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Mass, Exergy, Efficiency in the US Economy

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Contents

Abstract

This paper summarizes energy (exergy) flows for the US from 1900 through 1998. It then considers the various processes for converting crude exergy into 'useful work', as the term is understood by engineers and physicists. There are five types of work, namely muscle work by humans or animals, mechanical work by stationary or mobile heat engines (prime movers) and heat, either at high temperatures (for metallurgical or chemical processes) or at low temperatures for space heating, water heating, etc. The ratio of output work to input exergy is the thermodynamic efficiency of the conversion process. Efficiencies vary considerably from process to process, and over time. In general, primary conversion efficiencies have increased dramatically during the 20th century. While electric power may be regarded as (almost) pure work, it is convenient to define 'secondary work' as the work done by electricity, such as electric light, electromotive power, electric furnaces, electrochemistry and electronics. Surprisingly, the efficiency of secondary work has barely increased during the century, because high efficiency uses have declined in terms of market share, while low efficiency uses have increased share. In conclusion, it is argued that overall exergy efficiency constitutes a good measure of technological change and may prove to be an important explanatory factor for economic growth.

About the Author

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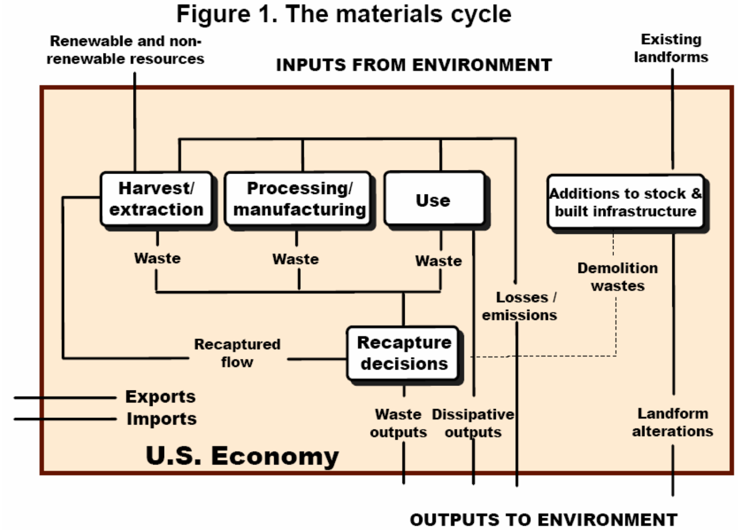
Robert U. Ayres

1 Mass flows and the life cycle

The materials 'life cycle' can be characterized schematically as shown in *Figure 1*. The term 'cycle' is potentially misleading because most materials and elements utilized by humans are not actually recycled, either by natural processes or by man. There is a common but false idea among ecologists that 'nature' recycles everything.[i]

Figure 1. The materials cycle



It is obvious that the stages of the life cycle correspond to familiar economic activities, already defined as 'sectors'. At the beginning are the extractive industries, consisting of agriculture, fishing, forestry, mining, quarrying, and drilling for oil and gas. Substantial quantities of waste are generated at this stage, but mostly these are left behind at or near the place where the extraction occurs, whether the farm, forest or mine.

The next stage consists of primary conversion, where 'raw' materials are cleaned, sorted, separated, upgraded (or 'beneficiated', in the case of metal ores), refined and purified into finished materials. Fuels are also cleaned, refined and converted into higher quality energy-carriers, ranging from clean natural gas to coke, gasoline, diesel oil and other hydrocarbon fuels, as well as petrochemical feed-stocks. Fuels are finally converted by combustion, through the agency of so-called 'prime movers' (i.e. heat engines) into mechanical power. Mechanical power, in turn, can be converted with very little loss, into electrical power. Indeed, electricity can be thought of as a 'pure' form of work. Or, fuels may produce heat that is used directly as such, either in metallurgical or chemical processes – such as metal ore reduction or petroleum refining – or by final consumers. A further conversion (mainly from mechanical power) generates electric power. Primary conversion processes, including combustion, from raw inputs (fuels, biomass) to finished fuels, finished materials[ii] and physical work, account for the vast majority of material wastes.

The third stage of the materials life cycle is another conversion, from finished materials outputs of the primary conversion stage – to finished products, including infrastructure and capital goods. Wastes at this stage arise mostly from intermediate recombination, especially in the chemical industry, where many intermediate materials, such as solvents, acids and alkalis are consumed (i.e. lost) in the conversion process and not embodied in final products. Most toxic and hazardous wastes arise from intermediate processing. The final stage, where finished products produce services, also generates wastes as the so-called final products are consumed, wear out or become obsolete in the course of providing their services to humans. This may happen almost instantly, as in the case of food and beverages, cleaning agents, paper and packaging materials, or over an extended period as in the case of appliances, vehicles, machines and structures. Recycling is essentially only applicable to paper, bottles, cans, and metal scrap, which cumulatively amounts to a tiny fraction of the total materials flow. A summary of the major mass flows in the US economy for the year 1993 is shown in *Figure 2*. (The date does not matter, for this purpose.) The units are million metric tons per year (MMT). I included overburden and erosion in this diagram, since estimates were available. The mass balance principle was used to estimate a number of flows that could not be measured directly. For instance, I used the mass balance to calculate the amount of oxygen generated by photosynthesis in agriculture and forestry, the amount of atmospheric oxygen required to burn all the fossil fuels (and wood) and the amount of water vapor generated by the combustion process. I used official estimates of carbon dioxide production from fuel combustion, and calculated the others as ratios, based on chemical reaction formulae. (Erosion is a special case, constituting topsoil losses from plowed fields, resulting in silting and sediment in rivers. But the material is merely moved from one location to another. Hence erosion 'losses' in the diagram are not balanced by inputs.)

As the life cycle perspective makes clear, economic value is added at each stage by human labor, capital services, and the application of exergy services, while material and exergy wastes are discarded (*Figure 3*). Value-added is sometimes equated with *embodied information* that increases the *order* embodied in useful products. In this view, usefulness is equated with order, or orderliness. Georgescu-Roegen, in particular, has argued that each stage of the process converts low entropy (ordered) materials into high entropy (disordered) wastes. In fact, he has insisted that, thanks to the second law of thermodynamics (the 'entropy law') this process is irreversible (Georgescu-Roegen, 1971). While his conclusions were much too apocalyptic, he was the first economist to characterize the economic system as a materials processor. On that score, he is right.

Figure 2: US economic system as a whole from a mass flow perspective (1993 in MMT)

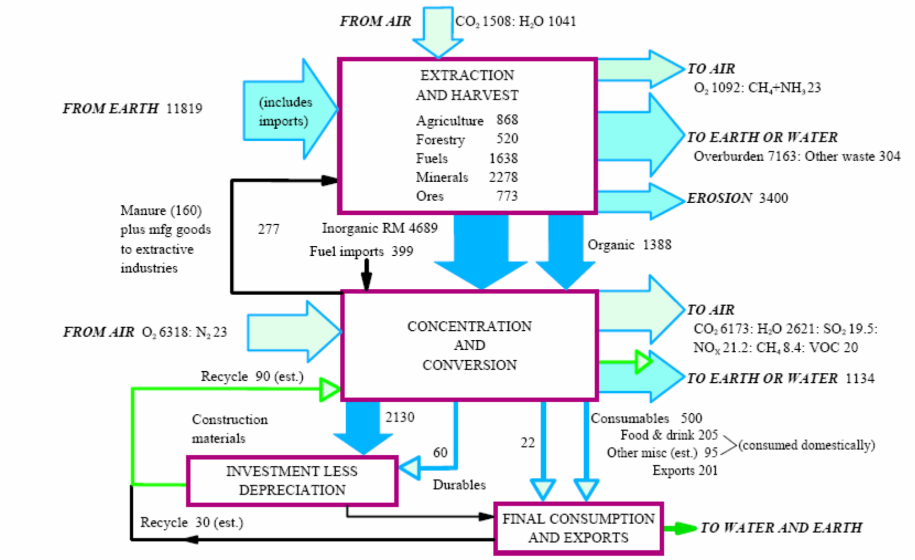
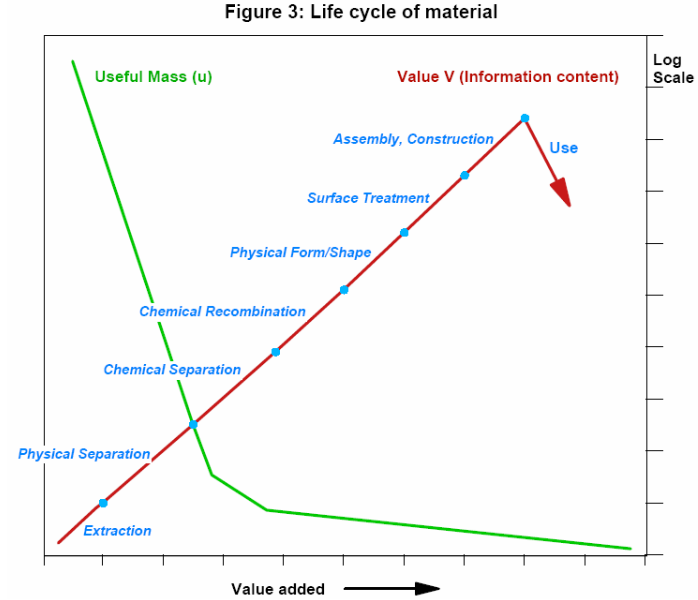


Figure 3: Life cycle of material



The word 'useful' is potentially ambiguous. In economic terms, useful products are those outputs with a well-defined market and market price. In general, many outputs are inputs for other 'downstream' products. Yet some of the physical outputs of the system are useful without having market prices. An industrial example of this is so-called 'blast furnace gas', a mixture of carbon monoxide, carbon dioxide, and nitrogen (plus other pollutants), with some heating value that makes it usable in the near vicinity of the furnace, but not marketable outside the facility. An agricultural example would be forage and silage fed to animals on the farm. Manure generated and recycled by grazing animals on the farm is another example; it would clearly be inappropriate to regard it as a waste. (In Indian villages this material is harvested, dried, and used as domestic fuel).[iii] A domestic example is heat for rooms, water and cooking. Finally, oxygen and water vapor — by-products of photosynthesis — are useful. All of these are *unpriced*, but not *unvalued* intermediates.

Conceptually, it seems reasonable to mark the boundary of the extractive sector by counting the weight of *finished materials*, i.e. materials that are embodied in products, or otherwise used, without further chemical transformation. Steel is an example. There is relatively little difference between the weight of raw steel produced (89 MMT in the US in 1993) and the weight of "finished" steel products. The small losses of steel in the rolling, casting and machining stages of production are almost entirely captured and recycled within the steel industry.[iv] The same can be said of some other "finished materials", from paper and plastics to glass and Portland cement: very little or none of the finished material is lost after the last stage of production, except as consumption or demolition wastes.

What of fuels and intermediate goods like ammonia, caustic soda, chlorine and sulfuric acid? Raw fuels are refined, of course, with some losses (such as ash and sulfur dioxide), and some fuel consumption (around 10% in the case of petroleum) to drive the refineries. But refined fuels are converted, in the course of use, mainly to heat, mechanical power and combustion wastes. Fuels cannot be recycled, by definition. The mass of raw hydrocarbon fuel *inputs* to the US economy was a little over 1600 MMT in 1993. It was mostly combined with atmospheric oxygen. The combustion of hydrocarbon fuels in the US, in 1993, generated around 5200 MMT of CO_2, the most important "greenhouse gas" (Organization for Economic Cooperation and Development 1995) p.39. This may be a slight underestimate, since some of the hydrocarbons produced by petroleum refineries do not oxidize immediately (asphalt, petrochemicals and lubricants, for instance) but, except for what is buried in landfills, all hydrocarbons do oxidize eventually.

Minerals such as salt, soda ash and phosphate rock, as well as petrochemical feed-stocks, are converted to other chemicals. Some of these chemicals — mainly polymers — end in finished goods with relatively long useful lives (like carpets, window frames and pipes)l some have intermediate lifetimes (e.g. tires) and still others have very short lives (like packaging materials). Some chemicals are dissipated in the course of use. The best examples are fertilizers, pesticides, cosmetics, detergents, lubricants, pigments and solvents. Others are converted to wastes as they are used. Examples include fuels, acids and alkalis. A model scheme (and accounting system) appropriate for environmental analysis should distinguish between *dissipative* intermediates, such as these, and *non-dissipative* materials embodied in finished durable goods that might (in principle) be repaired, re-used or re-manufactured and thus kept in service for a longer period.

"Final" goods are goods sold to "final" consumers in markets. This class of goods is reasonably well-defined. But so-called "final goods" (except for food, beverages and medicines) are not physically consumed. They are in a sense, producers of services. By this test, *all final outputs (with the above exceptions) are immaterial services and therefore weightless, the mass having been discarded 'en route' so to speak*.[v] However, it is also natural to consider finished products as materials that do have mass, as well as monetary value (counted in the GDP). In fact this category marks the downstream boundary of the manufacturing and construction sectors.

2 Exergy as a measure of material quantity and quality

Almost everybody uses mass as the measure of quantity applicable to material substances. On the surface of the earth, the mass of an object is proportional equivalent to its weight, which can be measured quite easily. To be precise, weight is equal to mass times the force of gravity.[vi] However, mass is not particularly interesting in resource accounting, except for comparisons of changing requirements for specific materials or groups over time (as illustrated in the previous section), or similar comparisons between countries. Aggregate mass is also generally proportional to the energy (exergy) requirements for mining and transportation. Hence many authors have attempted to establish the importance of 'dematerialization' as a strategy for achieving long-run sustainability.

However, in either context, total mass as such is almost irrelevant. Most of the mass of extractive resources consists of fossil fuels, biomass or abundant and relatively inert materials such as sand and gravel, limestone and iron ore. On the other hand, apart from fossil fuels and light metal oxides or carbonates, it is relatively scarce metallic elements such as copper, molybdenum, cobalt, chromium, nickel, silver, and platinum, plus reactive halogens (chlorine, bromine, fluorine) that are most essential to industrial activity. And, along with combustion products – including dioxins – and pesticides, it is comparatively tiny amounts of highly toxic by-product metals such as arsenic, cadmium, lead, mercury that dominate the environmental health literature (e.g. Nriagu and Davidson, 1986; Nriagu and Pacyna, 1988).

From the environmental impact perspective it makes little sense to aggregate materials as disparate as hydrocarbons, crops, inert construction minerals, metals and reactive chemicals into one category, using total mass as a measure in a macroeconomic context. Yet, for reasons of familiarity (one supposes) this approach has been emphasized, e.g. (World Resources Institute 2000; Adriaanse et al., 1997). Luckily it is not necessary to aggregate in that way. As pointed out by several authors, another measure, called *exergy* is available and more suitable for the purpose (Wall, 1977; Ayres et al., 1998). Unfortunately, *exergy* is still an unfamiliar term, except to engineers, chemists or physicists.

Exergy was formerly, and still is sometimes, called *available energy*. More precisely, it is defined as the maximum amount of work that can theoretically be recovered from a system as it approaches equilibrium reversibly (i.e. infinitely slowly) with its surroundings. In effect, exergy is also a measure of distance from thermodynamic equilibrium, which makes it a measure of *distinguishability* of a subsystem from the surroundings. From another point of view, exergy is really what non-technical people usually mean when they speak of *energy*. The exergy embodied in a fuel can be equated approximately to the *heat of combustion* (or *enthalpy*) of that fuel. But an important difference is that exergy cannot be recycled; it is used up, or 'destroyed' to use the language of some thermodynamicists. On the other hand, *energy* is always conserved; it cannot be destroyed.

There are several kinds of exergy, including physical exergy (kinetic energy) and thermal exergy (heat). However for macro-economic purposes – as in this lecture –

only *chemical exergy* need be considered. The exergy content of various fuels is given in *Table 1*.

Table 1: Typical chemical exergy content of some fuels

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

Data source: expanded from (Szargut et al., 1988)

The next figure (*Figure 4*) provides a better sense of the sources and losses of useful work (and power) in the economy. Fuels, hydro-power, nuclear heat and products of photosynthesis (biomass) — crops and wood — are the major sources of exergy input to the economy. Most other materials, such as metal ores, have very little exergy in their original form, but they may gain exergy (from fossil fuels) as in metal reduction or ammonia synthesis. Nevertheless, the exergy content of materials is an interesting comparative measure, especially in contrast to the traditional measure (mass).

Figure 4: World energy flows 1949

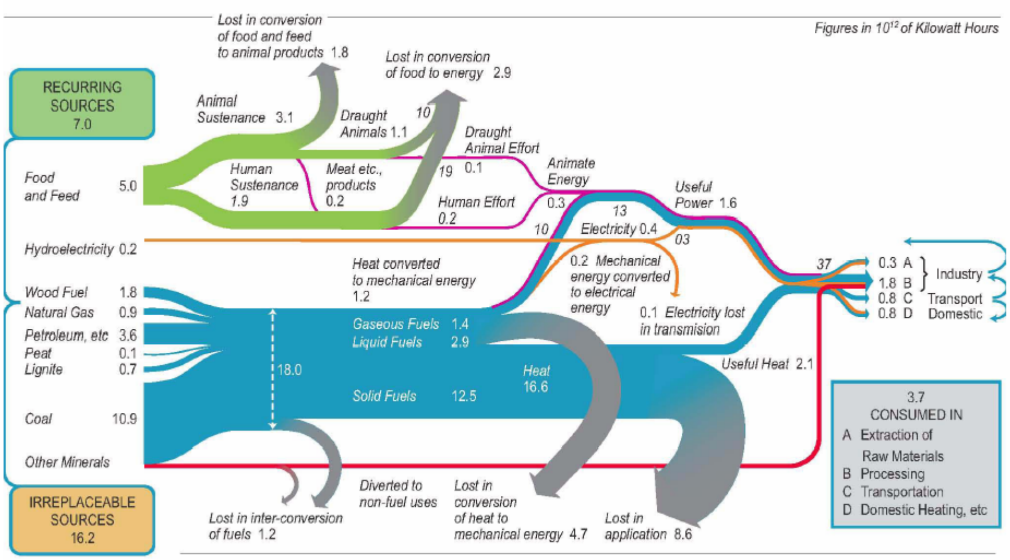


Figure 3.4 from: N.B. Guyol, (1949). *Energy Resources of the World*. Department of State Publication 3428. Washington, DC, US Government Printing Office.

In this section I have emphasized that the exergy content of fuels and other raw materials can be equated to the theoretical maximum amount of useful (physical) work that can be extracted from those materials as they approach equilibrium reversibly. I discuss useful work next.

3 Useful work

The term '*useful work*' is familiar to engineers, but familiarity (in this case) may be dangerous. Thus, a brief explanation is helpful, even though a precise definition is surprisingly elusive. In physics texts, work is usually defined as 'a force operating over a distance'. However this definition is not helpful if force is also undefined. The best explanation may be historical. Useful 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. During the past two centuries several other types of work have been identified, including thermal work, chemical work and electrical work.

Combustion is an *exothermic* process, meaning that it produces excess heat. A combustible substance reacts with oxygen rapidly and generates combustion products – such as carbon dioxide and water vapor – that subsequently diffuse and thus equilibrate with the atmosphere. The heat of combustion can do useful work by means of a *heat engine* depending on the temperature difference with respect to ambient. The so-called *Carnot cycle* is an ideal cycle that maximizes the work that can theoretically be extracted 'reversibly' from the heat. However, a point seldom appreciated, even by experts, is that there is a conflict between maximizing work and maximizing power output. (Power is work per unit time.) The slower and more reversible the process, the more efficient it can be. In the limit, as the cycle approaches reversibility, the maximum power output approaches zero.[vii]

Of course, oxidation need not be rapid. Rusting of iron is an example of slow, almost reversible, oxidation. Heat is generated, but so slowly (and at ambient temperature) that it generates no power, and is not noticeable. But in finely divided form with a lot of surface area, iron (like most other metals) will burn and liberate heat rapidly, even explosively. Similarly, the respiration process in animals is another form of oxidation. This is why the energy— actually exergy — content of food is expressed in units of heat energy, namely kilocalories or *Calories* (with a capital C.)

There are some economically important processes that are essentially the reverse of combustion, in the sense that chemical exergy is not released but, rather, is consumed (but not created) and is embodied in one of the reaction products. Such processes are *endothermic*. Photosynthesis is an example: exergy from solar radiation is captured and embodied in carbohydrates, which are combustible chemical substances.[viii] Carbo-thermic reduction of metal ores are endothermic: iron oxide in contact with carbon monoxide at high temperatures is converted to a pure iron[ix] plus carbon dioxide. The exergy of the smelted iron is less than the exergy of the fuel used (e.g. coke) because the combination of oxygen from the metal oxide with carbon from the coke is disguised combustion. Ammonia and methanol synthesis are other examples. In the ammonia case, natural gas plus air is converted to ammonia plus carbon dioxide by a series of catalytic processes at high temperatures and pressures, which also amount to disguised combustion.

Because of the conflict between maximizing work and maximizing power output, noted above, the actual amount of *useful work* done by the economic system is considerably less than the theoretical maximum. There are other reasons for this, as well. Real industrial systems do not consist only of simple heat engines; there are important *heat transfer* components, where losses are proportional to temperature gradients. A boiler or radiator is an example of a heat transfer device. Moreover, all real machines and industrial systems require extensive use of mechanical, hydraulic or electrical power transmission systems (gears, pipes and pumps, wires), that simply move power from one location to another, with significant losses due to frictional resistance. The power train, oil pump (for lubrication) and the water pump (for cooling) in an automobile engine are familiar examples. These losses are *irreversibilities*; they create *entropy* and destroy exergy.

It is important to emphasize that the ratio of actual work output to the theoretical maximum can be regarded as the *technical efficiency* (as opposed to *economic efficiency,* a very different concept) with which the economy converts raw materials into finished materials. This, in turn, as I hope to demonstrate later, can be regarded as a rather good measure of the state of technology. Over time, technical efficiency is also a useful measure of technological progress or what economists now call *total factor productivity* (TFP).

As already mentioned, *power* is defined as work performed per unit time. Before the industrial revolution there were only four sources of mechanical power, of any economic significance. They were human labor, animal labor, water power (near flowing streams) and wind power. (The advent of steam power in the early 18^{th} century led to the first quantification of power in terms of equivalent 'horsepower' by James Watt.) Nowadays mechanical power is mainly provided by *prime movers*, which are either hydraulic or steam turbines (used to generate electrical power) or internal combustion engines. The three major types of internal combustion engines are *spark ignition* (gasoline) engines, *compression ignition* (diesel) engines and *gas turbines*.

More generally, one can say that whatever increases the exergy of a subsystem can be called 'work' (it being understood that the subsystem is contained within a larger system in which energy is always conserved, by definition). Electricity can be regarded as 'pure' useful work, because it can perform either mechanical or chemical work with very high efficiency, i.e. with very small frictional losses.

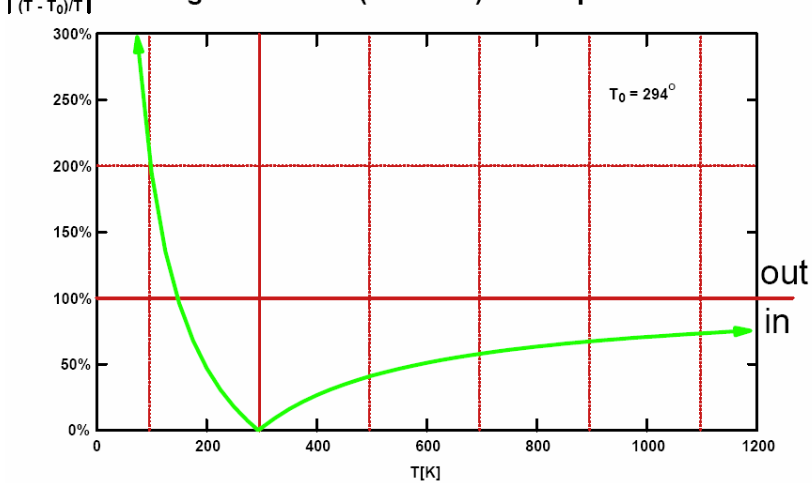
Of course, electricity is also a commodity, produced by a well-defined sector and sold at a well-defined price in a well-defined market. Since electricity is not a material good, it is commonly regarded as a 'utility' service. Unfortunately, this is not true of other kinds of physical work done in (and by) the economic system. Motive power, for instance is produced by human muscles, animals (horses and mules) or machines and also consumed within the productive sectors of the economy as well as within households (e.g. motorcars.) Similarly, heat is both produced and consumed within virtually all sectors, as well as in households. It follows that non-electrical useful work and useful heat can be regarded as *exergy service*, even though this service is often consumed where it is produced and therefore it is not conventionally measured or priced.

If this concept seems strange, at first, it may help to think in terms of the 'electrical equivalent' of motive power (from an engine), or the electrical equivalent of chemical work or heat. The electrical equivalent of motive power is already a reality, for instance, in electrified railroads, where electric motors drive the wheels. The electrical equivalent of chemical work is also exhibited by storage batteries, for instance, which convert electricity into chemical potential, and vice versa (albeit with some resistive losses in each direction). Similarly, high temperature industrial heat provided by fuel combustion and heat exchangers could be equated to the amount of electricity required to produce that heat, at the point of use, by an electric stove or toaster, or an electric arc furnace.

Admittedly the conversion from electrical work (power) to other kinds of work is always subject to some loss, thanks to the second law of thermodynamics. But electric power can be converted into mechanical motion (via a motor) and *vice versa* (via a generator) with an actual efficiency of 90% to 95% where high efficiency is the goal. Fuel cells are not quite as efficient at converting chemical energy into electricity, although they are improving and the theoretical potential of fuel cells (at very high temperatures) is in the 80% range.

This inter-convertibility between forms of work does not apply to heat, as such, however. As Count Rumford showed in a classic experiment (carried out while he was boring cannons for the Bavarian government) kinetic energy can be converted into heat with no loss. Similarly, it is true that electricity can be converted into heat (by a resistor) with 100% efficiency. But heat cannot be reconverted into kinetic energy or electricity with anywhere near as high efficiency. As Sadi Carnot pointed out at the beginning of the 19th century, even the most efficient possible heat engine can only convert heat to work with a maximum efficiency based on the temperature difference between two reservoirs. Similarly, the amount of work needed to move heat from a lower temperature to a higher temperature is also a function of the temperature difference (*Figure 5*). For this reason, we use the term *second-law efficiency* to characterize the efficiency of low temperature heating systems in relation to theoretical limits (American Physical Society, 1975).

Figure 5: Work (in or out) vs temperature

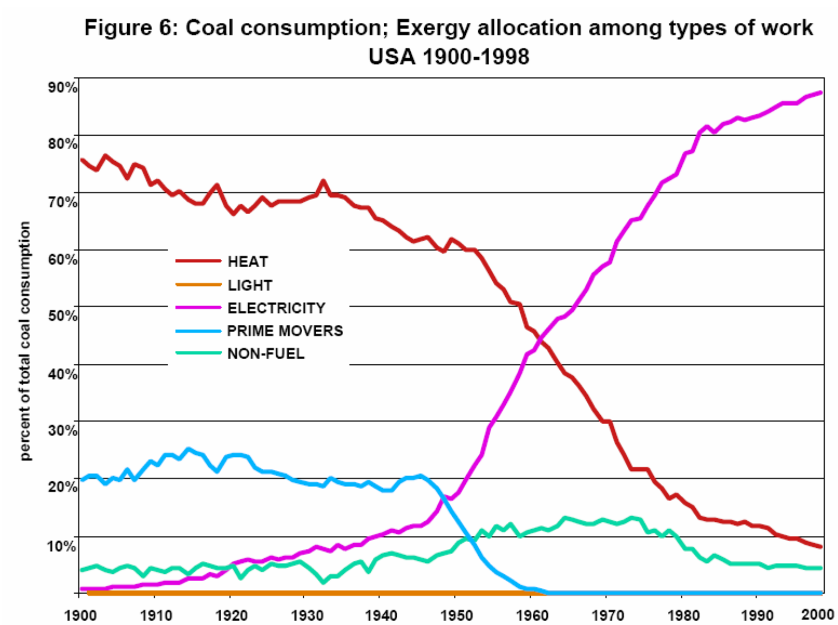


4 The conversion of exergy to useful work

The notion of *energy conversion* efficiency is commonplace in engineering and physics. It is easily generalized to exergy. As noted already, exergy is the maximum work theoretically obtainable from a subsystem as it approaches equilibrium with its environment. Exergy conversion efficiency is therefore the ratio of *actual* work (output) to *maximum* work (exergy) input, for any given process. For instance, a heat engine converts the heat of combustion of a fuel into useful mechanical work.[x] In recent decades a number of authors have applied exergy analysis at the industry level.[xi] I have tried to generalize this concept to the economy as a whole. The starting point is to identify the different types of useful work done in the economy and allocate the exergy resource inputs to each type of work. For our purposes, the types of work done by the economy can be classified as muscle work (by human and animal muscles), mechanical work (by stationary or mobile prime movers) and heat (high temperature or low temperature.

It is helpful for some purposes to define *primary* and *secondary* work. Primary work is done by the first stage of energy conversion (e.g. electric power generation by means of a heat engine or possibly a hydraulic turbine). Secondary work is work done later by electrical devices or machines. I 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). In all cases the physical units of work are the same as the units of energy or exergy. Hence thermodynamic efficiency is a dimensionless number between zero and unity.

Useful work can be divided into several categories. These include muscle *work* (by humans or farm animals), *mechanical work* by stationary or mobile prime movers (e.g. heat engines), and *heat delivered to a point of use* (e.g. industrial process heat, space heat, cooking). It is instructive to note that an increasing fraction of the fossil fuel (exergy) inputs to the economy have been utilized for 'prime movers', i.e. heat engines. The next four figures, *Figures 6 to 9* show the allocation of exergy inputs to conversion to the major categories of work by coal, oil, gas, and by all fossil fuels taken together. *Figure 10* shows the exergy inputs to the US economy by source (fossil fuels, biomass, hydroelectricity, etc.)



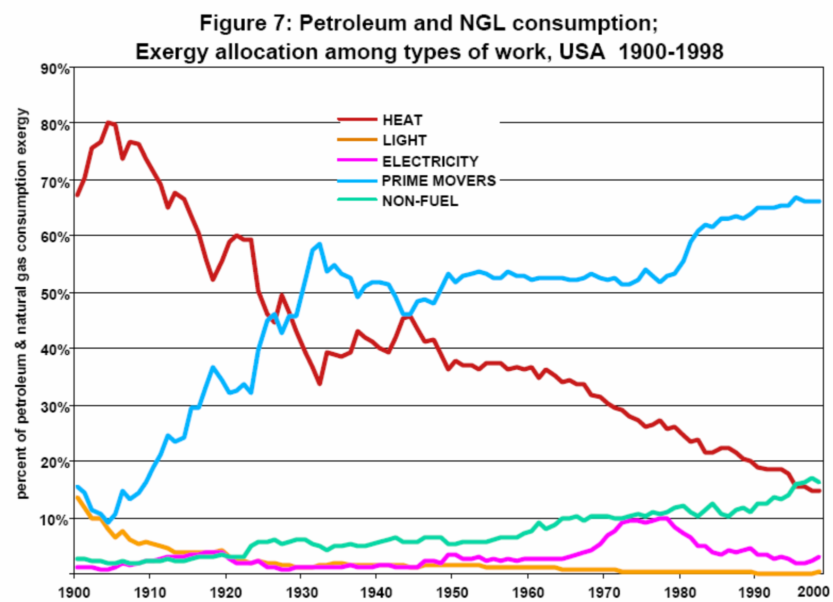


Figure 7: Petroleum and NGL consumption;
Exergy allocation among types of work, USA 1900-1998
percent of petroleum & natural gas consumption exergy
HEAT
LIGHT
ELECTRICITY
PRIME MOVERS
NON-FUEL
90%
80%
70%
60%
50%
40%
30%
20%
10%
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

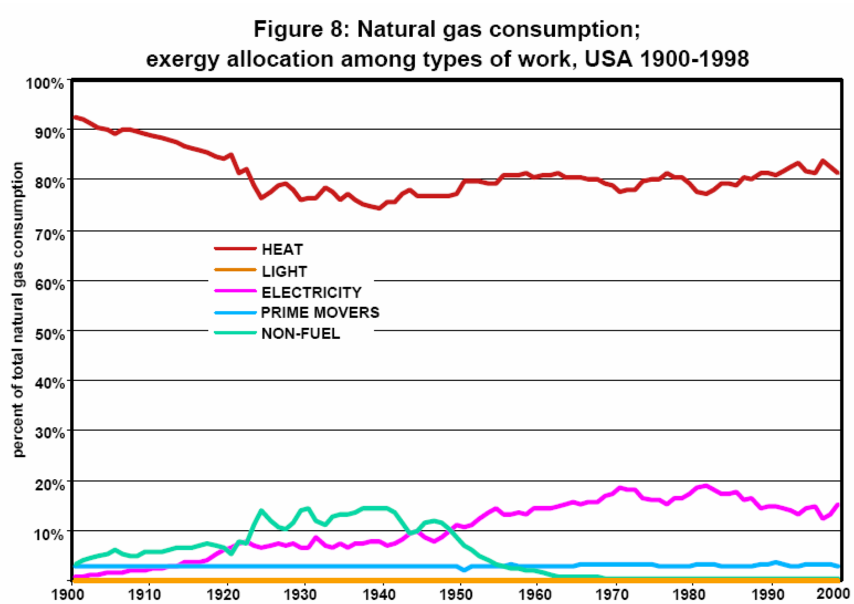


Figure 8: Natural gas consumption;
exergy allocation among types of work, USA 1900-1998
percent of total natural gas consumption
HEAT
LIGHT
ELECTRICITY
PRIME MOVERS
NON-FUEL
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

Figure 9: Exergy inputs to the US economy by type: 1900-1998

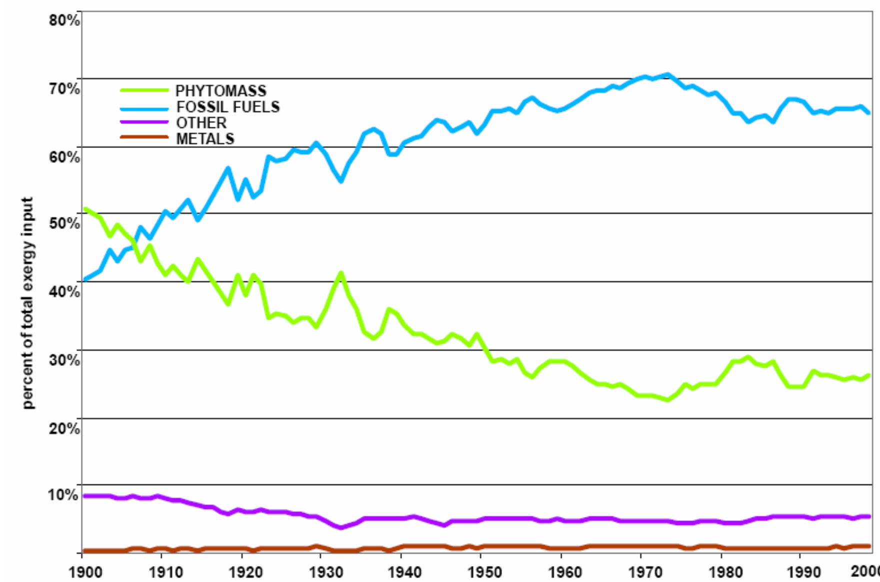
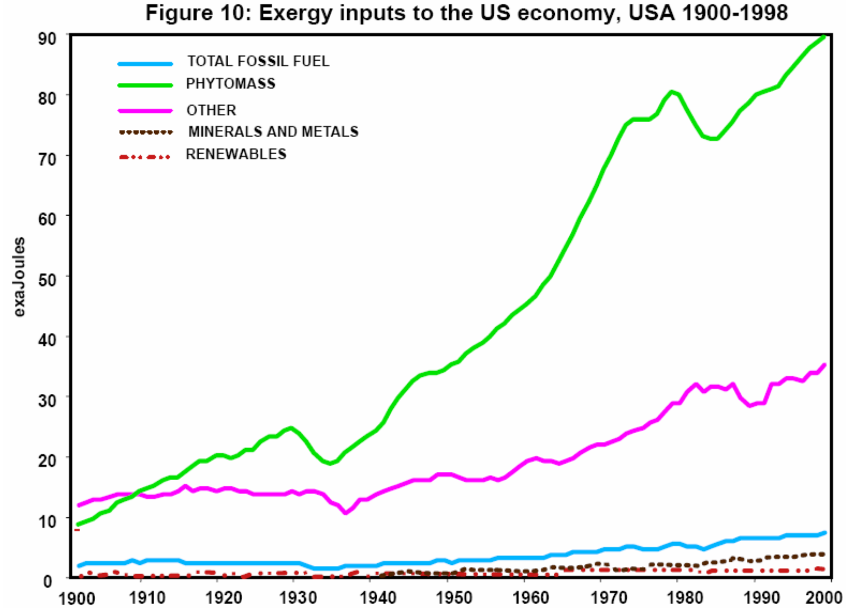


Figure 10: Exergy inputs to the US economy, USA 1900-1998



As already explained, electricity can be regarded as a pure form of useful work, since it can be converted into mechanical work, chemical work (as in electrolysis) or heat with little or no loss. Using the exergy flow and conversion efficiency data, the aggregate useful work (exergy services) performed by the US economy since 1900 can be calculated. However, such a calculation presupposes that energy conversion efficiency data are available. In practice (i.e. in official statistics) this is only true for electric power generation.

To very good first approximation, the efficiency of muscle work, whether by horses or humans, has not changed, at least in the past ten thousand years. The only change in this regard is the fraction of total work done in the economy by muscles. In the industrialized countries this fraction was already small in 1900 and is now negligible. However, in developing countries with large rural populations – like India or China – muscle work cannot (yet) be disregarded. Since muscle work is relatively inefficient as compared to modern machines, a country with a large component of muscle work will be less efficient overall at producing work than its industrialized neighbor.

As regards heat delivered to a point of use, not much has changed either, except to the extent that or space heating insulation has been improved and is being utilized more. *Figures 11 to 12* show how exergy inputs are allocated among the different kinds of work, displayed as fractions of by source and as fractions of the total. Evidently the fraction devoted to heat – once by far the dominant use – has fallen to around a third, whereas the fraction devoted to generating electric power has risen to a similar level. The most visible improvements in energy conversion efficiency are found in so-called *prime movers*, namely vehicles powered by IC engines, and electric power generating systems. As regards IC engines, *per se*, efficiency is a direct function of the fuel-air compression ratio (*Figure 13*) and the key to increasing fuel efficiency (mpg) has been to increase the compression ratio. I need not repeat the story of why tetraethyl lead (TEL) was important, or why it was finally banned except to note that average US compression ratios and ICE efficiency has actually declined since the ban took effect in 1970 (*Figure 14*).

Figure 11: Exergy: All fuels and fuels for prime movers US 1900 - 1998 (petajoules)

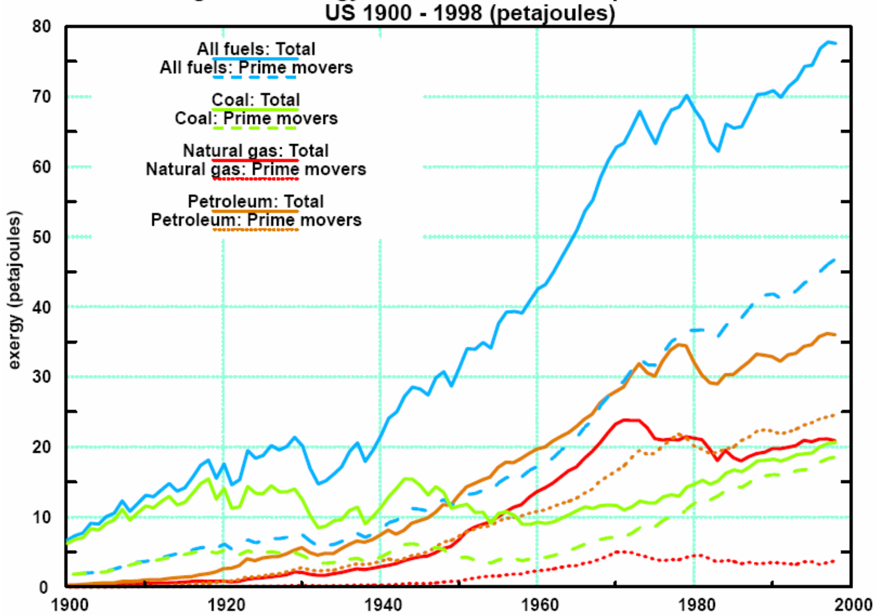


Figure 12: Fossil fuel consumption exergy allocation, USA 1900-1998

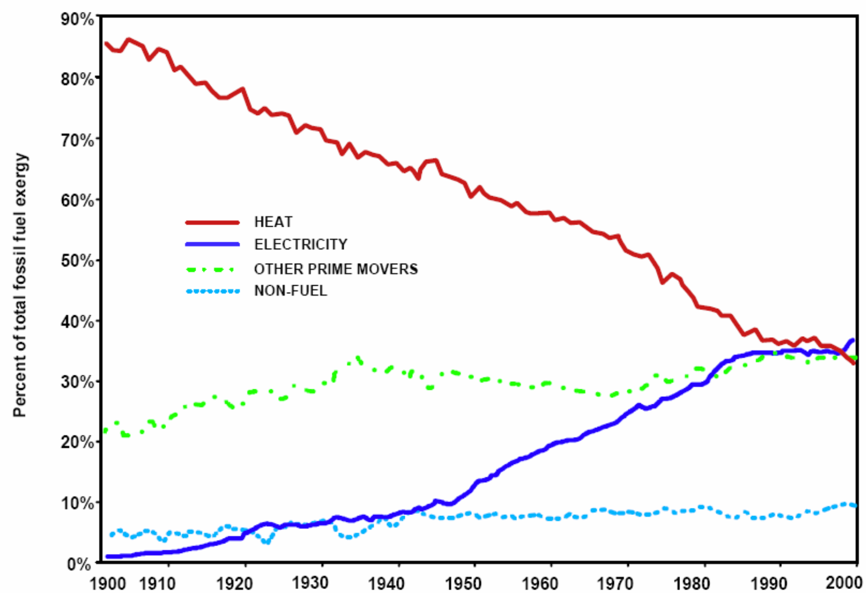
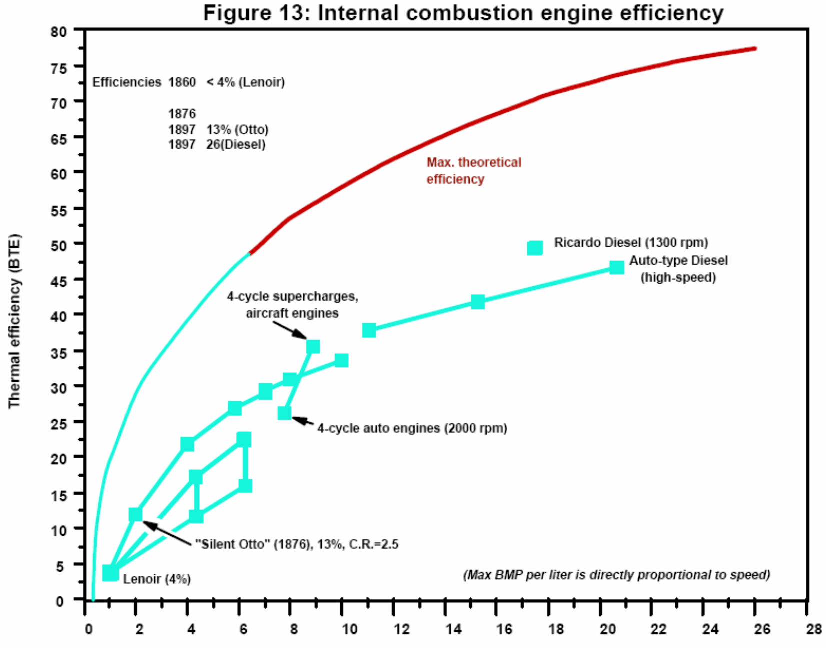
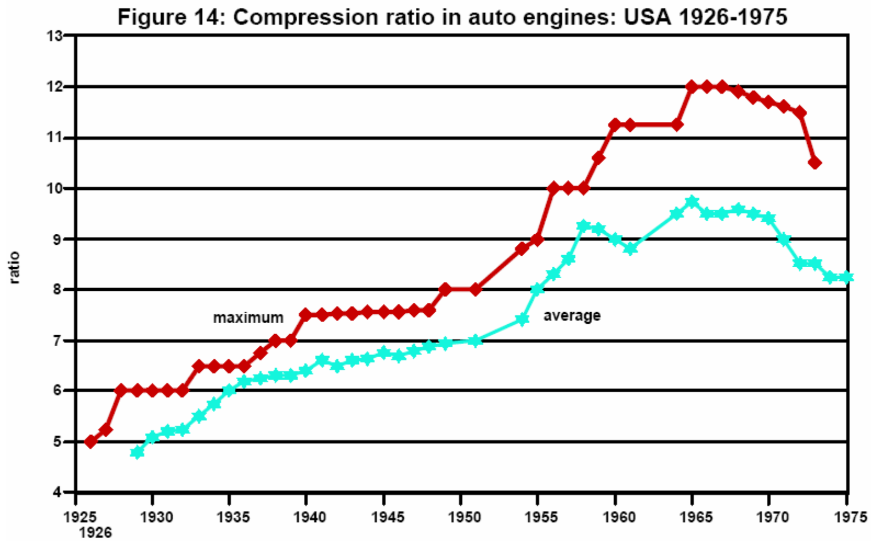


Figure 13: Internal combustion engine efficiency



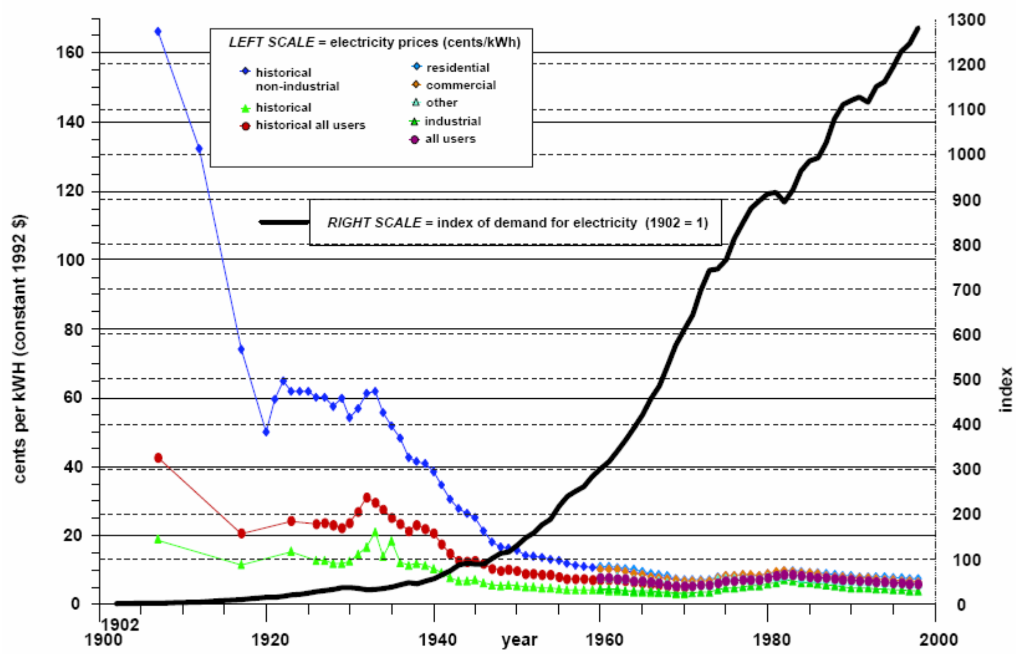


Such improvements as have been made in the fuel efficiency of automobiles since the 1970s are entirely due to reduced vehicle weight, reduced air resistance, better transmissions (e.g. five gears) better tires and better electronics. Much the same can be said for aircraft. Gains in fuel efficiency are not attributable in any significant degree to the gas turbines themselves, since gas turbine efficiency is a function of operating temperature and pressure, and these have not increased significantly since the advent of turbine blades made of super-alloys several decades ago. Improvements are largely due to reduced air resistance. This results partly from the use of sophisticated 3-D design and simulation programs, plus wind tunnels, and partly due to larger sizes, which reduce the surface area-to-volume ration. Air resistance is proportional to surface area, *ceteris paribus*.

As regards electric power generating systems, again, the gains in single-pass systems due to higher operating temperatures and pressures and larger size had been mostly exhausted by the 1960s. The overall efficiency of electricity production and distribution rose from around 3% at the turn of the century (1900) to over 30% by 1960; it has remained at about 33% ever since 1960 (*Figure 15*). This is because operating temperatures and sizes for single stage generating systems have peaked. Carbon steel (for boilers and steam turbine blades) cannot withstand the high centrifugal forces at high rotational speeds, at temperatures above 1000 C. Super-alloys, used in aircraft gas turbines, are too costly for this application, and ceramic materials that can be fabricated by known techniques are not yet – and may never be – sufficiently tough. (Single crystals would be ideal, but nobody knows how to produce them in complex shapes.)

There are other ways of increasing conversion efficiency. One is the so-called combined cycle, which consists of a gas turbine whose hot exhaust gases then drive a steam turbine. Such combinations can achieve thermal efficiencies upward of 60%. However the major drawback is that the gas turbine requires highly purified natural gas as a fuel. Almost any impurity causes unacceptable corrosion problems. Coal gasification is an expensive and not very satisfactory substitute, and if a coal gasification plant is included in the complex, the overall efficiency is only modestly better, and more costly, than the best single stage steam turbines can achieve.

Figure 15: Electricity demand and price: USA 1902-1998



Data sources: 1960-1998: Annual Energy Review Table 8.13 1907-1970: Historical Statistics: Vol 1, Series S116,118, 119

Another more immediate option is what has been called ‘waste heat recycling’, or ‘combined heat and power’ (CHP). In effect, the heat rejected by a prime mover is utilized locally *as heat*. The efficiency of the electricity generation may be slightly reduced (if the thermal offtake is at a temperature higher than ambient) but the ‘recycled’ heat replaces fuel that would otherwise be burned to produce that same low temperature heat. The result is a ‘double dividend’ in the sense that fuel is saved, overall costs are lower and pollution is reduced at the same time.

CHP is a technology that is currently feasible mainly in large industrial establishments such as steel mills, coking plants or oil refineries that have substantial quantities of low grade combustible wastes (like blast furnace gas) that can be used locally to provide steam for other operations, or to generate electric power to be used within the plant. Unfortunately, electric utilities, with a legal monopoly over the sale and distribution of power, are very reluctant to purchase surplus electric power from CHP operations, except at prices well below their own marginal cost. By the same token, they tend to overcharge for connections with the grid, to discourage decentralized power generation, even though there are significant advantages in terms of improved system stability and reliability when there are more generators. The magnitude of the under-utilized CHP potential is evident in a few countries, like the Netherlands and Finland, where the legal restrictions have been removed. There, CHP is now supplying up to 40% of the national power consumption, as compared to a much smaller fraction (around 15%) in the US.

Whereas it seems sensible to discuss the exergy-efficiency of vehicles, rather than simply engines, the foregoing discussion evidently neglects the efficiency with which electricity is converted into ‘secondary work’ after delivery to industrial or domestic users. The first use of electric power was for lighting purposes, but that use now accounts for only a small fraction of the total. Another small fraction is used for electric furnaces, including steel recycling in so-called mini-mills. Induction heaters are now commonplace in the chemical industry, having largely replaced steam generators. Electric heating, including ovens and stoves for cooking, in homes and restaurants constitute a related use, which also happens to be growing. Electrolytic processes, notably for aluminum and chlor-alkali production, constitute a third significant use category. Electronic devices, from radios and TVs to PCs and related items (such as printers) are by far the fastest growing category, but still the smallest.

But by far the biggest share of electric power – about half – goes to electric motors, for several purposes. One of the biggest, and certainly one of the fastest growing in recent decades, has been refrigeration and air-conditioning. These can be lumped together since the underlying technology is the same: a motor drives a compressor. The compressor provides the work that cools by allowing the compressed working fluid to expand rapidly and 'moves' heat from a cool place to a warmer one (as in refrigeration) or vice versa (as in a heat pump.

The second large category of motor uses is for pumping liquids or gases: pumps are used in oil and gas wells, underground mines, gas pipelines, water pumps for domestic wells and farm irrigation, urban water and sewer operations, throughout the chemical industry, and of course in homes and apartments. A third use is for operating stationary (and some mobile) machines, ranging from machine tools and transfer lines in factories, elevators and escalators, motors to drive trams and electric trains. A fourth use, the one that has expanded most rapidly, is for fractional horsepower AC motors powering a host of domestic appliances, including washing machines, dishwashers, vacuum cleaners, power tools, blenders, mixers, coffee grinders, garbage grinders, electric shavers, toothbrushes, not to forget synchronous motors for record players, and hard disks for PCs and DVDs. *Figure 16* shows the major historical uses of electricity in the US.

Some of the uses of electricity, notably for lighting and electronics, are comparatively inefficient, but have become increasingly efficient over time. But electronic uses, where the efficiency gains are greatest, are still only a tiny fraction of the whole. Efficient uses, such as high temperature heating and electrolysis have not gained much in efficiency but have lost share. Motors have maintained share but gained only slightly in efficiency (thanks to electronic controls). Unfortunately, it is very inefficient uses like electric heating and air conditioning, and electronics, that have gained share. As a consequence, the overall efficiency of electricity usage has gained only slightly during the century from 1900 to 2000, because the efficiency gains in some uses have been largely compensated by the increased share of the least efficient uses, notably air conditioning and electric heat. *Figure 17* shows the secondary efficiencies of electric power use in the US.

It is difficult to generalize as regards the efficiency of other endothermic industrial processes, such as iron and steel manufacturing and ammonia synthesis. The available data for several processes are shown in *Figure 18*. Since integrated iron and steel – excluding electric mini-mills, that recycle scrap – accounts for a significant (albeit declining) fraction of the energy consumption of the industrial sector, I think it can be taken as a surrogate for the sector as a whole.

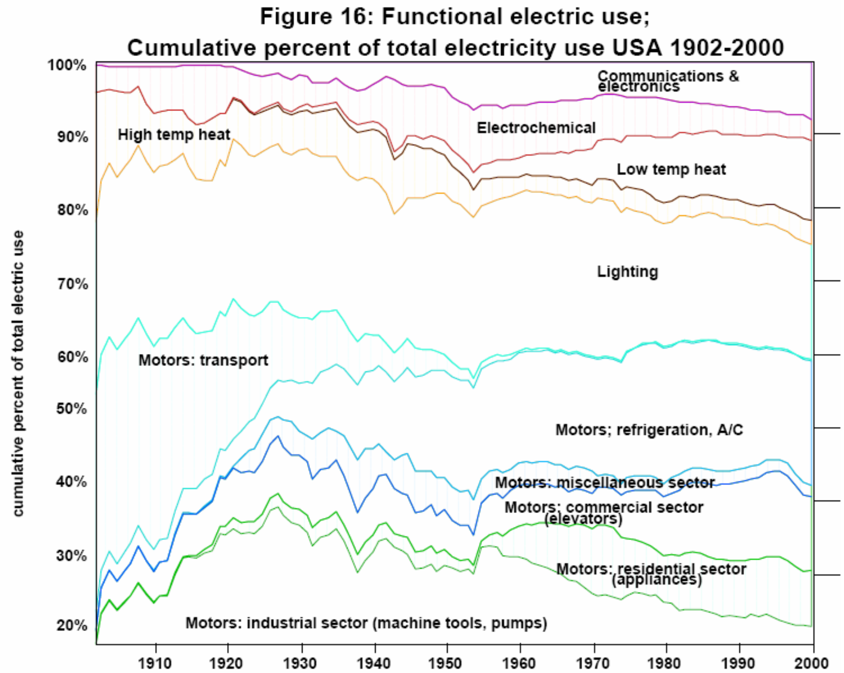


Figure 16: Functional electric use;
Cumulative percent of total electricity use USA 1902-2000
cumulative percent of total electric use
100%
90%
80%
70%
60%
50%
40%
30%
20%
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Communications & electronics
High temp heat
Electrochemical
Low temp heat
Lighting
Motors: transport
Motors; refrigeration, A/C
Motors: miscellaneous sector
Motors: commercial sector (elevators)
Motors: residential sector (appliances)
Motors: industrial sector (machine tools, pumps)

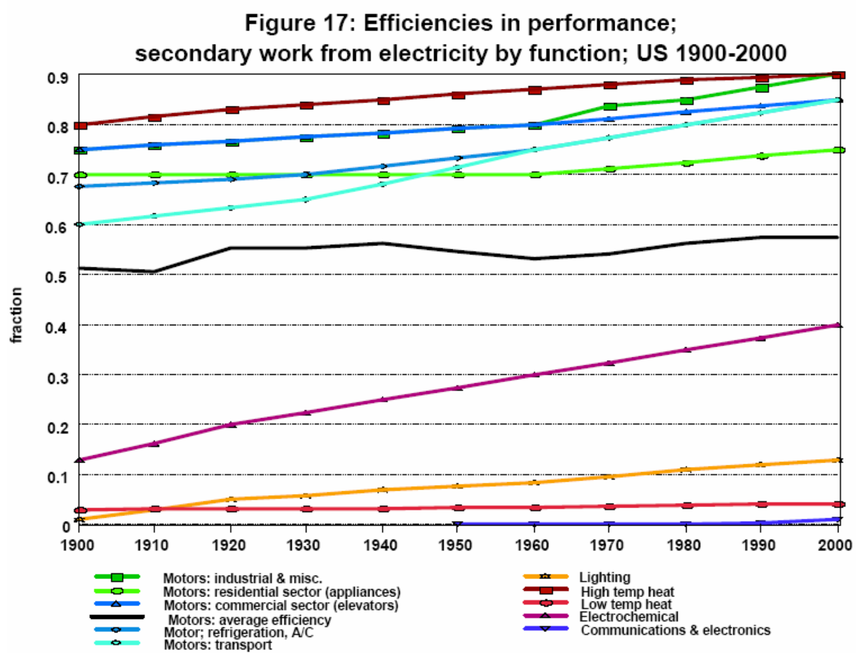
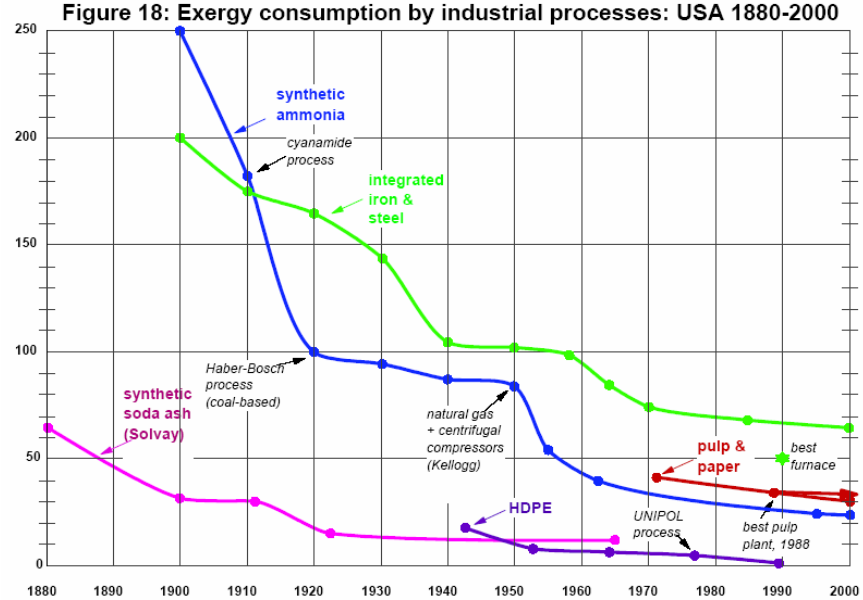


Figure 17: Efficiencies in performance;
secondary work from electricity by function; US 1900-2000
fraction
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Motors: industrial & misc.
Motors: residential sector (appliances)
Motors: commercial sector (elevators)
Motors: average efficiency
Motor; refrigeration, A/C
Motors: transport
Lighting
High temp heat
Low temp heat
Electrochemical
Communications & electronics

Figure 18: Exergy consumption by industrial processes: USA 1880-2000

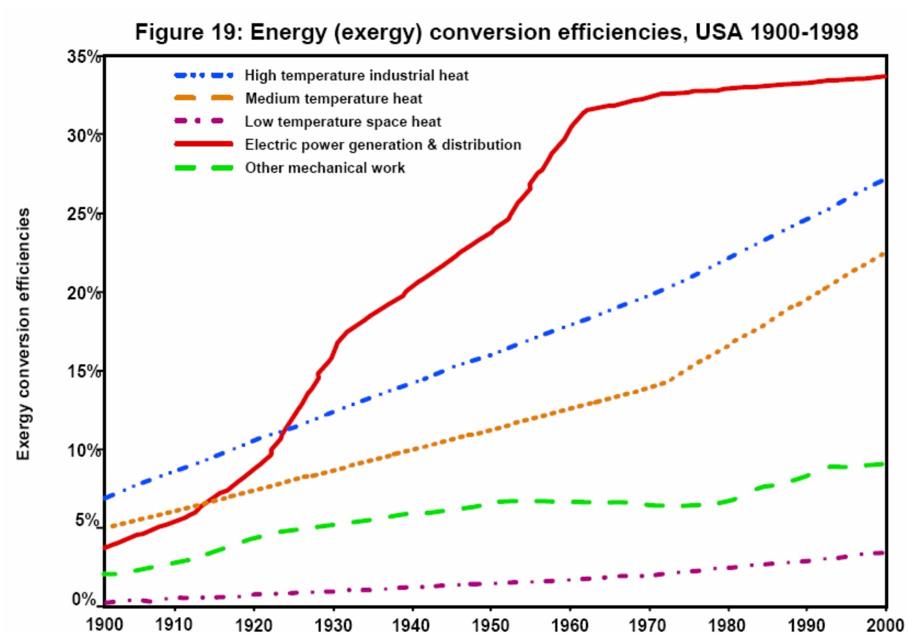


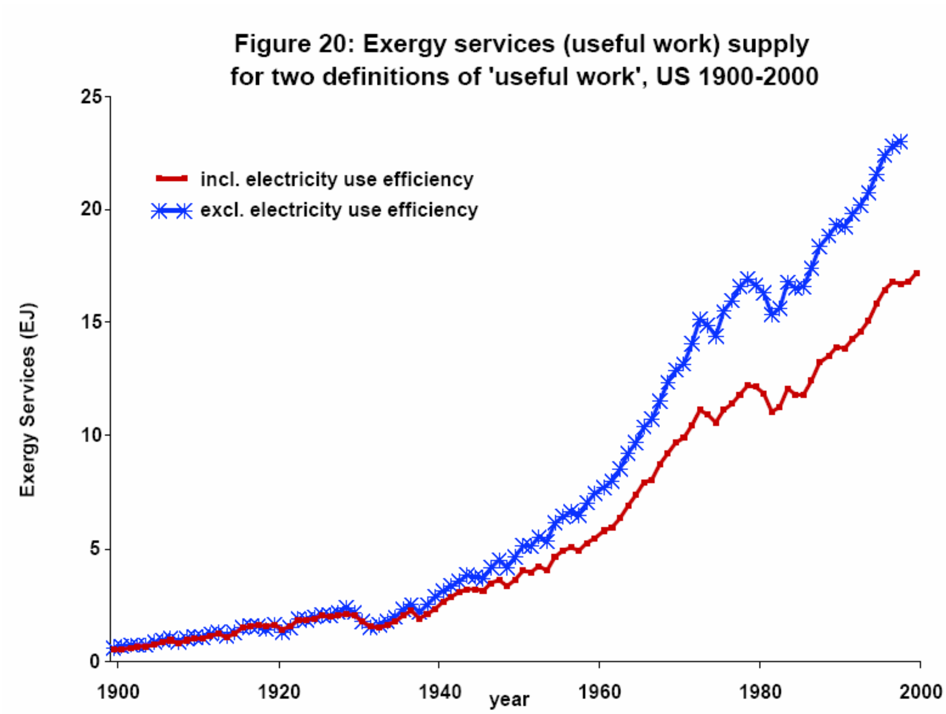
What remains to be accounted for is the fuel required for space heating, water heating, cooking and other domestic purposes. Heating efficiency has increased somewhat and can increase more in the future. In 1900 houses were generally heated, if at all, only by coal or gas fires in fireplaces, or by kitchen stoves. Wooden structures were thermal sieves, leaking through every orifice, especially windows, as well as through walls and roof. (Stone houses in Europe were somewhat better insulated but only by virtue of the thickness of the walls.)

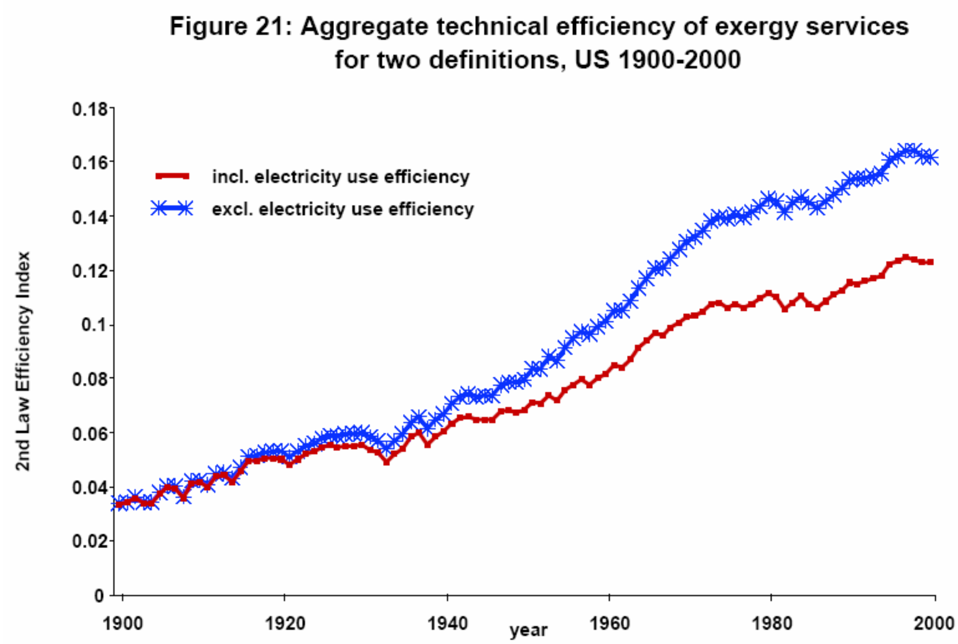
Central heating was introduced fairly widely in the US in the 1920s and 1930s, and this innovation reduced losses up the chimney. Moreover, some insulation, often asbestos, was routinely used for the furnace itself and as wrapping for the steam pipes. Later, insulation – usually 'rock wool' or fiberglass – was sometimes introduced between inner and outer walls and between ceilings and floors. However, as long as the construction was essentially artisanal, taking place entirely on-site, insulation was haphazard. Windows, in particular, consisted of a single pane of glass in a wooden frame, which was effective for keeping out rain and wind, but not very effective at retaining heat.

Since the discovery that asbestos is a dangerous carcinogen, much of the asbestos used in structures built before 1970 (or even later) has had to be removed at considerable cost. Mineral wool (made from slag) and fiber-glass have been effective replacements, in some instances, though nowadays new houses are increasingly constructed from prefabricated panels, which incorporate thermal insulation. Foamed poly-styrene ('styro-foam') has become rather a standard construction material, used entirely for insulation. Meanwhile, single pane glass windows, once standard and produced individually on-site, are being increasingly replaced by prefabricated double pane windows, sometimes even with argon or other inert gas 'fillers' to trap infra-red and/or filter out incoming UV radiation. Because of these innovations the average newly built structure today loses far less heat through walls, roof and windows than its predecessors.

However, I have not found any quantitative historical data on this topic, so I have made rather crude estimates. Bringing together all of the data available, first by type of work and then overall has led to the results indicated in *Figure 19*. Combining the various exergy inputs and their conversion efficiencies, and summing, one obtains an overall work done by the US economy, as shown in *Figure 20*. Dividing total work by total exergy input yields an overall exergy efficiency estimate for the US economy since 1900 (*Figure 21*). Both figures are shown for two cases, with and without allowing for the secondary efficiency of electric power use.







I could stop here, but I think it is interesting to see one of the uses of these results. This is not the place for an extended discussion of economic models. It is sufficient to say that the standard neoclassical approach assumes that economic output is a function of capital services and labor services, both of which are proportional to the respective stocks.[xii] Attempts to take into account the obvious importance of energy (exergy) inputs to production, using a standard production function, have not been successful. The reason is simply that exergy inputs have not grown as fast as the GDP (as indicated by the long-term decline in energy intensity, or Exergy/GDP (*Figure 22*). In order to account for the unexplained difference it is usual to introduce an exogenous multiplier, originally called 'technological progress' and, more recently 'total factor productivity' of TFP. Virtually all economic models assume that TFP will continue to increase at historical rates, like 3% per annum.

However, it is interesting to note that if we replace exergy inputs to production by inputs of *useful work*, as defined above and plotted in *Figure 20*, and if we discard the assumption that marginal productivities should correspond to payments shares in the national accounts, then historical US economic growth can be explained remarkably well without any exogenous multiplier. In other words, TFP is effectively explained by increasing exergy efficiency. Results for both the US and Japan are shown in *Figure 23*. Complete derivations and statistical tests are published, or will be published, elsewhere (Ayres and Warr, 2002; Ayres et al., 2003; Ayres and Warr, 2005).

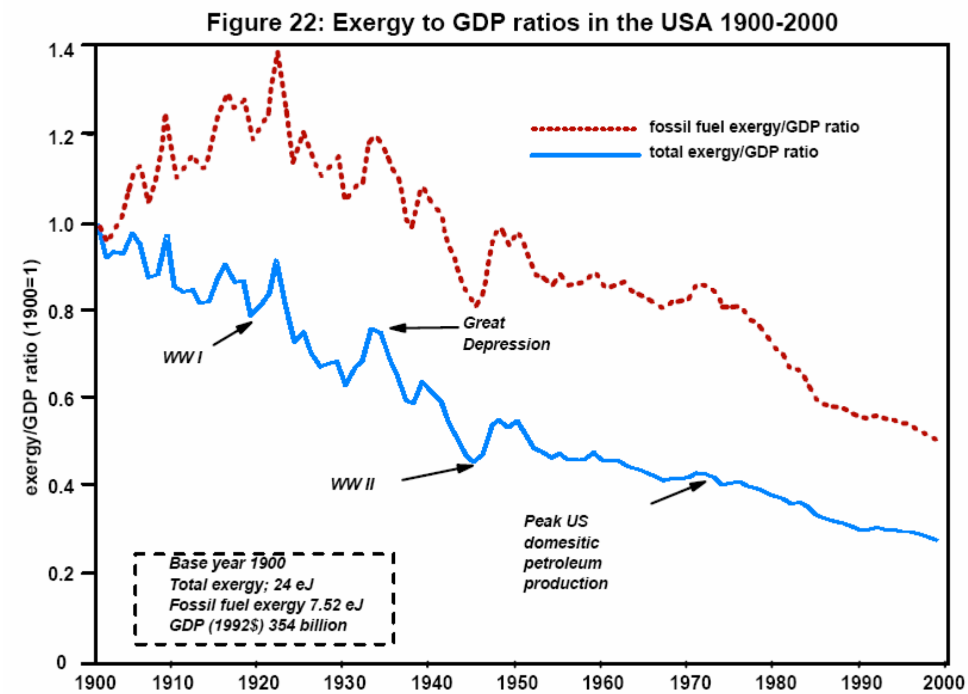


Figure 22: Exergy to GDP ratios in the USA 1900-2000
fossil fuel exergy/GDP ratio
total exergy/GDP ratio
exergy/GDP ratio (1900=1)
WW I
Great Depression
WW II
Peak US domesitic petroleum production
Base year 1900
Total exergy; 24 eJ
Fossil fuel exergy 7.52 eJ
GDP (1992$) 354 billion
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

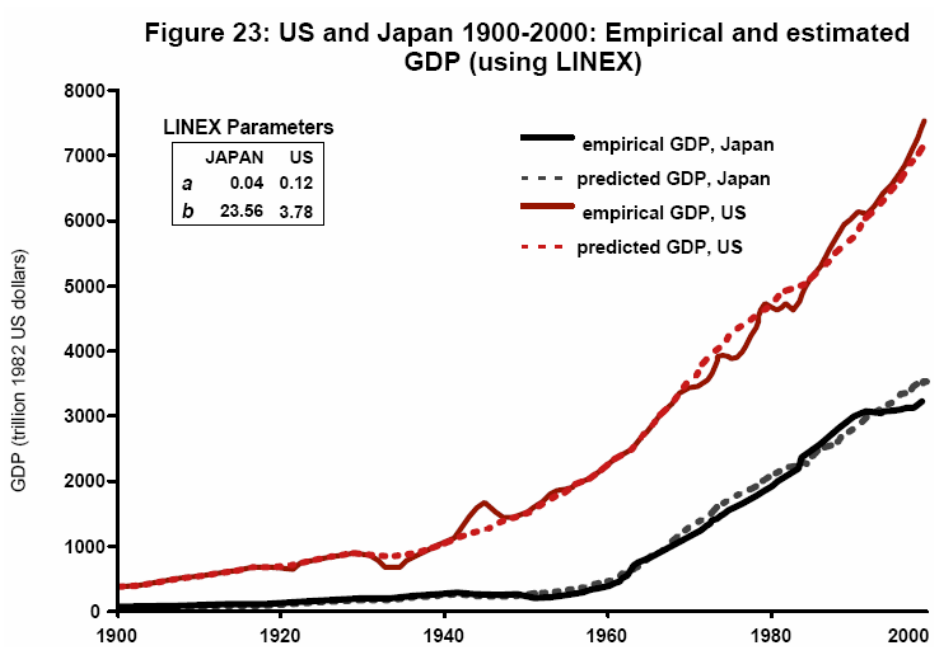


Figure 23: US and Japan 1900-2000: Empirical and estimated GDP (using LINEX)
LINEX Parameters
JAPAN US
a 0.04 0.12
b 23.56 3.78
empirical GDP, Japan
predicted GDP, Japan
empirical GDP, US
predicted GDP, US
GDP (trillion 1982 US dollars)
8000
7000
6000
5000
4000
3000
2000
1000
0
1900
1920
1940
1960
1980
2000

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i. It is true that oxygen is a waste product of photosynthesis by plants, and is essential for animal metabolism, so the carbon-oxygen cycle is well-known. There is also a somewhat less efficient nitrogen cycle that fixes atmospheric nitrogen – essential for proteins – and replaces nitrogen lost in excretion and decay processes. However calcium, phosphorus, sulfur, iron and other trace elements– which are equally essential – are not effectively recycled biologically. In the case of phosphorus, which is scarce, this could be a potential future problem.

ii. It is useful to distinguish between two kinds of work. In some sense, *disembodied* physical work in the form of muscular effort, mechanical propulsion, electric power, and useful heat. It is convenient to consider finished materials, from food (grain, dairy, meat), and wood (lumber, paper) to cement, refined metals (steel, aluminum) and plastics, as a corresponding category of *embodied* work, applicable to materials. Evidently finished materials also embody both chemical energy and the energy-as-work required to extract and refine them. But quantitatively, the embodied work in materials is a tiny fraction of the disembodied energy-as-work generated by the economy as a whole.

iii. On the other hand, animal manure generated in large industrialized feedlots *is* a waste.

iv. Actually 51 MMT of the 89 MMT of steel produced in the US in 1993 was recycled scrap. Domestic pig iron inputs were only 48 MMT. (The two input streams add up to 99 MMT; the weight difference consists mostly of slag and CO_2).

v. It can be argued that food and beverages are also service-carriers, inasmuch as they pass through the body and become wastes almost immediately, except for the tiny fraction that is retained in body mass. Even that is returned to the environment at the end of life, except for the annual incremental increase in the mass of the human population.

vi. However, in a more general physics context mass is a quantity only known from its influence. Originally the notion of mass was inferred from the observed fact of inertia. Some objects were more difficult to accelerate, or decelerate, than others. The "something" that explained this difference was called mass (Newton's law was "force equals mass times acceleration"). Isaac Newton applied this law to explain planetary orbits by equating the centrifugal force (proportional to mass) with the attractive gravitational force exerted by the sun (also proportional to mass). Later still Einstein proved that mass and energy are inter-convertible through his famous formula: energy (E) is equal to mass (m) times the velocity of light ©) squared, probably the second most famous formula in physics. The reality of this inter-convertibility was demonstrated over Hiroshima and Nagasaki in August 1945.

vii. A number of authors have considered the problem of power maximization as applied to thermodynamic systems. Key references in the literature include (Novikov 1958; Curzon and Ahlborn 1975; Gordon and Huleihil 1991; Gordon, 1991; Bejan 1988; De Vos 1992).

viii. Oxidation of carbohydrates (actually sugars) activates muscles, and this process takes place at ambient temperature although the process is nothing like combustion as we normally see it.

ix. Actually, in real blast furnaces, the output is not pure iron, but a mixture of iron with some dissolved carbon that must be removed in a subsequent process, as described in LECTURE 1.

x. This particular conversion process was first analyzed in detail by the French engineer Sadi Carnot. The maximum efficiency of an idealized heat engine operating between two infinite reservoirs is a function only of the temperature difference between the two reservoirs. Real (non-ideal) engines are necessarily less efficient than the Carnot limit. Carnot's work was the real basis of modern thermodynamics.

xi. Perhaps the best example comes from the Ford Foundation Energy Policy Study in the early 1970s, viz (Gyftopoulos et al., 1974).

xii. The function in question is called a production function. A variety of mathematical forms have been used, of which the most common (and simplest) is the Cobb-Douglas form, viz. $Y(t) = A(t)K^aL^{(1-a)}$ where Y is GDP, A(t) is the progress (TFP) multiplier, K is capital stock, L is the labor supply and the exponent a is the capital share of payments in the national accounts. Evidently 1-a is the share of payments to labor. It is easy to show that a and 1-a are the marginal productivities, respectively, of capital and labor. The assumed identification of marginal productivity with share of payments in the national accounts is linked to the so-called income allocation theorem in economics, but that theorem only applies to a very simplified model economy that bears little resemblance to the real situation. In particular it no longer applies to a multi-sector economy where raw materials are extracted, concentrated, refined and subsequently converted into components and products, and finally into services, as indicated in *Figures 2, 3* with value added at each step of the sequence (Ayres, 2001)