TECHNOLOGICAL PROGRESS: A PROPOSED MEASURE

by

ROBERT U. AYRES*

97/101/EPS

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Royal Dutch/Shell and Sandoz AG.

* Sandoz Professor of Management and the Environment at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.

Technological Progress: A Proposed Measure

Robert U. Ayres
Center for the Management of Environmental Resources
INSEAD
Fontainebleau, France

October 1997

Abstract

The paper suggests a direct measure of technological progress that can be quantified with reasonable confidence on the basis of historical data. The proposed measure is the efficiency with which resources (mainly energy sources) are converted into final services. It decomposes into two components, namely the thermodynamic efficiency of converting an energy source into mechanical work and the efficiency with which mechanical work is used to produce final services. The first part of this can be estimated, by sector, with fair accuracy. The second part can only be estimated with reasonable accuracy in a few cases (such as transportation and illumination), but the results are sufficient to permit some plausible extrapolation.

The proposed measure is of interest in itself. But perhaps it is more important insofar as it suggests a way to construct an economic production function that explicitly reflects technological change, rather than treating "technical progress" as an unexplained residual.

Technological progress and production

In another paper [Ayres 1997] I have suggested that the conventional two factor (or multi-factor) production function based on historical relationships between labor, capital, resources and production is likely to be inappropriate for long-run forecasting, because these relationships will not describe a future economic system. The contrast suggested by Kenneth Boulding between a "cowboy economy" and a "spaceship economy" is pertinent [Boulding 1966].

It is not unreasonable to retain the conventional two factor (capital K and labor L) production function for the "cowboy" case, even in the simple Cobb-Douglas form. The other limiting "spaceship" case can also be characterized by two factors, namely knowledge or information capital H and environmental resource (exergy) inputs R. I have used a different symbol for knowledge capital (H instead of K) to alert the reader to an important *caveat.* While capital in both the cowboy and spaceship economies can be conceptualized in the same way (i.e. as incorporating knowledge, organization and skills, as well as tangible reproducible capital) it is not necessarily measurable by the same proxy as capital in the cowboy economy. Moreover, the parameters of the production function (such as the exponents of the factors) may well be different in the two limiting cases.

One of the clear implications of a detailed analysis of limiting cases is that the common assumption of constant elasticities of substitution between capital and labor, or between capital and resources *over time* is inappropriate and must be discarded. Both labor and capital change their nature and become less material intensive (i.e. less physical) and more information intensive as the economy evolves from the cowboy stage to the spaceship stage. In the long run labor and tangible physical capital will inevitably become less scarce, or —

in the case of unskilled labor — not scarce at all. Their ability to command scarcity rents will therefore decline, except insofar as they can be preserved by cartelization (e.g. labor unions).[1]

The composite production function proposed in (1) evidently allows for this possibility.

The point is that in a cowboy economy labor and capital were the scarce factors, so production was essentially limited by their availability. However in a future spaceship economy, assuming continued economic growth for many decades, labor and capital will no longer be scarce, whereas environmental resources (such as renewable energy) and technology or knowledge will be the limiting factors. Certainly there are indications of this trend already: unskilled labor is clearly in surplus supply and the world is awash with capital looking for profitable investments, whereas environmental resources such as biodiversity, tropical forests and fresh water are already being depleted rapidly and are becoming scarce in some locations.

The important point is that during this transitional period, the real economy consists of two components. It is partly "cowboy" and partly "spaceship". A natural implication of the argument presented briefly above is that a generalized production function should reduce to the "cowboy" case in one limit (say 1800) and to the "spaceship" case in the other (say 2200). A linear combination of the form

$$F = (1 - A)F^1 + AF^2 \qquad 0 < A < 1 \tag{1}$$

where A(z) is some monotonically increasing function of an argument z discussed below. The functions F^1 and F^2 may be Cobb-Douglas, CES, or translog functions, as may be convenient for the application.

The form of A(z) must clearly be an elongated S-curve, rising slowly at first, then more rapidly, and again more and more slowly is it approaches the upper limit of unity. If the argument $z(t)$ is already monotonically increasing, and always less than unity, the simplest form for A(z) is then of the form

$$A(z) = z^n \tag{2}$$

where the exponent n is chosen by an econometric fit. The determination of n is best left until after $z(t)$ itself is quantified. The most natural procedure will be to select the value of n which best matches recent rates of growth.

We now seek a suitable proxy for the state of technology z. A number of possibilities can be considered. Expenditure on R&D, and on education, have been proposed as possible measures of investment in knowledge, but they do not provide much help in estimating knowledge stocks. Alternatively, one might plausibly measure the state of technology more directly in terms of the number of patents issued, or the number of technical journals in existence, or even the number of books in print. In the future "spaceship" earth, where the latter sort of information will probably be stored in computer memories, the available memory capacity and the information transmission/processing capacity would also be possible proxies.

However most of these — and some others that have been proposed — are measures of only one type of knowledge, namely the codified "free floating" type that can be found in libraries or patent offices. What we need is a proxy for information that is embodied in materials, structures, processes, systems, skills, organizations and cultures. This is a deeper and more difficult question.

The answer proposed here is that a reasonably good proxy for the state of technology $z(t)$ at any given time is *technical efficiency*, defined as the efficiency with which "raw" exergy from inanimate sources or animals is converted into final services. (*Exergy* is the correct technical term for what is normally meant by *energy* as this term is used casually; it is explained briefly in the Appendix.) This, in turn, can be decomposed into a product of two subsidiary ratios, as follows:

$$z = uv \tag{3}$$

The first factor u is the *exergy delivery efficiency*. This is the ratio of delivered exergy — meaning electric power, space heat, process heat (or steam), or mechanical work delivered to a driveshaft — to the exergy embodied in fuels, animal feeds, or hydraulic energy inputs. The second term in (3), namely v, is the *service delivery efficiency*. It is the ratio of final service output to delivered exergy or work input, as defined above. The first of these ratios can be estimated with fair accuracy by extrapolation from available energy statistics and technical analysis. The second term involves somewhat more qualitative and cruder — but feasible — estimates, as will be seen. In both cases, the estimates can be made at the sectoral level. In fact, sectoral detail makes the task easier.

The variable z is, in essence, a measure of the productivity of resources. In the first place, the efficiency of conversion of raw exergy inputs into final service outputs is obviously dependent on technological capacities in virtually every field of activity, from metallurgy and materials science to electrical and electronic engineering. It reflects progress in the technology of material processing and manufacturing, insofar as finished materials (such as steel and plastics) are being produced more efficiently from raw materials.

In the second place, finished products are similarly producing more and more "performance" in the broad sense — taking into account all the attributes contributing to consumer satisfaction — from fewer material inputs. This applies to housing, household management and transportation as well as telecommunications and entertainment. Electrification and chemistry were the major drivers of dematerialization in the late 19th century. Microelectronics, digital information processing, and biotechnology are the major engines of dematerialization today. Dematerialization is, of course, the obverse of materials productivity.

To calculate an overall technical efficiency z one must aggregate over all the different exergy sources and conversion pathways to final services. The first step is to estimate historical energy consumption *per se*.

Historical sources of exergy

Total energy statistics can be divided into two main categories, namely thermal energy from fuel used as such (for space heating, water heating, cooking, and metallurgical operations) and non-thermal energy used initially as mechanical work. The latter includes work done by animals, water power, wind power and heat engines. Electric power, up to very recently, has been produced only from generators driven by mechanical power, either from hydraulic sources or heat engines. This will change in the future, however, thanks to the introduction of direct conversion via photovoltaic (PV) cells. Electric power, however, can be regarded for our purposes as the purest form of mechanical work, since it can be converted directly into work — by an electric motor — with little or no loss.

The classification problem is somewhat confused by the fact that electricity can also be converted into heat, as in a resistance heater (such as an electric furnace or water heater) or a microwave oven. The situation is even further confused by the use of mechanical power to "pump" heat from one reservoir to another — without actually producing or destroying it — as in a refrigerator, air conditioner or heat pump. However all of these are developments of the present century. During the first two thirds of the 19th century, thermal energy was used almost only for household purposes, with iron and steel and other industrial uses of heat becoming significant only towards the end of the period.

A scattering of quantitative estimates is available from 1850 on, but reasonable extrapolations can be made to back to 1800. In 1850 heat energy from firewood alone was estimated at 2,140 trillion BTU, mostly for households [Schurr & Netschert 1960, Tables 1 & 2]. Thus, firewood was by far the dominant source of energy for household purposes. Per capita use was not changing rapidly. Thus, it seems safe to extrapolate aggregate firewood use back to 1800, simply in proportion to population. On that basis, aggregate firewood use in 1800 must have been close to 490 trillion BTU.

In colonial America most mechanical work not done by humans was done by horses and mules, supplemented by water mills and windmills. There are no data on livestock prior to 1867. In that year there were 6.8 million horses and 1 million mules, mainly on (approximately) 2.4 million farms, or roughly three animals per farm. Rural population for 1880 was 36 million, of which 60% (22 million) lived on 4 million farms, or 5.5 persons per farm. In 1800 the total population of the country was 5.3 million, of which 5 million were classed as "rural". One can probably assume that about 60% (3 million) were farmers, living on roughly 550,000 farms at that time. Using these ratios, one can estimate the horse/mule population in 1800 to have been about 1.7 million. In 1850 it is likely that the working animal population in the US was around 5.4 million.

Assuming each animal produced 1000 hp-hrs per year, this would imply 1.7 billion hp-hr in 1800 and 5.4 billion hp-hr in 1850.[2] The number of horses and mules in service combined reached 20 million in 1900, peaked at about 26 million between 1914 and 1920, and only declined slowly thereafter (to 15 million in 1938 and 10 million in 1947), as tractors and other equipment driven by internal combustion engines increasingly took over farm work. As noted, horses and mules were mainly used on farms, but as many as one third, in the 19th century, were probably used for transportation purposes. (There are no firm data on this, however).

Mechanical work done by inanimate power sources in 1850 has been estimated at 2.7 billion hp-hr, of which 52% was windpower, 33% waterpower and 15% steam power (@1.1% efficiency) [Dewhurst 1955]. Windpower was almost exclusively used in agriculture (for water pumping and grinding of grain). Water power, on the other hand, was entirely used for driving machines — mainly in the textile industry. Extrapolating back to 1800, it would appear that total work done (mainly by water power) must have been of the order of 0.5 billion hp-hr. Energy consumed by industry prior to the 1860s or so consisted of hydraulic power — most of which was used by mills of various kinds — and some charcoal and, later, coal, used for iron smelting and forging purposes. The composition of mechanical power sources was changing rapidly. By 1870, the total output had risen to 5.8 billion hp-hr, or of which the water share had fallen to 29% and the steam share had risen to 52%. Wind power use for irrigation (on prairie farms) had peaked in 1860 at 2.1 billion hp-hr (48% of the total) but had a decade later it had already declined sharply to below the 1850 level. In any case, animals were by far the dominant source of mechanical power in the U.S. 1867. It was only long after 1900 that the role of animals as a power source declined significantly.

As late as 1870 three quarters of U.S. energy consumption (not counting animal power) was still supplied by wood [Schurr & Netschert 1960], mostly still for home heating. In 1879 only 4.5% of wood fuel was used in the form of charcoal used for iron making [*ibid* p. 53]. By the end of the 19th century horses were being phased out of transport applications and coal burning steam engines were the prime movers for railroads, ships, factories and electric power plants. Today, steam or water turbines still supply electric power while internal combustion engines supply power for mobile applications. Heat and light were supplied by direct combustion until the electric light arrived on the scene around 1880 and since then electricity has steadily increased its share.

A rough breakdown of national energy use since 1800 can be constructed, as shown in *Table I.* A fairly detailed breakdown by use was available from the Census Bureau for 1970 and 1979. (Later these compilations were dropped, due to federal budget cuts). Data for 1990 was compiled carefully, but it is unofficial and incorporates a number of estimates. In particular, I suspect the figure for "machine drive" to be too low, while lighting and refrigeration and A/C may be over-estimated. Electrolysis was not specifically accounted for, and may have been aggregated with one of the above categories. I have interpolated the figures for 1900 and 1940, although historical research could doubtless refine and improve my guesses. The figures for 1850 are largely derivable from the two main sources cited above, as discussed in the text. Note that the rapidly growing "other" category includes petrochemical feedstocks, as well as a host of minor applications of electricity, including small appliances, radios, TVs, battery chargers, telecommunications, computers, xerox copiers, radar, X-ray machines, electrostatic smoke control devices, electrostatic printers, and so on.

Exergy conversion efficiency

In the case of fuels used to produce space heat, the conversion efficiency is the ratio of heat radiated or convected into the space to be heated to the total heat generated by the combustion process. In 1800, and still in 1850, most wood was burned in large fireplaces, not stoves, to avoid the extra labor needed to chop the wood into stove sized pieces [Schurr & Netschert 1960, p.50]. Since the fuel was essentially free, there was no economic incentive to use it efficiently. In fact, it was used extremely inefficiently. Most of the heat generated in a large fireplace is carried up the chimney. The thermal efficiency of heating by this method was about 8% in 1850 (and probably about the same in 1800 . Thanks to the introduction of wood stoves, then central heating and better insulation, this measure of efficiency had reached 60% by 1955 [Schurr & Netschert 1960 p. 49] and probably 70% by 1979.[3]

It is difficult to make exact comparisons between animals and machines in terms of thermodynamic efficiency, but a rough estimate for humans suggests that the efficiency is about 10%.[4] (Heat engines did not reach this level of efficiency until well into the 20th century.) In terms of the unit more commonly used by energy analysts in the U.S., one million horses or mules produce 2.54 trillion BTU/yr of "useful work", while consuming about 25.4 trillion BTU/yr in feed. Thus the feed equivalent of working animals on farms in 1800 must have been around 43 trillion BTU, with an uncertainty of 10% or so. For 1850 the feed consumption (for 5.4 million animals) was about 137 trillion BTU. By 1900 it had reached 508 trillion BTU, for 20 million animals; it peaked at 650 trillion BTU in 1918.

Steam engines were used mostly by railroads and riverboats before 1850; they were only installed for factories where water power was unavailable, as in seaports such as Baltimore, Philadelphia and New York. In 1850 the average efficiency of steam power, in terms of power delivered to the wheels of a locomotive (or a loom) by a drive shaft, was calculated to be 1.1%; it rose gradually to 1.8% by 1870, 3% in 1900 and 7% in 1920 [Dewhurst 1955]. These figures reflect the large number of small and inefficient engines in use. Large steam engines used for producing electric power, starting in the late 1880s, were more efficient, albeit seldom more than 10%. As high pressure steam turbines were introduced after the turn of the century, however, large central units became far more efficient than smaller engines.

The most advanced single cycle thermal power plants of today operate at 45% efficiency (including the generator) and combined cycle plants can do better still.

Wind power (from stand alone windmills) enjoyed a brief period of popularity during the middle of the last century, especially between 1850 and 1870. The efficiency of these machines at converting wind energy to mechanical power has been estimated at 18% [Dewhurst 1955].[5] I think this is probably too high, but I have no better estimate. Modern windmills, using light materials and aerodynamic design can do considerably better than older designs; however they have not yet achieved widespread use.

Water power was the only source of mechanical power for manufacturing in New England, during the colonial period, and was still significant in mid century. In the early period the technology was the simple water wheel. Hydraulic turbines (c. 1840) constituted a major breakthrough inefficiency. It is difficult to estimate the efficiency of those crude early water wheels; 20% seems a reasonable guess. The water power driving the wheels used in 1800, therefore, would have been of the order of 5 trillion BTU. After the invention of hydraulic turbines efficiencies increased considerably. By 1850 the conversion efficiency had nearly doubled to 39% [Dewhurst 1955]. A modern hydraulic turbine can capture over 90% of the potential energy in the falling water. Water power suddenly became very important after 1890, as falling water — beginning with the exploitation of Niagara Falls — became the cheapest source of electricity.

Internal combustion engines are the most important source of mechanical power today. There are three types. The most common is the spark ignition (gasoline) engine, which dominates in automotive applications. Thermodynamic efficiency at constant speed, without parasitic loads, is about 33%. Losses between the driveshaft and the final service output (passenger km) are discussed later. Pressure ignition (diesel) engines are the next most common type. They are used for some automobiles, heavy trucks, buses diesel electric locomotives, small ships, and offroad equipment. They achieve slightly higher efficiencies, about 36%, under ideal conditions. Finally, gas turbines are used mainly for aircraft, but also for some peak load electric power production. Efficiencies are comparable to diesel engines, although large units can do better.

The efficiency of electric power generation in the early 19th century was extremely low, but since the quantity produced was also infinitesimal, a precise estimate is pointless. Generators achieved roughly 50% efficiency in converting mechanical work to electric power by the 1860s, but virtually the only use was for arc lights, initially in lighthouses. Edison's "Jumbo" generator design of 1878 was the real breakthrough, reaching 80% conversion efficiency. Since then, efficiencies for large units have reached and exceeded the 95% level. The mechanical power, in most cases, is provided nowadays by a steam turbine, so that overall efficiencies — from fuel to electricity at the generator — now range up to 48% at the high end. The average, including transmission losses, is currently (c. 1991) about 33%.

The primary or "first law" energy conversion efficiencies (see endnote 10), by category, are summarized in *Table II* below. As in the case of *Table I*, one can estimate early and recent efficiencies reasonably accurately, but some of the intervening years are interpolations. Doubtless these numbers could be improved by serious historical research, but my purpose here is simply to demonstrate that such analysis is feasible.

Service delivery efficiency

Services can be subdivided into two categories, intermediate and final. Intermediate services are performed for other sectors. For instance, space heat, illumination, industrial heat and freight transportation are all partly used by other sectors. Manufacturing and "feedstocks" are consumed only by other productive sectors, not by final consumers. It is possible to estimate service efficiencies (as illustrated below) for some of these cases, but not for all. In particular, it is impossible to estimate directly the efficiency with which manufactured products provide final services to consumers. Facing this difficulty can be postponed, however.

It is convenient to start by considering straightforward energy services, namely heating, cooling and lighting. Here it is important to distinguish between two methods of calculating efficiency, which is especially important when discussing heat and it's uses. The crude thermal efficiency of space heating by fuel combustion, discussed in the previous section, was calculated as the ratio of heat delivered to the room (or one minus the heat lost up the smokestack) to the total heat generated by the fire. It did not reflect the fact that the heat was generated at a high temperature that *could have* accomplished a lot of useful work (for instance, by generating electricity) which could, in turn, have "pumped" lower temperature heat from some reservoir into the space — or better still — into the immediate vicinity of the persons occupying the room. An electric blanket offers as good or better foot warming service to sleepers in a bed than a warm bedroom, not to say a warm house.[6]

Anybody with a good imagination can see ways of reducing energy requirements for space heating to nearly zero, given unlimited capital. However, it is helpful to look at the question more narrowly, in terms of the ratio between the minimum amount of energy (actually exergy) required to achieve a given function — say, maintaining the temperature of a house at 70 degrees F — *vis a vis* the actual exergy consumed for this purpose at a given point in time. The ratio just defined has been called "second law efficiency". In general, second law efficiency is much lower than first law efficiency. The space heating case, in particular, has been examined in some detail by engineering analysts, for a variety of different configurations. An overall estimate of 6% for the second law efficiency for space heating in the U.S. as of 1970 [Carnahan *et al* 1975, Table 2.8]. Recall that the "first law" energy efficiency for space heating (as previously noted), was already 60% by 1955. In earlier years the second law efficiency would have been lower in proportion. Thus, if first law efficiency was 8% in 1850, second law (exergy delivery) efficiency would have been around 0.8%.

The foregoing takes into account the delivery of warm air in the room; it does *not* yet take into account true final service delivery efficiency — the efficiency with which the occupant of the room is warmed. In fact, a well insulated house that captures a reasonable amount of the solar energy impinging on it's windows requires little or no heating at all, as has been demonstrated many times by architects. Similarly, a good warm sweater can be a good substitute for space heating. At night, an electric blanket can be more effective than a radiator. Anyone who writes, types or plays the piano has noticed that warm hands are important, but the rest of the body can be much cooler. Why not an infrared heater focussed specifically on the hands? A footwarmer may also be a more efficient substitute than a room heater, for many situations. However, while these considerations imply that the potential for future energy conservation is considerably greater than the efficiency figures tabulated in *Table II* imply, they do not affect the utility of the latter as measures of the state of technology over time.

Water heating in the first half of the 19th century was a parasitic batch process; a bucket of water was heated "on the hob" by the heat of the fire in the fireplace. Assuming the service in question was (mainly) for washing clothes and bathing persons, this process was even less efficient than space heating, since the warm water quickly lost much of it's heat to the bucket or the bathtub. When stoves were introduced the situation improved significantly. However, to be conservative, one can apply the same rule as for space heating. The estimated second law efficiency of water heating in the U.S. in 1970 was only 3% [Carnahan *et al* 1975]. This implies an efficiency of 0.3% in 1850 — which is probably generous. NB it should be pointed out that even the 3% figure does not reflect potential savings through the use of cold water detergents that have since become available and which sharply reduce the amount of hot water needed for laundries and dishwashers.

Cooking in the early 19th century was also largely dependent on the fire in the fireplace. Later stoves were introduced specifically for cooking purposes, but at first these were available only to the urban middle class. Not until the end of the century were kitchen stoves more generally available. Subsequent innovations include the substitution of gas for wood, coke or coal, electrification (using resistance heat), and most recently microwaves. First law efficiency in this case would be defined as the ratio of heat delivered to the cooking apparatus (e.g. the pan) to the amount generated by the fuel. More efficient delivery by well-designed ranges and pans has been counteracted, however, by the increased penetration of electric heat. Because of heterogeneity and lack of detailed data, the second law efficiency of cooking — defined in terms of heating the food — was not specifically estimated by the AIP Summer Study [Carnahan *et al* 1975], but it would probably be roughly comparable to the efficiency of water heating, for all periods.

From a service efficiency perspective, it is also important to consider ways to reduce the amount of heat *needed* for cooking. Microwaves are a great step forward in this regard, since they eliminate the need to heat a lot of dead mass (pans and water) in addition to the food itself.[7] To be conservative, I assume that end-use efficiency for cooking and washing is 50%.

Similar considerations hold for refrigeration and air conditioning. Refrigeration was available only from ice (stored in insulated iceboxes), in the 19th century and well into the present one. Ice was a major export product of New England). Small electric motors and compressors made refrigeration feasible on the domestic scale. The average second law efficiency, as calculated by Carnahan *et al* for 1970 was about 6%. Since then, thanks to pressure by governments and consumer groups, major improvements have occurred and the best performing units on the market are nearly three times as efficient (i.e. 18%). Also, the market has grown, so many units are less than 10 years old. However, refrigerators and air conditioners last up to 20 years, whence many older units are still in service. I estimate current average second law efficiency to be about 13%.

Again, the major final service provided by refrigeration is preservation and storage, of perishables. (Provision of ice cubes and chilled drinks is a minor aspect). In principle, it is only the perishables that need to be kept cold, not the containers. Also, cold is only a way of inhibiting spoilage, i.e. a substitute for sterilization; it is not really necessary in many cases. Already, alternative methods of preservation and storage are being introduced — e.g. for milk — that do not require refrigeration. Also, thanks to marketing by manufacturers, people tend to refrigerate things that would be better left at room temperature (such as butter). Thus, it is difficult to estimate the true service efficiency in this case, except that it is surely considerably less than the second law efficiency of the equipment *per se*.

Air-conditioning is the complement of space heating. Insulation is an effective substitute in many situations (hence adobe houses), and ventilation plus evaporative cooling may be quite adequate in a dry climate. Also, it is not necessary to cool all the air in a house to be comfortable. However, while it is very difficult to estimate the minimum need in this case, it is difficult not to believe that the true minimum is far less than current practice. To be conservative I assume the end use efficiency of refrigeration and air-conditioning services, taken all together, to be 20%. This is probably much too high.

Lighting is a special case, since the technology has changed radically. In 1800 the primary source of light (apart from open fires) was candles. By 1850 various sorts of oil lamps, and some gas lamps were being used. Arc lights were being introduced in the 1870s.

Edison's incandescent light was a big step forward, but of course it did not replace all other forms of illumination for many years. In 1900 oil lamps and gas lamps were still widely used. However, by 1940, lighting had become essentially fully electrified and the tungsten filament incandescent light was standard. Fluorescent lamps have higher lighting efficiency, but they had not yet achieved really wide use. Nordhaus has tabulated lighting efficiencies in terms of lumen/watt (equivalent) delivered at the lamp [Nordhaus 1994, Table 3]. A tallow candle of 1800 or 1850 delivered 0.0757 lumens/watt; a sperm oil lamp c. 1850 delivered 0.135 lumens/watt. A Welsbach gas mantle of c. 1900 delivered 0.6 lumens/watt (town gas); an incandescent electric lamp of the same period produced 3.71 lumens/watt (electricity). By 1940 that figure had increased to 11.9. By 1980 it had increased only slightly further to 12 lumens/watt or 6%of the theoretical maximum of 200 lumens/watt. It is interesting to note that modern compact fluorescent lamps produce 68 lumens/watt, which makes them nearly 5 times more efficient, or about 34% of the maximum. These compact lamps have made significant progress in market penetration during the last decade or so.

It is necessary to adjust all these figures to allow for inefficiencies (losses) in refining tallow or sperm oil, producing town gas, and generating electric power. Very roughly, animal oil refinery efficiencies were probably of the order of 80% (perhaps more, since high temperatures were not needed); town gas efficiency was probably around 50%. Electric power generating efficiency was discussed in the last section. The overall efficiency of lighting in 1800 was, therefore, about .03%; by 1850 this had risen to perhaps .05%. For 1900 it is difficult to estimate, given a heterogeneous mix of candles, kerosine lamps, gaslight and electric light. Assuming the gas mantle to have been average, the efficiency would have been 0.15%. Electric lighting at the time would have been around 0.3% efficient. By 1940 electric light was universal and the efficiency had risen to about 1.9%, taking into account the inefficiency of electric power generation and transmission.

As in the previous cases, light delivered at a lamp is not actually the final service. The latter would be light delivered to the object being viewed. Thus, a small light source, with a parabolic reflector can be more effective than a much brighter light that is unfocussed. However, I see no need to attempt to include such considerations in the technical efficiency measure at this stage.

Transportation is a well documented category of service where the distinction between input and output is relatively easy to comprehend. The input, as noted previously, is power delivered to the wheels, and mechanical energy dissipated as heat by the brakes — as opposed to energy lost in a variety of other ways. The final output, however, can be characterized crudely as passenger km or freight MT km. Obviously these measures do not describe the service fully; for passengers, and perishable goods, speed is an important attribute of the service. Comfort, convenience, prestige and so fort are also relevant. But, to simplify, I consider only the crude measures. The equivalent first law efficiency of transport has been equated (roughly) to the maximum theoretical thermal efficiency of the prime movers involved, viz, gasoline or diesel engines, diesel electric locomotives or gas turbines [e.g. Bridges 1973].

But this simplistic measure clearly does not reflect losses in service delivery, of which there are many. Thus, a gasoline engine operating under ideal conditions at constant speed with no parasitic loads can convert 33% of the chemical energy in the fuel to mechanical energy. (A diesel engine can do about 36%). However, a few years ago the situation looked more or less as follows [Carnahan *et al* 1975]: operating under realistic traffic conditions, with acceleration, deceleration, gear changing and idling, the maximum efficiency drops by a third, to 22%. Frictional losses in the drive train — mainly the clutch, transmission and universal gears — cost another quarter (to 17%). Parasitic loads, such as water pump, oil pump, power brakes, electrical system and air conditioning, as well as the emissions control system, bring the average down to 11% or so, not counting automatic transmission which costs another 2% to 3%. (Most American cars are automatics, today.) Also, there are losses at the petroleum refinery (about 9% of input) which account for another percent. So the second-law efficiency of the typical American automobile at the time was of the order of 7%.

A more recent calculation, classifies losses somewhat differently: starting from a fuel input to automobiles, trucks and other mobile equipment of 19.2 Q (quadrillion BTU), 3 Q is consumed in idling, 9.8 Q is lost as heat out the tailpipe during driving, 2.4 Q is consumed to overcome engine friction and operate engine accessories, 0.8 Q is lost overcoming driveline friction, and 1.6 Q is used to overcome aerodynamic drag (i.e. to push air around). This leaves 1.8 Q as "useful work" defined as heat dissipated in the brakes. The ratio of 1.8/19.2 yields an efficiency estimate of 9.4% for all ground vehicles taken together.[8] Although the final result looks reasonable, the above numbers imply a first law thermal efficiency of [1 - (9.8/16.2)] or 39.5% when the vehicles are not idling. This is clearly too high for Otto cycle engines or any but the very largest diesels. However, assuming a more realistic first-law thermal efficiency of 35% or so (33% for Otto cycle; 36% for diesel) will evidently result in a proportionally lower second-law efficiency as well, probably about 8.5%. This does not take into account the additional losses of 10% in petroleum refining.

To be sure, manufacturers have reduced fuel consumption significantly in recent years. But they have not done so by increasing the thermodynamic efficiency of the engine. In fact, since the abolition of lead as an antiknock additive, engine compression ratios have actually dropped significantly to accommodate lower octane fuels. Improved fuel economy has been achieved simply by reducing the power required to run the vehicle by (1) cutting weight, (2) reducing tire friction, and (3) reducing air friction. Internal losses have also been reduced to some extent by adding an extra gear and utilizing more electronics to achieve finer engine controls.

But that applies only to the vehicle. The biggest single loss in the transportation system arises from the fact that the engine must move not only the passenger or payload, but the entire vehicle, including itself. Most of the mass moved is deadweight. This was also true for pre-automotive transport, although the weight of a cart or carriage was normally a smaller multiple of the payload weight; on the other hand, due to primitive bearings and poor roads, frictional losses were far higher. In the case of an automobile, with an average weight of 1000 kg, and a load factor of 1.6 or so, the weight of the passengers and their belongings, on average, is less than 200 kg. So 1000 kg of vehicle (plus some fuel) is moved for the sake of moving 200 kg or so of payload. This amounts to a *payload efficiency* of the order of one part in five or 20%. (Incidentally, this has increased significantly from 1970, thanks to lighter cars). Combining the thermal efficiency and the payload efficiency brings the overall efficiency of service delivery down to around 1.5% or so for automobiles.

The real advantage of public transportation is that payload efficiencies can be higher. Airlines, for instance, routinely operate at load factors in the 70% range; on the other hand they are forced to carry very large parasitic loads of fuel. As a rule of thumb, the payload of an airliner in service is about equal to the weight of the fuel (fully loaded) and the unloaded weight of the aircraft itself. The overall service efficiency of air passenger transportation is therefore around 5.5% [Ayres 1989]. Assuming air travel accounts for 10% of passenger miles, the overall passenger transport service efficiency comes to about 2%.

Freight transportation deserves special comment. Long distance diesel tractor trailers typically operate near full load capacity by treating trailers as portable containers, leaving empty trailers at each destination for reloading and switching to fully loaded trailers for the next leg of the journey. On the road they also accelerate and decelerate much more gradually, operating more of the time at optimum speed and requiring far less power per unit weight of load than passenger vehicles. Finally, they waste comparatively less energy on operating parasitic equipment than passenger cars. The thermal efficiency of such a vehicle can be as high as 20% or even more, and it's average payload efficiency can also be better than 50%, for an overall efficiency in excess of 10%. Railways are significantly better still, in these terms, but count for a relatively small fraction of overall transportation energy. Diesel electric unit trains may achieve combined thermal and payload efficiencies as high as 25%. Small trucks and vans, on the other hand, are often used as private vehicles and, being bigger and heavier, they are even less efficient than private automobiles.

Averaging the service efficiencies of passenger and freight transportation together comes to around 6%, for the present mix, give or take one or two percent. Transportation efficiency in 1900 was considerably higher for passengers, but lower for freight. Long distance freight transport was mostly by rail or ship, while urban passenger transport was by rail or streetcar. By 1940 automobiles and trucks were common, but not nearly as dominant as they have since become. Thus, combined transport efficiency probably peaked in the late 19th century.

Manufacturing is much more difficult to analyze. A thorough analysis of exergy efficiency in the manufacturing sector would be a major study in itself. (In fact, such studies have been done for the process industries [e.g. Gyftopoulos *et al* 1974; Hall *et al* 1975]). There are three generic components of the manufacturing process: physical separation, chemical transformation (reduction, purification, synthesis) and physical transformation (shaping and forming). Physical separation tends to be quite inefficient in second law terms but the total amount of energy expended on this stage is not great. Metallurgical and chemical transformations range from 20% to 30% conversion efficiency, in second law terms. These efficiencies have been calculated for the most energy intensive sectors (e.g. steel, aluminum, copper, cement, paper, chlorine, petrochemicals). There have been improvements of a few percentage points in the last twenty years, but these are all mature capital intensive sectors where technical change involves large scale investment.

Many complex chemical processes are much less efficient, but again they do not consume much energy *in toto*. Rolling, stamping, extrusion, drawing and molding also probably average 20%–30% efficiency. Machining and grinding of ores and metals, however, is an exception; efficiency may be as low as 1%. Hence, an estimate of 25% "first law" efficiency for the manufacturing sector is probably not too low, though it may be much too high [Ayres 1989]. As regards "second law" efficiency, taking into account all possible ways of producing the same final services generated by products, I cannot estimate it directly. Nor can I estimate the efficiency with which intermediate sectors like agriculture and construction deliver their services to other sectors. I do not attempt it.

Instead, I make the rather heroic assumption that the ratio between first and second law efficiencies for these categories is the same as for direct energy services, namely about a factor of ten. In short, I estimate final service delivery for industry, construction and agriculture as one tenth of the corresponding first law thermodynamic efficiencies as estimated in *Table II*. This assumption is defensible on two grounds. First, the total amount of energy involved is considerably less than that consumed in direct services. And second, it is consistent with the notion that energy efficiency is a reasonable proxy for technical efficiency in general.

Actually the true ratio or first and second law efficiencies is probably much larger. It is increasingly obvious that many "final services" — certainly education, communication and entertainment — really consist of nearly pure information. Information has an infinitesimal energy "content" Tribus & McIrvine 1971]. Certainly, the service output of information processing systems per unit of energy input has been rising spectacularly for several decades.

The limits are probably still far away. The path-breaking science-fiction book *Neuromancer* by William Gibson illustrates a world in which humans utilize special microchips (embedded in their skulls) that by-pass the normal sensory channels and permit them to "jack in" directly to "cyberspace". While this notion is somewhat fanciful, it is not scientifically altogether out of bounds. This being so, my factor of ten is probably quite conservative.

Table III presents the final (combined) service efficiency estimates, based on the foregoing (semi-qualitative) arguments. The categories for agriculture, construction, machine drive, industry and "other" do not deliver final services to consumers, and are therefore left out of the table. The results are plotted in *Figure A.1.*

Combined technical efficiency

Multiplying the efficiency estimates of *Table II* and *Table III* above with the share data in *Table I*, yields a composite estimate of the technical efficiency for each category of use and for the economy as a whole. Recalling that all of the tables were presented in terms of percentages, the product is given as a decimal fraction in *Table IV.*

It is worthwhile calling attention to three points. First, it will be noted that the curve is vaguely S-shaped: it has a distinct resemblance to the so-called "logistic" curve, but it is not symmetric around the point of inflection. The inflection point occurs between 1850 and 1900 at a very low level of technical efficiency. Second, even if I have considerably overestimated or underestimated the second-law efficiency of industry and the intermediate sectors, the results would not be qualitatively different. Third, and most important, there is still a great deal of room for technical efficiency improvements.

As noted above, the rising trend of technical efficiency is an elongated S-curve, but not a symmetric one. In other words, the point of inflection where the second derivative vanishes does not occur at the halfway point, (as it does in the case of the well-known logistic curve). On the contrary, it occurs very near the zero level. If the curve continues along its current path, technological progress can be expected to continue indefinitely, but the rate of increase will decline monotonically.

A suitable functional form for z that is readily estimated can be derived from the Mahajan-Schoeman differential equation for generalized diffusion processes [Mahajan & Schoeman 1977; Skiadas 1985], viz.

$$\dot{z} = a(1 - z) + b(1 - z)z \tag{4}$$

which has the solution

$$\ln\left(\frac{1 - z}{a + bz}\right) = -(a + b)(c + t) \tag{5}$$

and the inflection point (see *Figure 1*)

$$z_{in} = \frac{b - a}{2b} \tag{6}$$

which can be solved for a or b when z_{in} is known. From *Fig 1* it can be seen that $z_{in} = 0.015$. Solving for a

$$a = (1 - 2z_{in})b = 0.97b \qquad (7)$$

This leaves two parameters (b, c) to be determined by some other means, such as a least squares fit. However, an approximate fit can easily be obtained by introducing values of z for t = 1800 and t = 1980. Without going into great detail, it is easy to verify that $b \approx 10^{-4}$ and $c \approx 5 \times 10^{4}$. Greater precision is obviously inappropriate.

The appropriate value for the exponent n (equation 2) remains to be determined. This is important because the value of n will determine the relative importance of the "cowboy" and "spaceship" sectors in today's transitional economy. There may be several ways to approach this question, and I suspect it is a research topic in itself. For what it is worth I suspect that the "spaceship" component corresponds roughly with the share of the information services sector today. If so, it is clear the $n \ll 1$. Since it makes no sense to forecast z, or z^n for more than a few decades, at most, a simple extrapolation (a straight line on log paper) is probably the best that can be done for the moment.

It would be foolish and premature to suggest that the above results, as they stand, are sufficient to use for serious economic forecasting purposes. They are merely suggestive. For one thing, the precision is low. It is probable that serious research into the history of technology would uncover much better numerical values for some of the tables, although the final results would not be greatly affected. Nevertheless, this line of research seems worthy of attention.

Appendix: Energy and exergy

Physical measures of energy (E) and materials (M) introduce both conceptual and practical difficulties. Most analysts have considered energy (E) and materials (M) flows separately. But the term "energy" is not used correctly in most economic studies, as noted below. Physical mass (M) is meaningful for engineering calculations, but it a very unsatisfactory and nearly meaningless measure for heterogeneous material resource inputs (or outputs). Moreover, both energy and mass are physically conserved quantities. Neither is gained nor lost in the economic process. Hence they cannot be "used up" in any sense; they cannot be factors of production.

For these reasons, economists have used monetary measures (dollar value) almost exclusively. This is quite satisfactory for some purposes, such as comparing monetary outputs per unit of aggregate mass input, over time, or between countries, for a given industry (say steel, or petrochemicals). But comparing one sector or product, or resource, with another in this manner introduces serious conceptual difficulties. While mass is definable for all materials, and hence mass inputs and outputs are definable for all sectors, the relationship between aggregate mass input and monetary outputs cannot meaningfully be compared, either between sectors or from period to period.

As noted above, the term "energy", is used incorrectly by most people, although the problem is mainly terminological. What is normally measured in practice and labelled "energy" is the potential heat of combustion (technically, *enthalpy*) of a fuel, while on the output side the usual measure is *mechanical work* or power delivered over time. Electric power is regarded as pure work. (That is, it can be converted into work with almost 100% efficiency). For the sake of conceptual precision it should be replaced by the word *exergy*, which refers to that part of the energy flux that is available to do useful work and, which can be used up in an economic process as work is done and energy becomes less available.[9] The important difference between energy and exergy is that exergy is not a conserved quantity.

Exergy is measurable. As applied to dry fossil hydrocarbon fuels, exergy is nearly equal to the standard heat of combustion because that combustion generates rather high temperatures (over 1500°C). This heat can be converted to work, *in principle*, with comparably high Carnot efficiency $(T-T_0)/T$ where T_0 is the ambient temperature of the surface of the earth, about 300 degrees above absolute zero on the Kelvin scale. The same cannot be said of firewood, which burns at much lower temperatures (even when comparatively dry) and wastes much of it's heat output on vaporizing water. In the case of steam, at temperature T, it is equal to heat content times the Carnot efficiency. But the fact that fossil fuels are so dominant, at present, has encouraged energy analysts to measure energy in terms of heat of combustion (e.g. BTU or terajoules) and to speak of coal or oil equivalents.[10]

What is not commonly realized is that exergy is definable and measurable for all materials, not just fuels. It is as fundamental a measure as mass, except for one restriction: exergy is only defined *jointly* for a material and the environmental medium or reference state — or "sink" — with which it must ultimately reach thermodynamic equilibrium. Once the reference state has been specified (usually the atmosphere, ocean or earth's crust) exergy can be calculated quite precisely from thermodynamic data that are already collected and compiled in reference books [see Szargut *et al* 1988; Ayres *et al* 1997-a].The exergy measure applies equally well to organic materials and inorganic substances. Thus it can be determined equally well for physical process inputs (resource flows, including fuels), process outputs (material products and byproducts), waste heat, and material waste effluents.

Since the exergy measure is applicable to and computable for *all* materials, as well as all forms of energy, it can be used for purposes of aggregation in situations where the monetary measure is inappropriate or inadequate. For instance, the *stock* of all known mineral resources in a given country, at a given time, can be presented as a single number combining fossil fuels, forests, hydroelectric resources, metals and other minerals. Similarly, the consumption of all resource inputs to a country or an industry — including minerals, agricultural and forest products — can be expressed as an aggregate in exergy terms. This approach to resource accounting has been proposed, in particular, by Wall [Wall 1977, 1986, 1990]. By the same token, the aggregate output of useful products, as well as the generation of material wastes, can also be expressed, separately, in exergy terms [Ayres *et al* 1997-a].[11]

Endnotes

1. In point of fact, the massive increase in returns to financial capital in recent years, especially in the U.S., is surely related to the decreased ability of the U.S. labor movement to appropriate monopoly rents, even though labor productivity has been growing and capital productivity has not.

2. The unit "horsepower" was introduced by James Watt in 1783 and defined as 33,000 foot-lb of work per minute. It was based on estimates of the work done by horses used for pumping water out of flooded mines. A horse working on a farm does not work continuously at that degree of intensity; the accepted approximation for a working horse or mule is an output of 1000 hp-hr/yr [Dewhurst 1955]. The power output of a human laborer working an eight hour day is estimated to be about one tenth hp [Encyclopedia Britannica "Power"].

3. It is important to note that these figures are so-called "first law" efficiencies; i.e. they measure the fraction of total heat produced that is captured for space heating purposes (as opposed to going up the chimney). They do not refer to "second law" efficiency, which is the ratio of energy needed to accomplish the purpose in the most efficient possible way to energy actually consumed. A very careful analysis of this issue carried out in 1975 by a summer study sponsored by the National Science Foundation and the American Institute of Physics [Carnahan *et al* 1975] concluded that home heating based on the use of a furnace, steam boiler and conventional radiators is still very inefficient compared to theoretical possibilities, such as heat pumps. In fact, with careful design, good insulation and solar heating,

virtually no external energy source is required at all, even in quite cold climates. This point is exemplified by the Rocky Mountain Institute, located in Old Snowmass, Colorado, at an altitude of 8000 feet (2300 meters), which has no central heating system at all. Admittedly, such efficient "high tech" structures are rare and relatively costly today, but the existence of even one example makes two important points: (1) that current heating systems are very inefficient in terms of theoretical potential and (2) that the potential for substituting capital for energy is nearly unlimited.

4. The food intake required by a 70 kg man doing heavy work for an 8 hour day is approximately 5000 Calories. Assuming his work output to be 0.1 hp, this translates into 0.8 hp-hr per day. It follows that 1 hp-hr work output (equivalent 746 watt-hrs or 2.69 megajoules in energy units) involves a food intake of 6225 Calories, or 26.2 MJ. The ratio of output to input is slightly over 10%. It is reasonable to assume that the same ratio would hold for a horse.

5. I think this is probably too high, but it doesn't matter much.

6. There may be other health problems arising from the use of electric blankets, but if so they are irrelevant to the point being made.

7. At first glance the popularity of frozen convenience foods suggests the opposite — that more heat will be needed. However this appearance is deceptive. In the first place, centrally prepared foods can be cooked much more efficiently than foods prepared in individual kitchens. In the second place, frozen foods are easily thawed by contact with water, and they can be heated very quickly by microwaves even without thawing.

8. The source of this calculation is a presentation entitled "United States Energy System" by David Bennet of EPA's Office of Pollution Prevention (March 1992). Data provided by EPA on CD-ROM.

9. In effect, as energy becomes unavailable, it generates *entropy*. (Entropy is measured in units of energy divided by temperature). Thus the economic process necessarily generates entropy. It can be characterized as a process that converts low entropy resources into high entropy wastes. For an extensive discussion of the economic process from this perspective see [Georgescu-Roegen 1971]. The so-called "entropic" school notes that fossil fuels and metal ores constitute a finite stockpile of "low entropy" resources that is being rapidly exhausted by economic activity.

10. In the case of hydroelectricity, wind, or nuclear power, special calculations are needed, depending on the details of the assumed conversion process. However, for convenience, exergy content can be equated to the electric power output.

11. The physical units for exergy are exactly the same as for energy or heat, namely Joules, Calories, BTUs, kilowatt hours or horsepower hours. Energy analysts have made matter worse by introducing other units such as million tons of coal equivalent (MTCE), million tons of oil equivalent (BTOE), and "quads" (for quadrillion BTUs). The confusion of units is a major hazard of energy analysis.

References

[Ayres 1989] Ayres, Robert U., *Energy Inefficiency in the US Economy: A New Case for Conservatism*, Research Report (RR-89-12), International Institute for Applied Systems Analysis, Laxenburg, Austria, November 1989.

[Ayres & Martinás & Ayres 1997] Ayres, Robert U., Katalin Martinás & Leslie W. Ayres, ``A Overview of Eco-Thermodynamics: Exergy & Life Cycle Analysis", *Energy-The International Journal*, 1997.

[Ayres 1997] Ayres, Robert U., *Towards a Theory of Endogenous Growth* (in progress).

[Boulding 1966] Boulding, Kenneth E.. ``Environmental Quality in a Growing Economy", in: Garrett(ed), *Essays from the Sixth RFF Forum*, Johns Hopkins University Press, Baltimore, 1966.

[Carnahan *et al* 1975] Carnahan, Walter, Kenneth W. Ford, Andrea Prosperetti, Gene I. Rochlin, Arthur H. Rosenfeld, Marc H. Ross, Joseph E. Rothberg, George M. Seidel & Robert H. Socolow *Efficient Use of Energy: A Physics Perspective*, Study Report (399), American Physical Society, NY, January 1975.

(Report of the "Research Opportunities" Group, Princeton NY, July 1974)

[Dewhurst 1995] Dewhurst, J. F. & Associates, *America's Needs & Resources: A New Survey*, Twentieth Century Fund, NY, 1995.

[Georgescu-Roegen 1971] Georgescu-Roegen, Nicholas, *The Entropy Law & the Economic Process*, Harvard University Press, Cambridge MA, 1971.

[Gyftopoulos *et al* 1974] Gyftopoulos, E. P., L. J. Lazaridis & T. F. Widmer, *Potential Fuel Effectiveness in Industry* (Series: Ford Foundation Energy Policy Project), Ballinger Publishing Company, Cambridge MA, 1974.

[Hall *et al* 1975] Hall, E. H., W. H. Hanna, L. D. Reed, J. Varga Jr., D. N. Williams, K. E. Wilkes, B. E. Johnson, W. J. Mueller, E. J. Bradbury & W. J. Frederick, *Evaluation of the Theoretical Potential for Energy Conservation in Seven Basic Industries*, Final Report (PB-244,772), Battelle Columbus Laboratories, Columbus Ohio, July 11, 1975. (for United States Federal Energy Administration)

[Hirst & Moyers 1973] Hirst, Eric & John C. Moyers, ``Efficiency of Energy Use in the United States", *Science* **179**(4079), March 23, 1973 :1299-1304.

[Mahajan & Schoeman 1977] Mahajan, Vijay & M. E. F. Schoeman, ``Generalized Model for the Time Pattern of the Diffusion Process", *IEEE Transactions on Engineering Management* **1**, 1977 :12-18.

[Nordhaus 1994] Nordhaus, William D., *Managing the Global Commons: The Economics of Climate Change*, MIT Press, Cambridge MA, 1994.

[Schurr & Netschert 1960] Schurr, Sam H. & Bruce C. Netschert, *Energy in the American Economy, 1850-1975*, Johns Hopkins University Press, Baltimore, 1960.

[Skiadas 1985] Skiadas, Christos, ``Two Generalized Rational Models for Forecasting Innovation Diffusion", *Journal of Technological Forecasting & Social Change* **27**, 1985 :39-61.

[Szargut *et al* 1988] Szargut, Jan, David R. Morris & Frank R. Steward, *Exergy Analysis of Thermal, Chemical, & Metallurgical Processes* (ISBN 0-89116-574-6), Hemisphere Publishing Corporation, New York, 1988.

[Wall 1977] Wall, Goran, *Exergy: A Useful Concept within Resource Accounting*, (77-42), Institute of Theoretical Physics, Chalmers University of Technology & University of Goteborg, Goteborg, Sweden, 1977.

[Wall 1986] Wall, Goran, ``Exergy Conversion in the Swedish Society", *Energy* **11**, 1986 :435-444.

[Wall 1990] Wall, Goran, ``Exergy Conversion in the Japanese Society", *Energy* **15**, 1990.

Table I: Energy share allocation, by year: (% of national total)

<table>
<tr><th>Category</th><th>1800</th><th>1850</th><th>1900[1]</th><th>1940</th><th>1960[2]</th><th>1979[3]</th><th>1991[4]</th></tr>
<tr><td>Space heat</td><td>89</td><td>85</td><td>40</td><td>25</td><td>18.5</td><td>13.3</td><td>15.5</td></tr>
<tr><td>A/C & refrigeration</td><td>na</td><td>na</td><td>na</td><td>2</td><td>3.7</td><td>6</td><td>13.7</td></tr>
<tr><td>Cooking & washing</td><td>(a)</td><td>(a)</td><td>5</td><td>5</td><td>5.5</td><td>5.7</td><td>7.6</td></tr>
<tr><td>Lighting</td><td>1</td><td>1</td><td>2</td><td>2</td><td>3</td><td>4</td><td>6.6</td></tr>
<tr><td>Farming & construction</td><td>5</td><td>5.6</td><td>8</td><td>6</td><td>6</td><td>6</td><td rowspan="2">27.7</td></tr>
<tr><td>Transport drive[b]</td><td>3</td><td>3.8</td><td>10</td><td>20</td><td>25</td><td>25</td></tr>
<tr><td>Machine drive[c]</td><td>1</td><td>1.5</td><td>5</td><td>6</td><td>7.4</td><td>8</td><td>4.1</td></tr>
<tr><td>Industrial, heat</td><td>1</td><td>3</td><td>25</td><td>30</td><td>26</td><td>20</td><td>15</td></tr>
<tr><td>Other(inc. feedstock & ore reduction)</td><td>na</td><td>na</td><td>3</td><td>4</td><td>5.9</td><td>12</td><td>9.8</td></tr>
</table>

(a) included in space heat category (row 1) for 1800 and 1850
(b) assuming one third of working animals used for transportation purposes
(c) not including machines producing electric power
(d) included in category "Industry"
(1) except as discussed in the text, data in this column is estimated by the author
(2) data in this column is largely taken from [Hirst & Moyers 1973]
(3) data in this column is largely taken from [Ayres 1989]
(4) data in this column courtesy of David Bennett, Pollution Prevention Division, EPA

Table II: Energy conversion efficiencies, first law: (%)

Category	1800	1850	1900[1]	1940	1960[2]	1979[3]	1991[4]
Space heat	8	8	20	40	60	70	72
A/C & refrigeration	na	na	na	4	5	8	13
Cooking & washing	na	na	60	50	50	50	50
Lighting[a]	8	10	18	28	32	33	33
Farming & construction	10	10	10	20	30	32	32
Transport drive[b]	10	8	5	18	15	14	15
Machine drive[c]	20	2	10	20	25	28	30
Industrial heat[d]	10	10	25	45	65	72	75
Other(inc. feedstock)[e]	5	10	25	40	50	60	65

(a) assuming delivered exergy for light to be flame before 1900 and electric thereafter.

(b) assuming one third of working animals used for transportation purposes, and that animals were the only source of transport power in 1800. Assuming "useful work" to be equivalent to heat dissipated in brakes (for autos and trucks) and to be one third of total for aircraft.

(c) steam engines or electric motors; not including steam turbines producing electric power

(d) comparable to, but slightly more efficient than residential/commercial space heating; assuming industrial steam to be equivalent to "useful work".

(e) equated to the carbon- efficiency of pig iron smelting.

(1) except as discussed in the text, data in this column is estimated by the author

(2) data in this column is largely taken from [Hirst & Moyers 1973]

(3) data in this column is largely taken from [Ayres 1989]

Table III: Second law/service delivery efficiencies: (%)

Category	1800	1850	1900	1940	1960	1979	1991
Space heat	0.8	0.8	3	5	6	7	8
A/C & refrigeration	na	na	na	0.6	1	1.5	2.5
Cooking & washing	na	na	3	5	6	7	8
Lighting	0.03	0.05	0.15	1.9	1.95	2	2.5
Transport	2	4	8	7	6	5	6

Table IV: Technical efficiency of the economy

Category	1800	1850	1900	1940	1960	1979
Space heat	0.00712	0.00680	0.01200	0.01250	0.01110	0.00931
A/C & refrigeration	0	0	0	0.00060	0.00185	0.00360
Cooking & washing	a)	a)	0.00150	0.00150	0.00165	0.00285
Lighting	0.000003	0.00001	0.00003	0.00038	0.00039	0.00080
Farming & construction	0.00050	0.00056	0.00080	0.00120	0.00180	0.00192
Transport drive	0.00060	0.00152	0.00800	0.01400	0.01500	0.01500
Machine drive	0.00020	0.00003	0.00050	0.00120	0.00185	0.00224
Industrial heat	0.00005	0.00030	0.00375	0.00600	0.00650	0.00540
Other (inc. feedstock & ore reduction)	0	0	0.00030	0.00072	0.00118	0.00264
TOTAL	**0.00847**	**0.00921**	**0.02688**	**0.03810**	**0.04132**	**0.04376**

a. Included with space heat (from wood stoves and open fires)

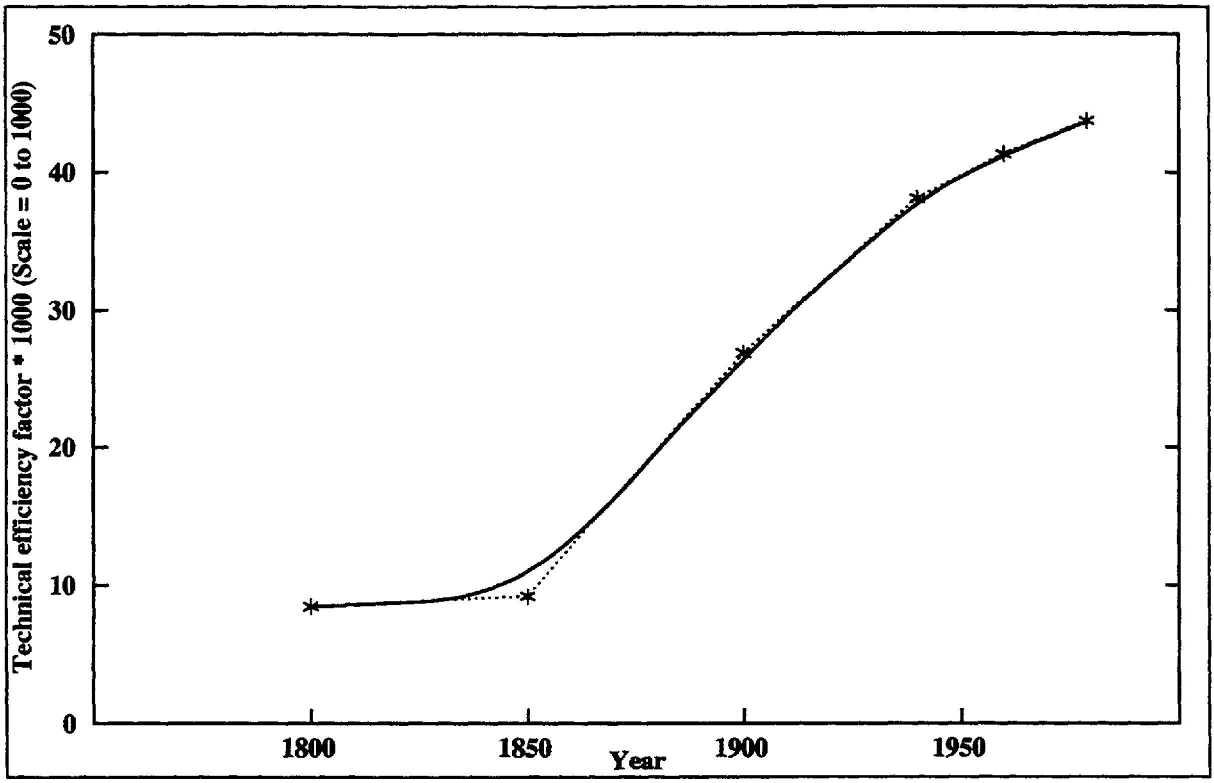

Figure 1: Technical efficiency of the economy