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by

R. U. AYRES*
L. W. AYRES**
and
B. WARR***

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* Emeritus Professor of Economics and Political Science at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.

** CMER Former Research Assistant at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.

*** Research Associate at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France

EXERGY, POWER AND WORK IN THE US ECONOMY, 1900-1998

Robert U. Ayres, Leslie W. Ayres, Ben Warr

Center for the Management of Environmental Resources (CMER)
INSEAD, Boulevard de Constance
77305 Fontainebleau, France
Email: robert.ayres@insead.fr

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 growth impetus due to fossil fuel discoveries – oil followed coal – and new applications continued through the 19th century and into the 20th, with internal combustion engines, and — most potent of all — electrification. The advent

of ever cheaper electricity in unlimited quantities 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 electrification of the US economy constitutes an extreme case of the `rebound effect'. We argue that the `rebound effect' in this case (and others) has been, in fact, the main driver of economic growth during the 19th and 20th centuries. It follows that dematerialization is unlikely to be compatible with growth. This poses important questions for the future of the world economy.

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 [Ayres 1998, 2000, 2001]. 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. The entire process also results in `learning by doing' which also increases efficiency. All three of these phenomena push costs down and complete the cycle. The `growth engine' is illustrated schematically in *Figure 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)[1] and production of entropy.[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* or *exergy*. 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 [e.g. Szargut et al 1988]. 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 fom 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 [Szargut et al 1988]. 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 (for process design) but also in economics and environmental science, as will be seen hereafter.

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.

The situation is considerably complicated by the fact that the three end-states noted above 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.[3]

However oxygen is extremely reactive and all fuel combustion is the spontaneous recombination of hydrocarbons or carbohydrates with 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*.)

There are very few physico-chemical processes that can occur spontaneously without involving oxygen. However, the oxides of most elements do not remain in the atmosphere permanently. Carbon dioxide dissolves in water as carbonic acid and reacts with other elements in solution. Sulfur oxides end as sulfurous or sulfuric acid that is deposited on the earth and which reacts further with other elements, forming sulfates. Similarly with nitrogen oxides react with water and are deposited as acid rain. In these cases, either the terrestrial surface (topsoil) or the ocean are the ultimate sinks. Metal oxides tend to be relatively insoluble (depending on the ambient acidity or pH) and in normal circumstances they remain in the soil, either bound to clay particles or as organic ligands.

Roughly speaking, unavailable energy can be equated to waste exergy, *W* discussed in a later section. It is proportional to entropy. The second law of thermodynamics states that the available fraction of total energy decreases in every process in an isolated system, although the available fraction in a given subsystem can be increased at the cost of decreasing the availability of energy in the surroundings. This is another way of saying that entropy increases in the `system' as a whole.[4]

Exergy inputs to the economy and the Kuznets curve.

As noted in the previous section fuel exergy is proportional to the usual measure of fuel energy (i.e. heat of combustion, or enthalpy.) Most economists have traditionally considered only fossil fuels as `energy' inputs to the economy. Fuelwood has generally been ignored, while agricultural inputs – which also have energy (exergy) values have been totally neglected. Perhaps this was justified because fuelwood data have been hard to locate, most fuelwood was gathered locally and consumed locally without passing through a market, and fuel wood has been relatively unimportant in recent years. The omission of agricultural inputs – both harvested crops and crop wastes – is harder to explain. We have explicitly included them, along with exergy associated with mineral inputs such as metal ores.

The various exergy inputs are tabulated in *Appendix A* and plotted for the US economy since 1900 in *Figure 2. Figure 3* shows the ratio of exergy inputs to GDP over the same period. It will be noted that when only commercial fossil fuels are considered there is an increase in the total exergy / GDP ratio during the first quarter of the twentieth century, followed by a gradual decrease. This has been called the Kuznets curve and is commonly interpreted in terms of increasing investment in infrastructure and so-called heavy industry. The gradual decline since the mid 1920s is generally interpreted in terms of the increasing efficiency and growing service content of the GDP. The latter interpretation is not unreasonable. However, when other commercial exergy inputs (fuelwood and agricultural biomass) are taken into account there is no peak in the curve; the decline is more or less continuous, although the *rate* of decline decelerates in the period 1900-1920 and accelerates again in the 1930s. The increase in commercial fuels share early in this century is largely a substitution effect. This, in turn, resulted in part from the deforestation of much of the eastern half of the nation during the second half of the 19th century and the rising price of fuelwood.

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 18th century in terms of a horse pulling a plow or a pump raising water against the force of gravity.[5] Since the discovery of the pendulum it has been realized that raising a bucket of water or going up a hill 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. Effectively a change in the pressure of a subsystem can generate a force capable of acting against resistance or accelerating a mass. 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. However, it turns out that whereas kinetic and potential energy are inter-convertible without loss (in principle), this is not true of heat and pressure. 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 19th century the notion of potential energy was generalized by J. Willard Gibbs to chemicals [6]. 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 for a non-technical reader, 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’. This is not a totally satisfactory definition, perhaps, but the foregoing examples of `doing work’ may help. 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.

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 and reproduced here [Dewhurst 1955 Appendices; Schurr & Netschert 1960 p.55, footnote].

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

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

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 and water power (near flowing streams) and wind power . (The advent of steam power in the early 18^{th} 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 not 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 20^{th} century and remained significant until mid-century until trucks and tractors displaced horses and mules (*Figure 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 [Dewhurst *et al* pp. 1113, 1116, cited in Schurr *et al* 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 [Grübler 1998, 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 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 *Figures 5-7*. (Fuelwood has never been used to a significant extent for driving prime movers, except in early 19th century railroads or Mississippi River steamboats, and there are no statistics.)

The first of these graphs (*Figure 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,

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 [*Historical Statistics*, Table S 1-14, p. 818) Electric power generation gradually became the by far the dominant use of coal, as it is today [*Historical Statistics* Tables M-113,114, p.591 and S-100, p. 826[7]] and [*Annual Energy Review*, 1998].

Figure 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 [*Historical Statistics*, M-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.

Figure 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 [*Historical Natural Gas Annual* Nov. 1999, 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 (*Appendix A-5*). Finally, *Figure 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'.

Exergy conversion efficiency trends since 1900

Figures 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 in factories and workshops. The other is increasing efficiency of converting heat or other power sources into useful work. (Needless to say, efficiency changes 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. In other words, increasing efficiency did not lead to reduced fuel consumption. Exactly the contrary occurred: prices fell sharply and demand rose even more sharply. This phenomenon has been called the `rebound effect'.[8]

The fuel required to perform a unit of mechanical work (e.g a horsepower-hour or kilowatt hour) has decreased dramatically during the same period. In the case of electric power, the heat rate (BTU per kwh) has fallen from 90,000 in 1900 to just about 10,000 today. The heat rate is the inverse of conversion efficiency, which 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 *Figure 9* [Federal

Power Commission, various years]. We have plotted the retail price of electricity (in constant dollars) to residential and commercial users on the same chart, for later convenience. It will be noted that the average price fell continuously before 1972, but has risen sharply since then.

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. On the other hand, the consumption of electricity in the US has increased over the same period by a factor of 1200, and continued to increase rapidly even after 1960, as shown in *Figure 9*. As a consequence the exergy consumed for electric power generation – and the exergy destroyed in the generating process – have also increased rapidly. This is a prime example of the so-called `rebound effect' noted above.

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 compound `triple expansion' engines – generated up to 5 MW at efficiencies above 20% [Smil 1999 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 c. 1900 had a thermal efficiency of 6%, with 50% frictional losses, the net exergy efficiency was 3% [Dewhurst *et al* 1955 Appendices 25-3,25-4 cited in Schurr *et al* 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 whereas the use of steam power in railroads was peaking (*Figure 10*) [Devine 1982].

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, rising only slightly during the next twenty years. About half of the power was lost in the belt drive systems that were standard, resulting in an overall efficiency of something like 3%, and seldom more than 5%.

By contrast a central generating plant together with it's transmission and distribution system operated at nearly 10% by 1920 and reached 33% in the mid-60s. Electric motors were then capable of 80% or so efficiency in reconverting electric power to rotary motion. rising to 90% plus in recent times.[9] 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 drive 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 about 9 percent of the national energy total and accounted for a slightly lower share (35%) of all electric power. (Recent data are unavailable, but probably comparable in percentage terms.)

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 (c. 1970) achieved 35% [Summers 1971]. 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 c. 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% [Ayres & Scarlott 1952, Tables 6,7.] But the corresponding efficiency of diesel electric locomotives c. 1950 was 28%, taking internal losses into account (ibid. Tables 7, 8). The substitution of diesel-electric for steam locomotives began in the 1930s and accelerated in the 1950s (see *Figure 11).*

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-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 trucks, buses and cars operating in urban traffic under 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 [Ayres & Ezekoye, 1991]. See *Figure 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 (typical of engines in 1920) the thermal efficiency would have been about 22% [*Figure 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. 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 AC compressor alone, when it is operating.[11]

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 [APS 1975], and perhaps 10% for a comparable European or Japanese car of the same size with manual transmission.[12] In 1972 US passenger vehicles averaged 13.5 miles per gallon [EIA 1999], 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.

A more detailed analysis of energy losses in automobile transportation (c. 1990) that distinguishes between urban driving (12.6%) and highway driving (20.2%)

is summarized in *Figure 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% which implies that 100% conversion efficiency would correspond to only 125-135 mpg.

On the other hand, the average thermodynamic efficiency of motor transportation (including trucks) in 1989, as calculated by the USEPA, was only 8.33%.[13] This seems more plausible, 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 Goldemberg et al 1987; Bleviss 1988; Lovins 1996; Lovins et al 1996].[14]

The passenger vehicle fleet of 1990 achieved about 50% more vehicle miles per gallon of fuel than it did in 1972. This was only partly to drive train efficiency gains but mainly to weight reductions.[15] 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 [EIA 1999].[16]

We can roughly equate VMT with work done, which implies (for purposes of this paper) that overall exergy conversion efficiency for all motor vehicles is roughly proportional to average mpg. The proportionality constant is uncertain, but normalizing to 1989 (15.9 mpg, 8.33% efficiency) we take it to be mpg times 0.52, as shown in *Figure 14.* 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 discussed later.

For aircraft up to 1945 most engines were piston-type spark ignition ICEs and fuel was high octane gasoline (so-called aviation fuel). Engine efficiencies were comparable to those achieved by a high-compression engines (12:1) under variable 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 war, 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 below [Smil 1999 p.164]:

1955	first generation turbojets (Comet); index 100
1960	early turbofans; index 85
1970	second generation turbofans; index 70
1980	third generation turbofans; index 65
2000	advanced turbofans; index 55

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.

Direct heat and quasi-work.

Obviously a considerable fraction of the fuel inputs to the economy is still used for heat, although the fraction is somewhat less than it was a century ago. 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 chemical processes like ammonia synthesis and petroleum refining. The second case is intermediate, viz. 100°C - 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 hot air.

There are no 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 [Lovins 1977, Figure 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. In the residential and commercial sector low temperature heat is used for space heat, cooking, and hot water for washing. These allocations are simplistic but not implausible.

As indicated, process heat and space heat do not `do work' in the usual sense, so it is not possible to calculate an exergy output/input (`first law') efficiency in all cases. However, process improvements that exploit improvements in heat utilization may be classed as thermodynamic efficiency gains, no less than the use of turbo-chargers 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 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' [APS 1975]. The product of second-law efficiency times exergy input can be regarded as `useful' heat delivered to a point-of-use, or perhaps `pseudo-work'. The same approach can also be used to evaluate residential and commercial heat uses, such as space heating and water heating.

We consider high temperature industrial heat first. The iron and steel industry is the obvious examplar. 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 Fe/C ration is a true measure of efficiency, as regards the use of this resource. In 1900 the Fe/C ratio for the best available technology was about 20-25% expressed in terms of the theoretical maximum of 100%. By 1970 the best available technology for iron ore reduction had increased to 80% as shown in *Figure 15* [Ayres *et al* 1994, *Fig. 5*]. 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 [Smil 1999 p. 167].

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 [NAS/NRC 1989]. 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 [Elliott 1991]. 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 [de Beer 1998]. 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. Rolled steel output embodies 6.62 GJ/t, with other 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.) 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. Gyftopoulos et al 1974; Hall et al 1975; also Ayres 1989].

If the best available technologies c. 1973 had been used, the second law efficiencies would have been 35% for iron and steel, petroleum refining, 12% for petroleum refining, 16.8% for aluminum and 17% for cement [Gyftopoulos *et al* 1974]. Given a 20 year half-life for industrial plants [Salter 1960; Landsberg *et al* 1963], 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.

The case of exothermic industrial processes was mentioned in the previous section. A prime example is pulp and paper manufacturing, which is a major energy consumer (2.46 quadrillion BTU in 1985 and 2.63 quads in 1994 – about 3% of the national total – about half of which was purchased electricity or fuel. The best 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. 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 hemi-cellulose 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 [Herzog & Tester 1991]. 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.

There is a major breakthrough possibility in the near future. 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) [Herzog & tester 1991]. However, gasification of the lignin waste followed by gas-turbine co-generation offers the potential of becoming self-sufficient in both heat and electricity (ibid). However, this may be optimistic, since theoretical analysis suggests that the absolute minimum exergy consumption for kraft paper manufacturing is slightly greater than zero [Hall *et al* 1975].

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 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 [Williams *et al* 1994].

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 [Joyce 1991]. The dramatic reduction in energy requirements (over ten-fold) is one of the reasons why prices have fallen and demand has risen accordingly. Of course, this is somewhat misleading, since it does not include exergy embodied in the plastic itself, which is non-trivial.

A few exceptions to the `no data' rule are worthy of mention. Ammonia production is probably the most dramatic example. 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 catalytic synthesis process – the original version of the process now employed everywhere – achieved 100 GJ/tonne by 1920 (using coal as a feedstock) [Smil 2001 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 [de Beer 1998 chapter 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 steel, pulp and paper, ammonia, HDPE and soda ash are plotted in *Figure 15*.

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 data, at least in a convenient form. If one takes the efficiency improvement in the steel industry (roughly 3-fold) as a model for the efficiency gains for high temperature heat elsewhere in manufacturing (*Figure 14*), it would follow that the average exergy efficiency of high temperature heat use in the industrial sector as a whole in 1900 was around 7 %. We make this assumption in *Table 1* below.

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 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% [APS 1975; OTA 1983]. A British study obtained a lower estimate of 14% [Olivier at al 1983]. 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% [Ayres & Scarlott 1952, Table 12]. Incidently, 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 much too high.

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 [APS 1975] concluded that heat 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. However another factor must be considered: a `typical' house is poorly insulated and uses around 8 times as much heat as a well-insulated one [Ayres 1989]. 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.[18]

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. The penetration of new technologies, such as solar heating and electric heat pumps has been very slow so far.

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 (*table 1, figure 16*). This table incorporates numerous assumptions, 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.

Improved performance in domestic and commercial space heating has been due mainly to better insulation. 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 1* and plotted in *Figure 16*, we calculated the primary (thermodynamic) work done by the US economy since 1900, by source, shown in *Figure 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.

Table 1. AVERAGE EXERGY EFFICIENCY OF PERFORMING WORK, PERCENT					
Year	Electric power generation & distrib.	Other mechanical work, e.g. 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	10			
1960	31.3	9.6			
1970	32.5	9.3	20	14	2
1980	32.9	10.4			
1990	33.3	13.4	25	20	3

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.

Service output per unit work (SOPUW) 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. ton-miles or passenger miles per unit of fuel), 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 or SOPUW measures rather than primary work. 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 consider secondary and tertiary services performed by electric power and mechanical power.

We consider electric power first. Electrolytic reduction of aluminum, magnesium, chlorine and a few other materials is a good example of secondary work. Aluminum production from aluminum oxide (alumina) is the best example where historical data are available. 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 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) [Schurr *et al* 1960 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 [Spreng 1988].

The `practical limit' for electrolytic reduction is said to be 5 kwh/kg and the thermodynamic limit is 2.89 kwh/kg [Atkins *et al* 1991]. (To this, of course, must be added the consumption of carbon electrodes. However, it is clear that the potential for future efficiency gains is now rather limited. Note that the above does not take into account the energy consumed in the prior bauxite processing stage (currently 3 GJ/t), 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 (20-40 MJ/kg) or even copper (40-60 MJ/kg).

Metal cutting, drilling and grinding, an important subclass of machine drive, 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 [Ayres 1991]. 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 20th century rotational speeds were limited to a few hundred rpm. Today tools state of the art machines operate at much higher speeds, up to a few thousand rpm. Higher rotational speeds mean faster cutting with less heat loss and lower energy requirements. Future gains of ten-fold or more therefore appear possible in the realm of metal cutting efficiency. 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 [Ayres 1989 Appendix A].

The APS study cited earlier estimated second law efficiencies of 4% for refrigerators and 5% for air conditioners in 1970 [APS 1975]. 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 *Figure 9*. According to one source, 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' [McMahon 1991]. Another source records even greateer progress in residential refrigerator efficiency, from 1726 kwh/yr in 1972 to 690 kwh/yr in 1993 [EPRI 1993]. Even larger gains are possible (and have been achieved in Scandinavia and Japan).[19] 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.

Electric light can be regarded as another sort of secondary work. Electric light accounted for about 14% of electric power output and 3.5 % of all US energy consumption in 1979 [Ayres 1989, Appendix A]. The improvement in the efficiency of `best case' electric lighting, from 1900 on is shown below [Nordhaus 1994, Table 3]:

Table 2. Improvements in efficiency of electric lighting from Nordhaus 1994, Table 3.			
Date	Type of light	Efficiency, lumens/watt	Lumen-hrs/mbtu
1900	incandescent, carbon filament	3.714	1089
1910	do	6.5	1905
1920	incandescent, tungsten filament	11.82	3464
1930	do	11.84	3471
1940	do	11.9	3488
1950	do	11.925	3495
1960	do	11.95	3502
1970	do	11.975	3510
1980	do	12.0	3517
1990	do	14.167	4152
1992	compact fluorescent bulb, 1st generation	68.278	20011

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 efficiency terms. Evidently incandescent lamps achieved no more than 1.5% efficiency at first, and 5% efficiency at best, while the best compact fluorescents available today are now about 31% efficient. Unfortunately, we have no data on the average performance of installed lighting systems.

The efficiency of light production is not the whole story, of course. Much more can also be done to increase end-use efficiency by distributing light where it is needed. A 15W light focused directly on the page of a book is as effective as a 100W 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.)

Summarizing 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 [e.g Lovins]. In short we lack a baseline figure for the end-use efficiency with which electricity is used in the US economy. Nevertheless, 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.

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. Green estimated the efficiency of passenger cars in 1990, as noted previously, as 15-16% [Green ?]. The measure commonly used is vehicle miles traveled (VMT), rather than passenger (or payload) miles traveled. The latter would make more sense and which would correspond better to measures used in bus, rail and air transport modes.

The average fuel economy of the vehicle fleet (in VMT) increased significantly from the early `70s until about 1988, entirely thanks to government regulation.[20] But the increase owed little or nothing to improved engine thermal efficiency. The 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 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 $0.2 \times 0.16 = 3$ % 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. 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 ton-miles. From 1920 to 1950 the improvement by this measure was 3-fold, 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 war because diesel engines were far more fuel-efficient – probably by a factor of 5[21] – and also required significantly less maintenance. But from 1950 to 1960 the VMT output per unit exergy input quadrupled and from 1960 to 1987 there was a further gain of over 50% [Summers 1971; DOT various years]. The overall performance increase from 1920 to 1987 by this measure (ton-miles per unit of fuel input) was around 20-fold. In 1920 US railways consumed 135 million tons of coal, which was 16% of the nation's energy supply. By 1967 the railways share of national energy consumption had fallen to 1% and continued to decline thereafter [Summers 1971; DOT various years].

This implies that end-use efficiency for railroads in the early part of the century must have been very low indeed, since it has been increasing so rapidly. 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 100 kg/hp. By 1950 this had fallen to about 25 kg/hp and by 1980 to around 18 kg/hp [Larson et al 1986 p. 38]. The lighter the engine, the less power is needed to move it. (This is another 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 end-use 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.

In the transportation domain, fuel consumption per unit of service output by new passenger cars (measured in VMT) nearly halved between 1970 and 1989, thanks mainly to the CAFE standards. But for the motor vehicle fleet as a whole (including trucks) the end-use efficiency improvement since 1970 has also been about 30%.

Theoretically if the end-use efficiency (SOPUW) gains are interpreted as `secondary work' and if the statistics were readily available, they could be added to the efficiency gains of primary work to further modify the estimate of useful work input to the economy, further modifying the work estimate in *figure 17.*

Conclusions: efficiency, growth and the rebound effect

The first conclusion from the above analysis 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.

The second conclusion from our analysis is that thermodynamic efficiency improvements in the production of primary work can account for most of the so-called `Solow residual', namely that portion of economic growth attributable to `technical progress.' Secondary work (end-use efficiency improvements) in transportation and some uses of electric power e.g. for lighting) may account for a considerable part of the remainder. We conjecture that the unexplained part of the Solow residual (since 1980) may be mostly attributable to the impact of information technology.

The third important conclusion is that, technical progress in the past notwithstanding, there is still an enormous potential for future reductions in exergy consumption, especially in the residential and commercial heating area.

A fourth and final conclusion of this paper is that the locus of technical progress has moved from energy (exergy) conversion efficiency to end-use efficiency or service output per unit of work (SOPUW). Purely thermodynamic efficiency improvements 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 other factors. 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.

A subtler but related, and arguably more important, question is whether the rebound effect is still the primary driver of economic growth 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 the publication *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 the *Economic Report of the President, 1996* (Tables B-32 and B-43) for labor and both from the US Government Printing Office. 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 *Survey of Current Business*, May 1997, 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.)

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 *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 the US Department of Energy, *Annual Review of Energy Statistics*. Data on other minerals and metal ores are from the US Bureau of Mines, *Minerals Yearbooks* and (since 1995) from the US Geological Survey. We have calculated the exergy for all fuels as a multiplier of heat content; exergy for other materials was calculated using standard methods [Szargut et al 1988; Ayres et al 1998].

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. 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 percent 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 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.

1. Exergy is a technical term with a precise definition in thermodynamics [Szargut et al 1988], but for our purposes it is `useful' or `available energy', which is what non-specialists mean when they use the term energy.

2. 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.

3. Another perspective is that if the earth-sun system were in thermal equilibrium, the earth would have to radiate energy at the same temperature as the solar flux it receives (6000°K). The fact that the earth's surface exists at a much lower temperature (300°K) is a consequence of the disequilibrium state. This disequilibrium means that the solar flux is doing work on the surface of the earth and, in so doing, reducing its entropy. In lay terms, the reduced entropy is equivalent fo increasing `order' which means increasing the diversity and distinguishability of forms and materials on the earth's surface. The hydrological cycle is, of course, on of the major engines for `terraforming' by creating valleys, eroding hillsides and creating alluvial land, providing rainfall in continental interiors, convecting heat from the tropics to the temperate and polar regions, and so forth. The biosphere is an even more potent agent of diversification and landscape modification. The entropy-reducing processes are essentially information creating processes. The diverse, inhomogeneous earth is an

enormous storehouse of information. Human activity, which creates new shapes and materials adds still more to the information-creattion of natural processes. It is very tempting to equate value added by human activity to information added by local entropy reduction. We return to this point later.

4. The `system’ is another undefined concept. To be more precise, a system may be open or closed. An open system can exchange energy and mass with other systems. A closed system can exchange energy but not mass. An isolated system can exchange neither. Entropy always increases in an isolated system, but strictly speaking this applies only to the universe as a whole. The solar system is closed but not isolated, since it radiates light and heat to the rest of the universe. The earth is also (approximately) closed from a material standpoint but it is not isolated, since it receives a steady influx of exergy from the sun and re-radiates low termperature thermal heat to the rest of the universe. Solar exergy can be intercepted (e.g. by photosynthetic organisms) and stored on earth, thus increasing terrestrial `negentropy’. However the entropy law still holds for the universe as a whole.

5. 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.

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

7 Unfortunately, the two tables do not agree; the differences are small but not negligible.

8. This is, of course, the `rebound effect' that has recently preoccupied energy conservation advocates. The point is that in some circumstances energy efficiency gains translated into price reductions result in demand increases that over-compensate for the efficiency gains, thus undermining the case for attempting to achieve conservation through efficiency. See [Lovins 1977; Brookes 1979, 1990, 1992,1993; Khazoom 1980, 1987; Saunders 1992; herring 1998,1999]

9. 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% 9and as low as 30% in extreme cases) [Lovins 1977].

10. The following analysis is taken largely from a report from Ford Motor Co. [Kummer 1974] and an American Physical Society (APS) summer study held in 1975 [Carnahan et al 1975]

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.

12. An earlier but similar analysis based on 1947 data arrived at an estimate of 6.2% for automobiles, based on gasoline input [Ayres & Scarlott 1952]. The authors point out that starting from crude oil, and allowing for a 10% loss in refining and another 10% loss in distribution, the effective net efficiency of fuel use would be 5%.

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 (3Q). waste heat out 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. Needless to say, such a vehicle would have to be much lighter than the current ones, which would depend upon radical design changes and use of light composites (dematerialization). Indeed 200 mpg is theoretically possible [Smil 1999].

15. Contrary to widespread assumptions, there has been little or no improvement in engine thermodynamic engine 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.

16. 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 [Summers 1971].

17. As noted above, aluminum smelting is an electrolytic process (as are copper refining and chlor-alkali production). Hence this discussion properly belongs in the previous section where electrolytic processes were discussed. N.B. the graph of aluminum smelting efficiency (*Figure 15*) refers only to the electrolytic stage of the process; a more complete analysis must take into account all of the associated processes, including bauxite processing and electrode manufacturing [Gyftopoulis *et al* 1974].

18. 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 [Schurr & Netschert 1960 p. 49,

footnote].

19. The Swedish Electrolux company produced models back in 1958 consuming 3.8 kwh/24hrs 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 undated].

20. In particular, the so-called Corporate Average Fuel Economy (CAFE) standards, imposed after the Arab oil embargo and oil crisis of 1973-74.

21. According to a study published in 1952, diesel engines can perform 10 times as much work as steam engines in switching operations, 5 times as much in freight service and 3 times as much in passenger service [Ayres & Scarlott 1952 p. 311]. The overall gain might have been about a factor of 5.

Table A-1a: Sources for Coal

Material	**Title**	**Period**	**Source**	**Mass (1 short ton = .9071847 metric tons)**		**Heat Content (1 Btu = 1055.056 joules)**	
				Reference	**Series name and/or formula**	**Reference**	**formula**
Coal Exergy = Heat* 1.088	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

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

Table A-1b: Sources for 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**	**formula**
Petro-leum 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				

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-1c: Sources for Natural gas

Material	Title	Period	Source	Mass (cubic feet=metric tons*50875.05)		Heat Content (1 Btu = 1055.056 joules)	
				Reference	**Series name and/or formula**	**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				

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-1d: Sources for Fuelwood and biomass

Material	**Title**	**Mass (million cubic feet roundwood equivalent*(.017to.022)=MMT. Multiplier time dependent**			
Fuel wood Exergy= Heat* 1.152	Fuelwood production = consumption	**Period**	**Source**	**Reference**	**formula**
		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

Figure 1. The Salter Cycle growth engine

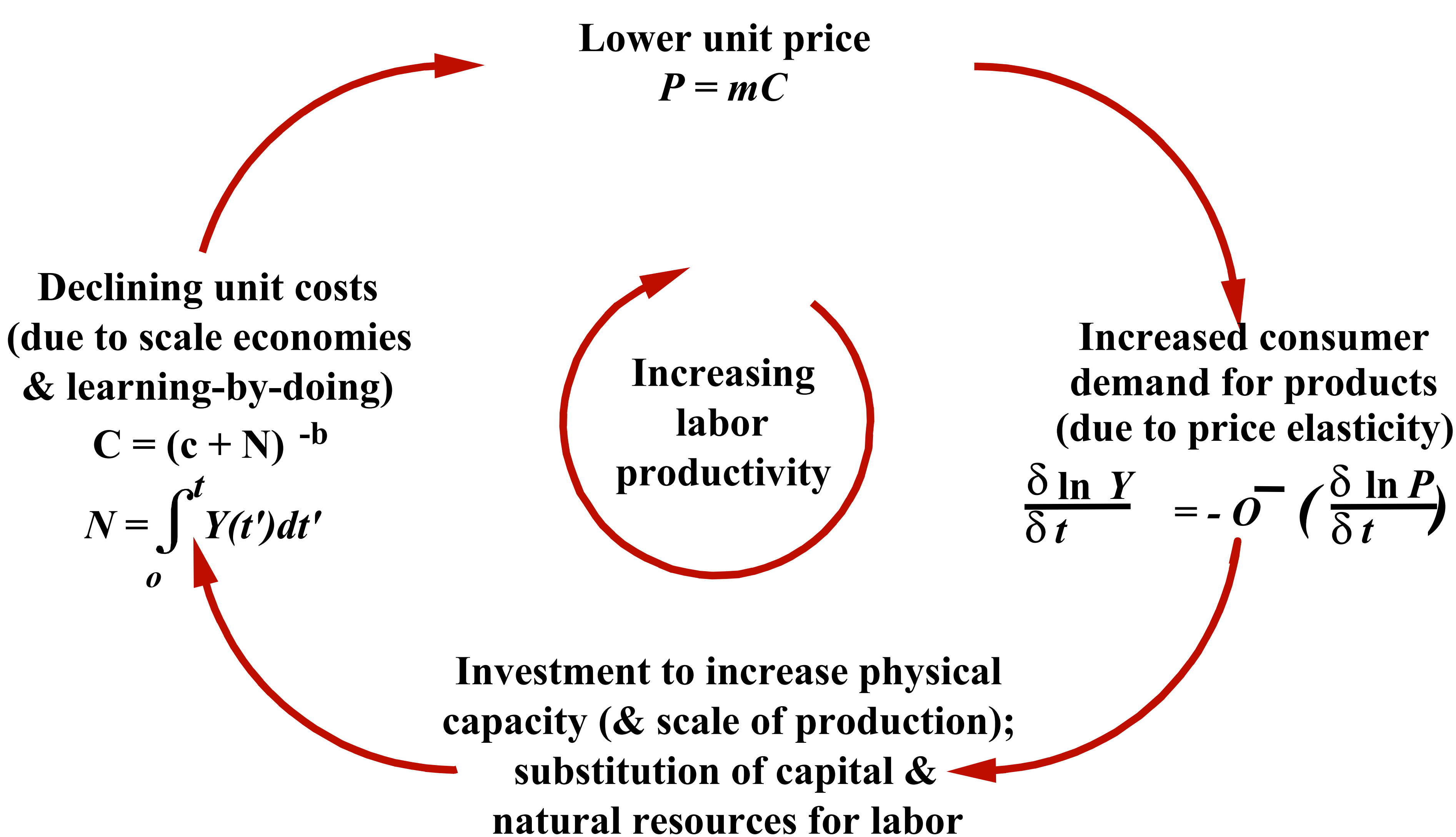


Figure 2. Breakdown of Exergy Input into the Economy, USA 1900 - 1998

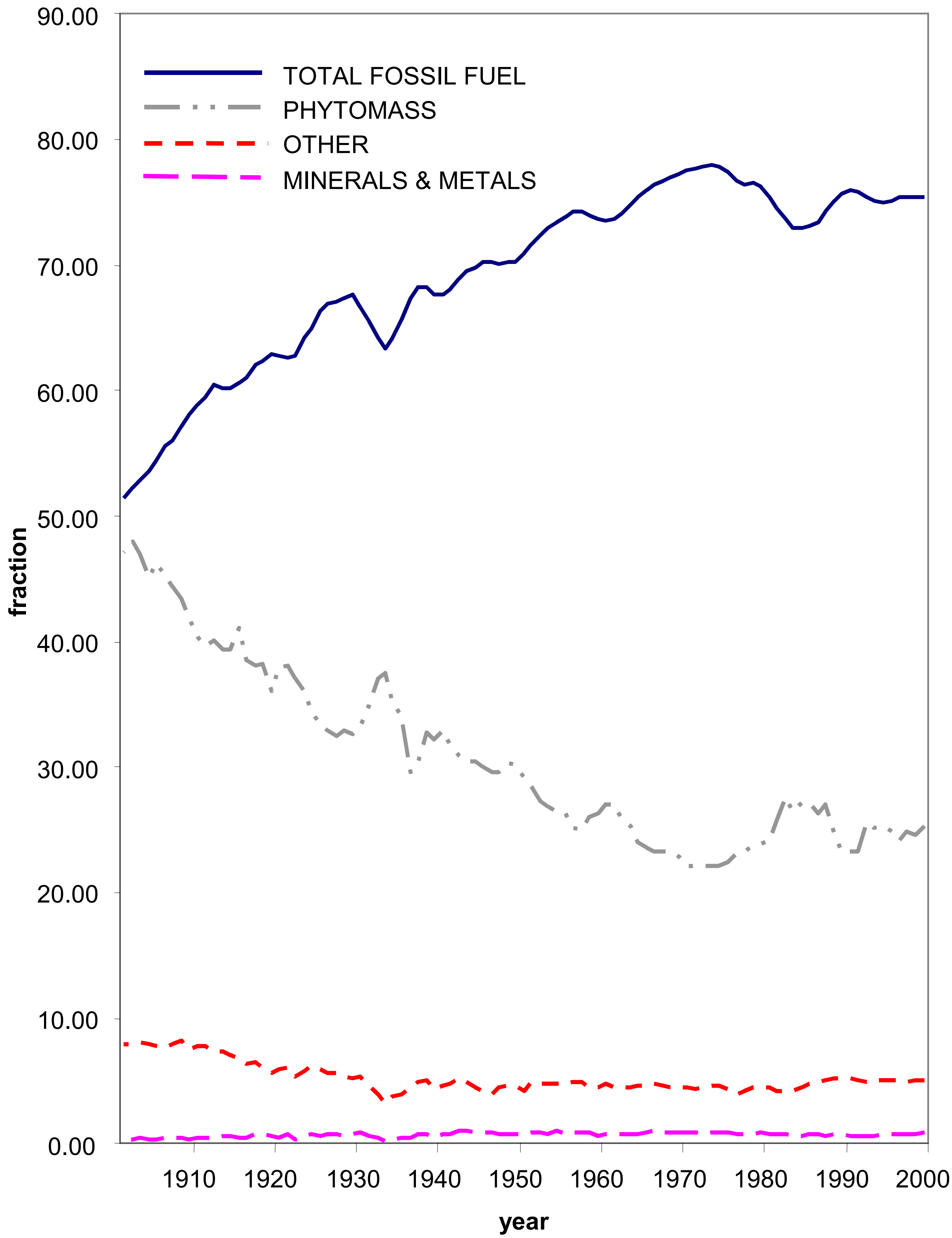


Figure 3. The ratio of exergy inputs to GDP, USA 1900-1998

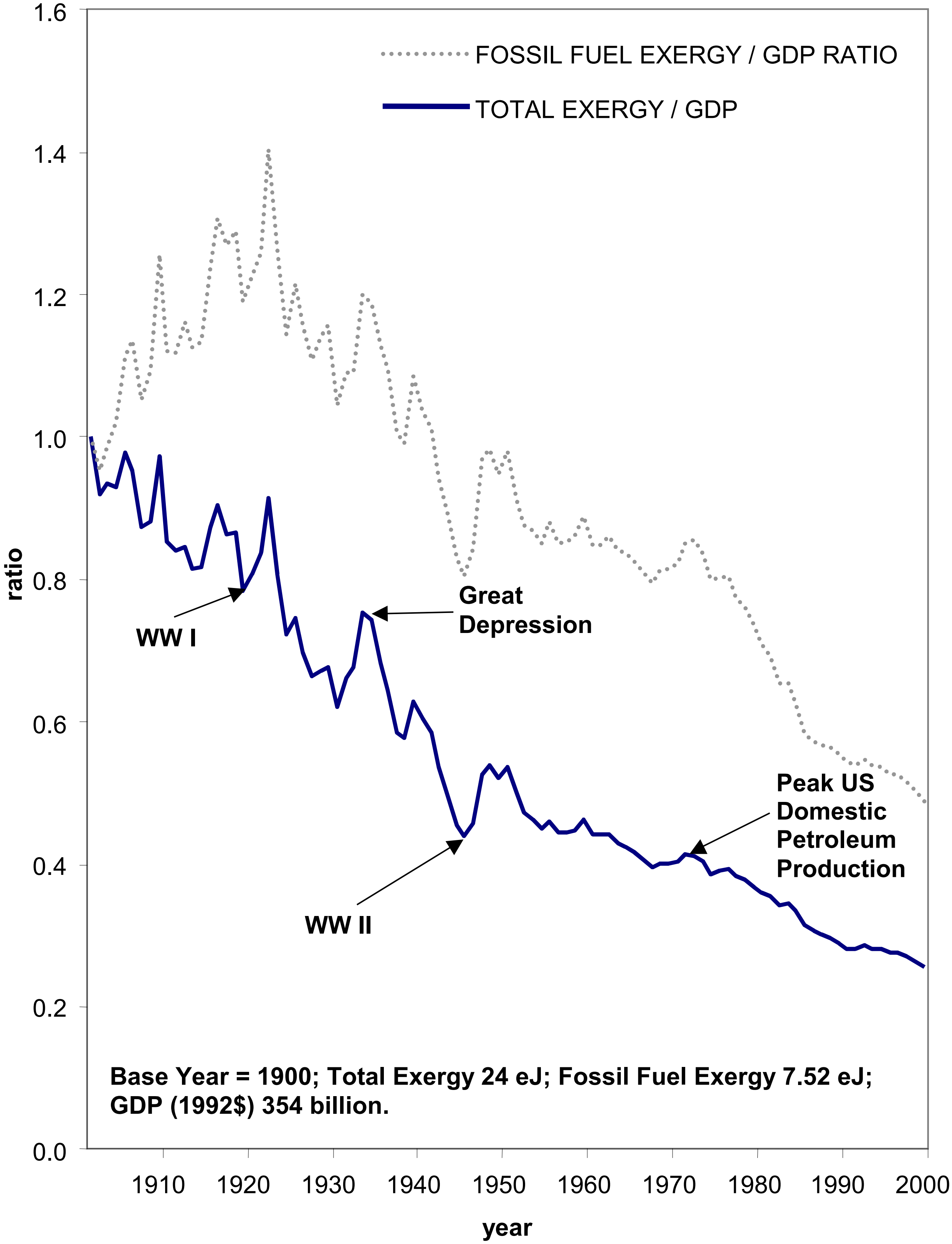


Figure 4: Farm mechanization
Substitution of machinery for animals

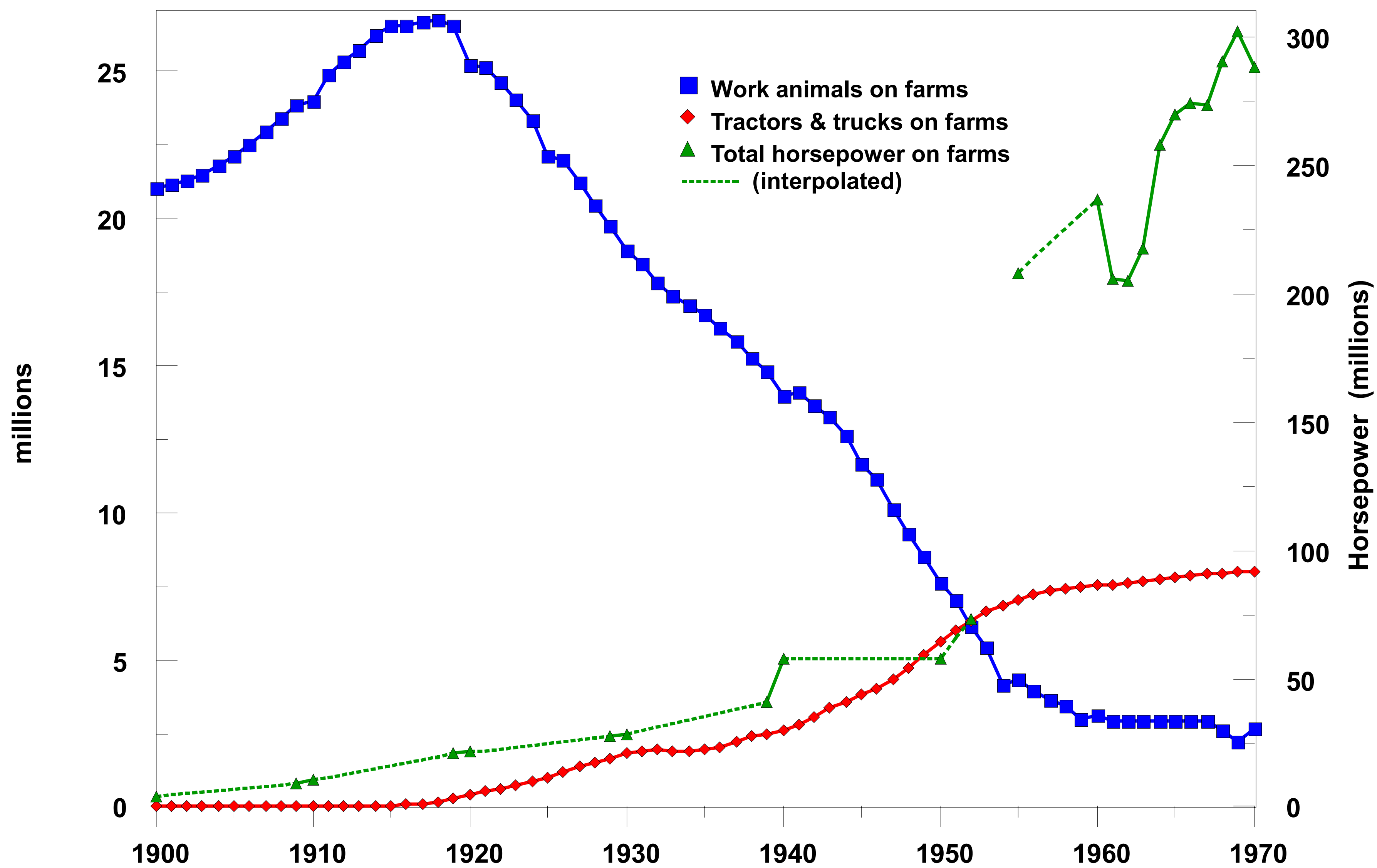


Figure 5. Coal: Fractions of coal exergy apparent consumption, USA 1900-1998

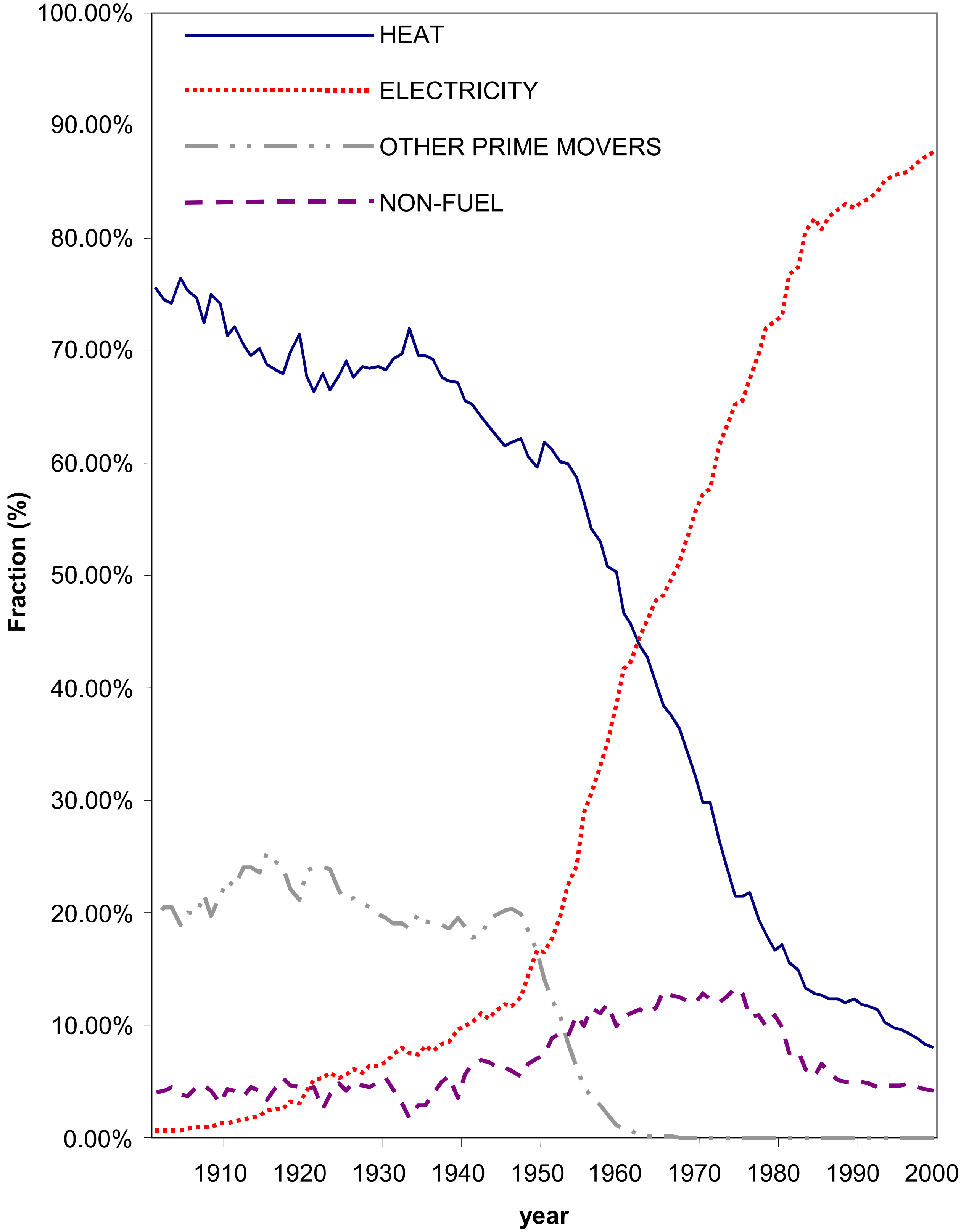


Figure 6. Petroleum: Fractions of petroleum exergy apparent consumption, USA 1900-1998

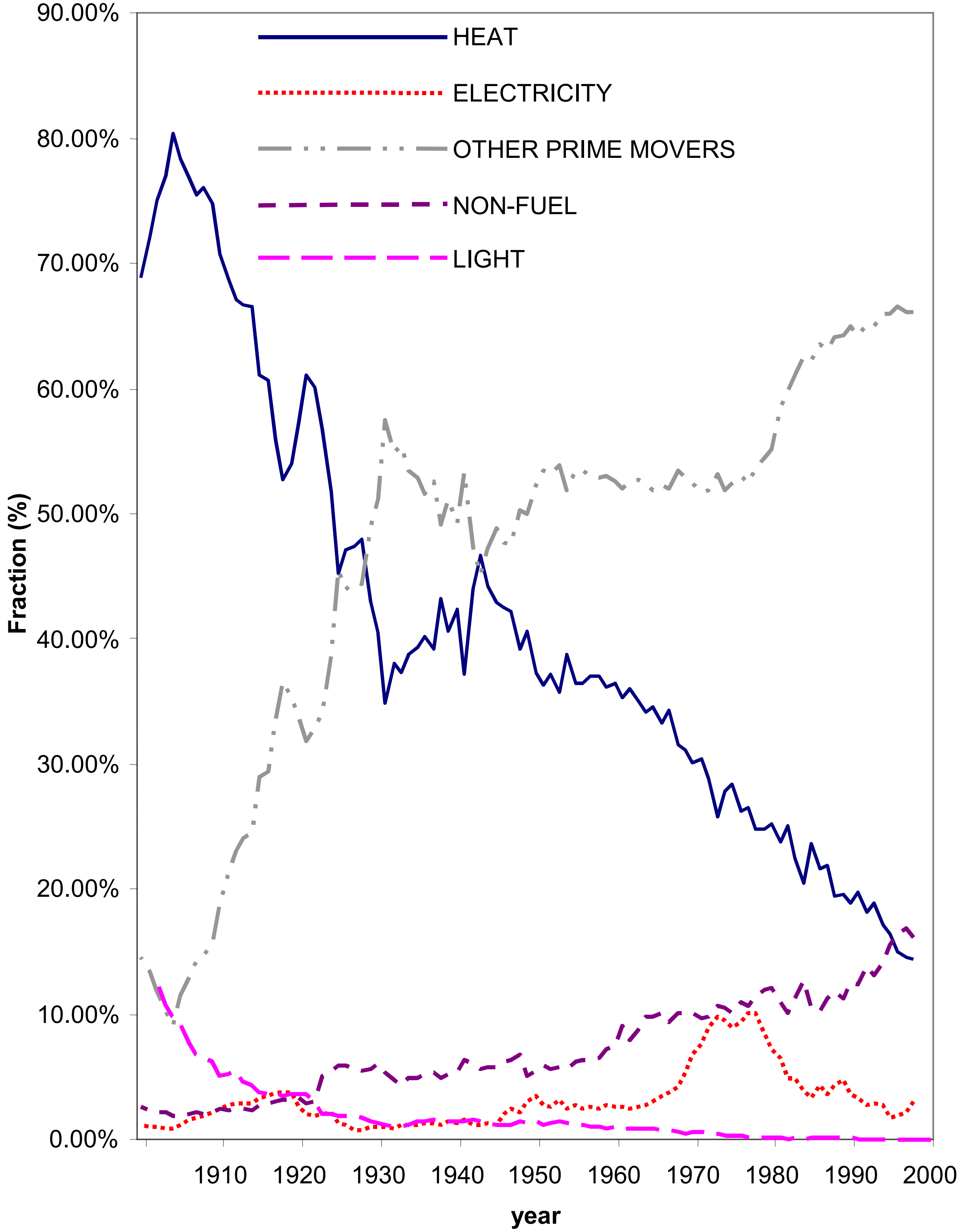


Figure 7. Gas: Fractions of gas exergy apparent consumption, USA 1900-1998

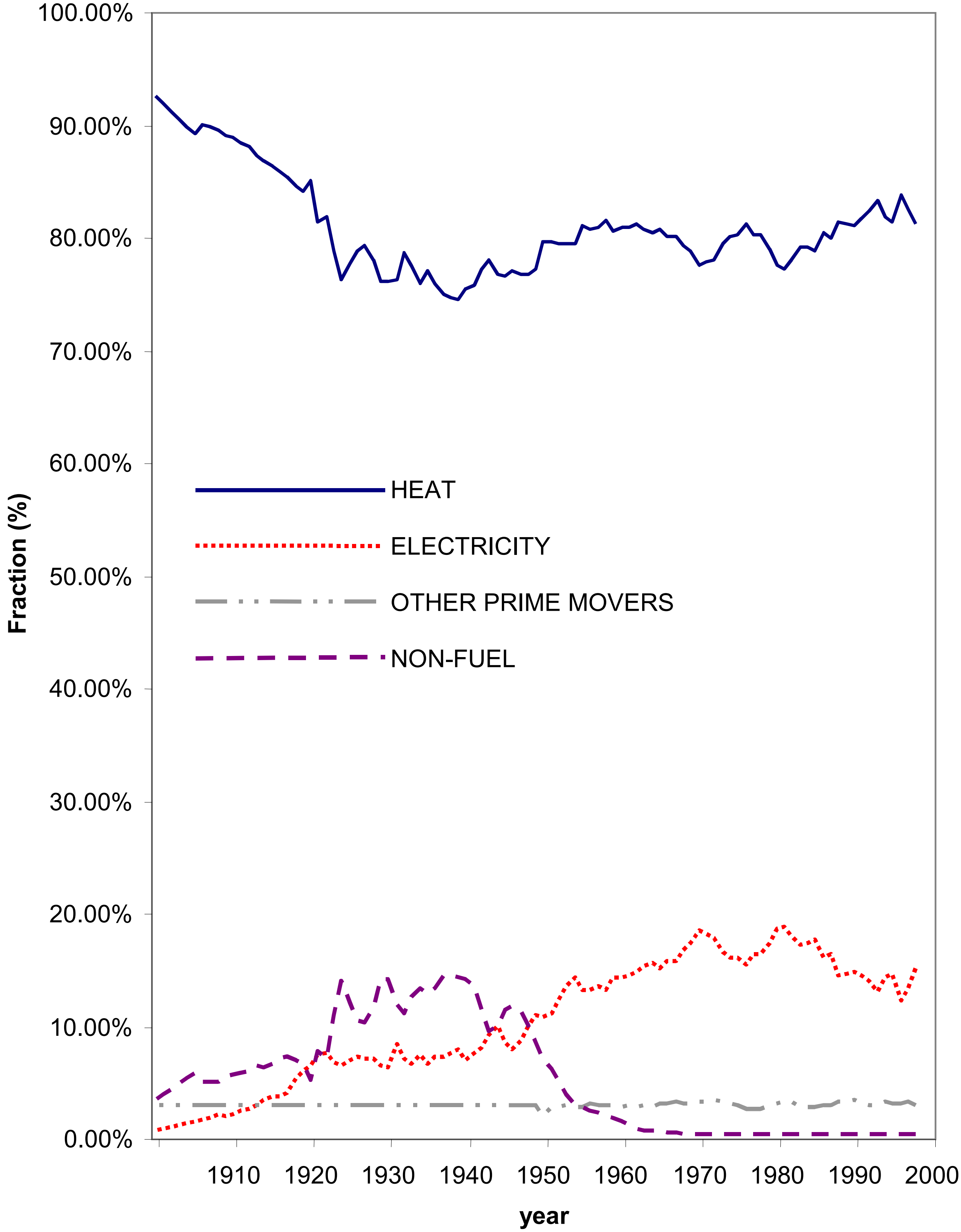


Figure 8. Fractions of fossil fuel exergy apparent consumption, USA 1900-1998

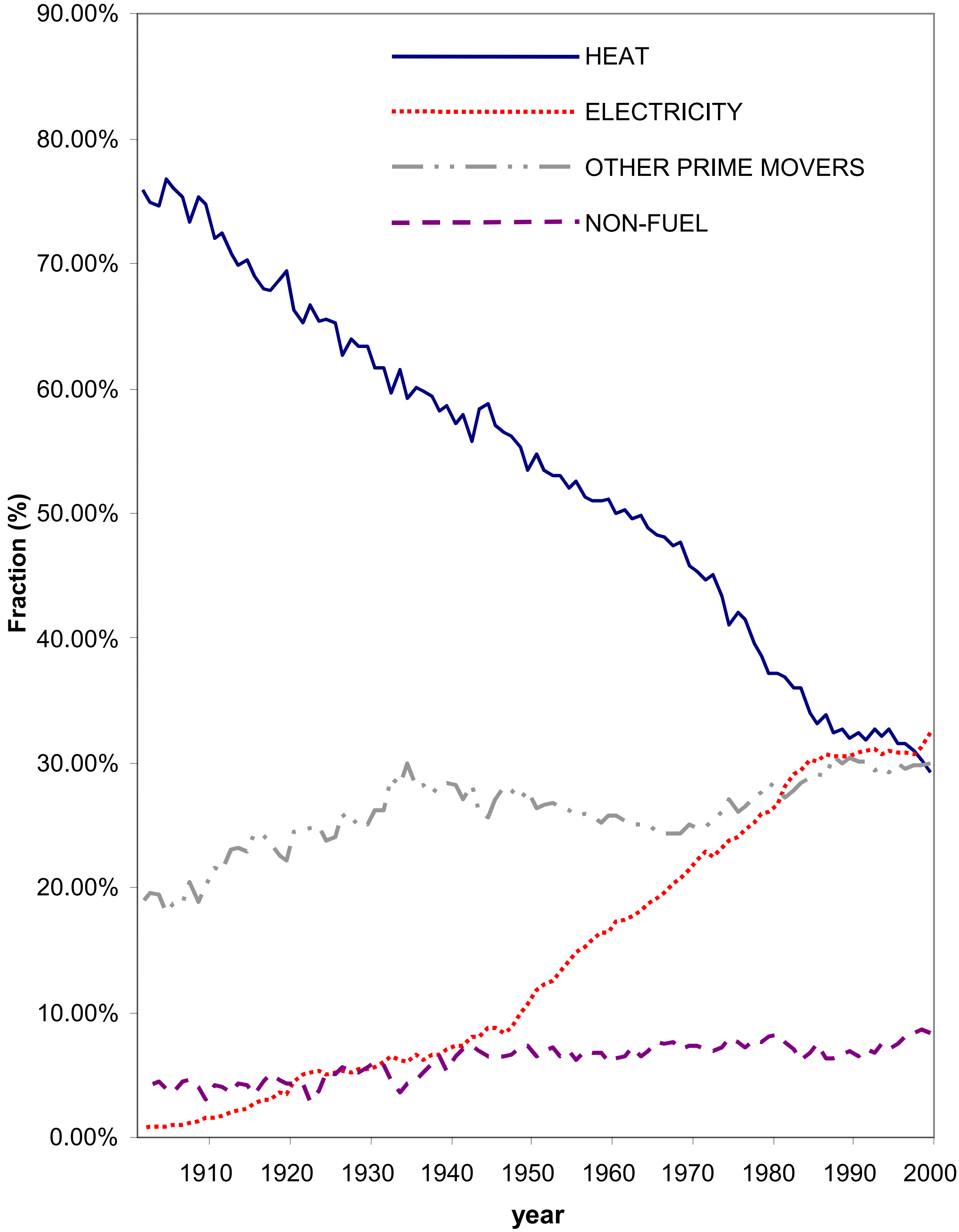


Figure 9. Electricity production and conversion efficiency

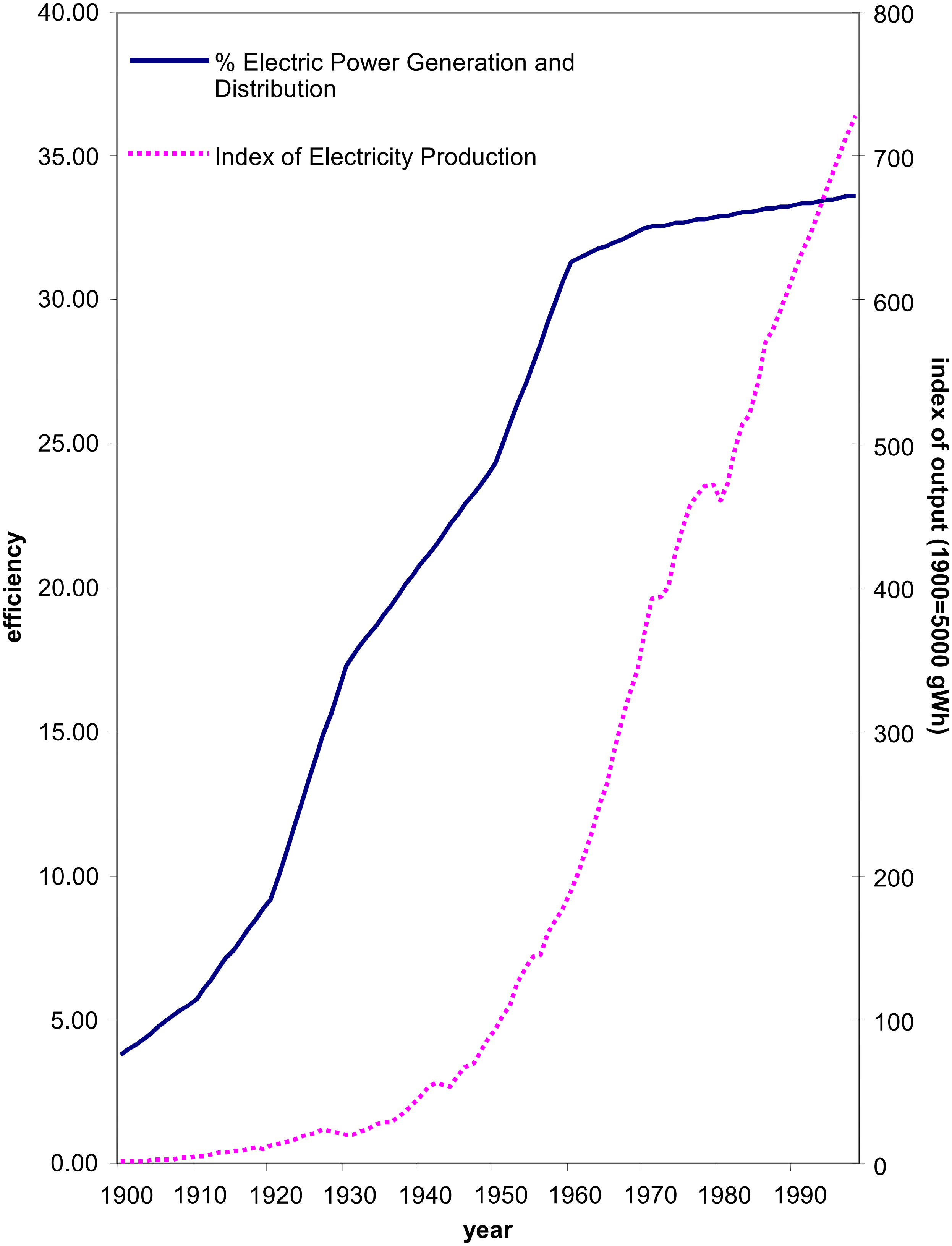
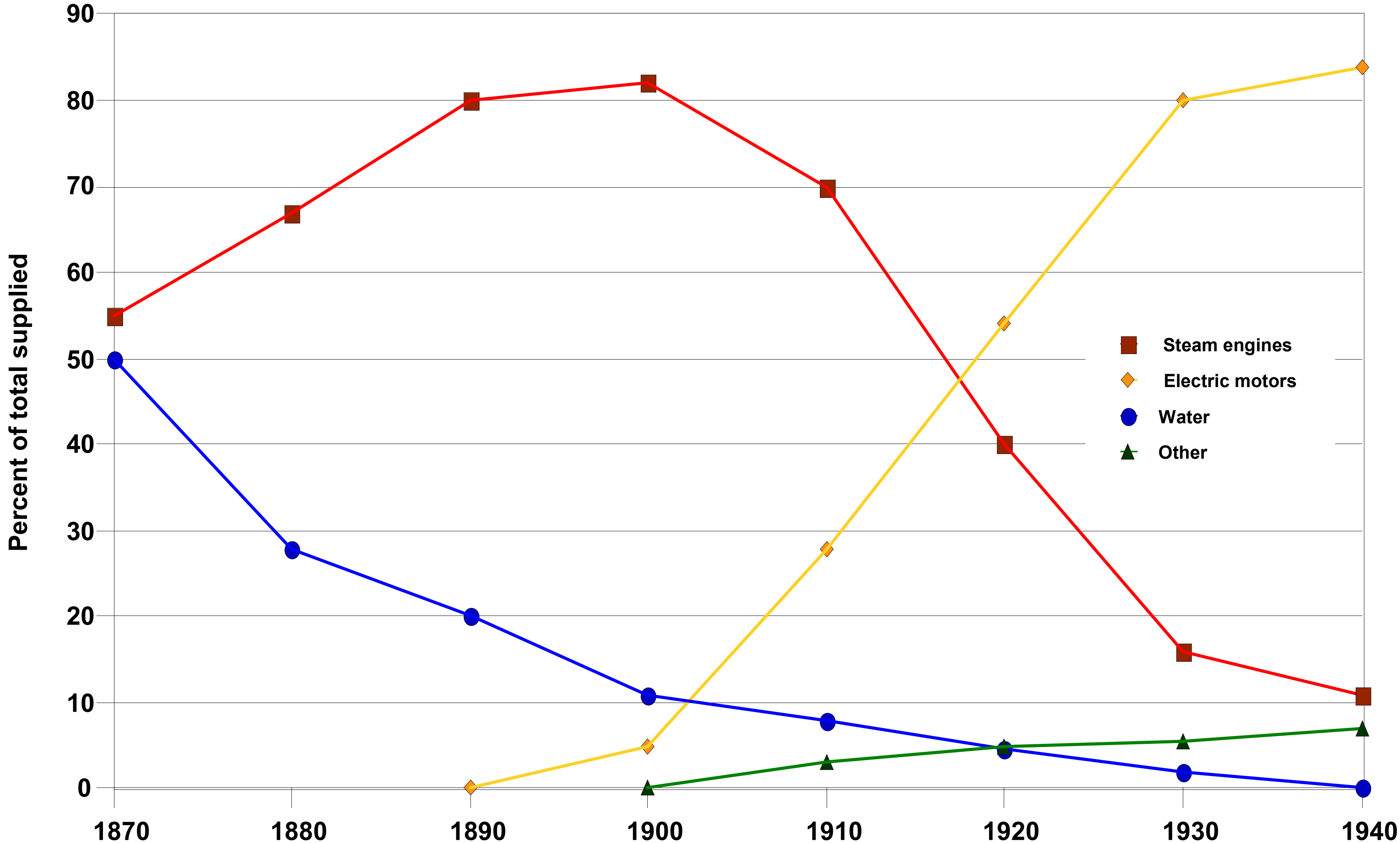


Figure 10: Sources of mechanical drive in manufacturing establishments: USA 1869-1939



Source: [Devine 1982]

Figure 11: Substitution of Diesel for steam locomotives in the USA, 1935 -1957

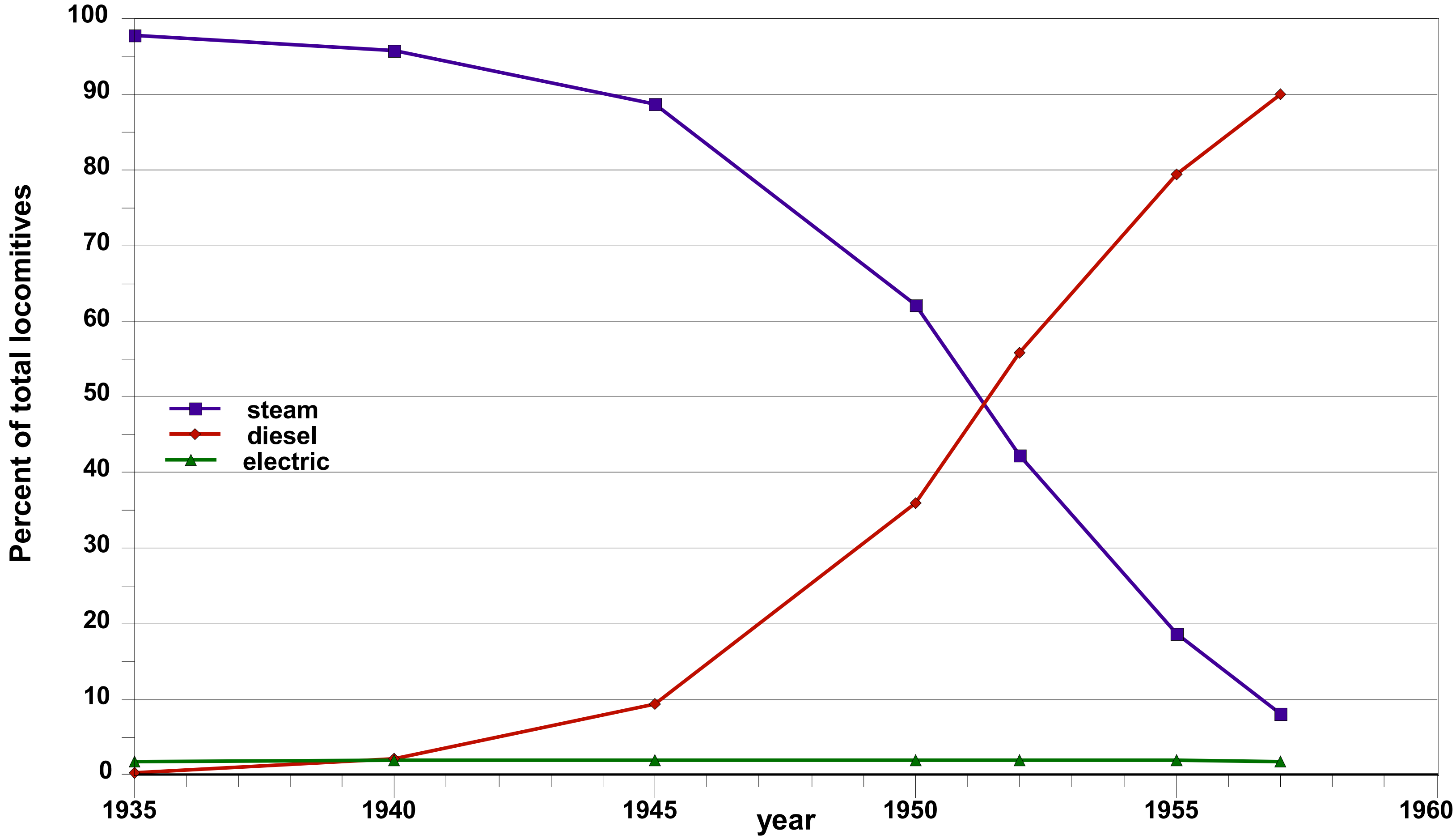


Figure 12: Compression ratio in auto engines: USA 1926-1975

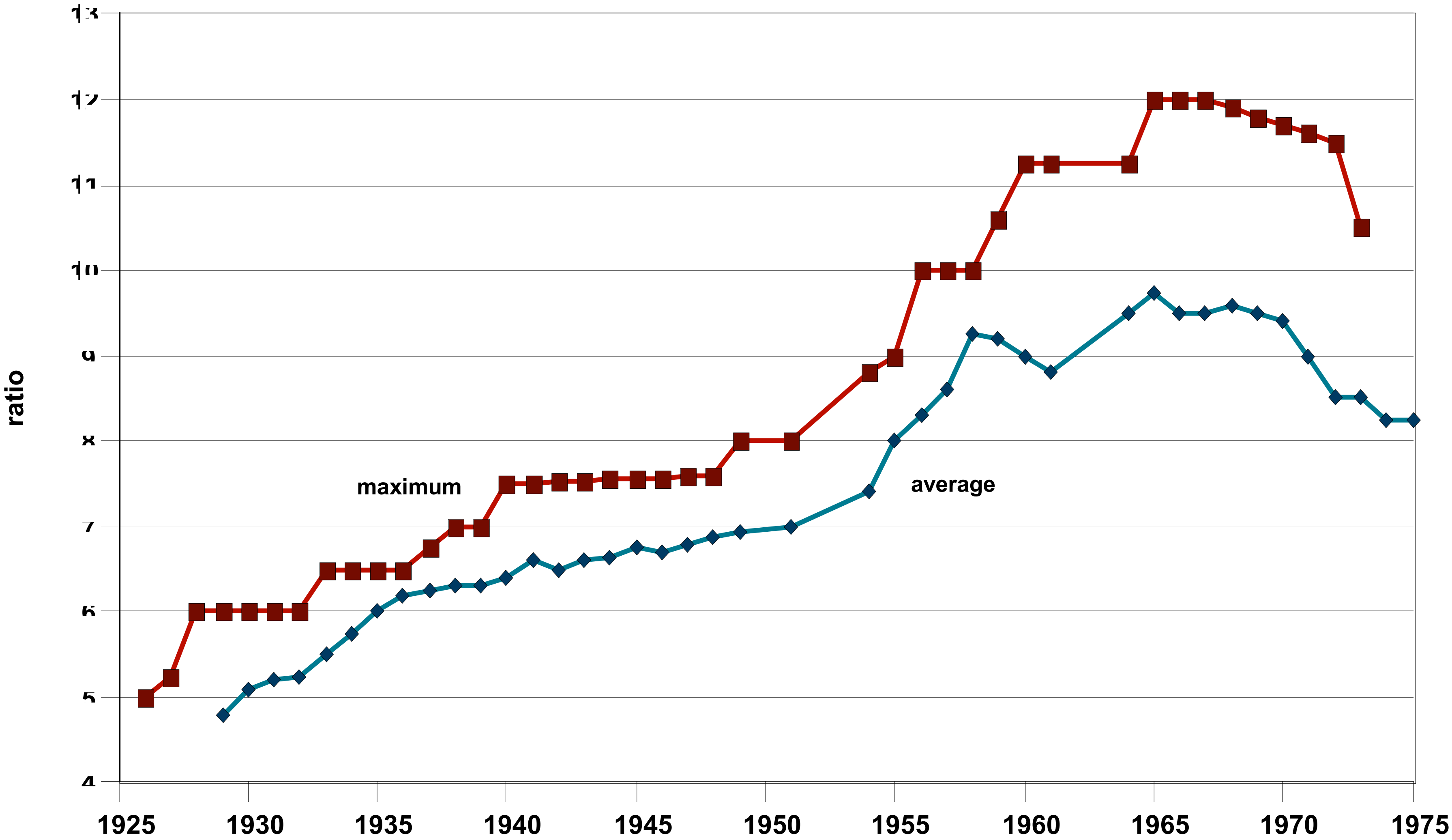


Figure 13: Internal combustion engine efficiency

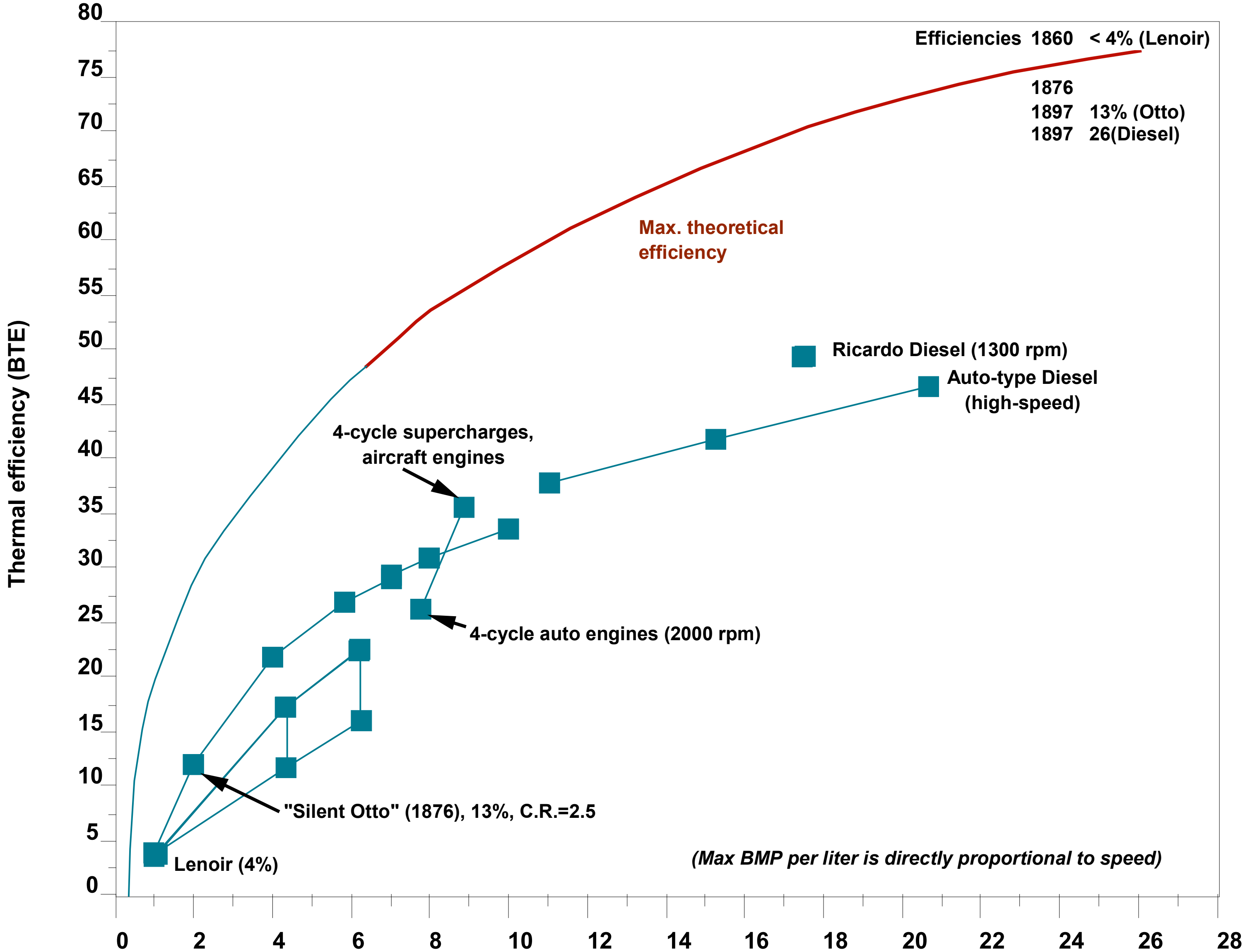


Figure 14. Vehicle fuel rates and energy conversion efficiency.

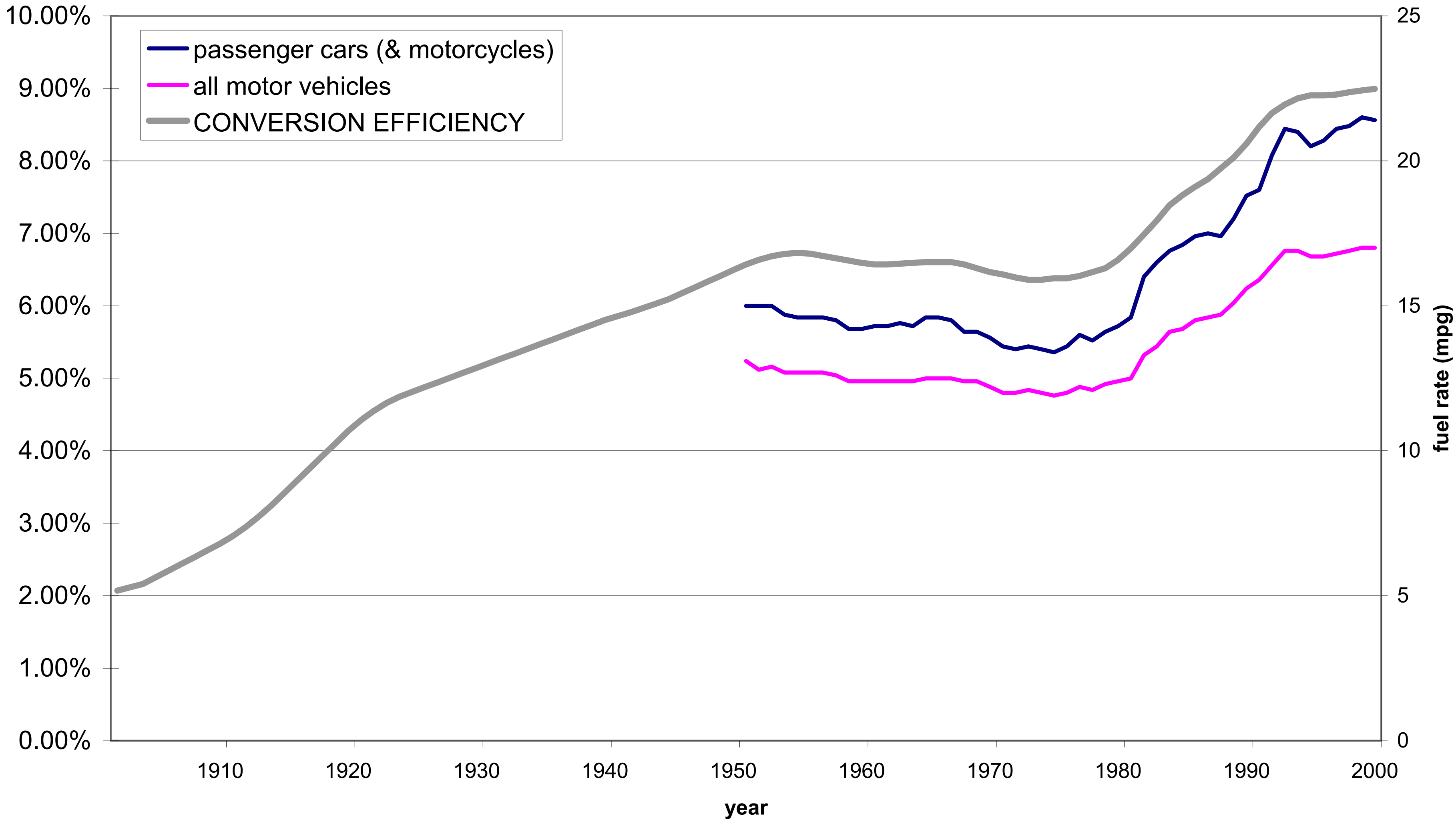


Figure 15: Exergy consumption by industrial processes: USA 1880-2000

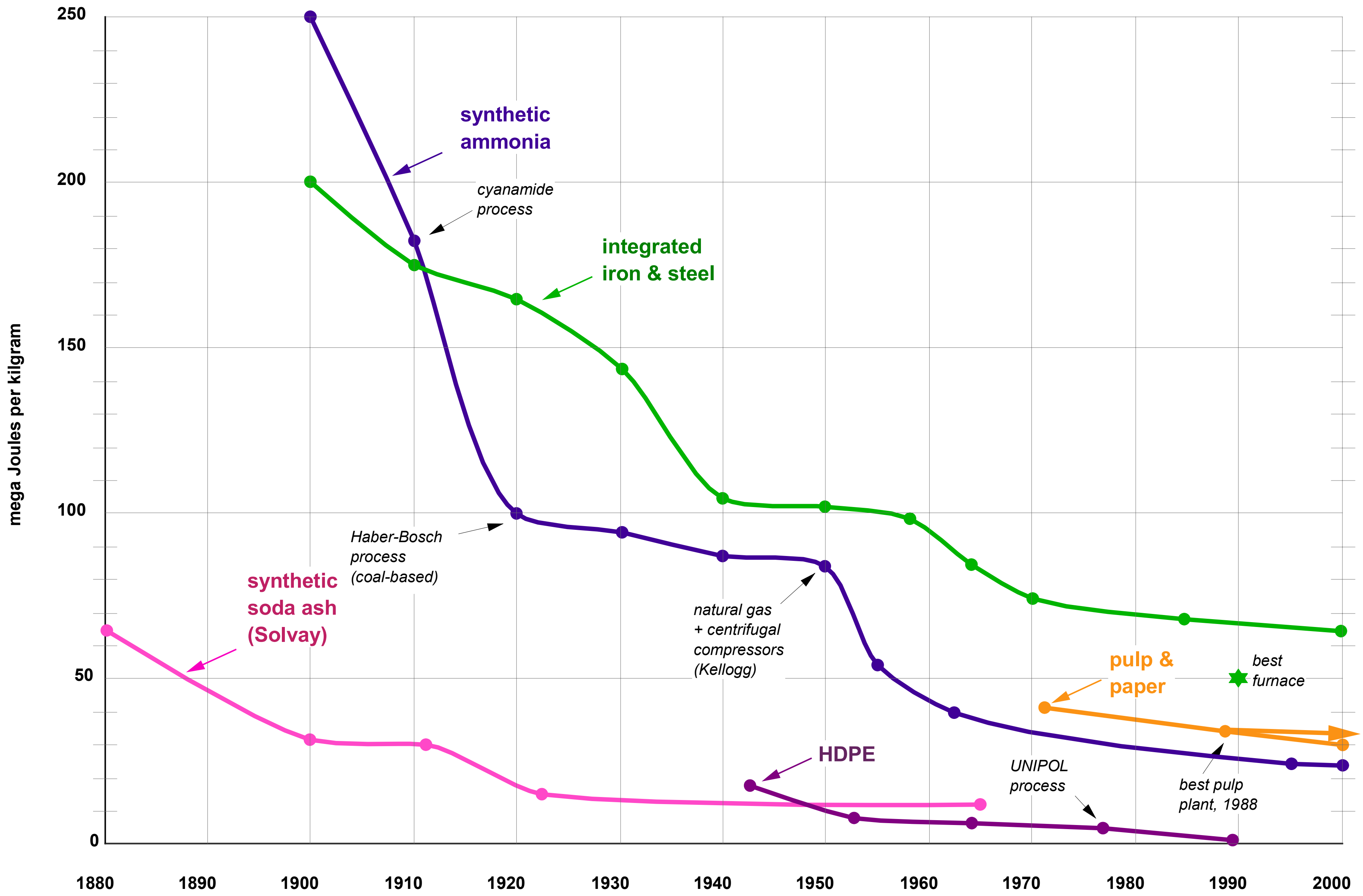


Figure 16. Energy (exergy) conversion efficiencies, USA 1900-1998

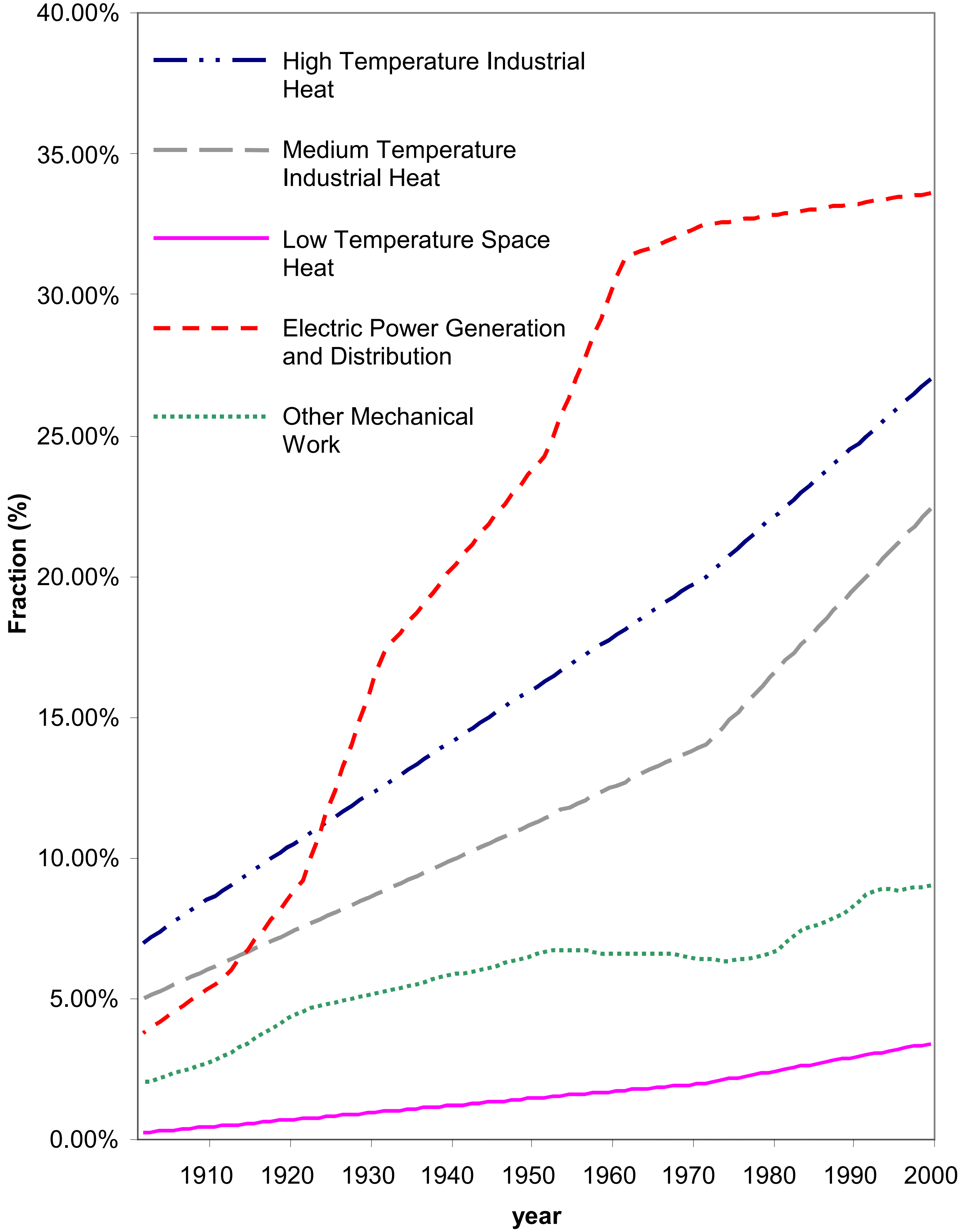


Figure 17. Primary work and the primary work / ratio, USA 1900-1998