas, Melville's bold chronicling of a quest on

the high seas, Monet's colorful suburban scenes, or Michelson's ingenious measurement of the speed of light – had little to do with any specific consumption level or any particular qualities of energy usage that prevailed during the respective times of those achievements. Physically and thermo-dynamically, everything can be reduced to conversions of energy; but why and how we have deployed those energies has been always subject to human aspirations and fears. Considering both of these perspectives should bring a deeper understanding of history.

There is clearly an ambivalent link between energy and history. Energy sources and prime movers delimit the options of human history and deter-mine the tempo of life, and, everything else being equal, thermodynamics requires that higher socio-economic complexity must be supported by more intensive flows of energy. And yet neither the possession of abundant energy sources nor their high consumption guarantees a nation's security, economic comfort, or personal happiness. Access to energies and the modes of their use constrain the options for our action but do not explain the sources of our aspirations and reasons for our choices, and do not preordain success or failure of individual societies at a particular time in history.

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