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Exergy, power and work in the US economy, 1900–1998

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Abstract

Conventional economic growth theory assumes that technological progress is exogenous and that resource consumption is a consequence, not a cause, of growth. The reality is different and more complex. A 'growth engine' is a positive feedback loop involving declining costs of inputs and increasing demand for lower priced outputs, which then drives costs down further, thanks to economies of scale and learning effects. In a competitive environment prices follow. The most important 'growth engine' of the first industrial revolution was dependent on coal and steam power. The feedback operated through rapidly declining fossil fuel and mechanical power costs. The advent of electric power, in growing quantities and declining cost, has triggered the development of a whole range of new products and industries, including electric light, radio and television, moving pictures, and the whole modern information sector. The purpose of this paper is to reformulate the idea of the 'growth engine' in terms of the service provided by energy inputs, namely 'useful work', defined as the product of energy (exergy) inputs multiplied by a conversion efficiency. We attempt here to reconstruct the useful work performed in the US economy during the twentieth century. Some economic implications are indicated very briefly.

1. Background

One of us has argued elsewhere that energy consumption (and resource consumption generally) within the economy is as much a driver of growth as a consequence of growth [1–3]. The growth mechanism is a feedback process. Declining costs lead to declining prices which drive increased consumption. That, in turn, triggers investments in new capacity (resulting in increased economies of scale) or R&D aimed at cutting production costs. 'Learning by doing' also increases production

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efficiency. All three of these phenomena push costs down and complete the cycle. The 'growth engine' is illustrated schematically in Fig. 1.

While energy and other natural-resource-based products can be regarded as economic intermediates insofar as they are produced by industrial activity, this is no less true of capital. Adam Smith and others, including Marx, regarded labor as the sole source of economic value. (In fact, the skills and knowledge embodied in the labor force, too, are products as well as inputs). Of course, it can be argued that, while capital and labor stocks can be augmented in the future, current economic output is only dependent on the quantities of these factors that currently exist. But the same statement is also true of energy and physical resource flows. They are limited by past investment, both in supply and capacity for utilization. Neither can be increased instantaneously beyond fixed limits. To a naive observer, energy and material resources are not less 'factors of production' than labor or capital. Nothing can be produced without labor and capital. But equally, nothing can be produced (not even information) without some transformation of natural materials, expenditure of energy (exergy) and production of entropy.[1]

2. Energy and exergy

In ordinary language energy is 'what makes things go'. Energy to a physicist is different. It is a conserved quantity. The first law of thermodynamics says that the total energy in a hypothetical isolated system, including the universe itself, cannot change. Only its form can change. It is important to distinguish between energy that is *available* (to perform useful work) and energy that is not available. Available energy is also known as *available work*, which is confusing because

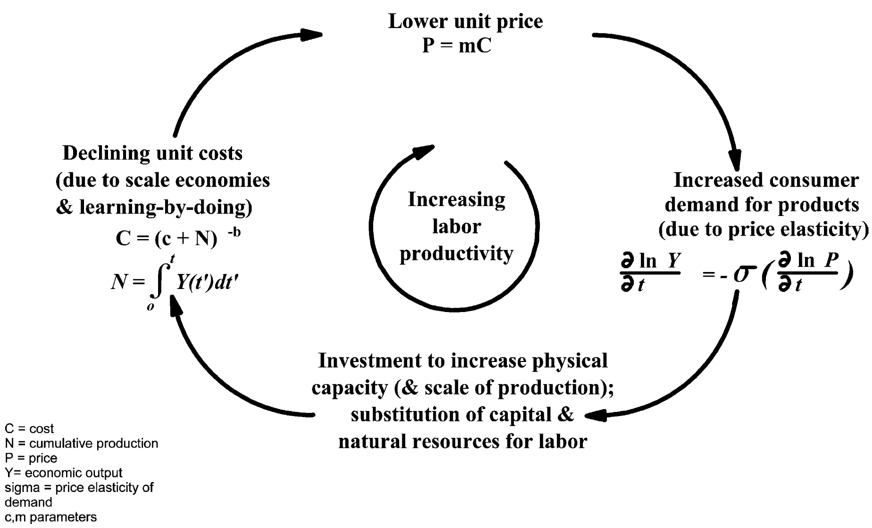

Fig. 1. Salter cycle growth engine.

[1] The same is also true of some environmental services, especially those services supporting agriculture — without which the rest of the modern economy could not exist.

available work and actual work performed are not the same. For example, heat energy at a very high temperature can do work. Heat energy at ambient temperature cannot.

Technically, exergy is defined as the maximum amount of work that can be done by a subsystem as it approaches thermodynamic equilibrium with its surroundings by a sequence of reversible processes. Equilibrium is a homogeneous unchanging state in which there are no gradients of any kind, including the time dimension. This implies uniformity of temperature, pressure, density, chemical composition as well as uniform gravitational and electro-magnetic fields. The equilibrium state is also one in which no part of the system can be distinguished from any other part of the system. Thus, the exergy of a subsystem is also a measure of its *distinguishability* from its surroundings, which is a measure of its 'distance' from equilibrium.

It is usual to define several kinds of exergy, including mechanical exergy, thermal exergy and chemical exergy [e.g., 4]. The first two are more familiarly known as kinetic energy and heat, respectively. They are of interest mainly in mechanical engineering (e.g., machine design). The third is of interest in chemical engineering and thermo-economics (for process optimization) but also in economics and environmental science. For our purposes in this paper only chemical exergy need be considered.

Evidently exergy is only defined with respect to some ultimate state to which the subsystem being investigated will finally merge or become indistinguishable. For chemical exergy this end-state is generally taken to be the surroundings or local environment of the subsystem. On earth, in practice there are three possible end-states: namely, the atmosphere, the ocean, or the top layer of the earth's crust. The exergy 'embodied' in any substance is, effectively, the work that can be extracted from it (in principle) as it merges with one of those three sinks, if all possible chemical reactions are allowed to occur. Of course, the exergy of atmospheric air, ocean water and average crustal rock are, by definition, zero.[2]

Fuel combustion is the spontaneous recombination of hydrocarbons or carbohydrates with atmospheric oxygen, resulting in their mutual chemical equilibrium state. For this reason, the heat of combustion (*enthalpy*) of a fuel is nearly equivalent to its exergy content. There is a slight technical difference related to the fact that some heat is lost in vaporizing water and some work is done 'on' the atmosphere by the dissipation of the combustion products. (See Appendix A, Table A-2.) In general, when people who are not readers of this journal speak of energy, they really mean enthalpy (of fuels), or, effectively, exergy. However, the oxides of most elements do not remain in the atmosphere permanently, so the pertinent equilibrium end-state is not the atmosphere, but either the oceans or the earth's crust. For non-fuels, chemical exergy is a measure of distinguishability from the surroundings. Thus, a high-grade ore has more embodied exergy than a low-grade ore, whence less exogenous exergy will be needed for further purification. Thus, exergy embodied in a raw material, such as an agricultural product or a metal ore, is a more realistic measure of magnitude than mass, for instance [5].

[2] The situation is complicated by the fact that the three end-states (sinks) are in long-term stable states but not in true thermodynamic equilibrium with each other, any more than the earth itself is in thermodynamic equilibrium with the universe. This is because biological activity on the earth's surface over billions of years, driven by a flow of exergy from the sun, has broken the chemical bonds between carbon and oxygen in carbon dioxide, and between hydrogen and oxygen in water. Large amounts of carbon have been sequestered in the form of hydrocarbons and carbonates, leaving free oxygen in the atmosphere. This disequilibrium situation is maintained by the continuing solar flux and the biosphere.

The various exergy inputs are tabulated in Appendix A and plotted for the US economy since 1900 in Fig. 2. Fig. 3 shows the ratio of exergy inputs to GDP over the same period.

3. Work

The term '*useful work*' was introduced above without definition. In physics texts energy is sometimes defined as the ability to do work, but that is not very helpful. Work is usually defined as a force operating over a distance, which is scarcely better if force is undefined. The best explanation may be historical. Work was originally conceptualized in the eighteenth century in terms of a horse pulling a plow or a pump raising water against the force of gravity.[3] Since the discovery of the pendulum it has been realized that raising a bucket of water or going up a hill

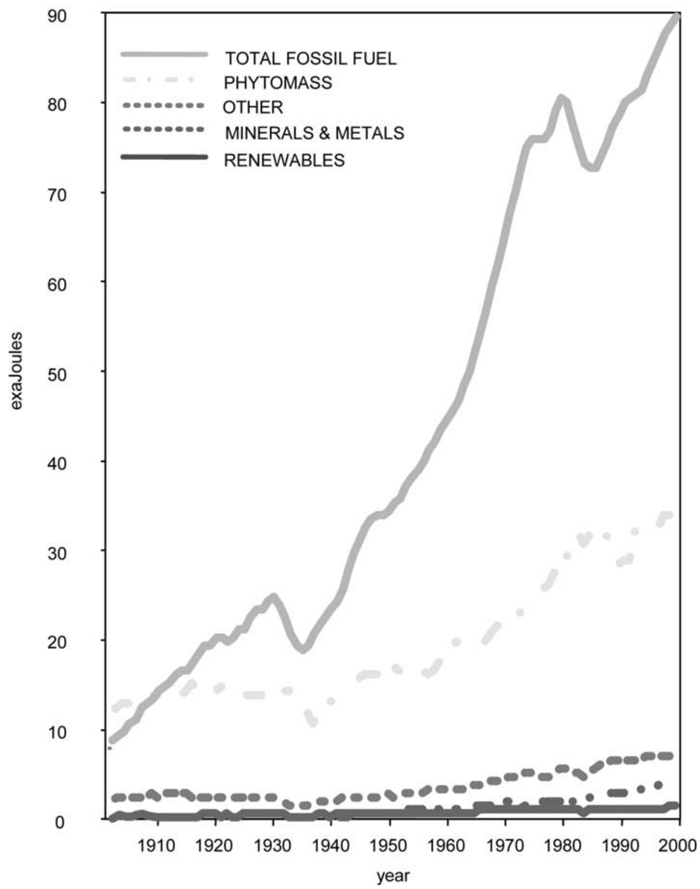

Fig. 2. Breakdown of exergy input to the US economy; 1900–1998.

[3] The first steam engines were used for pumping water from mines, an application where horses had previously been used. This enabled a direct comparison to be made. Ever since then power has been measured in terms of horsepower or a metric equivalent.

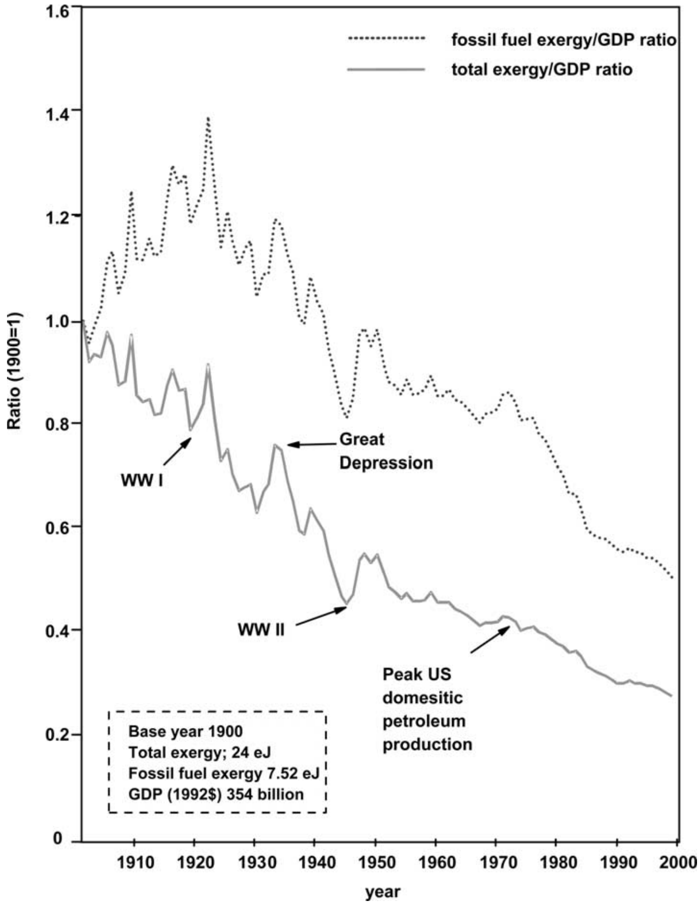

Fig. 3. Ratio of exergy inputs to GDP, USA 1900–1998.

converts kinetic energy into potential energy (of gravitation) and that gravitational potential can be converted back into kinetic energy by reversing the process. In the absence of frictional losses the two forms of energy are equivalent. (Frictional heat becomes unavailable, of course.) Work is also performed when a force acting on a mass increases its velocity and hence its kinetic energy, which is essentially mechanical exergy.

Subsequently, it was realized that a piston compressing a gas does work by increasing the pressure of the gas, just as a gas expanding against a piston can do work by turning a wheel. Adding heat to a compressible fluid in a fixed volume (increasing its temperature) increases its pressure. This fact makes it possible to convert heat into work. The theory of heat engines, beginning with the work of Sadi Carnot (1816) and subsequently extended to other engines (Rankine, Stirling, etc.) is all about converting 'thermal energy' in the form of heat into 'kinetic energy' — i.e., doing work.

Later still it was realized by Michael Faraday and Joseph Henry that electric and magnetic fields also constitute forms of potential energy analogous to the gravitational field, and that kinetic energy and electromagnetic field energy are inter-convertible through the phenomenon of magnetic

induction. It follows that changes in electro-magnetic potential — known as voltage — can also generate a force and do work. Similarly, kinetic energy of motion — as when a conductor moves through a magnetic field — can generate a voltage and a current. Normally there are frictional losses in both processes (known as electrical resistance), but in their absence the two forms of energy (kinetic and electromagnetic potential) are essentially equivalent.

Finally, in the late nineteenth century the notion of potential energy was generalized by J. Willard Gibbs to chemicals.[4] Combustion is a process that converts chemical energy — strictly, chemical potential energy — into kinetic energy (motion) and electromagnetic radiation at the molecular level. This heat energy can, in turn, perform physical work by means of a heat engine as mentioned above. But there are also chemical processes that generate electrical potentials directly without producing (much) heat, as in storage batteries. Similarly, there are chemical and electrochemical processes that convert heat, chemical potential and/or electromagnetic potentials into chemical potential, albeit with some entropic losses. Obvious examples are carbothermic reduction (smelting), e.g., of iron or electrolytic reduction, e.g., of aluminum. Such processes can also be considered as examples of doing (chemical) work.

Summarizing the above, one can say that whatever increases the kinetic or potential energy of a subsystem (within a larger system in which energy is always conserved, by definition) can be called ‘work’. Electricity can be regarded as ‘pure’ work, and is so regarded hereafter, since it can perform either mechanical or chemical work with very high efficiency, i.e., with very small frictional losses. Of course, electricity is a commodity, produced by a well-defined sector and sold at a well-defined price in a market. Since electricity is not a material, it can also be regarded as a ‘utility’ service.

This is not true of other kinds of physical work done in (and by) the economic system. Motive power, for instance, is produced and consumed by animals (horses and mules) or machines within the agricultural, construction, and (mainly) transportation sectors, as well as by consumers (in their motorcars.) Similarly, heat is produced and consumed within virtually all sectors, as well as in households. We argue, hereafter, that non-electrical work can still be regarded as a ‘shadow’ service, even though it is not conventionally measured or priced. If this concept is too strange, it may be easier to think in terms of the ‘electrical equivalent’ of motive power, or heat. The electrical equivalent of motive power is already a reality in railroads, where diesel engines run electrical generators that provide power to electric motors that drive the wheels. The electricity in this case is not counted in the statistics, but it is real enough. The electrical equivalent of high-temperature industrial heat provided by fuel combustion and heat exchangers would be the amount of electricity required to produce that heat, at the point of use, via a resistive heater (such as an electric furnace). Needless to say, some heat is currently provided in just this way, both in industry and in residences.

For low-temperature heat, however, there is a conceptual problem, namely that resistive heating for low-temperature heat is less efficient than the use of (electric) heat pumps. For this reason, we have chosen not to use the term ‘electrical equivalent’ hereafter. Instead, we use the term ‘second law efficiency’ introduced by the well-known summer study sponsored by the American Physical Society [6].

[4] The notion of potential energy has been further extended (in the twentieth century) to include the binding energy of atomic nuclei.

Estimates of mechanical work output in billions of horsepower-hours (hph) in the US from all sources except humans, for the period 1850—1920, have been compiled as shown in Table 1 [7, Appendices, 8, p. 55, footnote]. Inanimate sources of work exceeded animal work for the first time in 1870.

Later in this paper we will define primary and secondary work. Primary work is done by the first stage of energy conversion (e.g., by means of a heat engine or hydraulic turbine). We also introduce the notion of 'quasi-work' done by driving an endothermic chemical process or moving heat energy from one place to another across some thermal barrier. (Metal smelting is an example of the first; home heating is an example of the second.) Secondary work is work done by electrical devices or machines. In all of these cases the physical units of work are the same as the units of energy or exergy

4. Power

In physical terms, power is defined as work performed per unit time. Before the industrial revolution there were only four sources of mechanical power of any economic significance. They were human labor, animal labor, water power (near flowing streams) and wind power. (The advent of steam power in the early-eighteenth century led to the first quantification of power in terms of equivalent 'horsepower' by James Watt.)

It is possible to estimate human and animal contributions to mechanical work crudely on the basis of food or feed intake times a biological conversion efficiency adjusted for the fraction of time spent doing physical (muscle) work. However, since human labor is treated independently in economic analysis — and since human muscle power is no longer an important component of human labor in the industrial world as compared to eye–hand coordination and brainwork — we neglect it hereafter. (The magnitudes would be trivial in any case.) However, work done by animals, especially on farms, was still important at the beginning of the twentieth century and remained significant until mid-century, when trucks and tractors displaced horses and mules (Fig.

Table 1
Estimates of mechanical work output, US 1850–1920 in billions of horsepower-hours

Year	From animals	From inanimate sources
1850	5.4	3.6
1860	7.6	5.9
1870	8.4	8.5
1880	11.1	16.0
1890	14.4	30.3
1900	16.9	57.6
1910	18.0	142.8
1920	15.2	268.1

Sources: [7 Appendices, 8, p. 55 footnote]

4). The effective conversion efficiency for work animals has been estimated as 5.4%. On average, 18.5 units of animal feed are needed to generate one unit of work [7, pp. 1113–1116, cited in [8] footnote 19, p. 55]. To confuse matters, however, more recent estimates by several authors converge on 4% efficiency or 25 units of feed per unit of work [9, Box 7.1 p. 321 and references cited therein]. We choose the latter figure, right or wrong. Luckily, higher precision is probably unnecessary for the quantitative estimates in the US case because the magnitude of animal work is relatively small compared to inanimate power sources.

However, only during the present century has the contribution from combustion and heat engines using fossil fuels outstripped the contribution from biomass (agriculture and forests), and then only for industrial countries. In many developing countries the agricultural and forest contributions to total work are still dominant.

Prior to the eighteenth century, essentially the only source of chemical work (needed mainly for iron and copper smelting, cement, quicklime and plaster-of-Paris production, ceramics and glass manufacturing) was heat from charcoal-fired furnaces. Coal had entirely replaced charcoal in England before 1800 because of prior deforestation. In the US, the substitution process took about a century longer. Other fossil fuels, especially natural gas, now play a significant role as an industrial fuel.

For purposes of empirical estimation, it is helpful to distinguish between two categories of fuel use. The first category is fuel used to generate heat *as such*, either for industry (process heat and chemical energy) or for space heat and other uses such as hot water for washing and cooking heat for residential and/or commercial users. The second category is fuel used to do mechanical work, which means fuel driving so-called ‘prime movers’, including all kinds of internal and external combustion engines, from steam turbines to jet engines. (Electric motors are not included in this category, because electricity is essentially equivalent to mechanical work, as already noted. Electric power is mostly generated by a prime mover of some other sort.) Historical statistics have never been compiled to distinguish between these two categories of fuel use, so the detailed

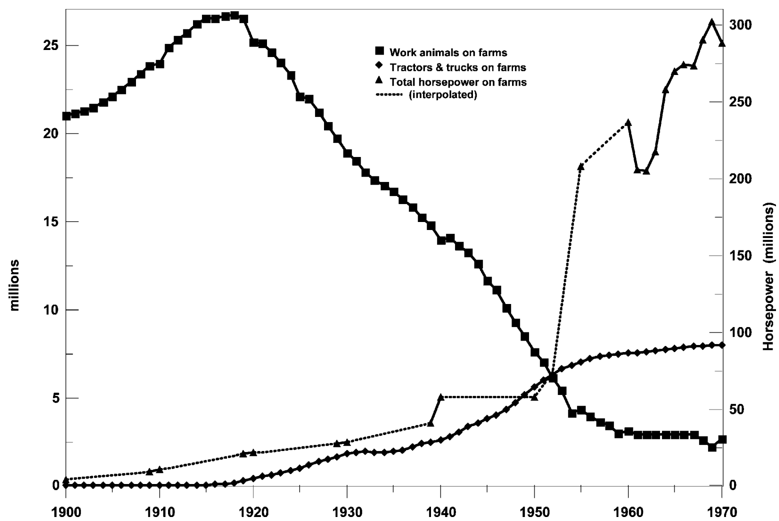

Fig. 4. Farm mechanization; substitution of machinery for animals.

statistics are provided in the Appendix to this paper. The results for the three major fossil fuels (coal, petroleum, and natural gas) are plotted in Figs. 5–7. (Fuelwood has never been used to a significant extent for driving prime movers, except in early nineteenth century railroads or Mississippi River steamboats, and there are no statistics.)

The first of these graphs (Fig. 5) shows the fraction of coal consumption fuel allocated to mechanical work since 1900. During the first half of the century steam locomotives for railroads were the major users, with stationary steam engines in mines and factories also significant contributors. These uses are not distinguished in published US statistics prior to 1917 [e.g., 10], and industrial uses for heat and work are not given anywhere, so we had to estimate them separately. That was done by assuming that fuel consumption for each category is proportional to total horsepower in that category of prime movers, for which data have been estimated separately [10, Table

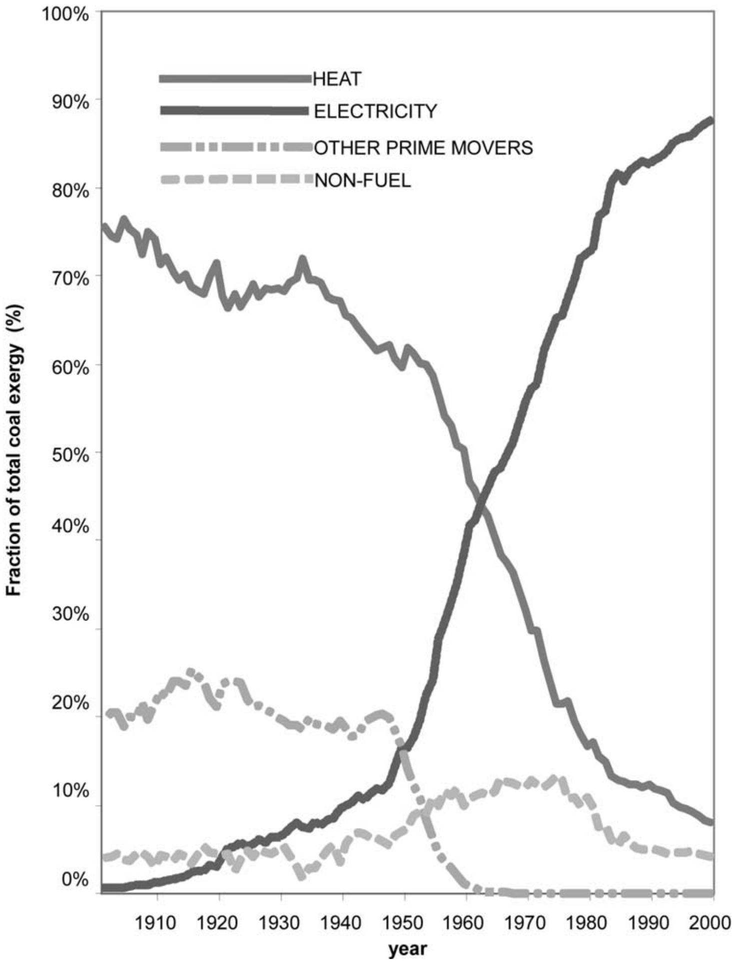

Fig. 5. Coal consumption; exergy allocation among types of work, USA 1900–1998.

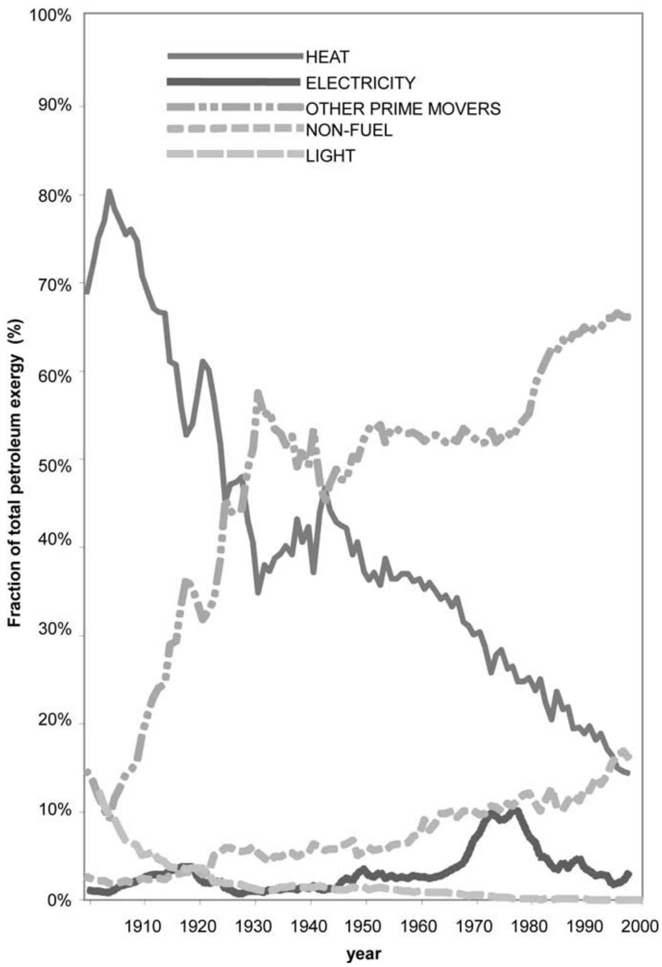

Fig. 6. Petroleum consumption; exergy allocation among types of work, USA 1900–1998.

S 1-14, p. 818]. Electric power generation gradually became by far the dominant use of coal, as it is today [10, Tables M-113,114, p.591 and S-100, p. 826][5] and [11,12].

Fig. 6, for petroleum, is based on published data for liquid fuels, by type. At the beginning of the century only natural gasoline — a very small fraction of the petroleum consisting of hydrocarbons with 6 to 12 or so carbon atoms — was used for motor vehicles. The heavier, less volatile fractions had little value except for 'illuminating oil' (kerosine) used for lamps in rural areas. The rapid increase in motor vehicle production and use created a correspondingly rapid growth in demand for gasoline, which led to a series of technological developments in 'cracking' heavier petroleum fractions. Thermal cracking was later supplanted by catalytic cracking, until today roughly half of the mass of petroleum is converted into gasoline, with other liquid fuels (diesel oil, jet fuel, residual oil) accounting for much of the rest. The basic sources of data are[10, M-

[5] Unfortunately, the two tables do not agree; the differences are small but not negligible.

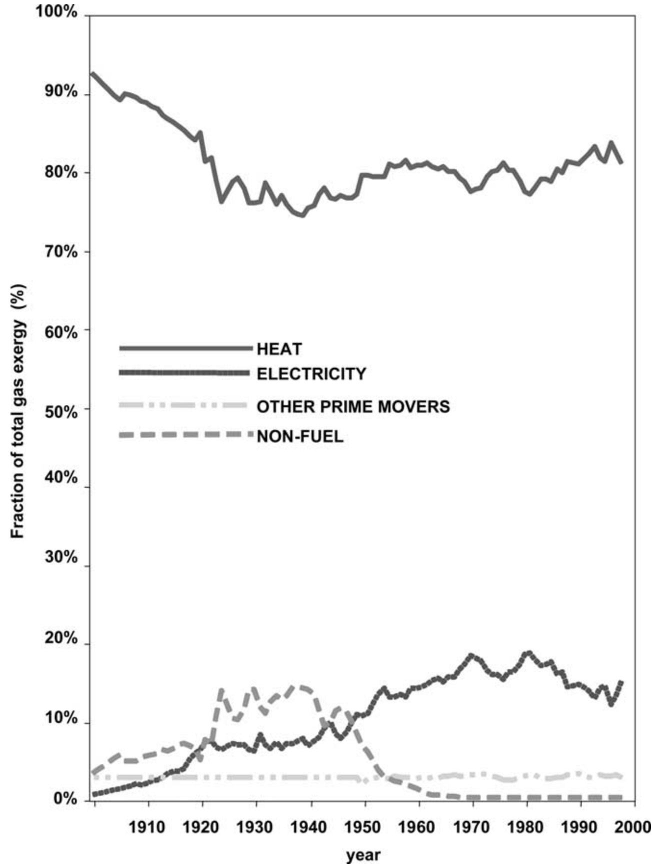

Fig. 7. Natural gas consumption; exergy allocation among types of work, USA 1900–1998.

162–177 p. 596, and *Annual Energy Review*, 1998]. Evidently the fraction of crude oil used to drive prime movers, rather than for heating, has been increasing for a long time.

Fig. 7, for natural gas, is comparable. It shows the fraction of all gas consumption that is used to drive compressors in the gas pipelines, plus the fraction used by electric utilities to generate electric power [13, Table 3]. The next step is to combine the three sources of mechanical work according to the contribution of each fuel to the national fossil energy supply. Finally, Fig. 8, combining the other three, shows the fraction of all fossil fuel exergy used to drive prime movers and perform mechanical work — either for purposes of generating electric power or mobile power. This fraction has been increasing more or less continuously since the beginning of the century, mostly because of the increasing fraction of fossil fuels that has been devoted to electric power generation. The other uses of fuel exergy are chemical or thermal: they include industrial heating (direct or via steam), space heating, water heating, and cooking. We classify these as 'quasi-work'.

5. Exergy conversion efficiency trends since 1900

Figs. 5–8, discussed above, reflect two different phenomena. One is structural change, most notably the substitution of machines for animals in transportation and agriculture, and for humans

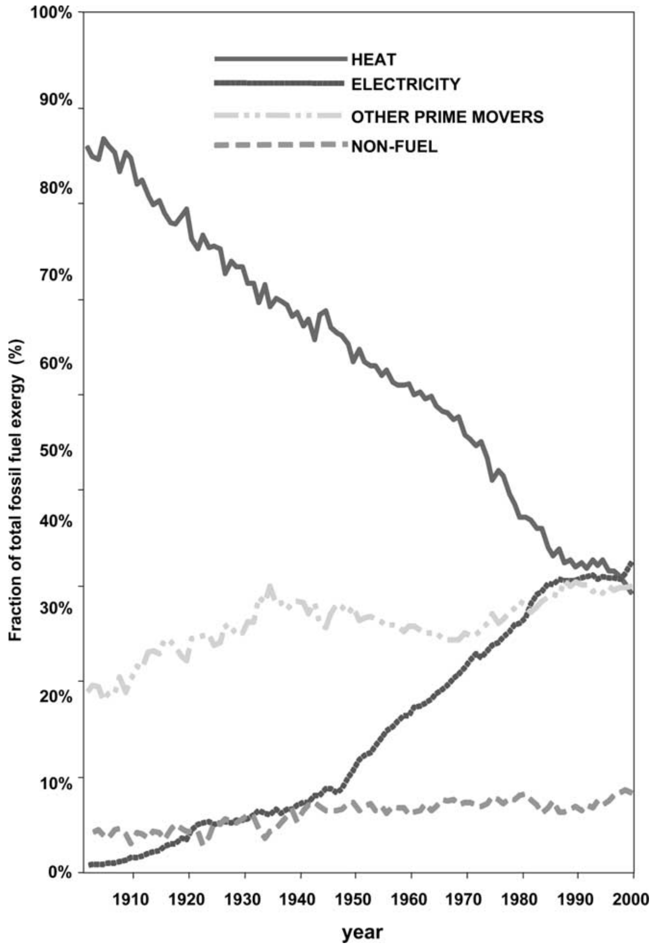

Fig. 8. Fossil fuel consumption; exergy allocation among types of work, USA 1900–1998.

in factories and workshops. The other is increasing efficiency of converting heat or other power sources into useful work. (Needless to say, efficiency changes led to cost reductions, which drove some of the structural changes mentioned.) It is worth noting that the dramatic increases in demand for fuels, for purposes of doing mechanical work have occurred despite — indeed, arguably because of — dramatic technological improvements in exergy conversion efficiency.

Steam turbine design improvements and scaling up to larger sizes accounted for most of the early improvements. The use of pulverized coal, beginning in 1920, accounted for major gains in the 1920s and 30s. Better designs and metallurgical advances permitting higher temperatures and pressures accounted for further improvements in the 1950s. Since 1960, however, efficiency improvements have been very slow, largely because existing turbine steel alloys are close to their maximum temperature limits. The conversion efficiency of steam–electric power plants has increased by nearly a factor of ten, from 3.6% in 1900 or so to nearly 34% on average (including distribution losses) and 48% for the most advanced units (Fig. 9; data from Federal Power Com-

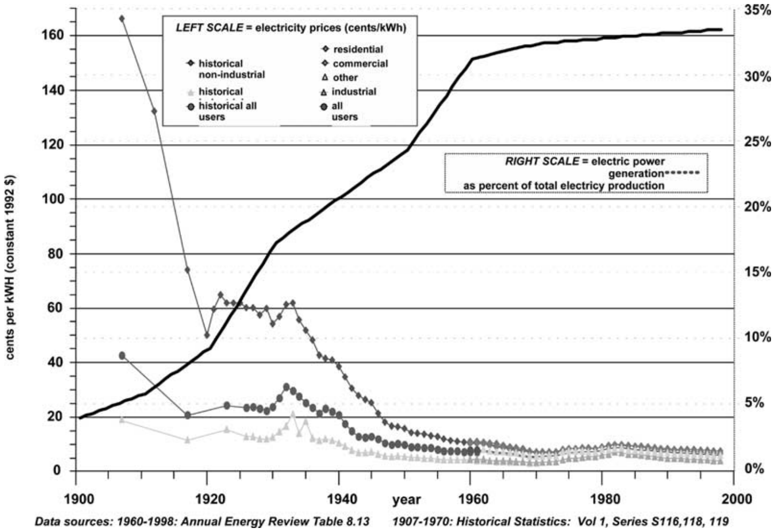

Fig. 9. Electricity; conversion efficiency and retail price in the USA 1900–1998.

mission, various years). As shown on the same diagram, prices, especially in the retail sector, decreased dramatically prior to 1950 and by a factor of two since then.[6]

On the other hand, the consumption of electricity in the US has increased since 1900 by a factor of 1200, and continued to increase rapidly even after 1960. This is a prime example of the so-called 'rebound effect'.[7]

The thermal efficiencies of internal and external combustion engines used for both stationary (factory) power at the beginning of the twentieth century and for mobile power since 1930 or so have followed a somewhat similar trajectory. The largest stationary steam piston engines — cross-

[6] The historical figures on electric power production and consumption must be interpreted with some care, because hydroelectric power is normally expressed for statistical purposes as thermal equivalents, i.e., the amount of coal or other fossil fuel required to generate that power at the time. However, falling water is converted to electric power in a hydraulic turbine at much higher efficiencies than early heat engines. Fourneyron turbines were capable of nearly 40% efficiency by 1850, and modern hydraulic Pelton wheel or reaction turbines achieved between 60% and 90% efficiency by 1950, depending on load factor. A conversion efficiency of at least 50% by 1900 can be assumed. This explains why a very high percentage of electric power generated in the US was hydroelectric in origin until the 1960s. Starting in 1902 the figures were 36.5%, falling gradually to 30.1% in 1925, and 31.3% in 1930, increasing again to 35.9% in 1935 and 33.1% (thanks to the TVA and Boulder (Hoover) Dam projects which came on stream in 1935–36). There was another gradual decline until 1941, but in 1942 hydroelectric power capacity took another leap up with the completion of the enormous Grand Coulee dam and generating plant, just in time for the wartime uranium isotopic separation projects. (The AEC consumed 3.1 billion kwh in 1945 and 3.8 bkwh in 1950, but this increased to 50.1 bkwh in 1955 and 60.66 bkwh a year later, the peak. AEC consumption fell to 38.7 bkwh in 1965, and 19.7 bkwh in 1970.). Hydroelectric power capacity has continued to increase since 1942, but much slower than total demand. It was still 26% of the total in 1950, down to 18.5% in 1955, and 10% by 1990. However, the efficiency of hydroelectric plants was much higher than the efficiency of steam–electric plants in the early years, and power-intensive industrial processes, such as chlor-alkali, aluminum and uranium isotope separation tended to cluster around hydroelectric power sources in remote areas such as Niagara Falls, the Tennessee River Valley, and the Columbia River valley. On the other hand, urban light and electric traction (tram) consumption requirements had to be generated by means of steam turbines near the consumers. (e.g., new York, Chicago) because long-distance transmission infrastructure was still relatively undeveloped.

[7] The 'rebound effect' has recently preoccupied energy conservation advocates. The point is that efficiency gains do not yield reductions in energy use if cost/price reductions result in demand increases that over-compensate for the efficiency gains. This phenomenon can undermine attempts to achieve conservation through higher efficiency. See [14–23].

compound ‘triple expansion’ engines — generated up to 5 MW at efficiencies above 20% [24, p. 145]. In the case of large stationary or marine steam engines operating under optimal conditions (at constant loads), the thermal efficiency exceeded 15% in the best cases. However, locomotive steam engines were not nearly so efficient — between 4% and 8% on average — and the *best* locomotive engine in 1900 achieved around 11%, increasing to perhaps 13% by 1910 (ibid.).

Factory engines were generally older and even less efficient and transmission losses in factories (where a central engine was connected to a number of machines by a series of leather belts) were enormous. For instance, if a stationary steam engine for a factory with machines operating off belt drives circa 1900 had a thermal efficiency of 6%, with 50% frictional losses, the net exergy efficiency was 3% [7], Appendices 25–3, 25–4 cited in [8] footnote 19, p. 55. The Dewhurst estimate, which took into account these transmission losses, set the average efficiency of conversion of coal energy into mechanical work at the point of use at 3% in 1900 (when most factories still used steam power) increasing to 4.4% in 1910 and 7% in 1920, when the substitution of electric motors for steam power in factories was approaching completion (Fig. 10)[25].The use of steam power in railroads was peaking during the same period.

The electric motor drive replaced stationary steam engines in factories during the period 1890–1940. As we have noted above, the stationary engines in factories operated at something like 6% thermal efficiency in 1900, on average, rising only slightly during the next twenty years. About half of the power was lost in the belt drive systems that were standard in factories, resulting in an overall efficiency of something like 3%, and seldom more than 5%. By contrast, a central generating plant together with its transmission and distribution system operated at nearly 10% by 1920 and reached 33% in the mid-60s. Electric motors were then capable of 80% (70–90%) efficiency in reconverting electric power to rotary motion, rising to 90% plus in recent times.[8]

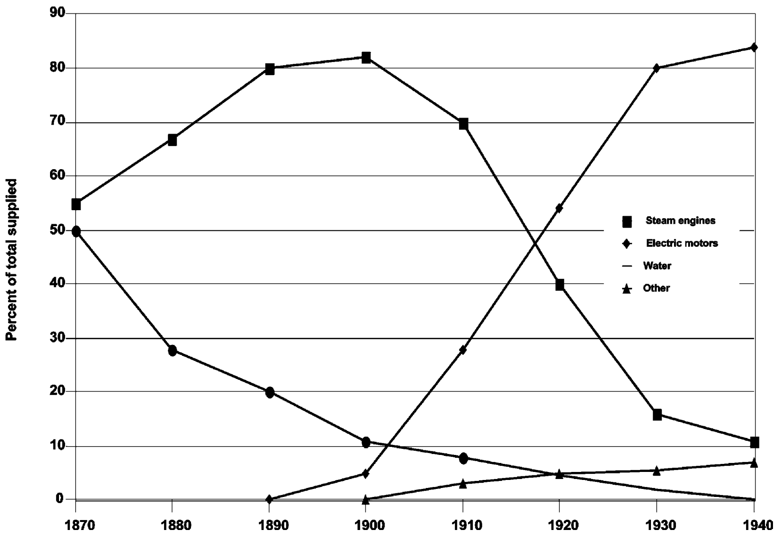

Fig. 10. Sources of mechanical drive in manufacturing establishments: USA 1869–1939. Source: [25].

[8] That motors can be 80% or 90% efficient does not mean that they are in practice. Studies of individual plants have discovered that efficiencies tend to be much lower, more like 60% and as low as 30% in extreme cases) [14].

So, the combined efficiency of the generator–motor combination was at least 8% by 1920; it reached 20% by mid-century and 30% by 1960. Hence, the overall efficiency gain in this case (from 1920 to 1960) was of the order of 5-fold — more than enough to explain the shift. By 1968 electric motor drives in industry accounted for 7.9% of US national energy consumption and consumed over 38% of all electric power generated; by 1979 the electric drive share had grown to 77% of industrial electricity, 35% of all electricity and about 9% of national energy total, declining slightly in recent years.

In the case of railroad steam locomotives, average thermal efficiency circa 1920 according to another estimate was about 10%, whereas a diesel electric locomotive half a century later (circa 1970) achieved 35% [26]. Internal friction and transmission losses and variable load penalty are apparently not reflected in either figure, but they would have been similar (in percentage terms) in the two cases. If these losses amounted to 30%, the two estimates (Dewhurst and Summers) are consistent for 1920. Coal-burning steam locomotives circa 1950 still only achieved 7.5% thermal efficiency; however, oil-burning steam engines at that time obtained 10% efficiency and coal-fired gas turbines got 17% [27, Tables 6, 7]. But the corresponding efficiency of diesel electric locomotives c. 1950 was 28%, taking internal losses into account [27, Tables 7,8]. The substitution of diesel–electric for steam locomotives began in the 1930s and accelerated in the 1950s (see Fig. 11).[9]

The work done by internal combustion engines in automobiles, trucks and buses (road transport) must be estimated in a different way. In the case of heavy diesel-powered trucks with a compression ratio in the range of 15–18, operating over long distances at highway speeds, the analysis is comparable to that for railways. The engine power can be optimized for this mode of operation and the parasitic losses for a heavy truck (lights, heating, engine cooling, air-conditioning, power-

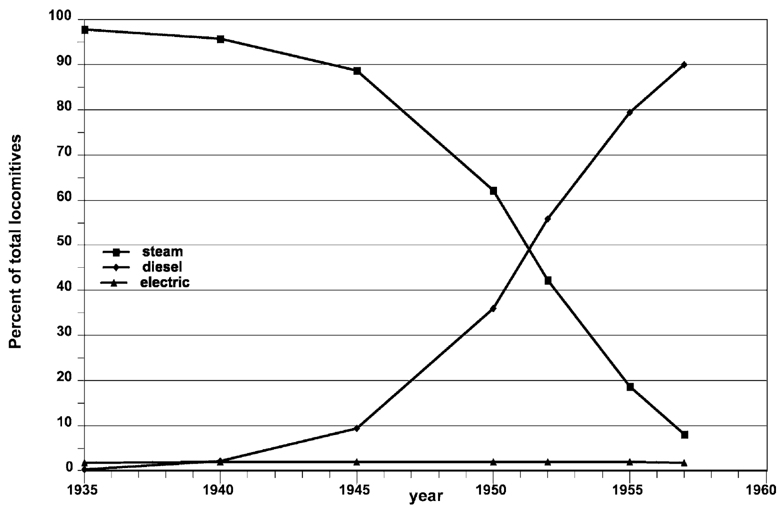

Fig. 11. Substitution of diesel for steam locomotives in the USA, 1935–1957.

[9] Diesel–electric trains in 1950 were 5.8 times as efficient as steam-powered trains in 1920, according to ICC statistics, cited in [8], p. 179. However, part of the improvement was due to systemic changes, especially the shift away from passenger traffic and toward long-haul freight.

assisted steering, etc.) are minor. Internal friction and drive-train losses and losses due to variable load operation can conceivably be as low as 20%, though 25% is probably more realistic.

For vehicles operating in urban traffic under variable load (stop–start) conditions, the analysis is quite different.[10] Gasoline-powered ICE engines nowadays (2001) have an average compression ratio between 8 and 8.5. This has been true since the early 1970s, although average US compression ratios had been higher in the 1960s, in the heyday of use of tetraethyl lead as an anti-knock additive [29] (see Fig. 12). The thermal efficiency of a ‘real’ fuel–air 4-cycle auto (or truck) engine operating at constant speed (2000 rpm) is around 30%. By contrast, with a compression ratio of 4:1 (typical of engines in 1920), the maximum thermal efficiency would have been about 22% (Fig. 13). Internal engine friction would reduce these by a factor of about 0.8, while the penalty for variable loads in stop–start urban driving introduces another factor of 0.75. With a manual transmission (European average) there is a multiplier of 0.95 to account for transmission losses, but for American cars with automatic transmissions the transmission loss is more like 10% for small cars, less for larger ones.[11] Other parasitic losses (lights, heating, air conditioning, etc.) must also be subtracted. These items can account for 4.5 bhp on average, and up to 10 bhp for the air-conditioning compressor alone, when it is operating.

The net result of this analysis suggests that for a typical ‘mid-size’ American car with automatic transmission the overall exergy efficiency with which the engine converts fuel energy into so-called brake horsepower at the rear wheels — where the tire meets the road — was as low as 8% in 1972 [6], and perhaps 10% for a comparable European or Japanese car of the same size

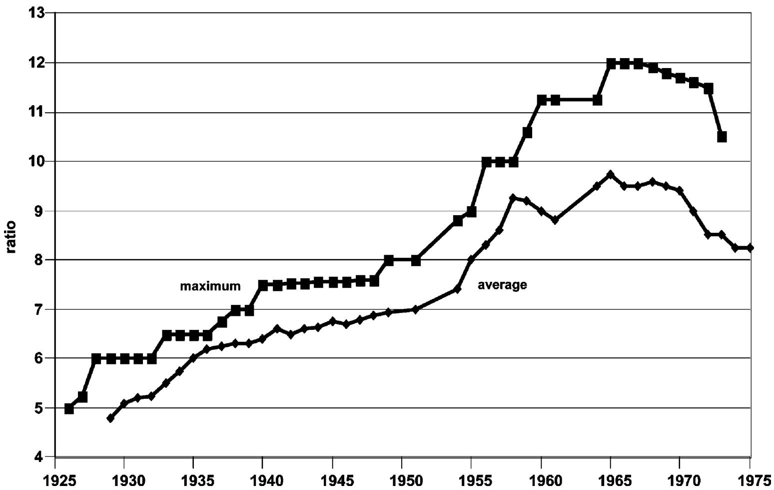

Fig. 12. Compression ratio in auto engines: USA 1926–1975.

[10] The following analysis is taken largely from a report from Ford Motor Co. [28] and an American Physical Society (APS) summer study held in 1975 [6].

[11] Turbochargers were not considered by the APS study because they were rare at the time. Their principal advantage is to increase passing power at high rpms, rather than to improve fuel economy per se. However, since a turbocharged 100 hp engine may have the same performance at high rpm as a non-turbocharged 150 hp engine, the net result could be a reduction in the size of engine needed to achieve a given performance level. This would improve low-speed fleet average fuel economy somewhat. Again, hp is the standard unit for automotive power in America, and (surprisingly) it is also used in Europe.

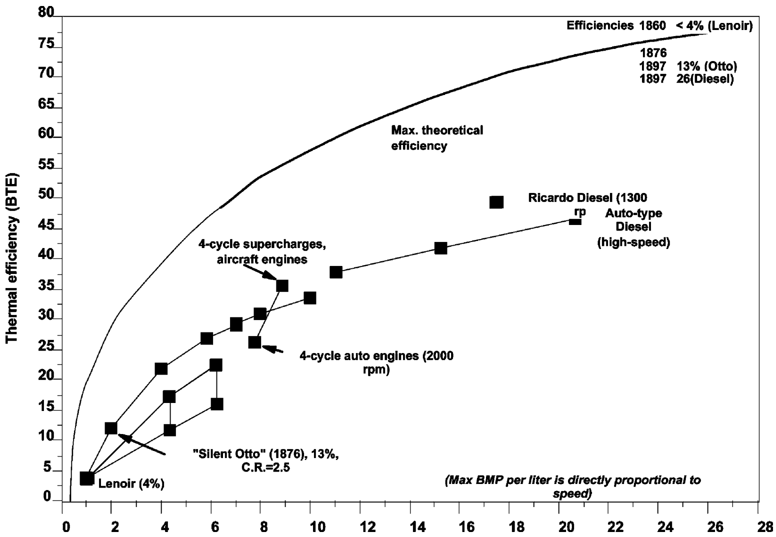

Fig. 13. Internal combustion engine efficiency.

with manual transmission. An earlier but similar analysis based on 1947 data arrived at an estimate of 6.2% efficiency for automobiles, based on gasoline input [27].[12] In 1989, the average thermodynamic efficiency of *all* motor transportation (including trucks, buses, railroads and aircraft) as calculated by the USEPA, was only 8.33%.[13]

Contrary to widespread assumptions, there has been little or no improvement in engine thermodynamic efficiency since the 1970s and not much prior to that after the mid-twenties. Overhead cams, four valves per cylinder, electronic control and fuel injection have been collectively responsible for perhaps 10% cumulative reduction in engine losses since 1972. Heavier vehicles (light trucks, vans and SUVs) exhibit lower fuel economy (10.3 mpg for 1972; 17 mpg in 1990). Heavy trucks exhibit still lower fuel economy, around 6 mpg. From 1970 to 1990 overall average motor vehicle fuel economy in the US increased from 12.0 mpg to 16.4 mpg; from 1990 to 1998 there has been a very slight further increase to 17.0 mpg [11].[14]

Thanks to regulations, known as the Corporate Average Fuel Economy (CAFE) standards, imposed in the aftermath of the 1973–74 Arab oil boycott, the US passenger vehicle fleet of 1990 achieved about 50% more vehicle miles per gallon of fuel (i.e., liters per hundred km dropped

[12] In 1972, US passenger vehicles averaged 13.5 miles per gallon [11], which — based on 8% thermodynamic efficiency — suggests that an idealized vehicle of the same size and weight capable of converting fuel exergy into work at 100% efficiency would have achieved a fuel rate of 165 mpg. (The European measure of fuel economy, liters per 100 km, is unfamiliar to Americans, and vice versa. However, the American unit is proportional to efficiency, whereas the European version is inversely proportional.)

[13] The Pollution Prevention Division of the USEPA prepared a graphical diskette document in 1990 entitled "United States Energy System" using 1989 data. It defined 'useful work' as energy (exergy) dissipated in the brakes of the vehicles (1.6 Q). Fuel input to highway transportation was 19 Q. This corresponds to just 8.3% efficiency. The rest of the input energy went to idling in traffic jams (3 Q), waste heat out of the tailpipe (9.5 Q), engine friction and parasitic accessories (2.4 Q), driveline friction (0.5 Q), and overcoming aerodynamic drag (1.6 Q).

[14] In terms of vehicle-miles per gallon, the average in 1920 was 13.5, declining slightly to 13.2 in 1930 (as cars became heavier) and increasing to a peak of 13.8 in 1940, probably due to a depression-era preference for smaller cars. From 1940 to 1970 the mpg declined steadily to 12.2 [26].

by one third) than in 1972. This was due partly to drive train efficiency gains but mainly to weight reductions, smaller engines, improved aerodynamics, and better tires. However, these improvements must be classified as secondary rather than primary efficiency gains.

A more detailed analysis of energy losses in automobile transportation (c. 1990) that reflects the impact of CAFE standards and distinguishes between urban driving (12.6%) and highway driving (20.2%) is summarized in Fig. 14. In that year passenger cars in the US averaged 20.2 mpg. Unfortunately, the distinction between urban (stop–start) and highway driving is not clear in the highway statistics. Assuming urban vehicle miles traveled accounted for something like 40% of the total (VMT), the average thermodynamic efficiency would have been between 15% and 16%.[15]

For aircraft up to 1945 most engines were piston-type spark ignition ICEs and fuel was high (100 plus) octane gasoline. Engine efficiencies were comparable to those achieved by high-compression engines (12:1) under constant load. This would be about 33% before corrections for internal losses (a factor of 0.8) and variable load penalty (a factor of 0.75), or roughly 20% overall. Gas turbines began replacing piston engines during the World War II, and more rapidly thereafter. The turbo takeover in the commercial aviation market began around 1955 and accelerated in the 1960s. Fuel consumption fell (i.e., efficiency increased) rapidly from the early turbojets of 1955, as shown in Table 2. These improvements can be categorized as thermodynamic. Of course, it takes a number of years before a new engine type penetrates the fleet, so fleet averages lag significantly (a decade or so) behind state-of-the-art.

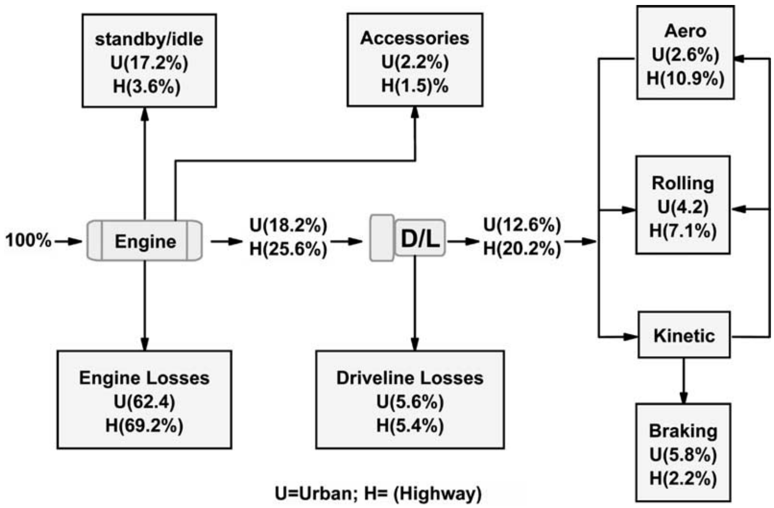

Fig. 14. Breakdown of energy requirements for a typical mid-size automobile (shown for US federal urban (highway) driving cycles as a percent of the energy content of the fuel).

[15] This implies that 100% conversion efficiency would correspond to only 125–135 mpg. This seems rather low, considering the fact that the most fuel-efficient cars on the market today (2002) achieve 60 mpg and proposals for radically new vehicles capable of up to 100 mpg or more are not at all fanciful, e.g., [30–35].

Table 2
Index of fuel consumption in turbojet aircraft (1955 = 100)

Year	Engine type	Index
1955	first generation turbojets (Comet)	100
1960	early turbofans	85
1970	second generation turbofans	70
1980	third generation turbofans	65
2000	advanced turbofans	55

Source: [24]

6. Direct heat and quasi-work

A declining, but still considerable fraction of the fuel inputs to the economy is still used for heat (Fig. 8). Process heat and space heat do not 'perform work' in the usual sense (except in heat engines). However, process improvements that exploit improvements in heat transfer and utilization may be classed as thermodynamic efficiency gains, no less than the use of turbochargers or recuperators in modern auto, truck or aircraft engines. It is possible in some cases to calculate the minimum theoretical exergy requirements for the process or end-use in question and compare with the actual consumption in current practice. The ratio of theoretical minimum to actual exergy consumption — for an endothermic process — is known as the 'second-law efficiency' [6]. The product of second-law efficiency times exergy input can be regarded as 'useful' heat delivered to a point-of-use, or'quasi-work'.

There are three different cases, viz. high temperature (say > 600 °C). High-temperature heat drives endothermic processes such as carbo-thermic metal smelting, casting and forging, cement manufacturing, lime calcination, brick manufacturing and glass-making, plus some use in endothermic chemical processes like ammonia synthesis and petroleum refining (e.g. cracking). The second case is intermediate-temperature heat, viz. 100–600 °C, but mostly less than 200 °C and mostly delivered to the point of use by steam. The third case is low-temperature heat at temperatures < 100 °C, primarily for hot water or space heat.

There is very little published data (that we know of) allocating industrial heat *requirements* (as opposed to consumption) among these cases by temperature. Based on a detailed survey covering 67 four-digit SIC groups and 170 processes, it appears that roughly half of all US industrial process heat in 1972 was required at temperatures greater than 600 °C and most of the rest was in the intermediate category [14, Fig. 4-1]. We assume hereafter that this allocation has been constant over time.

Intermediate- and low-temperature heat is required for many industrial purposes (usually delivered to the point of use via steam). Examples include increasing the solubility of solids in liquids, accelerating dehydration and evaporation (e.g., in distillation units), liquefaction of solids or viscous liquids for easier transportation or mixing, and acceleration of desired chemical reactions, many of which are temperature dependent. For purposes of back-casting to 1900, we have assumed that all coke and coke oven gas, as well as half of the natural gas allocated to industry (as opposed

to residential and commercial usage) were used for high-temperature processes. Most of the rest of the fuels used for industrial purposes are assumed to be for steam generation.

We consider high-temperature industrial heat first. The iron and steel industry is the obvious exemplar. In this case, the carbon efficiency of reduction from ore might appear to be a reasonable surrogate, since the reducing agent for iron ore is carbon monoxide. Thus, the C/Fe ratio is a true measure of efficiency, as regards the use of this resource. In 1900 the C/Fe ratio for the best available technology was about 1. By 1970 the best available technology for iron ore reduction had decreased this dramatically as shown in Fig. 15 [36]. However, for newer processes under development, this measure is less appropriate, and it overstates the improvements since only carbon in the form of coke is counted. Total energy consumption for iron smelting has declined at almost the same rate, however. In 1900 the average was about 55 MJ/kg; the Japanese average by 1900 was below 20 MJ/kg, and the best plant achieved around 15 or 16 MJ/kg [24].

From 1953 to 1974 total exergy consumption per ton of steel declined by 35% (adjusted for the 1973 ratio of pig iron to crude steel) while the carbon rate (coke to iron) declined even more, by 45%. During that period fuel oil replaced some of the coke, while electric power consumption (for electric arc furnaces, or EAFs) increased significantly [37]. In 1973 the average exergy consumption was 20.5 GJ per tonne of steel in the US (with 36% EAF in that year), as compared to 18.5 GJ/t in Japan (30% EAF) and 24.5 GJ/t in Canada [38]. The rate of improvement has certainly slowed since then, but final closure of the last open hearth furnaces and replacement of ingot casting by continuous casting has continued, as has the penetration of EAF scrap melting furnaces as a share of the whole.

A recent study of the steel sector provides a useful update [39]. A ‘reference’ integrated steel plant described in that study consumes a total of 22.6 GJ/tonne exergy inputs, of which 20.2 is coal and 1.87 is the exergy content of scrap.[16] Rolled steel output embodies 6.62 GJ/t, with other

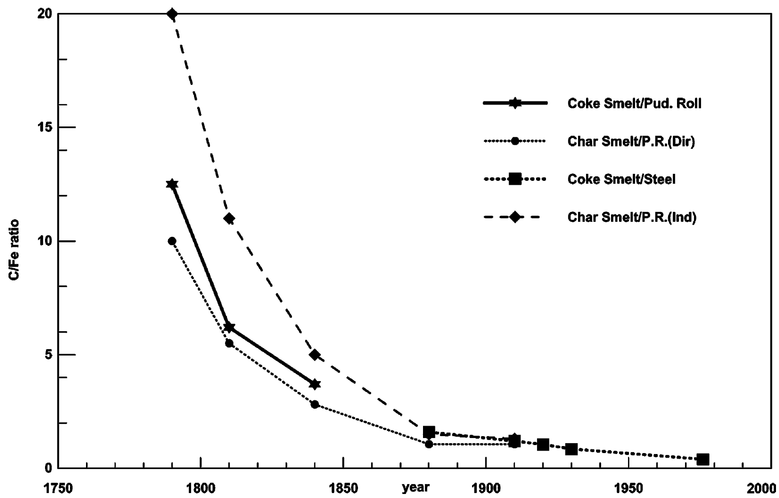

Fig. 15. Iron/steel production; carbon/iron ratio.

[16] A recent study for IISI (International Iron and Steel Institute) by Ecobilan [40] gives the average primary energy consumption as 24.98 GJ/kg for hot-rolled coil. The range was from 20.7 to 30.4.

useful by-products from gas to tar and slag accounting for a further 4.28 GJ/t. The remaining 11.62 GJ/t is lost exergy. The second law efficiency of such a plant would be very nearly 50%, counting salable by-products. Significant improvements are still possible, at least in terms of the primary product. The author expects future plants to achieve 12 GJ/t (with smaller by-product output, of course). EAF melting of scrap is much more exergy-efficient, current state-of-the art being around 7 GJ/t with near-term improvement potential to half of this, or 3.0 GJ/t.

Fairly detailed static (single year) exergy analyses have been carried out for a number of major energy-consuming industries, including iron and steel, aluminum, copper, chlor-alkali, pulp and paper, and petroleum refining. In second-law terms the calculated second law efficiencies based on 1970–72 data were as follows: iron and steel 22.6%, primary aluminum 13.3%,[17] cement production 10.1%, and petroleum refining 9.1% (e.g., [41–43]).

If the best available technologies c. 1973 had been used, the second law efficiencies would have been 35% for iron and steel, 12% for petroleum refining, 16.8% for aluminum, and 17% for cement [41]. Given a 20-year half-life for industrial plants [44,45], it is probably safe to assume that the higher figures in 1975 became 'average' by 1995 due to incremental improvements alone. In countries industrializing from scratch (e.g., South Korea), process efficiencies are likely to be higher. Some efficiency improvements have been made since the above-mentioned studies were carried out, primarily by improved 'housekeeping'. If the overall second law efficiency of the industrial sector's use of high-temperature process heat was 20% in 1980 — a fair assumption — it is unlikely to be much better than that — perhaps 25% — in 2000.

Though exothermic in principle, pulp and paper manufacturing is a major energy consumer (2600 PJ in 1985 and 2790 PJ in 1994 — about 3% of the US national total. About half of the total energy (exergy) consumed was purchased electricity or fuel. The best short-term measure of progress in the pulp and paper industry is tons of paper output per unit of fuel exergy input. A similar measure would be applicable to the copper mining and smelting sector, which is also exothermic in principle (for sulfide ores). Unfortunately we do not have reliable historical data for either of these industries. The major opportunity for future improvement is to make fuller use of the exergy content of the pulpwood feedstock, of which less than half (in mass terms) is incorporated in most grades of paper. (The exception is newsprint, which is made by a different process known as mechanical pulping, which does not separate the cellulose from the hemicellulose and lignin fractions.)

For kraft (i.e., 'strong') paper, the consumption of purchased energy per unit of output in the US has fallen more or less continuously, from 41.1 GJ per metric ton (air dried) in 1972 to 35.6 GJ/tonne in 1988 [46]. Those improvements were largely triggered by the so-called 'oil crisis' of 1973–74, as well as environmental regulations on the disposal of so-called 'black liquor'. However, it is noteworthy that the state-of-the-art (best practice plant) in 1988 consumed only 25 GJ/t or 70% as much energy as the average. Adoption of advanced technologies now being developed could bring this down to 18 GJ/t by 2010. At present, wet lignin waste is burned in a furnace for both heat and chemical recovery, but the first law efficiency of that process is low (about 65% compared to 90% for a gas-fired furnace) [46]. Gasification of the lignin waste fol-

[17] As noted above, aluminum smelting is an electrolytic process (as are copper refining and chlor-alkali production).

lowed by gas-turbine co-generation offers the potential for becoming self-sufficient in both heat and electricity (ibid).[18]

Significant process improvements have been recorded in the chemical industry. An example where a time series is available is high-density polyethylene (HDPE). This plastic was first synthesized in the 1930s and is now one of the most important industrial materials. In the 1940s energy requirements were 18 MJ/kg, (= GJ/tonne) down to 11.5 MJ/kg in the 1950s. Improvements in compressors reduced this to 9.4 MJ/kg on average in the 1970s. But Union Carbide's 'UNIPOL' process introduced in 1968 achieved 8.15 MJ/kg, which dropped to 4.75 MJ/kg in 1977 and 1.58 MJ/kg as of 1988 [48]. The ten-fold reduction in energy requirements is one of the reasons why prices have fallen and demand has risen accordingly.

Nitrogen fixation is another good example for which data is available. The electric arc process (c. 1905) required 250 GJ/tonne; the cyanamide process introduced a few years later (c. 1910) reduced this to something like 180 GJ/tonne. The Haber–Bosch ammonia synthesis process — the original version of the process now employed everywhere — achieved 100 GJ/tonne by 1920 (using coal as a feedstock) [49, Appendix K]. Incremental improvements and increasing scale of production brought the exergy consumption down steadily: to 95 GJ/t in 1930, 88 GJ/t in 1940 and 85 GJ/t in 1950 (ibid). Natural gas replaced coal as a feedstock subsequently, and the reciprocating compressors of the older plants were replaced by centrifugal turbo-compressors which enabled much higher compression ratios. By 1955 exergy requirements of the best plants had dropped to 55 GJ/t, and by 1966 it was down to 40 GJ/t. Global production soared, from 5 MMT in 1950 to around 100 MMT today. Since 1950 the decline in exergy cost has been more gradual, to 27 GJ/t in 1996 and 26 GJ/t in 2000 (ibid.). According to one author the theoretical minimum for this process is 24.1 GJ/tonne [39, Ch. 6]. Smil states that the stoichiometric exergy requirement for the process is 20.9 GJ/t. The latter implies that the second law efficiency of ammonia synthesis rose from 8.3% in 1905 to over 77% in 2000. Clearly there is not much more room for improvement in this case.

Synthetic soda ash produced via the Solvay process is another documented case. The first plant (c. 1880) achieved 54.6 GJ/tonne. By 1900 this had fallen by 50% to 27 GJ//t and by 1912 is was down to 25 GJ/t. Then progress accelerated briefly during the war and early postwar years. However, from 1925 to 1967 improvement was very slow (from 15 GJ/t to 12.9 GJ/t). Historical efficiency improvements for pulp and paper, ammonia, HDPE, and soda ash are plotted in Fig. 16.

Extrapolating back to 1900 is always problematic. Except for the above examples, it is difficult to estimate a figure for 1920 or 1900, since for many industries there are virtually no time series data, at least in a convenient form. If one takes the efficiency improvement in the steel industry (roughly threefold) as a model for the efficiency gains for high-temperature heat elsewhere in manufacturing, it would follow that the average exergy efficiency of high-temperature heat use in the industrial sector as a whole was around 7% in 1900. We make this assumption in Table 3.

As mentioned above, the second law approach is also applicable to the use of direct heat for steam generation in the industrial sector and for space heating, water heating and cooking in the

[18] Much the same arguments can be made about the agricultural and food processing sectors, which currently generate large amounts of combustible organic wastes, such as bagasse (from sugar cane production) while consuming equally large amounts of fossil fuels (in other locations) for direct heat. There is considerable interest now in gasifying these wastes and using them as fuel for small gas turbines to generate electric power [47].

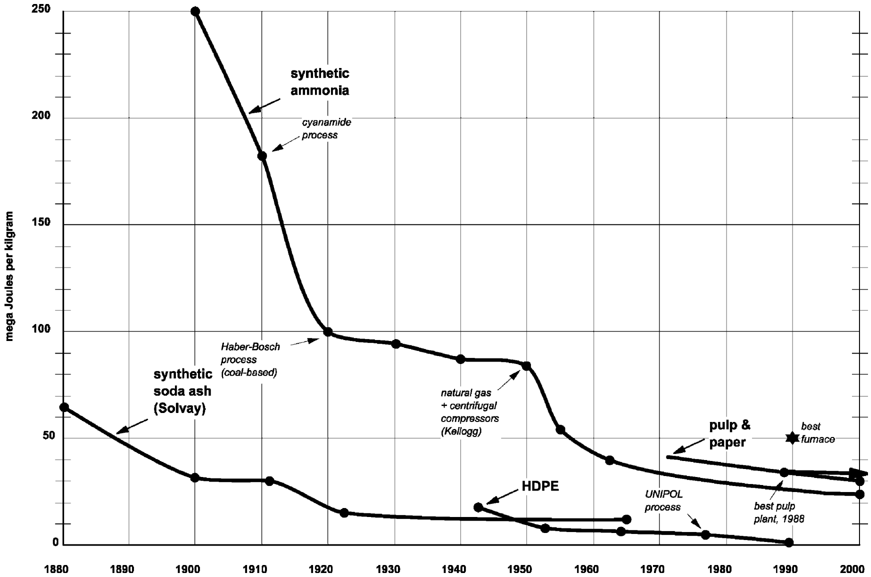

Fig. 16. Exergy consumption by industrial processes: USA 1880–2000.

residential and commercial (R&C) sectors. In the case of process steam, different authors assume different second-law efficiencies. The most optimistic assumption is 25% [6,50]. A British study obtained a lower estimate of 14% [51]. The technology of boilers has not changed significantly over the years. The differences mainly depend on the temperature of the steam and the efficiency of delivery to the point of use. We think the lower estimate is more realistic. (An important difference between this and most earlier (pre-1975) studies is that different measures of efficiency are used. The older studies used what is now termed 'first law' efficiency, namely the fraction of the chemical energy (enthalpy) of the fuel that is delivered to the furnace walls (or the space to be heated.)

Based on 'first law' analysis, in 1950 an open fireplace was about 9% efficient, an electric resistance heater was 16.3% efficient (allowing for 80% losses in the generating plant), synthetic 'town gas' was 31% efficient, hand-fired coal furnace was 46%, a coal furnace with a stoker yielded 60% and a domestic oil or gas furnace gave 61% [27, Table 12]. Incidentally, the authors calculated that a heat pump with a coefficient-of-performance of 4 would be 65% efficient. However, as noted earlier, if alternative ways of delivering the same amount of comfort to the final user are considered, the above efficiencies are too high. In 1950 space heating accounted for 42% of all exergy consumption in the residential and commercial sector, with cooking and hot water adding 2.5% and 3.2% respectively.

The APS summer study previously cited [6] concluded that heat that was delivered by a conventional central oil or gas furnace to heat the rooms of a typical house to 70 °F by means of hot water or hot air would correspond to a second-law efficiency of 6%, while the second-law efficiency for water heating was perhaps 3%. It made no estimate for cooking on a gas range, but similar arguments suggest that a 3% figure might be appropriate in this case too, for 1970.

It is difficult to make a meaningful estimate for 1900, since the basic furnace technology from 1900 to 1970 changed very little, except that coal or coke were the fuels of choice in the early

part of the century whereas oil and gas had replaced coal by 1970. The oil burner or gas burner lost considerably less heat up the stack than its clumsy predecessor, and far less than a wood stove or open fireplace. We guess that the heating systems of 1970 were at least twice as efficient as those of 1900, in second law terms. According to this logic, space heating systems in 1900 were probably 3% efficient in second-law terms.

A 'typical' wood-frame house in North America is poorly insulated and uses around eight times as much heat as a well-insulated one [43]. Assuming houses in 1900 were essentially uninsulated, while houses in 1970 were moderately (but not well) insulated, it appears that the overall efficiency of space heating in 1970 was something like 2%, whereas houses in 1900 achieved only 0.25% at best. It is interesting to note that the overall efficiency of space heating in the US by 1960 had already improved by a factor of seven-plus since 1850, due mainly to the shift from open fireplaces to central heating [8]. However, we have to point out that most of the gains were due to systems optimization, rather than increased efficiency at the equipment level.

Recent investments in heating system modernization, insulation, upgrading of windows and so forth may conceivably have doubled the 1970 figure by now. Progress since 1970 has been slightly accelerated (thanks to the price increases of the 1970s), but space heating systems are rarely replaced in existing buildings, which have an average life expectancy of more than 50 years, based on average economic depreciation rates of 1.3% pa [52]. The penetration of new technologies, such as solar heating and electric heat pumps has been very slow so far.

7. Putting it together: total primary work

Disregarding the efficiency with which electric power performs (secondary) work, discussed below, we have arrived at something like the following. This table incorporates numerous assump-

Table 3
Average exergy efficiency of performing work, percent

Year	Electric power generation & distribution	Other mechanical work, e.g., auto transport	High temperature industrial heat (steel)	Medium temperature industrial heat (steam)	Low temperature space heat
1900	3.8	3	7	5	0.25
1910	5.7	4.4			
1920	9.2	7			
1930	17.3	8			
1940	20.8	9			
1950	24.3	9			
1960	31.3	9			
1970	32.5	8	20	14	2
1980	32.9	10.5			
1990	33.3	13.9	25	20	3

Source: authors

tions, of course. The most surprising conclusion is that the exergy efficiency of transportation probably peaked around 1960, when gasoline engines (in the US Automobile fleet) operated at higher compression ratios, and wasted much less power on accessories than is true today. Increased fleet average fuel economy since 1970 (discussed later) is not attributable to thermodynamic efficiency improvements at the conversion/transfer level, but to systems optimization. Much the same can be said of improvements in the utilization of heat. Improved performance in domestic and commercial space heating has been due mainly to better insulation and better design. However, since insulation is a normal method of improving heat economy in thermodynamic systems of all kinds, we take it into account here.

Using the efficiencies shown in Table 3, we calculate the primary (thermodynamic) work done by the US economy since 1900, by source, in Fig. 17. The work/GDP ratio is also shown. We note with interest that, whereas the exergy/GDP ratio does not exhibit a pronounced 'inverted U' shape, the work/GDP ratio does exhibit such a pattern, with a peak around 1970.

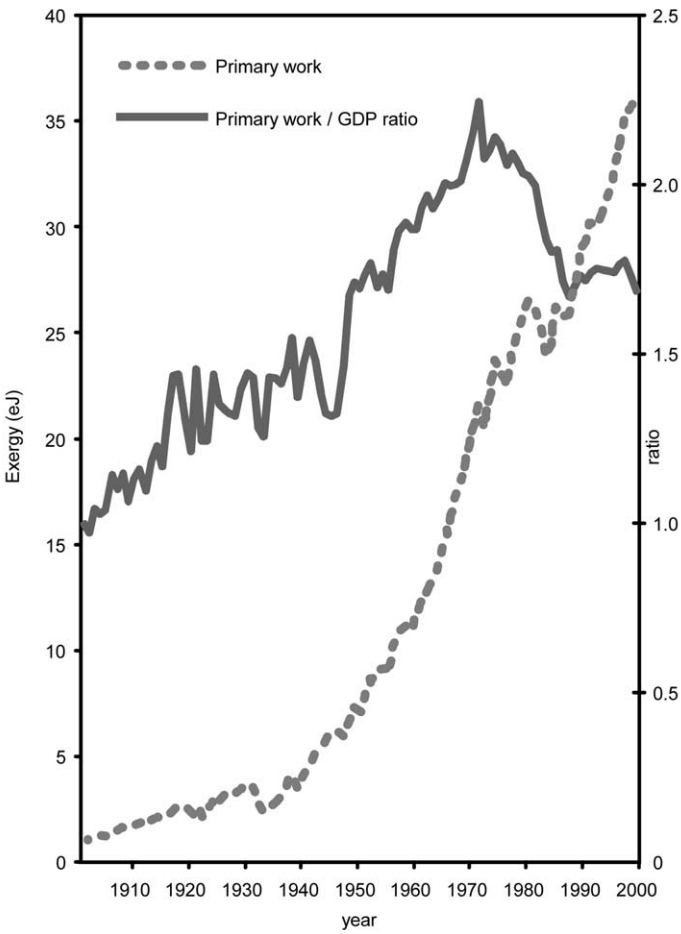

Fig. 17. Primary work and the primary work/GDP ratio, USA 1900–1998.

8. Secondary work and end-use efficiency

Secondary work refers to further conversion steps by means of which electric power produces either mechanical work (via motor drives) or high-temperature heat, including electrolytic reduction processes, electric furnaces, air conditioning and heat pumps, refrigeration or microwave cooking. The last four are thermodynamic insofar as they involve heat removal and heat delivery, respectively. These are types of work comparable to primary work or quasi-work and measurable in the same units, whence efficiency measures (output over input) are dimensionless numbers, as before. The efficiency of secondary work is, of course, the product of several efficiencies, namely the efficiency of exergy conversion to primary work and the efficiency of secondary work per unit of primary work (e.g., electric power) input.[19]

Service output per unit work refers to gains in the quantity of a specific product or service per unit of exergy or work input. The output should be a measurable intermediate or final service, such as transport (e.g., tonne–km or passenger–km per unit of fuel), refrigeration (heat removal per kWh) or lighting (lumens per watt). These gains can be measured by index numbers with reference to a given year, but they are not thermodynamic efficiency measures. Indeed, published data often refer to secondary work measures rather than primary work performed. In some cases, as will be seen, the secondary or tertiary service outputs from a unit of work have increased much more than the primary exergy efficiency per se. In this section we discuss secondary (downstream) services performed by electric power and mechanical power.

Electric light is a good example of secondary work. The electrical industry was really kicked off in the 1880s to supply electric light. Electric light still accounted for 30% of total demand for electricity in 1950 [27] and 14% (and 3.5% of all US energy consumption) as recently as 1979 [43, Appendix A]. The improvement in the efficiency of 'best case' electric lighting from 1900 on is shown in Table 4 [60].

Other innovations that were not directly competitive with incandescent lamps, especially standard fluorescent lamps (introduced in the 1930s) and halogen lamps (used for street lighting) have been omitted. Evidently the rate of progress from 1920 through 1990 — while electricity prices were steadily declining — was very slow. However, the events of the 1970s triggered changes, especially the diffusion of compact fluorescent lighting. This will sharply increase the apparent rate of improvement over the next decade or two. There is a theoretical upper limit for white light, which is 220 lumens/watt. Thus, dividing by 220, the above data on lumens/watt can be presented in secondary efficiency terms. Evidently incandescent lamps achieved no more than 1.5% efficiency at first, and 5% efficiency at best, while the best compact fluorescent lights available today are now about 31% efficient. Unfortunately, we have no data on the average performance of installed lighting systems at the national level.

The efficiency of light production is not the whole story, of course. Much more can also be

[19] Strictly speaking, we should take into account the differences in electric power generation efficiency between hydraulic turbines and steam turbines, especially during the first half of the twentieth century. To a first approximation, electric light, traction power for urban transportation systems, and electric motor drive for factories and appliances was (and is) largely from steam–electric plants, whereas electro-chemistry (e.g., chlor-alkali), electro-metallurgy (e.g., aluminum, ferro-alloys) and uranium isotope separation activities were all clustered around large hydro-electric facilities. In effect, this segregation increases the combined primary and secondary efficiencies of the latter activities, at the expense of the former. However, electric power is fungible, so we feel justified in aggregating both the sources and the uses of electricity.

Table 4
Improvement in efficiency of 'best case' electric lighting

Date	Type of light	Efficiency lumens/watt	Lumen-hrs /MBTU
1900	incandescent, carbon filament	3.714	1089
1910	incandescent, carbon filament	6.5	1905
1920	incandescent, tungsten filament	11.82	3464
1930	incandescent, tungsten filament	11.84	3471
1940	incandescent, tungsten filament	11.9	3488
1950	incandescent, tungsten filament	11.925	3495
1960	incandescent, tungsten filament	11.95	3502
1970	incandescent, tungsten filament	11.975	3510
1980	incandescent, tungsten filament	12.0	3517
1990	incandescent, tungsten filament	14.167	4152
1992	compact fluorescent bulb first generation	68.278	20011

Source: [60, Table 3]

done to increase end-use efficiency by distributing light where it is needed. A 15 W light focused directly on the page of a book is as effective as a 100 W light several feet away without a reflector. We have no data on the absolute efficiency with which electric light is currently being utilized. However, it is clear that further gains can be achieved by optimum placement of lighting, better use of reflective surfaces and, incidentally, by automatic controls that turn off lights when people leave the room.

Electrolytic reduction of aluminum, magnesium, chlorine and a few other materials are good examples of secondary work. Aluminum production from aluminum oxide (alumina) is a well-documented example. The Hall–Heroult electrolytic process for reducing aluminum oxide to metallic aluminum, discovered simultaneously in the early 1880s by Hall in the US and Heroult in France, was industrially established by the turn of the century. The electrolytic smelting step required 50 kWh/kg of aluminum when first introduced in 1888 and 30 kWh/kg in 1900. Average power consumption fell more or less gradually thereafter from 26 kWh/kg in 1935 to 20 kWh/kg in 1956, according to US government statistics (which included magnesium) [8 Table A-28]. Exergy requirements of new cells dropped to 25 kWh/kg already by 1905, however, and continued downward to 18 kWh/kg in 1940, with virtually no further improvement until 1960, then a further drop to 14 kWh/kg in 1970 and 13 kWh/kg by 1990 [53].

The 'practical limit' for electrolytic reduction is said to be 5 kWh/kg and the thermodynamic limit is 2.89 kWh/kg [54]. To this, of course, must be added the consumption of carbon anodes. The anode carbon is petroleum coke, which is a by-product of petroleum refining, or a synthetic version made from powdered coal and coal tar, amounting to 48 MJ/kg. About 0.44 kg of carbon is used per kg of aluminum, down slightly from earlier decades. It is clear that the potential for future efficiency gains is now rather limited. The above does not take into account the energy consumed in the prior bauxite calcination stage (currently 3 MJ/kg), where improvements in recent years have been modest. The practical limit for this process is said to be 1.75 GJ/t and the

thermodynamic limit 0.75 GJ/t (ibid.). Despite historical improvements, considering all steps in the process, aluminum is still far more energy intensive (150 MJ/kg) than either steel (20–25 MJ/kg) or even copper (40–50 MJ/kg).

Comparing 1984 with 1972, US electric power utilities had to pay 240% more for oil and 385% more for gas[55]. Electricity prices rose with fuel costs, and a general recession in the mid-70s pushed electricity demand growth down sharply, from 7% a year throughout the 1950s and 60s, to only 2.5% a year at the end of the 1970s [55].

In response, the use of electricity generally in the chemical industry became much more efficient in the immediate post-1973 period. For example, the electrical intensity of the US chemical industry (measured in terms of electricity consumption per unit of production, as measured by the Federal Reserve Board (FRB) Index), dropped from 570 in 1977 to 506 in 1981, a decline of 11% in just four years [56, Table D-1]. Even more dramatic changes were recorded in other countries. For instance, the chemical industry of East Germany (DDR) reduced its electric power consumption by 17% per unit output (in constant monetary terms) during those same years (1977–1981) and by 35% from 1973 through 1983 [57]. Unfortunately, we know of no study covering the whole twentieth century, or even the whole post-war period.

Metal cutting, drilling and grinding, an important subclass of electric machine drives, is another example of secondary work. For instance, data from Sweden's Sandvik steel company record the number of minutes required to machine a steel axle of standard dimensions. From 660 minutes in 1860 it dropped to 100 minutes in 1895, mainly due to the introduction of Taylor–Mushet 'high-speed' tungsten steel cutting tools. Tungsten carbide cutting tools cut the time to 40 minutes by 1916. By 1980 the time required was down to five minutes or less [58]. Higher rotational speeds of cutting tools was made possible by harder materials — starting with silicon carbide (carborundum) in the 1880s and synthetic abrasives like corundum, to tungsten carbide to synthetic diamond coatings — have accounted for most of this progress. In the early years of the twentieth century rotational speeds were limited to a few hundred rpm. Today, state-of-the-art machines operate at much higher speeds, up to a few thousand rpm.[20] Higher rotational speeds mean faster cutting with less heat loss and lower energy requirements. Unfortunately we have no absolute baseline efficiency data for metal cutting.

Non-industrial motors driving pumps, compressors, washing machines, vacuum cleaners, and power tools also account for quite a lot of electricity consumption in the residential and commercial sector. (It has been suggested that motors use as much as half of all electric power.) Air-conditioning and refrigeration in the residential and commercial sectors accounted for just under 23% of all electric power consumed in 1979, while cryogenic oxygen-separation plants for the steel industry and freezers in the fish and frozen food sectors must have added significantly to this total; [43, Appendix A].

The APS study cited earlier estimated second law efficiencies of 4% for refrigerators and 5% for air conditioners in 1970[6]. Prior to 1970 electricity prices in constant dollars had declined continuously. But after 1972 energy prices (in current dollars) increased sharply, if only temporarily, and this triggered a considerable effort by industry, encouraged by government and consumer groups, to improve the performance of appliances in Fig. 9. According to one source,

[20] The increased drill speeds are very evident in dentist's offices.

refrigerators improved by 95%, freezers by 80% and air conditioners by 30%, between 1972 and 1987 — due largely to regulatory and public concern with energy-efficiency provoked by the 1973–74 'energy crisis' [59]. Another source records even greater progress in residential refrigerator efficiency, from 1726 kWh/yr in 1972 to 690 kWh/yr in 1993 (Electric Power Research Institute, 1993). Even larger gains are possible (and have been achieved in Scandinavia and Japan).[21] These gains are mainly attributable to the use of more efficient compressors and better insulation. Note that, even if the efficiencies of earlier (c. 1970) models have increased by 50% since 1970, this would only bring average efficiency up to 7% or so, which suggests quite a large potential for further gains.

As regards air-conditioning, it must be pointed out that the amount of cooling required (for a given climate) is a function of the design of the building. A very-well-insulated building can get by with very little supplementary cooling, even in a hot climate, by a variety of means, including very thick walls, reflective exterior surfaces and thermal barriers in windows. Unfortunately we have no data on the absolute minimum cooling requirements of a structure, so no estimate of absolute end-use efficiency can be made. Nor is there any evidence that residential or commercial buildings have significantly improved in terms of thermal design since 1970.

Summarizing, then, the period since 1970 has seen substantial acceleration in the secondary efficiency of electric power use. It is not easy to make precise calculations, since the available data reflect best available technology rather than averages. Moreover, we do not have accurate data on the allocation of electric power consumption by functional use. Finally, we do not know the efficiency with which electric motors and other intermediate devices are utilized. Metal cutting, for instance, appears to be very inefficient in absolute terms. For pumping and other such uses, there is also reason to believe that system optimization offers major potential gains [61]. In short, we lack a baseline figure for the end-use efficiency with which electricity is used in the US economy.

The service performed by transportation systems, such as motor vehicles and railroads, is to move people and goods from one place to another. A typical passenger car today weighs around 1000 kg, whereas passengers (plus baggage, if any) typically weigh only 100–200 kg, depending on occupancy. The measure commonly used is vehicle km traveled, rather than passenger (or payload) km traveled. The latter would make more sense and would correspond better to measures used in bus, rail, and air transport modes.

We can roughly equate vehicle–km traveled with work performed by motor vehicles, which implies (for purposes of this paper) that overall exergy conversion efficiency for all motor vehicles is roughly proportional to average mpg (or inversely proportional to the European measure, liters per 100 km). The proportionality constant is uncertain, but normalizing to 1989 (15.9 mpg, 8.33% efficiency) we estimate efficiency to be mpg times 0.52, as shown in Fig. 18. It is important to emphasize that, in using mpg as a surrogate efficiency measure, we effectively assume that the objective is to move the vehicle itself, as well as the passengers and baggage it carries. The difference between exergy conversion efficiency and payload efficiency is not discussed here.

The average fuel economy of the US vehicle fleet increased significantly from the early '70s

[21] The Swedish Electrolux company produced models in 1958 consuming 3.8 kWh/24 hrs to cool a volume of 100 liters. In 1962 this had been reduced to 1 kWh/24 hrs. By 1993 the company was making refrigerators that consumed barely 0.1 kWh/24 hrs per 100 liters cooled [Electrolux Company brochure, undated].

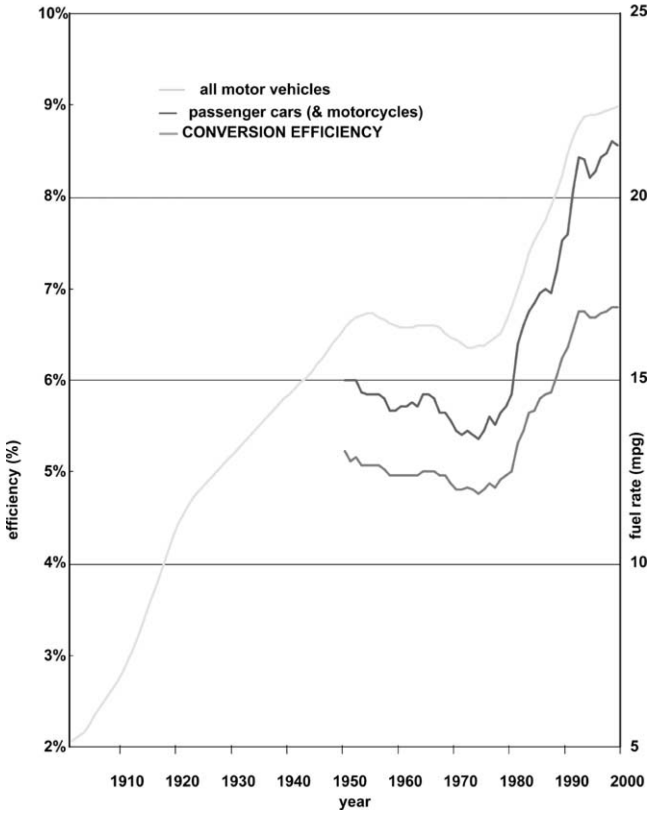

Fig. 18. Vehicle fuel rates and secondary conversion efficiency.

until about 1988, entirely thanks to government regulation, as already mentioned. The CAFÉ standard fuel economy standards were met primarily by reducing average vehicle size and weight (by using thinner steel sheet and more plastic). The average weight of new cars dropped by 1000 lb (450 kg) from 1970 to 1979, and by 600 lb (275 kg) from 1976 to 1979. The net effect was to increase system and payload efficiency, rather than thermodynamic efficiency.

However, if the overall (primary and tertiary) efficiency of producing VMT from fuel is 15% (probably high) and if passengers plus luggage weigh (on average) 200 kg in a 1000 kg car — which is also optimistic — the real payload efficiency is only 0.2–0.16 = 3% or so. It is clear that there is still plenty of room left for future improvements.

On the other hand, for trucks which carry cargo, the mpg is lower (5.6 mpg in 1972; 6.0 mpg in 1990) but payload efficiency is significantly higher than for cars, probably as much as 75% for a fully loaded heavy truck. However, conventional wisdom has it that trucks typically operate at half capacity, mainly due to empty return trips. Unfortunately we have no basis to estimate either absolute efficiency or improvements in recent decades, if any.

In the case of railroads the traditional performance measure is tonne–km. From 1920 to 1950 the improvement by this measure was threefold, most of which was due to the replacement of coal-fired steam locomotives by diesel–electric or electric locomotives. This substitution began in the 1930s but accelerated after the second World War because diesel engines were far more

fuel-efficient — probably by a factor of five[22] — and also required significantly less maintenance. But from 1950 to 1960 the service output (measured in vehicle–km traveled) per unit exergy input quadrupled and from 1960 to 1987 there was a further gain of over 50% [26,62]. The overall performance increase from 1920 to 1987 by this measure (tonne–km per unit of fuel input) was around 20-fold. In 1920 US railways consumed 122 million tonnes of coal, which was 16% of the nation's energy supply. By 1967 the railway's share of national energy consumption had fallen to 1% and continued to decline thereafter [26,62].

It is obvious that much of the improvement has occurred at the system level. One of the major factors was that trucks took over most of the short-haul freight carriage while cars and buses took most of the passengers, leaving the railroads to carry bulk cargos over long distances at (comparatively) high and constant speeds and with much less switching — which is very exergy-intensive. Under these conditions the work required to move a freight train is reduced because rolling friction and air resistance are minimized, while work required for repeated accelerations and decelerations was sharply reduced or eliminated.

Another factor behind the gains was that the work required to overcome air and rolling resistance had been reduced significantly by straightening some of the rights-of-way, improving couplings and suspensions, and introducing aerodynamic shapes. A third source of gain was increasing power-to-weight ratios for locomotives; locomotives in 1900 averaged 133 kg/kW. By 1950 this had fallen to about 33 kg/kW and by 1980 to around 24 kg/kW [63]. The lighter the engine, the less power is needed to move it. (This is an instance of dematerialization contributing to reduced exergy consumption.) If the railways in 1987 were achieving 30% thermal efficiency (almost certainly an over-estimate), and if the coal-fired steam locomotives of 1920 were averaging 7% (for an overall factor of four and a fraction), then an additional factor of five or so was achieved by increasing system efficiency in other ways. In effect, the work required to haul rail cargos has declined dramatically since 1960, but the exergy input required per unit of mechanical work done has hardly changed since then.

Summarizing the last section, we argue that improvements in end-use efficiency in refrigeration, lighting and other areas have cut at least 30% — and probably more — from the aggregate consumption of electrical work that the same services would have required at 1970 rates of use. In the transportation domain, fuel consumption per unit of service output by new passenger cars (measured in vehicle–km traveled) nearly halved between 1970 and 1989, thanks mainly to the CAFÉ standards. But for the motor vehicle fleet as a whole (including trucks) the end-use efficiency improvement since 1970 has also been about 30%.

If the end-use efficiency gains are interpreted as 'secondary work' and added to the primary work series exhibited in Table 3, we obtain Fig. 19.

9. Conclusions: efficiency, growth and the rebound effect

The first conclusion from the above analysis is that, during the past century, the locus of technical progress has moved from energy (exergy) conversion efficiency to end-use efficiency or

[22] According to a study published in 1952, diesel engines can perform ten times as much work as steam engines in switching operations, five times as much in freight service and three times as much in passenger service [27]. The overall gain might have been a factor of about five.

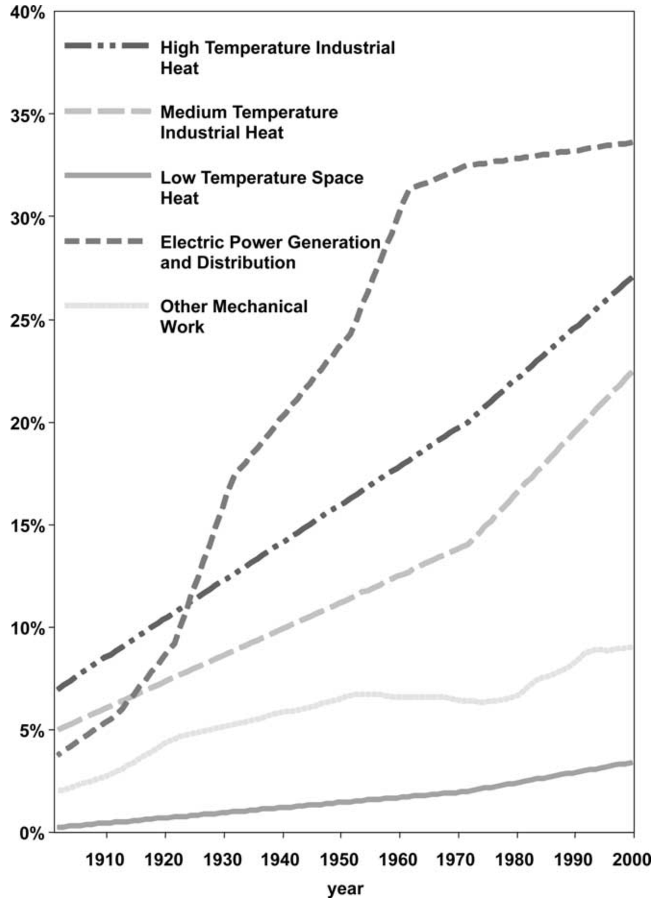

Fig. 19. Energy (exergy) conversion efficiencies, USA 1900–1998.

service output per unit of work. Purely thermodynamic efficiency improvements at the convertor (equipment) level were largely exhausted by the 1960s. This does not rule out the possibility of further thermodynamic improvements in the future. However, most gains since then have arisen from systems optimization and other factors, and this category of improvements will be even more important in the future. Although we have not attempted a detailed accounting of the latter category of improvements, it is very plausible that reduced material consumption per unit of service output has been a major driver of these gains, and that information technology will make increasingly important contributions in the future.

The second important observation is that growth in exergy consumption generally, and electric power consumption in particular, have had an enormous impact on past economic growth. The mechanism responsible has recently been dubbed 'the rebound effect', which conveys the notion that increasing efficiency tends to result in lower costs, which trigger increasing demand that (often) results in greater — rather than less — exergy consumption.

A hypothesis that emerges naturally from the historical analysis is that thermodynamic efficiency improvements in the production of primary work (and secondary work where it can be

measured) may account for much, or most, of the so-called ‘Solow residual’, namely that portion of economic growth attributable to ‘technical progress’. We conjecture that any unexplained part of the Solow residual may be mostly attributable to information technology.

A subtler but related, and arguably more important, question is whether the ‘rebound effect’ is still the primary driver of economic growth — as it has been in the past — and to what extent growth can be expected if the consumption of fossil fuels — the major source of primary exergy in the modern world — can be curtailed in order to stabilize the climate and minimize other kinds of environmental damage.

Appendix A. Data

We have compiled a number of historical data sets for the US from 1900 through 1995, indexed to 1900. All of the series are from standard sources. Both labor and capital series up to 1970 are found in [64] *Long Term Economic Growth 1860- 1970*, US Department of Commerce, Bureau of Economic Analysis. Tables (Series A-68 and A-65, respectively). More recent data (1947–1995) came from[65] *Economic Report of the President, 1996* (Tables B-32 and B-43). The earlier and later labor series are not exactly the same, but the differences during the period of overlap (1949–1970) are very minor. The capital series since 1929 comes from [66] *Survey of Current Business*, May 1997, and [67] *Business Statistics*, also the US Department of Commerce. Labor is counted as man-hours actually worked, and private reproducible capital stock, adjusted by the fraction of the labor force actually employed. (This same adjustment was also made by Solow in his 1957 paper [68].

The exergy series are much more complicated. In brief, we have compiled historical data on fuel consumption for all fuels, including wood, and for non-fuel material inputs with non-trivial exergy content, including non-fuel wood, and major metal ores (iron, copper) and minerals (limestone). Data for 1900 to 1970 are mostly from [10] *Historical Statistics of the US from Colonial Times to 1970*, various tables, with some interpolations and estimates for missing numbers. More recent data on fuels — both raw and processed (including electricity) — are from [11] US Department of Energy, *Annual Review of Energy Statistics*. Data on other minerals and metal ores are from [69,70] *Minerals Yearbooks* (US Bureau of Mines until 1995; US Geological Survey since then). We have calculated the exergy for all fuels as a multiplier of heat content; exergy for other materials was calculated using standard methods [4,71].

Finished materials include coal consumed by industry other than electric utilities, gas consumed by households or industry other than utilities, gasoline, heating oil, and residual oil (not consumed by utilities), plus electricity from all sources. Finished non-fuel materials with significant exergy content include plastics, petrochemicals, asphalt, metals, and non-fuel wood. Obviously large quantities of finished fuels are consumed by industry, for the manufacture of goods, and additional quantities are consumed in transporting those goods to final consumers (i.e., households).

There are no precise statistics on fuels and materials consumed by ‘final’ users vis-a-vis that which is consumed by intermediates. We do have a breakdown of energy usage since 1955, which distinguishes household use from industrial and commercial use. But transportation use is not subdivided in this way, either by the Department of Energy or the Department of Transportation.

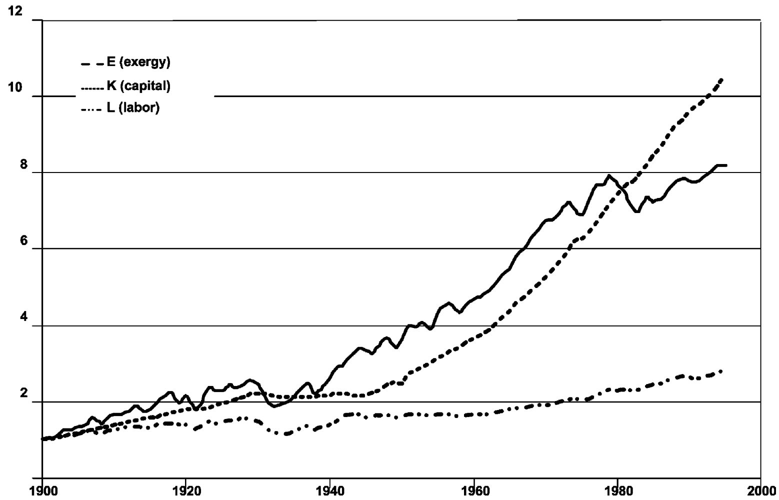

Fig. A-1 Indices of factor increase in the USA (1900 = 1).

The best supplementary source for transportation energy use is Oak Ridge National Laboratory (ORNL). We have rather arbitrarily assigned all gasoline use to households and all diesel fuel use to commercial establishments. This undoubtedly overestimates household use, especially during the early decades of the century before small diesel engines became competitive. There is a further ambiguity, arising from the fact that as much as 40% of all automobile travel is for the purpose of travel to work. It could be argued that this fraction properly belongs to the 'commercial' category rather than the 'private' category, although we have not done so. Simply, we have calculated the household fraction of all fuels and assumed that the same percentage applies to the exergy content of all final goods.

The major time series for *K*, *L* and *E*, expressed in index form normalized to 1900, are shown in Fig. A-1. Conversion factors are given in Tables A-1 and A-2. Tables A-3a, 3b, 3c, 3d give

Table A-1
Conversion factors for petroleum products

Substance	**Barrels/day to metric tons/year (bd/MT) IEA *Energy balances*, p. vii**	**Barrels to million Btu (MBtu/bbl). EIA *Annual energy report.* Appendix A: table 1**
Crude oil	50	5.8
Asphalt/road oil	60.241	6.636
Distillate fuel oil	52.356	5.825
Jet fuel/kerosene	46.948	5.67
LPG	31.348	4.13
Motor gasoline	36.496	5.253
Residual fuel oil	55.866	6.287
Lubricants	52.083	6.065
Aviation gasoline	42.918	5.048
Other products	48.077	5.248

Table A-2
Typical chemical exergy content of some fuels

Fuel	***Exergy coefficient***	***Net heat. value [KJ/kg]***	***Chemical exergy [KJ/kg]***
Coal	1.088	21680	23587.84
Coke	1.06	28300	29998
Fuel oil	1.073	39500	42383.5
Natural gas	1.04	44000	45760
Diesel fuel	1.07	39500	42265
Fuelwood	1.15	15320	17641

Data source: expanded from [4]

the original data sources and Table A-4a, 4b, 4c present the full database for the US from 1900 to 1998.

References for this Appendix

Sources have often been abbreviated in the tables — these abbreviations are shown in bold capitals at the end of each relevant citation. Brackets indicate the main textual citation.

- ANNERG = *Annual energy review* [11]
- BEA = *Long term economic growth 1860–1970* [64]
- BUSTAT = *Business statistics* [67]
- CEA = *Economic Report of the President* [65]
- EIA = *Annual energy review* [11]
- HISTAT = *Historical statistics of the United States: Colonial times to 1970*, 1975 [10]
- HNGA = *Historical natural gas annual* [13]
- IEA = *Energy balances of OECD countries*, annual [72]
- MINYB = *Minerals yearbooks*, annual [69,70]
- P&C = Potter and Christie [73]
- S&N = Schurr and Netschert [8]
- SCB = *Survey of current business*, monthly [66]
- STATAB = *Statistical abstract of the United States* [74]
- Szar = Szargut [4]

Table A-3a
Sources for Table A-4; Coal

Material	Title	Period	Source	Mass (1 short ton = .9071847 metric tons) Reference	Series name and/or formula	Heat Content (1 Btu = 1055.056 joules) Reference	formula
Coal	Raw coal production	1949–1998	Annual Energy Review	Table 7.1, Col 1	Production	Table 7.1 Col 1 Table A5 Col 1	(7.1.1)∗(A5.1) Production
		1850–1948	Historical Statistics - Volume 1	M93+M123	Sum “Production”; Bituminous coal + Pennsylvania anthracite	M77+M78	Same definition as for Mass
	Raw coal apparent consumption	1949–1998	Annual Energy Review	Table 7.1, Col 6	“Coal consumption” = Production + Imports - Exports - Stock change - Losses & unaccounted for	Table 7.1 Col 6 Table A5 Col 1	(7.1.6)∗(A5.1, production)
		1880–1948	Historical Statistics - Volume 1	M84, M85 interpolated before 1900	(Bituminous consumption in btus)/25.4 + (Anthracite consumption in btus)/26.2	M84+M85 interpolated before 1900	Sum “Consumption in Btus”: Bituminous coal + Pennsylvania anthracite
		1850–1879	Historical Statistics - Volume 1	M93+M123	Consumption assumed equal to production	M77+M78	Consumption assumed equal to production
Exergy = Heat ∗ 1.088	Coal, apparent consumption as finished fuel	1949–1998	Annual Energy Review	Table 7.1, Col 6 Table 7.3, Cols 2, 8 Table 7.7, Col 5	Finished fuel = Apparent consumption (7.1.6) - coal used in coke plants(7.3.2) - coal used in power plants(7.3.8) + coke consumption(7.7.5)	Table 7.1, Col 6 Table 7.3, Cols 2, 8 Table 7.7, Col 5 Table A5, Cols 1,3,7,10	Same definition as for Mass (7.1.6)∗(A5.1) - (7.3.2)∗(A5.3) - (7.3.8)∗(A5.7) + (7.7.5)∗(A5.10)
		1916–1948	Historical Statistics - Volume 1	M85 , M84, M116, M114, M122	Finished fuel =Apparent consumption (M84/25.4 +M85/26.2) - coal used in coke plants(M116) - coal used in power plants(M114) + coke production (M122=consumption)	M85 , M84, M116, M114, M122,	M84 +M85 - (26.8∗M116) - (25∗M114)+(24.8∗M122)
		1890–1915	Historical Statistics - Volume 1	M85 , M84, M114 extrapolated to zero in 1890, M122	Finished fuel =Apparent consumption (M84/25.4 +M85/26.2) - coal used in coke plants(1.51∗M122) - coal used in power plants(M114) + coke production	M85 , M84, M114 extrapolated to zero in 1890, M122	M84 +M85 - (1.51∗26.8∗M122) - (25∗M114)+(24.8∗M122)

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Table A-3a (*continued*)

Material	Title	Period	Source	Mass (1 short ton = .9071847 metric tons) Reference	Series name and/or formula	Heat Content (1 Btu = 1055.056 joules) Reference	formula
		1872–1889	Historical Statistics - Volume 1	M85 , M84 interpolated, M122	Finished fuel =Apparent consumption (M84/25.4 +M85/26.2) - coal used in coke plants(1.51∗M122) + coke production (M122=consumption)	M85 , M84 interpolated, M122	M84 +M85 - (1.51∗26.8∗M122) + (24.8∗M122)
		1850–1871	Historical Statistics V-1	M93+M123	Finished fuel assumed equal to production	M77+M78	Finished equal to production

Note: Multipliers (26.2, 25.4, 1.51) derived by exponential fits on years where both series were available.

Table A-3b
Sources for Table A-4; Petroleum

Material	Title	Period	Source	Metric tons: M(product)=F(product)∗B(product), F(P)=factor (lbs/gal) from Table X for product, B(P)=value in bbls/day∗365∗42(gals/bbl)/2204(lbs/tonne)		Heat Content (1 Btu = 1055.056 joules)	
				Reference	**Series name and/or formula**	**Reference**	**ormula**
Petroleum Exergy = Heat∗1.088	Crude oil production	1949–1998	Annual Energy Review	Table 5.2, Col 8	M(crude oil production)	Table 1.2 Col 3	Production
		1859–1948	Schurr and Netschert. Statistical Appendices	Table A1:I, Col 4	M(crude oil production)	Table A1:II, col 4	Production
		1850–1858	zero				
	Crude oil apparent consumption	1949–1998	Annual Energy Review	Table 5.2, Col 8. Table 5.1, Cols 5, 10	M(crude oil production + crude oil imports - crude oil losses) with stock changes + net exports for crude oil per se assumed zero	Table 5.2, Col 8, Table 5.1, Cols 5, 10 times. Table A2. Cols 1–2	M'(crude oil production + crude oil imports - crude oil losses) with stock changes + net exports for crude oil per se assumed zero
		1859–1948	Schurr and Netschert. Statistical Appendices	Table A1:VI, Col 4	M (crude oil apparent consumption)	Table A1:VII, Col 4	Apparent crude oil consumption
		1850–1858	zero				
	Petroleum products consumption as finished fuel	1949–1998	Annual Energy Review (EIA)	Table 5.12a, Cols 1–5, 7–14. Table 5.12b, Cols 1,7	Finished fuel = M(Asphalt/road) + M(Distillate) + M(Jet) + M(LPG total) + M(Gasoline) + M(Residual)+M(Other) for residential/commercial, industrial & transport	Table 2.1, cols 3, 9, 13	Finished fuel =consumption by residential, commercial, industrial and transport

(*continued on next page*)

Table A-3b (*continued*)

Material	**Title**	**Period**	**Source**	**Metric tons: M(product)=F(product)∗B(product), F(P)=factor (lbs/gal) from Table X for product, B(P)=value in bbls/day∗365∗42(gals/bbl)/2204(lbs/tonne)**		**Heat Content (1 Btu = 1055.056 joules)**	
				Reference	**Series name and/or formula**	**Reference**	**ormula**
		1920–1948	Schurr and Netschert. Statistical Appendices. Historical Statistics Vol II	Table A1:VI, Col 4. Table 8.8 col 5 (EIA). Table II:S45 (HIST)	Finished fuel= Apparent consumption (A1VI.4) - Energy sector use (8.85 extrapolated to zero in 1876 using rates from II.S45)	Table A1:VII, Col 4, Table 8.8 col 6 (EIA), Table II:S45 (HIST)	Finished fuel= Apparent consumption (A1VI.4) - Energy sector use (8.85 extrapolated to zero in 1876 using rates from II.S45)
		1850–1858	zero				

Note on finished fuel calculation: Comparison of values in Annual Energy Review from Table 5.12b (energy sector use) and Table 8.8 (electric utility use) in common units produce similar numbers for 1949–1998. This suggests that internal use by the petroleum industry of petroleum products has been excluded from apparent consumption. Hence it has not been subtracted twice.

Table A-3c
Sources for Table A-4; Natural gas

Material	Title	Period	Source	Mass (cubic feet=metric tons∗50875.05) Reference	Series name and/or formula	Heat Content (1 Btu = 1055.056 joules) Reference	Formula
Natural gas Base units = million cubic feet Exergy = Heat∗1.04	Natural gas production includes natural gas liquids	1936–1998	Historical Natural Gas Annual	Table 1, Col 1	Gross withdrawals	Table 1, Col 1, EIA. A4, Col 1	Gross withdrawals(t7.1)∗Dry production factor(A4.1)
		1930–1935	Historical Natural Gas Annual	Table 1, Col 5	1.25∗marketed production (1.25∗T1.5)	Table 1, Col 5, EIA.A4, Col 1	1.25∗marketed production∗Dry production factor(A4.1)
		1882–1929	Schurr & Netschert. Statistical Appendix I	Table I, Col 5	1.25∗marketed production (1.25∗TI.5)	Constant 1.035 from EIA.A4	1.035∗1.25∗marketed production∗
		1850–1881	zero				
	Natural gas apparent consumption includes natural gas liquids	1930–1998	Historical Natural Gas Annual	Table 2, col 8, Table 1, col 6	Consumption (T2.8) + NGL (T1.6)	Table 2, Col 8, Table 1, col 6 Table A4, Cols 1, 2	Dry consumption (t2.8∗A4.1) + NGL (T1.6∗A4.2)
		1882–1930	Schurr & Netschert. Statistical Appendix I	Table VI, Cols 5 & 6	Consumption (natural gas +NGL) interpolated 1882–1890	Table VII, Cols 5 & 6, Statistical Appendix I	Consumption (natural gas + NGL) interpolated 1882–1890
		1850–1881	zero				
	Natural gas consumption as finished fuel (excludes NGL)	1930–1998	Historical Natural Gas Annual	Table 3, Col 8, Table 3, Col 7	Finished fuel = Total delivered to consumers (T3.8) - electric utility use(T3.7) (total deliveries excludes pipeline and plant use). Same as sum(residential, commercial, industrial & transport (T3.1+T3.4+T3.5+T3.6)	Table 3, Col 8, Table 3, Col 7, EIA A4, Cols 3 & 4	Delivered to consumers (T3.8∗A4.4) - electric utility use (T3.7∗A4.3)

(*continued on next page*)

Table A-3c (*continued*)

Material	Title	Period	Source	Mass (cubic feet=metric tons∗50875.05) Reference	Series name and/or formula	Heat Content (1 Btu = 1055.056 joules) Reference	Formula
		1890–1929	Schurr & Netschert. Statistical Appendix I, Historical Natural Gas Annual	Table 3, Cols 8,7, extrapolated to zero in 1882 using rates from S&N Table VI, Cols 5, 6	Finished fuel = Delivered to consumers (T3.8 via VI.6) - electric utility use (T3.7 via VI.7)	Table 3, Cols 8,7extrapolated. Constant factor 1.035	Finished fuel = 1.035 ∗ [Delivered to consumers (T3.8 via VI.6) - electric utility use (T3.7 via VI.7)]
		1850–1881	zero				

Note: The multiplier 1.25 (marketed for gross) derived from fit on years where both series were available. The constant 1.035 is inferred from all values prior to 1940 in Table A4 of the Natural Gas Annual.

Table A-3d
Sources for Table A-4; Fuelwood and biomass

Material	Title	Mass (million cubic feet roundwood equivalent*(.017to.022)=MMT. Multiplier time dependent			
		Period	**Source**	**Reference**	**Formula**
Fuelwood. Exergy = Heat * 1.152	Fuelwood production = consumption = consumption as finished fuel				
		1997–1998	Annual Energy Review	Table 10.3, row 1	Wood energy (Btu)*1535
		1965–1996	Statistical Abstract	Table 1152, last row	Fuelwood consumption (mcfre)*multiplier
		1958–1964	interpolation		
		1900–1957	Potter & Christy	Table FO-13, Col B	New supply fuelwood*multiplier
		1850–1899	Schurr & Netschert	Table 7, Col 1	5–yr interpolations*multiplier
		Heat Content (1 Btu = 1055.056 joules)			
		Period	**Source**	**Reference**	**Formula**
		1981–1998	Annual Energy Review	Table 10.3, Row 1	Wood energy
		1970–1980		Table 10.3 row 1 & Table 1.2, Col 10	Wood energy & Energy from biomass, adjusted and interpolated
		1949–1969		Table 1.2, Col 10	Energy from biomass (=fuelwood only)
		1850–1949	Historical Statistics V.1	M92, interpolated	Fuel wood consumption

Table A-4a
Fuel mass & exergy database for the US 1900–1998; Coal and petroleum

	Coal: MASS Raw coal Production MMT	Apparent consump. MMT	Apparent consump. Finished MMT	Coal: EXERGY Raw coal Production eJ	Apparent consump. eJ	Apparent consump. Finished eJ	Petroleum: MASS Crude oil Production MMT	Apparent consump. MMT	Apparent consump. Finished MMT	Petroleum: EXERGY Crude oil Production eJ	Apparent consump. eJ	Apparent consump. Finished eJ
1998	1014.868	941.386	89.276	22.287	20.674	3.455	312.150	739.650	796.760	13.403	32.248	36.012
1997	988.741	933.675	90.610	21.714	20.504	3.460	322.600	734.100	784.202	13.851	31.991	36.165
1996	965.154	912.265	90.755	21.222	20.059	3.915	323.250	698.750	765.972	13.917	30.463	35.738
1995	937.122	872.712	93.667	20.609	19.193	3.990	328.000	689.500	741.558	14.084	29.939	34.588
1994	937.575	863.186	95.672	20.685	19.044	3.883	333.100	686.100	752.317	14.303	29.853	34.334
1993	857.653	856.473	95.708	18.943	18.917	3.792	342.350	681.850	734.785	14.699	29.666	33.348
1992	905.008	823.452	95.191	20.235	18.412	3.681	358.550	662.550	724.409	15.439	28.873	33.134
1991	903.465	805.217	95.817	20.200	18.003	3.627	370.850	659.850	718.934	15.923	28.650	32.209
1990	933.752	812.384	100.616	21.013	18.281	3.617	367.750	662.250	736.471	15.792	28.729	32.849
1989	889.829	807.122	100.906	19.972	18.116	4.079	380.650	672.650	757.087	16.345	29.113	33.083
1988	862.578	801.588	102.802	19.412	18.039	3.998	407.000	662.500	750.591	17.524	28.715	33.215
1987	833.518	759.223	99.473	18.843	17.163	3.587	417.450	650.950	712.595	17.925	28.126	32.148
1986	807.727	729.558	97.912	18.252	16.486	3.182	434.000	643.000	705.090	18.636	27.770	31.273
1985	801.717	742.077	101.750	18.081	16.736	3.106	448.550	608.550	666.832	19.261	26.169	30.337
1984	812.787	717.855	102.185	18.448	16.293	3.089	443.950	615.450	675.552	19.115	26.529	30.276
1983	709.475	668.323	94.665	16.134	15.198	2.842	434.400	600.900	661.550	18.653	25.833	28.995
1982	760.301	641.289	88.977	17.436	14.707	2.543	432.450	606.950	669.653	18.568	26.096	29.158
1981	747.335	664.604	107.819	17.192	15.289	2.773	428.600	648.600	724.317	18.403	27.880	30.236
1980	752.706	637.479	97.958	17.399	14.735	2.417	429.850	692.350	783.677	18.507	29.834	32.117
1979	708.675	617.339	117.780	16.409	14.295	2.571	427.600	752.600	861.539	18.360	32.341	34.416
1978	607.983	567.172	117.526	13.949	13.012	2.760	435.350	752.350	886.820	18.695	32.310	34.558
1977	632.454	567.263	113.072	14.738	13.219	2.778	412.250	741.750	866.053	17.701	31.875	33.795
1976	621.324	547.758	115.693	14.644	12.910	2.623	406.600	670.600	808.119	17.507	28.890	32.239
1975	593.862	510.382	114.931	14.022	12.051	2.319	418.750	623.250	751.115	17.980	26.794	30.073
1974	553.398	506.572	127.450	13.167	12.053	2.658	438.700	612.200	772.225	18.838	26.322	30.602
1973	542.953	510.382	131.605	13.088	12.303	2.790	460.400	621.900	804.985	19.769	26.725	31.853
1972	546.950	475.637	131.406	13.192	11.472	2.895	472.050	582.550	749.592	20.325	25.090	30.358
1971	508.864	455.044	134.073	12.335	11.031	2.985	473.150	556.650	683.604	20.317	23.917	28.547
1970	555.768	474.639	153.958	13.664	11.670	3.384	481.850	547.350	650.817	20.690	23.514	27.876
1969	517.978	468.470	161.996	12.969	11.730	3.569	461.900	531.900	609.369	19.833	22.853	27.225
1968	505.035	462.483	166.142	12.731	11.658	3.689	454.800	518.800	567.443	19.581	22.355	26.239

(continued on next page)

Table A-4a (*continued*)

	Coal: MASS			**Coal: EXERGY**			**Petroleum: MASS**			**Petroleum: EXERGY**		
	Raw coal Production	**Apparent consump.**	**Apparent consump. Finished**	**Raw coal Production**	**Apparent consump.**	**Apparent consump. Finished**	**Crude oil Production**	**Apparent consump.**	**Apparent consump. Finished**	**Crude oil Production**	**Apparent consump.**	**Apparent consump. Finished**
	MMT	**MMT**	**MMT**	**eJ**	**eJ**	**eJ**	**MMT**	**MMT**	**MMT**	**eJ**	**eJ**	**eJ**
1967	512.452	445.791	168.709	12.934	11.251	3.773	440.500	496.500	527.669	18.915	21.335	24.683
1966	496.069	451.506	182.181	12.599	11.467	4.169	414.750	475.250	507.450	17.810	20.436	23.920
1965	478.045	428.191	178.969	12.213	10.940	4.119	390.200	451.700	476.106	16.755	19.429	22.913
1964	457.386	404.332	175.758	11.716	10.357	4.053	380.700	440.200	455.960	16.393	18.990	22.039
1963	432.904	384.193	171.549	11.085	9.838	3.980	377.100	433.100	439.257	16.192	18.637	21.479
1962	398.293	364.960	168.845	10.198	9.344	3.974	366.600	422.600	424.059	15.742	18.184	20.838
1961	381.401	354.165	168.818	9.773	9.075	4.003	359.150	411.150	415.204	15.421	17.694	19.984
1960	394.017	361.150	178.670	10.120	9.276	4.218	351.750	402.250	401.676	15.147	17.362	19.699
1959	392.518	349.357	173.971	10.083	8.974	4.106	352.700	400.700	397.893	15.145	17.248	19.089
1958	391.556	349.901	186.753	10.088	9.015	4.460	335.500	381.500	376.997	14.405	16.422	18.347
1957	469.960	394.172	217.479	12.219	10.249	5.116	358.500	407.000	368.830	15.393	17.521	17.737
1956	480.603	414.493	240.966	12.448	10.736	5.700	357.550	401.550	366.078	15.395	17.330	17.787
1955	445.281	405.512	246.437	11.572	10.538	5.899	340.333	383.953	354.467	14.614	16.239	17.065
1954	381.733	353.711	222.278	9.863	9.139	5.353	317.122	354.823	325.271	13.617	15.001	15.682
1953	442.923	412.588	275.331	11.486	10.699	6.630	322.888	354.802	326.241	13.865	15.252	15.296
1952	460.327	411.953	287.178	11.913	10.661	6.969	312.819	337.186	310.263	13.469	14.690	14.777
1951	522.842	458.945	330.660	13.489	11.841	7.997	307.906	328.578	300.348	13.222	14.238	14.269
1950	508.375	448.240	337.128	13.153	11.598	8.255	270.353	298.670	279.999	11.609	12.586	13.058
1949	435.966	438.352	336.556	11.202	11.263	8.194	252.321	269.525	250.305	10.834	11.682	11.665
1948	595.710	517.205	397.420	15.600	13.544	7.994	275.982	280.414	271.618	11.883	12.107	11.736
1947	623.974	549.247	372.981	16.340	14.383	9.099	254.382	254.301	246.322	10.924	10.956	10.620
1946	539.257	502.834	361.767	14.121	13.168	8.875	237.526	235.020	228.057	10.199	10.128	9.837
1945	573.841	554.466	400.245	15.027	14.520	9.815	234.747	227.601	220.659	10.080	9.755	9.464
1944	619.859	588.754	420.561	16.232	15.418	10.301	229.222	216.675	209.575	9.870	9.392	9.092
1943	590.415	590.455	427.343	15.461	15.462	10.479	206.248	193.676	186.882	8.857	8.345	8.056

Table A-4a (*continued*)

	Coal: MASS			Coal: EXERGY			Petroleum: MASS			Petroleum: EXERGY		
	Raw coal Production	Apparent consump.	Apparent consump. Finished	Raw coal Production	Apparent consump.	Apparent consump. Finished	Crude oil Production	Apparent consump.	Apparent consump. Finished	Crude oil Production	Apparent consump.	Apparent consump. Finished
	MMT	MMT	MMT	eJ	eJ	eJ	MMT	MMT	MMT	eJ	eJ	eJ
1942	583.339	541.167	389.485	15.276	14.171	9.536	189.951	180.667	174.864	8.157	7.776	7.531
1941	517.564	494.213	352.783	13.553	12.942	8.632	192.086	193.265	188.124	8.248	8.320	8.107
1940	464.712	435.387	314.822	12.169	11.401	7.710	184.865	175.540	171.127	7.960	7.593	7.411
1939	404.915	386.272	288.296	10.603	10.115	7.087	173.282	161.168	157.186	7.441	6.938	6.775
1938	358.015	346.086	268.975	9.375	9.063	6.642	166.350	152.159	148.608	7.143	6.557	6.412
1937	451.222	436.498	329.995	11.816	11.430	8.112	175.227	155.513	151.803	7.524	6.698	6.546
1936	447.848	418.640	322.478	11.728	10.963	7.944	150.230	143.937	140.536	6.468	6.211	6.072
1935	385.129	369.622	294.144	10.085	9.679	7.269	136.520	129.569	126.597	5.862	5.577	5.456
1934	377.875	362.265	289.327	9.895	9.487	7.157	124.392	113.524	110.802	5.342	4.886	4.775
1933	347.608	333.189	270.956	9.103	8.725	6.712	124.062	114.047	111.497	5.327	4.913	4.809
1932	326.192	324.246	269.815	8.542	8.491	6.702	107.262	107.693	105.223	4.619	4.655	4.554
1931	400.735	390.357	313.519	10.494	10.222	7.759	116.586	117.050	114.324	5.006	5.035	4.924
1930	487.077	474.129	374.248	12.755	12.416	9.237	123.015	132.981	130.138	5.282	5.732	5.618
1929	552.310	536.145	419.481	14.463	14.040	10.337	137.989	124.554	121.678	5.925	5.369	5.252
1928	522.623	519.344	414.836	13.686	13.600	10.243	123.145	111.967	109.391	5.303	4.830	4.725
1927	542.369	521.172	419.023	14.203	13.648	10.355	123.442	103.333	100.980	5.301	4.439	4.343
1926	596.750	553.201	444.611	15.627	14.487	10.980	105.599	102.067	99.904	4.534	4.392	4.305
1925	527.864	510.975	411.094	13.823	13.381	10.157	104.622	98.095	96.178	4.493	4.215	4.139
1924	518.560	512.302	423.579	13.579	13.415	10.494	97.533	88.362	86.661	4.200	3.817	3.750
1923	596.841	549.697	442.649	15.629	14.395	10.930	100.330	88.852	87.254	4.308	4.087	4.025
1922	432.683	438.823	363.073	11.331	11.491	8.997	76.374	72.558	71.197	3.280	3.114	3.061
1921	459.394	429.825	371.946	12.030	11.256	9.260	64.683	63.212	62.052	2.778	2.712	2.666
1920	597.168	539.208	441.414	15.638	14.120	10.918	60.509	62.055	60.829	2.605	2.671	2.622
1919	502.537	480.169	399.883	13.160	12.574	9.902	51.831	50.996	49.934	2.226	2.190	2.147
1918	615.264	590.297	494.499	16.112	15.458	12.240	48.757	45.133	44.215	2.093	1.938	1.901
1917	590.943	563.975	468.992	15.475	14.769	11.601	45.934	41.458	40.665	1.973	1.780	1.748
1916	535.328	512.571	423.757	14.018	13.423	10.469	41.088	35.332	34.656	1.769	1.518	1.491
1915	482.277	462.665	392.903	12.629	12.116	9.737	38.507	33.319	32.740	1.653	1.431	1.408

Table A-4a (*continued*)

	Coal: MASS			**Coal: EXERGY**			**Petroleum: MASS**			**Petroleum: EXERGY**		
	Raw coal Production	**Apparent consump.**	**Apparent consump. Finished**	**Raw coal Production**	**Apparent consump.**	**Apparent consump. Finished**	**Crude oil Production**	**Apparent consump.**	**Apparent consump. Finished**	**Crude oil Production**	**Apparent consump.**	**Apparent consump. Finished**
	MMT	**MMT**	**MMT**	**eJ**	**eJ**	**eJ**	**MMT**	**MMT**	**MMT**	**eJ**	**eJ**	**eJ**
1914	465.863	449.099	390.313	12.199	11.760	9.697	36.406	31.184	30.690	1.563	1.339	1.320
1913	517.059	495.507	421.934	13.540	12.976	10.453	34.034	28.586	28.164	1.461	1.227	1.211
1912	484.860	467.588	398.369	12.697	12.245	9.869	30.456	24.925	24.565	1.311	1.073	1.059
1911	450.300	433.205	376.778	11.792	11.344	9.355	31.568	24.566	24.251	1.297	1.055	1.043
1910	455.040	442.474	378.517	11.916	11.587	9.379	28.706	23.775	23.500	1.232	1.021	1.011
1909	418.043	405.993	346.300	10.947	10.632	8.577	25.092	19.924	19.684	1.077	0.856	0.847
1908	377.246	366.307	325.484	9.879	9.592	8.098	24.389	19.313	19.104	1.050	0.832	0.824
1907	435.778	423.921	363.321	11.412	11.101	9.001	22.753	18.450	18.267	0.977	0.792	0.786
1906	375.717	366.892	313.006	9.839	9.608	7.750	17.328	13.109	12.955	0.744	0.563	0.557
1905	356.272	348.371	300.835	9.330	9.123	7.458	18.454	14.400	14.270	0.792	0.619	0.614
1904	319.163	311.926	276.455	8.358	8.168	6.874	15.995	12.587	12.478	0.689	0.542	0.538
1903	324.188	319.109	281.915	8.489	8.356	7.006	13.762	10.608	10.516	0.591	0.455	0.452
1902	273.599	269.920	232.998	7.165	7.068	5.775	12.160	8.604	8.526	0.522	0.369	0.367
1901	266.077	260.285	228.443	6.968	6.816	5.673	9.368	5.912	5.850	0.408	0.254	0.251
1900	244.653	238.410	208.382	6.407	6.243	5.173	8.578	5.420	5.376	0.374	0.232	0.231

Table A-4b
Fuel mass & exergy database for the US 1900–1998; Natural gas, fuelwood and biomass

	Natural gas: MASS			**Natural gas: EXERGY**			**Fuelwood/ Biomass: MASS**			**Fuelwood/ Biomass:EXERGY**		
	Production	**Apparent consump.**	**Apparent consump. Finished**	**Production**	**Apparent consump.**	**Apparent consump. Finished**	**Production**	**Apparent consump.**	**Apparent consump. Finished**	**Production**	**Apparent consump.**	**Apparent consump. Finished**
	MMT	**MMT**	**MMT**	**eJ**	**eJ**	**eJ**	**MMT**	**MMT**	**MMT**	**eJ**	**eJ**	**eJ**
1998	470.255	404.586	318.643	24.196	20.892	16.437	73.063	73.063	72.609	3.327	3.327	3.306
1997	475.924	409.432	334.851	24.488	21.143	17.269	71.552	71.552	71.096	3.249	3.249	3.229
1996	473.976	408.263	339.518	24.411	21.104	17.494	74.810	74.810	74.328	3.388	3.388	3.366
1995	466.705	401.263	323.610	24.037	20.737	16.673	73.638	73.638	73.227	3.322	3.322	3.304
1994	463.502	404.875	312.756	23.895	20.940	16.160	68.919	68.919	68.422	3.179	3.179	3.157
1993	446.695	390.533	310.573	23.006	20.183	16.027	67.465	67.465	66.980	3.035	3.035	3.013
1992	435.031	384.937	295.238	22.471	19.952	15.289	66.233	66.233	65.710	3.039	3.039	3.015
1991	427.520	380.679	285.318	22.083	19.728	14.771	65.491	65.491	64.970	2.880	2.880	2.857
1990	423.049	380.892	275.827	21.873	19.751	14.236	65.073	65.073	64.554	2.869	2.869	2.846
1989	414.239	371.098	281.368	21.418	19.246	14.550	62.381	62.381	61.968	3.291	3.291	3.269
1988	412.761	368.242	268.976	21.300	19.067	13.883	62.684	62.684	62.248	3.166	3.166	3.144
1987	395.876	358.628	249.596	20.468	18.607	12.902	63.334	63.334	62.894	3.045	3.045	3.024
1986	376.033	347.092	240.027	19.423	17.992	12.373	63.365	63.365	62.924	3.068	3.068	3.047
1985	385.389	355.510	250.949	19.945	18.463	12.954	70.296	70.296	69.808	3.096	3.096	3.074
1984	398.359	376.259	260.119	20.597	19.518	13.421	73.820	73.820	73.306	3.139	3.139	3.117
1983	366.762	347.395	244.832	18.963	18.027	12.662	65.459	65.459	65.068	3.086	3.086	3.067
1982	398.471	380.225	256.899	20.542	19.661	13.186	67.688	67.688	67.284	2.851	2.851	2.834
1981	424.323	407.476	278.993	21.854	21.044	14.305	63.757	63.757	63.376	2.823	2.823	2.806
1980	429.871	411.918	285.693	22.118	21.249	14.631	62.982	62.982	62.606	2.709	2.709	2.692
1979	430.139	418.262	287.975	22.024	21.472	14.643	45.243	45.243	44.974	2.346	2.346	2.332
1978	418.846	409.359	280.309	21.404	20.977	14.226	31.649	31.649	31.491	2.221	2.221	2.210
1977	414.684	410.575	277.888	21.233	21.084	14.169	20.777	20.777	20.673	2.003	2.003	1.993
1976	411.671	408.973	288.608	21.058	20.981	14.736	12.536	12.536	12.474	1.867	1.867	1.858
1975	414.811	412.401	283.060	21.239	21.179	14.460	11.976	11.976	11.917	1.634	1.634	1.626
1974	449.136	442.024	307.293	23.064	22.763	15.787	11.304	11.304	11.248	1.679	1.679	1.670
1973	473.065	463.176	317.741	24.222	23.781	16.239	10.729	10.729	10.686	1.667	1.667	1.660
1972	472.061	460.731	312.586	24.313	23.794	16.099	10.148	10.148	10.107	1.638	1.638	1.632
1971	473.474	459.481	307.836	24.480	23.820	15.916	10.257	10.257	10.217	1.561	1.561	1.555
1970	467.547	448.689	296.542	24.174	23.262	15.332	11.146	11.146	11.102	1.560	1.560	1.554
1969	445.782	423.878	286.820	23.049	21.978	14.830	12.975	12.975	12.923	1.570	1.570	1.563
1968	419.164	396.074	268.423	21.672	20.547	13.878	14.728	14.728	14.684	1.547	1.547	1.542

(*continued on next page*)

Table A-4b (*continued*)

	Natural gas: MASS			**Natural gas: EXERGY**			**Fuelwood/ Biomass: MASS**			**Fuelwood/ Biomass:EXERGY**		
	Production	**Apparent consump.**	**Apparent consump. Finished**	**Production**	**Apparent consump.**	**Apparent consump. Finished**	**Production**	**Apparent consump.**	**Apparent consump. Finished**	**Production**	**Apparent consump.**	**Apparent consump. Finished**
1967	398.069	372.596	254.060	20.602	19.340	13.149	16.394	16.394	16.345	1.461	1.461	1.456
1966	374.129	352.745	241.252	19.381	18.325	12.498	17.970	17.970	17.916	1.492	1.492	1.488
1965	353.083	330.088	222.150	18.273	17.135	11.497	19.562	19.562	19.504	1.455	1.455	1.451
1964	344.679	319.787	210.015	17.838	16.600	10.869	21.764	21.764	21.699	1.457	1.457	1.453
1963	333.629	303.035	196.381	17.250	15.716	10.154	23.966	23.966	23.918	1.442	1.442	1.439
1962	315.262	285.017	187.686	16.363	14.838	9.742	26.168	26.168	26.116	1.417	1.417	1.414
1961	303.888	272.166	176.860	15.773	14.169	9.180	28.370	28.370	28.314	1.412	1.412	1.409
1960	296.568	261.699	170.180	15.393	13.622	8.833	30.573	30.573	30.512	1.439	1.439	1.436
1959	279.691	246.576	159.300	14.517	12.835	8.268	32.775	32.775	32.709	1.475	1.475	1.472
1958	258.410	225.814	146.859	13.413	11.755	7.623	34.977	34.977	34.942	1.442	1.442	1.441
1957	253.693	218.455	140.829	13.168	11.372	7.310	37.200	37.200	37.163	1.454	1.454	1.453
1956	243.202	206.387	132.699	12.623	10.746	6.888	39.152	39.152	39.113	1.543	1.543	1.542
1955	230.364	192.276	121.162	11.957	10.011	6.289	39.394	39.394	39.354	1.552	1.552	1.551
1954	215.918	178.809	109.088	11.207	9.309	5.662	42.956	42.956	42.913	1.519	1.519	1.518
1953	209.254	171.734	103.070	10.861	8.941	5.350	44.380	44.380	44.358	1.547	1.547	1.546
1952	201.918	163.786	98.524	10.480	8.526	5.114	43.446	43.446	43.424	1.607	1.607	1.606
1951	190.454	152.329	92.468	9.885	7.929	4.799	47.878	47.878	47.854	1.673	1.673	1.672
1950	166.676	128.588	80.284	8.651	6.696	4.167	48.771	48.771	48.746	1.703	1.703	1.702
1949	148.340	110.940	70.481	7.699	5.777	3.658	60.630	60.630	60.600	1.688	1.688	1.688
1948	141.106	105.308	67.726	7.324	5.479	3.515	57.338	57.338	57.338	1.596	1.596	1.596
1947	132.348	93.777	61.322	6.869	4.880	3.183	57.808	57.808	57.808	1.424	1.424	1.424
1946	123.696	84.875	55.198	6.420	4.416	2.865	57.633	57.633	57.633	1.236	1.236	1.236
1945	117.939	82.593	52.233	6.122	4.297	2.711	64.142	64.142	64.142	1.374	1.374	1.374
1944	112.202	77.796	48.777	5.824	4.047	2.532	62.892	62.892	62.892	1.347	1.347	1.347
1943	98.761	71.495	45.541	5.126	3.719	2.364	60.129	60.129	60.129	1.173	1.173	1.173
1942	88.945	64.171	40.982	4.617	3.338	2.127	61.900	61.900	61.900	1.207	1.207	1.207
1941	81.928	59.145	37.619	4.252	3.077	1.953	77.726	77.726	77.726	1.368	1.368	1.368
1940	73.763	55.299	34.588	3.829	2.875	1.795	84.163	84.163	84.163	1.480	1.480	1.480
1939	66.577	51.344	31.484	3.456	2.670	1.634	90.717	90.717	90.717	1.595	1.595	1.595
1938	61.108	47.794	28.794	3.172	2.485	1.495	93.705	93.705	93.705	1.553	1.553	1.553
1937	60.630	49.999	31.079	3.147	2.600	1.613	88.350	88.350	88.350	1.463	1.463	1.463

Table A-4b (*continued*)

	Natural gas: MASS			Natural gas: EXERGY			Fuelwood/ Biomass: MASS			Fuelwood/ Biomass:EXERGY		
	Production	Apparent consump.	Apparent consump. Finished	Production	Apparent consump.	Apparent consump. Finished	Production	Apparent consump.	Apparent consump. Finished	Production	Apparent consump.	Apparent consump. Finished
1936	52.904	44.944	27.243	2.746	2.337	1.414	92.533	92.533	92.533	1.440	1.440	1.440
1935	48.377	39.793	23.671	2.511	2.069	1.229	97.917	97.917	97.917	1.523	1.523	1.523
1934	44.614	36.717	21.279	2.316	1.909	1.104	104.829	104.829	104.829	1.630	1.630	1.630
1933	39.230	32.333	18.863	2.036	1.681	0.979	108.815	108.815	108.815	1.892	1.892	1.892
1932	39.160	32.346	18.039	2.033	1.682	0.936	108.346	108.346	108.346	1.882	1.882	1.882
1931	42.307	35.070	19.156	2.196	1.824	0.994	95.576	95.576	95.576	1.837	1.837	1.837
1930	48.622	40.374	21.586	2.524	2.100	1.120	82.571	82.571	82.571	1.586	1.586	1.586
1929	47.965	37.248	21.237	2.610	2.118	1.102	69.111	69.111	69.111	1.327	1.327	1.327
1928	39.211	30.465	17.182	2.137	1.734	0.892	70.358	70.358	70.358	1.511	1.511	1.511
1927	36.143	28.077	15.874	1.969	1.594	0.824	69.861	69.861	69.861	1.499	1.499	1.499
1926	32.832	24.885	14.030	1.789	1.439	0.728	66.960	66.960	66.960	1.588	1.588	1.588
1925	29.720	23.137	13.165	1.619	1.296	0.683	70.504	70.504	70.504	1.671	1.671	1.671
1924	28.544	22.251	12.822	1.556	1.234	0.665	73.944	73.944	73.944	1.752	1.752	1.752
1923	25.179	19.630	11.236	1.371	1.088	0.583	73.885	73.885	73.885	1.603	1.603	1.603
1922	19.067	14.887	8.432	1.039	0.815	0.438	82.370	82.370	82.370	1.785	1.785	1.785
1921	16.555	12.923	7.334	0.902	0.709	0.381	93.607	93.607	93.607	1.843	1.843	1.843
1920	19.959	15.613	9.052	1.088	0.843	0.470	89.175	89.175	89.175	1.755	1.755	1.755
1919	18.327	14.671	8.586	0.988	0.820	0.446	89.455	89.455	89.455	1.759	1.759	1.759
1918	17.715	14.226	8.437	0.955	0.791	0.438	94.240	94.240	94.240	1.918	1.918	1.918
1917	19.536	15.630	9.477	1.053	0.862	0.492	88.809	88.809	88.809	1.807	1.807	1.807
1916	18.505	14.790	9.060	0.998	0.806	0.470	87.000	87.000	87.000	1.831	1.831	1.831
1915	15.444	12.335	7.551	0.833	0.670	0.392	87.500	87.500	87.500	1.840	1.840	1.840
1914	14.542	11.558	7.121	0.784	0.628	0.370	87.560	87.560	87.560	1.840	1.840	1.840
1913	14.297	11.353	7.052	0.771	0.614	0.366	83.321	83.321	83.321	1.805	1.805	1.805
1912	13.813	10.875	6.796	0.744	0.587	0.353	82.937	82.937	82.937	1.795	1.795	1.795
1911	12.604	9.949	6.231	0.679	0.537	0.323	89.064	89.064	89.064	1.985	1.985	1.985
1910	12.510	9.867	6.213	0.674	0.532	0.322	86.364	86.364	86.364	1.924	1.924	1.924
1909	11.811	9.337	5.895	0.637	0.504	0.306	84.544	84.544	84.544	1.882	1.882	1.882
1908	9.881	7.803	4.920	0.532	0.421	0.255	87.919	87.919	87.919	1.964	1.964	1.964
1907	9.991	7.902	5.006	0.538	0.426	0.260	84.659	84.659	84.659	1.890	1.890	1.890
1906	9.554	7.509	4.773	0.515	0.405	0.248	86.378	86.378	86.378	1.935	1.935	1.935
1905	8.624	6.801	4.331	0.465	0.367	0.225	89.761	89.761	89.761	2.009	2.009	2.009
1904	7.617	6.034	3.848	0.410	0.325	0.200	93.149	93.149	93.149	2.083	2.083	2.083
1903	7.297	5.799	3.708	0.393	0.312	0.192	96.542	96.542	96.542	2.074	2.074	2.074
1902	6.880	5.464	3.502	0.371	0.295	0.182	99.938	99.938	99.938	2.145	2.145	2.145
1901	6.462	5.130	3.298	0.349	0.277	0.171	103.340	103.340	103.340	2.128	2.128	2.128
1900	5.799	4.619	2.979	0.313	0.248	0.155	106.746	106.746	106.746	2.196	2.196	2.196

Table A-4c
Fuel mass & exergy database for the US 1900–1998; Fuel total

	Economic data		Total fuel: MASS			Total fuel: EXERGY		
	GDP billion	Population	Production	Apparent consump.	Apparent consump. Finished	Production	Apparent consump.	Apparent consump. Finished
	1992$	millions	MMT	MMT	MMT	eJ	eJ	eJ
1998	7552.1	270.3	1870.336	2158.685	1277.287	63.213	77.140	59.210
1997	7269.8	267.7	1858.817	2148.759	1280.759	63.302	76.888	60.123
1996	6994.8	265.2	1837.189	2094.088	1270.574	62.938	75.013	60.513
1995	6761.7	262.8	1805.465	2037.113	1232.061	62.052	73.191	58.556
1994	6610.7	260.3	1803.096	2023.080	1229.167	62.062	73.016	57.534
1993	6389.6	257.7	1714.163	1996.321	1208.046	59.683	71.799	56.179
1992	6244.4	255.0	1764.822	1937.172	1180.548	61.183	70.276	55.120
1991	6079.4	252.1	1767.326	1911.237	1165.039	61.086	69.261	53.464
1990	6136.3	248.8	1789.624	1920.600	1177.468	61.546	69.631	53.549
1989	6062.0	246.8	1747.098	1913.252	1201.329	61.025	69.765	54.981
1988	5865.2	244.5	1745.023	1895.014	1184.618	61.402	68.988	54.241
1987	5649.5	242.3	1710.178	1832.135	1124.558	60.282	66.942	51.661
1986	5487.7	240.1	1681.125	1783.015	1105.953	59.380	65.315	49.876
1985	5323.5	237.9	1705.953	1776.434	1089.339	60.383	64.464	49.471
1984	5140.1	235.8	1728.915	1783.384	1111.162	61.299	65.480	49.903
1983	4803.7	233.8	1576.096	1682.076	1066.115	56.835	62.144	47.566
1982	4620.3	231.7	1658.910	1696.151	1082.813	59.399	63.315	47.722
1981	4720.7	229.5	1664.015	1784.437	1174.505	60.272	67.036	50.120
1980	4615.0	226.5	1675.408	1804.728	1229.933	60.733	68.528	51.858
1979	4630.6	224.6	1611.657	1833.445	1312.267	59.140	70.453	53.961
1978	4503.0	222.1	1493.828	1760.530	1316.147	56.269	68.521	53.754
1977	4273.6	219.8	1480.165	1740.364	1277.686	55.675	68.181	52.736
1976	4082.9	217.6	1452.131	1639.868	1224.895	55.075	64.648	51.456
1975	3873.9	215.5	1439.400	1558.010	1161.023	54.875	61.659	48.478
1974	3891.2	213.3	1452.538	1572.100	1218.216	56.748	62.817	50.717
1973	3916.3	211.4	1487.147	1606.187	1265.018	58.746	64.475	52.541
1972	3702.3	209.3	1501.208	1529.065	1203.690	59.468	61.995	50.983
1971	3510.0	206.8	1465.746	1481.433	1135.730	58.693	60.328	49.003
1970	3397.6	203.3	1516.310	1481.824	1112.419	60.088	60.006	48.146
1969	3393.6	201.3	1438.635	1437.223	1071.108	57.420	58.129	47.187
1968	3293.9	199.3	1393.728	1392.085	1016.692	55.532	56.108	45.348

(*continued on next page*)

Table A-4c (*continued*)

	Economic data		Total fuel: MASS			Total fuel: EXERGY		
	GDP billion	Population	Production	Apparent consump.	Apparent consump. Finished	Production	Apparent consump.	Apparent consump. Finished
1967	3147.2	197.4	1367.415	1331.281	966.782	53.911	53.387	43.060
1966	3069.2	195.5	1302.918	1297.471	948.799	51.282	51.720	42.074
1965	2881.1	193.5	1240.890	1229.541	896.729	48.697	48.958	39.980
1964	2708.4	191.1	1204.529	1186.083	863.431	47.405	47.405	38.413
1963	2559.4	188.4	1167.599	1144.294	831.104	45.969	45.632	37.052
1962	2454.8	185.7	1106.324	1098.746	806.707	43.720	43.783	35.969
1961	2314.3	183.0	1072.810	1065.852	789.196	42.379	42.350	34.575
1960	2262.9	179.3	1072.907	1055.671	781.037	42.098	41.698	34.187
1959	2210.2	177.1	1057.683	1029.408	763.873	41.219	40.531	32.936
1958	2057.5	174.1	1020.443	992.192	745.551	39.348	38.633	31.870
1957	2078.5	171.2	1119.353	1056.827	764.301	42.234	40.596	31.614
1956	2040.2	168.1	1120.507	1061.581	778.855	42.010	40.355	31.916
1955	2001.1	165.1	1055.371	1021.134	761.420	39.695	38.341	30.803
1954	1868.2	161.9	957.730	930.300	699.550	36.206	34.968	28.215
1953	1881.4	159.0	1019.445	983.504	748.999	37.758	36.439	28.822
1952	1798.7	156.4	1018.510	956.371	739.389	37.469	35.484	28.466
1951	1734.0	154.0	1069.080	987.730	771.329	38.270	35.681	28.738
1950	1611.3	151.3	994.175	924.269	746.158	35.116	32.582	27.182
1949	1479.8	148.7	897.257	879.446	717.942	31.424	30.410	25.205
1948	1488.6	146.7	1070.135	960.263	794.101	36.402	32.726	24.841
1947	1426.2	144.1	1068.513	955.133	738.433	35.556	31.642	24.326
1946	1437.9	140.7	958.112	880.363	702.655	31.977	28.948	22.813
1945	1632.7	133.4	990.669	928.802	737.279	32.603	29.947	23.364
1944	1660.5	133.9	1024.175	946.117	741.805	33.273	30.204	23.271
1943	1551.6	135.1	955.553	915.756	719.896	30.617	28.698	22.072
1942	1370.4	134.6	924.135	847.904	667.232	29.256	26.492	20.401
1941	1213.3	133.7	869.305	824.349	656.252	27.422	25.707	20.060
1940	1044.7	132.5	807.503	750.389	604.699	25.438	23.350	18.396
1939	963.6	130.9	735.491	689.501	567.683	23.095	21.317	17.090
1938	887.5	129.8	679.177	639.744	540.082	21.243	19.658	16.101
1937	934.4	128.8	775.429	730.360	601.227	23.950	22.190	17.734

Table A-4c (*continued*)

	Economic data		**Total fuel: MASS**			**Total fuel: EXERGY**		
	GDP billion	**Population**	**Production**	**Apparent consump.**	**Apparent consump. Finished**	**Production**	**Apparent consump.**	**Apparent consump. Finished**
1936	888.7	128.1	743.516	700.055	582.790	22.382	20.950	16.869
1935	779.6	127.3	667.943	636.901	542.328	19.981	18.848	15.477
1934	709.6	126.4	651.710	617.335	526.236	19.182	17.911	14.666
1933	650.8	125.6	619.715	588.384	510.131	18.359	17.211	14.392
1932	663.7	124.8	580.960	572.632	501.423	17.075	16.711	14.075
1931	778.3	124.0	655.205	638.053	542.575	19.532	18.918	15.515
1930	843.5	123.1	741.285	730.055	608.543	22.146	21.834	17.561
1929	937.2	121.8	807.374	767.058	631.507	24.324	22.854	18.017
1928	878.3	120.5	755.338	732.134	611.767	22.636	21.675	17.371
1927	873.0	119.0	771.815	722.444	605.739	22.972	21.179	17.021
1926	873.2	117.4	802.141	747.114	625.506	23.538	21.906	17.602
1925	825.1	115.8	732.710	702.712	590.941	21.606	20.563	16.650
1924	760.9	114.1	718.580	696.858	597.006	21.087	20.219	16.661
1923	763.1	112.0	796.235	732.064	615.024	22.912	21.173	17.141
1922	680.3	110.1	610.495	608.639	525.072	17.434	17.206	14.281
1921	587.4	108.5	634.238	599.567	534.940	17.553	16.519	14.150
1920	643.6	106.5	766.811	706.050	600.469	21.086	19.389	15.765
1919	673.1	104.5	662.151	635.292	547.859	18.133	17.343	14.254
1918	698.7	103.2	775.976	743.896	641.390	21.078	20.105	16.498
1917	621.5	103.3	745.221	709.872	607.943	20.308	19.217	15.648
1916	617.1	102.0	681.922	649.693	554.473	18.616	17.578	14.262
1915	573.2	100.6	623.728	595.820	520.694	16.955	16.057	13.378
1914	578.3	99.1	604.371	579.401	515.684	16.386	15.567	13.226
1913	605.2	97.2	648.711	618.767	540.472	17.578	16.622	13.836
1912	598.1	95.4	612.067	586.325	512.668	16.548	15.699	13.076
1911	565.9	93.9	583.537	556.784	496.323	15.753	14.921	12.706
1910	552.3	92.4	582.620	562.480	494.594	15.746	15.064	12.636
1909	537.2	90.5	539.490	519.798	456.424	14.544	13.874	11.613
1908	461.6	88.7	499.435	481.343	437.427	13.425	12.809	11.142
1907	503.0	87.0	553.181	534.932	471.254	14.817	14.209	11.936
1906	494.4	85.5	488.977	473.889	417.112	13.033	12.510	10.490
1905	442.4	83.8	473.112	459.334	409.197	12.595	12.117	10.306
1904	413.1	82.2	435.924	423.697	385.930	11.540	11.118	9.695
1903	418.0	80.6	441.789	432.058	392.680	11.548	11.198	9.725
1902	399.0	79.2	392.577	383.927	344.964	10.203	9.877	8.469
1901	395.1	77.6	385.247	374.668	340.931	9.852	9.474	8.223
1900	354.0	76.1	365.776	355.194	323.484	9.290	8.920	7.754

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