"TECHNOLOGICAL TRENDS"

by

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TECHNOLOGICAL TRENDS

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Abstract

This is the third of a set of four linked papers under the general heading "FORECASTING AND SCENARIO ANALYSIS". It reviews technological trends likely to be of major importance in the next half century, from the perspective of contributing to ultimate environmental sustainability. It is assumed (for the most part, implicitly) that technologies contributing to environmentally unsustainable practices will gradually become economically costly and/or socially unacceptable. However, costs are not explicitly considered in this discussion.

Introduction

Technology has been regarded by some social critics like Lewis Mumford, Jacques Ellul, Theo Roszak and E.F. Schumacher as an autonomous force that is essentially incompatible with "human" values. It was widely blamed in the 1960's for many of the ills of our society, from the spread of nuclear weapons to the decline of family values, not to mention environmental deterioration. On the other hand, technology gives us economic growth and took us to the moon. To a few ideologues of the right, like Herman Kahn and Julian Simon, it became a panacea, the ultimate resource and the answer to all problems, especially environmental problems.

The truth in this case, as in many others, is in between the extremes. Technology is not, by any stretch of the imagination, "autonomous". While technological developments can have unexpected and undesirable side-effects — which was the reason for creating an Office of Technology Assessment (OTA) to serve the U.S. Congress — technology is our servant, not our master. It is not always a perfectly benign and omnipotent servant, like the legendary Jeeves. It frequently breaks some crockery. It occasionally plays nasty tricks, like the genie from the bottle in Arabian Nights. But on the whole, technology is controllable.

However, precisely because technology is not autonomous, it will not come to our rescue at need. Need is not enough. Economic incentives are required to call forth investment in R&D. Nor is technology omnipotent. It can overcome many apparent limits. but it is ultimately subject to limits.

Technological Drivers and Constraints

Technology can be regarded as the ability to manipulate nature for human purposes, using natural laws. Technological change in the broad sense is essentially a consequence of growing scientific knowledge, together with an accumulation of inventions, improvements and techniques ("know how") built on that knowledge base. From a broader historical perspective, this accumulation of knowledge began to accelerate only in relatively recent times. The convergence of paper manufacturing and of mechanical printing technologies around 1500 led to an explosion of libraries and a rapid spread of knowledge during the 16th and 17th centuries. This undoubtedly contributed to the emergence of natural science as an intellectual discipline, beginning with astronomy and mechanics. The industrial consequences of this — the Industrial Revolution — began to emerge in the late 17th and 18th centuries.

Most of the important technologies in the world today were literally inconceivable two centuries ago; many of them were inconceivable at the turn of the last century. The steamship was not an evolutionary development of the sailing ship; the automobile is not an evolutionary development of the horse and buggy; the transistor was not an evolutionary improvement on the vacuum tube, nor is the PC a recognizable descendant of the mechanical calculator. Even Jules Verne did not imagine television, holography, genetic engineering or nuclear weapons.

Partly because of this history of radical change, science and technology are often regarded (by economists, for example) as inherently unpredictable. The simplistic argument is sometimes advanced that "if an invention could be predicted it would already have been invented". The same truism would seem applicable to scientific discoveries. However this argument only applies in the most literal sense. To assert the converse — total unpredictability — is naive and simplistic. It is quite possible to predict some inventions in the *functional* sense, with fairly high confidence while others can be ruled out with even higher confidence.[1] There are three necessary conditions for a functional technological forecast: (1) a functional need or barrier to progress, (2) an economic demand (potential users who are willing and able to pay for the functional improvement), and (3) absence of fundamental physical barriers. Given these three conditions, inventors or firms seeking economic gain can be expected to invest in R&D to solve the problem.

The first two conditions need no comment. Considering the third condition, it is easy to identify a number of technologies that clearly do violate physical laws (insofar as we know them) and that can therefore be ruled out with high confidence, if not absolute certainty. These include time travel, interstellar travel faster-than light, anti-gravity, matter transmission, tractor fields and most of the "Star Trek" staples. However, there are other physical barriers of a subtler nature that may not be recognizable in advance. An example may be the practical application of nuclear fusion, which was once thought to be a relatively straightforward engineering problem, but is now regarded as almost impossibly difficult to achieve in practice.

[1] The sociologist of science, S.C. Gilfillan demonstrated the first half of this proposition in the 1930's by noting (i) that some invention was needed to permit aircraft to land safely in fog, or at night, and (ii) that several alternative means to solve the problem could be envisioned, without violating any known physical laws [Gilfillan 1937]. Indeed, Gilfillan identified around a dozen such conceptual possibilities. Ironically, the solution to the night landing problem turned out to be RADAR, which was not on his list.

Practical applications of superconductivity at room temperature may also prove to be virtually unattainable.

Thermodynamic Constraints: The First Law

The laws of physics most constraining to technology (and therefore to economics) are the first and second laws of thermodynamics. The first law of thermodynamics is the law of conservation of mass/energy. Since mass and energy are equivalent (Einstein's equation), this law actually implies that mass and energy are *separately* conserved in every process or transformation except nuclear fission or fusion. Putting it another way, any process or transformation that violates this condition is impossible. Something cannot be created from nothing.[2] This has surprisingly non-trivial consequences for neo-classical economics. Contrary to the more superficial versions of standard theory, where goods and services are mere abstractions, production of real goods from raw materials (*Figure 1*) inevitably results in the creation of waste residuals. In other words, "consumption" is metaphoric insofar as goods other than food or drink are concerned. Since waste residuals have no positive market value to anyone — in fact, negative value — but do not disappear by themselves, they tend to be disposed of in non-optimal ways. This is a built-in market-failure (externality) and a pervasive one [Ayres & Kneese 1969].

In fact, the quantity of waste materials associated with raw material extraction often far exceeds the amount of useful product. For instance, about 160 tonnes of ore must be processed to yield a tonne of virgin copper. For scarcer metals, like silver, gold, platinum and uranium, the quantities of waste material per unit of product are enormously large. The specific case of phosphate rock is worth illustrating (*Figure 2*) 1000 units of the ore, plus 793 units of sulfuric acid and 1762 units of makeup water yields 555 units of salable phosphoric acid (for fertilizer) and 39 units of salable fluosilicic acid, which is used by the aluminum industry.[3] But the process also yields 3000 units of "phospho-gypsum", which is unsalable because it is contaminated with radioactive thorium. Yet gypsum is concurrently being mined for use in building materials.

The materials balance principle, derived from the first law of thermodynamics, is a useful tool for estimating waste residuals from industrial processes, since the outputs of one sector become the inputs to another. Comparing inputs and outputs it can be seen that substantial mass is "missing" at each stage. A summary for the major wastes from materials processing sectors of the U.S. economy for 1988 is shown in *Table I* [Ayres & Ayres 1993a]. The case of organic chemical products for the U.S. in 1988 is summarized in *Figure 3* [Ayres & Ayres 1993]. It can be seen that purchased inputs (feedstocks) amounting to 60.3 million metric tons, plus another 33.8 million metric tons of oxygen from the atmosphere yielded 39 million metric tons of "finished" chemical products (such as plastics, synthetic rubber, synthetic

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[2] Tjalling Koopmans expressed this principle as " the impossibility of the land of ...", and made use of the theorem in developing his mathematical treatment of "activity analysis", an extension of Input-Output analysis [Koopmans 1951]. However, Koopmans did not discuss the environmental implications.

[3] The data comes from a contractor report to the U.S. government c. 1978, but the original source is untraceable.

fibers, solvents, anti-freeze, etc) and generated 54.3 million metric tons of wastes, including 29.3 million metric tons of carbon dioxide and 2.3 million metric tons of unburned hydrocarbons (according to our estimate). If all these hydrocarbons were oxidized, both oxygen inputs and CO_2 outputs would be correspondingly increased.

Table I: Preliminary Summary of Estimated U.S. 1988 Dry-waste Streams Excluding Water (million metric tons)

SIC		*Organic (waterborne or solid)*	*Overburden moved, erosion*	*Inorganic concentration waste ("dry")*	*Inorganic conversion waste (including slag & ash)*	*Emissions to air*
01-02	Agriculture	86.5	1500(a)	0	0	4.4 NH_3 0.7 CH_4
11	Metal mining & winning	0	1193	600(e)	NA	0.09 N_2O 0.27 NO_x
12-13	Fossil fuels, mining & drilling	0	5600	260	NA	?
14	Non-metallic minerals	0	47	36.5	NA	?
20	Food processing	94(b)	NA	0	0	1.5 (part.)
24-26	Wood, pulp & paper	36(b)	NA	6	0	1.15 (part.)
29	Oil refining	0	NA	0	3	2 VOC
32	Stone, clay & glass	NA	NA	NA	?	34 CO_2
33	Primary metals	NA	NA	NA	1.5 (c)	(d)
	Fossil fuel consumption	0	NA	NA	76 ash 14.4 FGD	4.3 VOC 30 SO_2 20 NO_x 4725 CO_2
	Total accounted for	196	8340	1087	95	4823

(a) Erosion losses of topsoil
(b) Not adjusted for possible combustion of organic waste (e.g. "black liquor") as fuel or to reduce volume
(c) Excluding iron/steel slag
(d) Included with fossil fuels
(e) Aluminum & phosphate rock wastes excluded her - they are counted in the Chemical Sector (SIC 28)
Source: [Ayres & Ayres 1993a]

Applying the materials balance method to individual chemical products the results shown in *Table II* are obtained [IEI 1991]. It is noteworthy that the "missing" (i.e. unaccounted for) mass in every case is far greater than the emissions reported the U.S.Environmental Protection Agency and published as the Toxics Release Inventory (TRI). While some of the missing mass, in some cases, may have been converted to other unreportable materials by oxidation it is painfully obvious that this could not account for the whole, or even a significant part, of the discrepancy. This suggests that current data collection and reporting methodologies are inadequate.

TABLE II: Toxic Chemicals; Materials Balance Estimates Compared to TRI (1000 metric tonnes)

Chemical	*Apparent Consumption*	*Materials Balance Estimates of* Direct Conversion & Use Losses	Other Incidental Emissions	Total Emission Losses	*TRI*	*Losses unaccounted for by TRI*	*TRI* metal	com-pounds
Benzene	7360.0	207.2	183.4	390.6	14.6	376.0		
Toluene	3071.7	361.4	984.0	1345.4	158.5	1186.9		
Xylenes, mixed	3419.2	295.2	544.2	839.4	86.5	752.9		
m-Xylene	34.6	6.9	0.2	7.1	1.6	5.5		
o-Xylene	509.6	101.6	2.6	104.2	1.3	102.9		
p-Xylene	2510.9	179.0	11.6	190.6	3.2	187.4		
Carbon tetrachloride	400.2	9.9	1.2	11.2	2.3	8.9		
Chloroform	224.8	26.5	19.9	46.4	12.2	34.2		
Methylene chloride	183.1	161.7	1.2	162.9	70.3	92.6		
Perchloroethylene	252.9	182.3	0.7	183.0	17.1	165.9		
Trichloroethylene	68.9	65.2	0.3	65.5	26.2	39.3		
1, 1, 1-Trichloroethane	303.4	281.5	1.6	283.1	88.1	195.1		
Methyl ethyl ketone	239.2	237.7	4.3	242.0	73.1	168.9		
Methyl isobutyl ketone	91.2	81.6	0.5	82.1	20.2	61.9		
Cadmium	3.6	3.6	1.0	4.6	0.9	3.7	0.16	0.72
Chromium	536.9	418.1	24.9	443.0	31.2	411.8	9.74	21.46
Mercury	1.6	1.3	0.3	1.6	0.1	1.5	0.13	0.01
Nickel	159.2	118.1	23.7	141.8	8.7	133.1	4.02	4.73
Cyanides	629.7	151.4	31.1	182.5	5.3	177.2		
Hydrogen cyanide	543.0	64.6	31.1	95.7	1.4	94.2		
Cyanides, other	86.8	86.8	0.0	86.9	3.9	82.9		
TOTAL	20000.8	2890.5	1836.7	4727.2	621.6	4105.6		

Basic data source: [IEI 1991], Source: [Ayres & Ayres 1993]

Thermodynamic Constraints: The Second Law

The Second Law of thermodynamics is known as the "entropy law". It states, in effect, that spontaneous processes in isolated systems tend toward thermodynamic equilibrium. It follows that there exists a non-decreasing function, known as *entropy*, which is defined for every system, and which reaches a maximum when that system reaches thermodynamic equilibrium with its environment. On the earth, where we live, thermodynamic equilibrium is far distant, but entropy is still a meaningful (and computable) variable.[4] In fact, it can be argued that the "potential entropy" of products and waste residuals is actually the most general measure of potential environmental disturbance resulting from human economic activities [Ayres & Schmidt-Bleek & Martinàs 1993; Martinàs & Ayres 1993]. The details need not concern us here. Suffice it to say that there are two components of potential entropy, viz. a thermal component (corresponding roughly to waste heat) and a material component.

Waste heat *per se* as not a global problem, and it is rarely a local one except in the vicinity of large thermal power plants. The reason is that the amount of waste heat generated by human activities as insignificant compared to the heat supplied by the sun and dissipated by natural systems such as ocean currents and weather. It is the material component of potential entropy (much of it associated with fossil fuels, to be sure) that is of far greater significance. The reason is that any change in the material composition of an evolved environmental system — especially the atmosphere, which is relatively "small" and relatively fragile — is potentially destabilizing to a system that has achieved a delicate balance over billions of years of natural evolution. Such a change can drive uncontrolled processes in unexpected directions. The greenhouse phenomenon and the ozone depletion problems are perfect examples. The changing carbon-dioxide concentration of the atmosphere affects the radiation balance of the earth. A very small injection of chemically unreactive CFC's into the stratosphere triggers a catalytic process that destroys ozone. These processes are now quite well known.

A Brief Digression on Economics

The dangers of unrestrained human interference with natural systems suggest that "environmental goods", such as the capacity to assimilate wastes, are not given sufficient value by the market system [Kneese *et al* 1970]. There are three basic approaches to correcting for market failures. The oldest approach is the law of torts. If a legal entity (person or firm) can absolutely prove that it has been damaged by the action or inaction of another, it is entitled to claim redress under the law. In practice, however, this approach has only been effective in the case of product liability. Pollution and damage to nature are not effectively controlled by litigation. By far the most common approach has come to be known as "command and control" regulation by a governmental body, like EPA. The instruments used in this approach

[4] Entropy computations are often difficult in practice, however, despite the fact that the theoretical formulation is deceptively simple. Since entropy is a property of systems it depends on all of the other variables that describe the system (including its material components) and its environment.

include emissions standards and outright bans of certain products, such as chlorinated pesticides, PCB's, CFC's and tetraethyl lead in gasoline.

In recent years the command and control approach has proliferated bureaucrats and detailed regulations, which have led to increasing administrative costs and inefficiencies. Economists have long advocated the use of market instruments rather than regulations wherever possible. A well publicized example is the creation of a market in tradeable permits for sulfur dioxide emissions by utilities in the U.S. However, in the economic literature on tradeable permits, the issue of enforceability is given too little attention. Tradeable permits will only have a market value as property rights if cheating is impossible (or at least too expensive to be worthwhile). This feasibility condition can be met in an industrialized country in a case where the number of potential polluters is small enough. However, this enforceability condition is unlikely to be met in most parts of the world for most kinds of pollution. It is very difficult to see how tradeable permit markets on a global scale could ever be created for damage to indivisible planetary attributes such as the ozone layer, the climate, the carbon cycle or the nitrogen cycle. The limitations of market-based approaches are indicated by ***Figure 4*** below.

An alternative to the use of markets for tradeable permits might be the use of emissions taxes. Here the market for ordinary goods and services would operate, but prices would be modified to reflect "unpaid" environmental damages. In principle, the allocation efficiency of the tax scheme would be as high as the permit scheme. (In fact, they are theoretically equivalent). There are two unresolved problems, however. First, unlike tradeable permits which are assets, taxes are viewed as pure costs, with no corresponding benefits, by those who have to pay. Second, the *level* of the tax must be determined by some process. In principle it might be done by an objective process based on scientific expertise. In practice, it would certainly be subject to the usual political pressures that would inevitably distort the results, perhaps totally out of recognition. Further, taxes directly on polluting emissions based on direct measurement would be difficult to enforce. A more attractive scheme would be to tax natural resources (leaving recycled materials untaxed) to discourage inessential uses.[5]

Finally, resource taxes at the national level would tend to favor importers and discriminate against local industry, creating competitiveness problems, unless countervailing duties were imposed. The method of computation of countervailing customs duties would have to be based on a "life cycle" approach consistent with the method of taxation at the national level. One could readily envision three alternative bases for taxation, viz. (1) mass, (2) energy and (3) potential entropy. Any imported commodity would be taxed at the point of entry on exactly the same basis that it would have been taxed had it been produced domestically. For instance, imported copper wire would be taxed on the basis of mass lost, energy consumed, or potential entropy lost in each prior stage, from mining through smelting through wire manufacturing. Since these processes occur outside the taxing country, it would be necessary to determine international norms with regard to "best available technology" for each process along the chain.

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[5] The materials balance principle could be used to apply the tax at each successive stage of production to *lost or unaccounted for* materials, rather than total throughput. This would be virtually equivalent to an emissions tax, but much easier to enforce, using an accounting framework similar to that now used to collect VAT.

The lost mass scheme for taxation is by far the simplest and probably the most feasible for early implementation [Schmidt-Bleek 1994]. The mass of purchased material inputs and salable outputs to any process is relatively easily determined for tax purposes by simple weighing. Buyers and sellers would have no incentive to collude, since each would be anxious to minimize his own tax liability and any tax avoided by one would be payable by the other. The lost energy approach is much less attractive, since tax liabilities at each stage would depend partly on calculations rather than on direct measurement. Moreover, there are a number of marginally different schemes for estimation, each of which has its adherents and critics. In the circumstances it would probably make more sense to develop the entropy approach, which has the virtue of being theoretically superior, albeit somewhat more difficult to apply. With some effort, tables of potential entropy "content", per unit mass, could be developed, for all traded goods and commodities. This would permit national tax authorities to shift eventually from a simple mass basis to an entropy basis. If this were done by an international body, it should be possible to reconcile this method of national taxation with GATT rules.

Unfortunately, the systematic use of resource/pollution taxation schemes along the above lines as an instrument for the protection of planetary attributes seems remote at present. More immediately, the only other effective instrument available to individual national governments or multi-national groupings like the EEC, is to subsidize technological developments in desirable directions. This possibility is discussed below.

Technological Trends and Accelerators

There is a category of technologies that are apparently consistent with the laws of physics, but that are currently regarded as extremely problematic (i.e. requiring an unknown, but very large, R&D effort to realize) but which are not obviously contradicted by any physical principle. Fusion power, underwater or orbiting cities, lunar colonies, artificial intelligence, cyborgs, rejuvenation, "custom-designed" organisms, self-reproducing robots and interstellar travel at sublight speeds would be examples.

However, it is not from these radical but problematic technologies that "technological fixes" for terrestrial problems would be likely to emerge in the next half century. Rather, breakthroughs are far more likely to result from unexpected synergies resulting from the convergence of well established current trends. Here are some straightforward examples:

- Product complexity (in terms of design information required) will continue to increase as a condition of achieving higher performance (*Figure 5*). However, complexity will increasingly be built *into* materials — as in the case of computer chips — rather than being achieved by assembling discrete parts.

- Energy Productivity or economic output per unit of energy consumed (by sector or for GDP as a whole) will increase. Putting it another way, energy consumed per unit of output will decline, at least for industrialized economies (*Figure 6*).

- Materials Productivity — or "dematerialization" — (by material and by sector) will continue. The trends towards higher power-to-weight ratios for prime movers (*Figure 7*) and miniaturization in electronics (*Figure 8*) will continue, for instance.

- The Hydrogen/Carbon ratio of fuels will probably increase (*Figure 9*).

- Electrification (i.e. electricity as a fraction of final energy use) will increase (*Figure 10*). Multi-component electro-mechanical devices will continue to be displaced by solid-state electronic devices, etc. The distribution system will begin to "dewire" as remote stand-alone small-scale electric power generating systems are introduced more widely.

- Information storage, transmission and processing technologies will continue to get faster and cheaper (partly by continuing to "dematerialize"). For instance, the number of circuit elements per square cm of active electronic materials will increase, while power consumption will decline. The number of bytes/sec transmitted by long-distance communications channels will increase, while costs will decline. The increasing use of portable cellular units will eventually obviate the need for physical wires and cables.

There are many possible generic performance measures of this kind, and much can be learned from this kind of trend analysis. Broadly speaking, it is safe to say that the information "content" of materials and products will continue to increase, the functionality of products and services will continue to increase, while the inputs of energy and materials per unit of functionality will tend to decrease. It is also safe to say that the productivity of labor and capital goods will tend to increase. All of these trends are essentially direct consequences of the irreversible accumulation of human knowledge.

The above trends are also consistent with one of the long-run conditions for sustainability: closing the materials cycle. It is quite obvious that human economic activities cannot depend indefinitely on the extraction of exhaustible raw materials, including metal ores and fossil fuels. While "available reserves" have not decreased in recent decades — in fact they have generally increased, due to accelerated mineral exploration activities — this cannot continue indefinitely. Most of the high quality mineral resources in Europe were depleted long ago, and the resource base of the continental U.S. is also rapidly being exhausted. Consequently, the most industrialized countries are increasingly dependent on raw material supplies in the rest of the world.

Nevertheless, exhaustion of mineral resources and fossil fuels is not the immediate threat that was postulated by "Limits to Growth" [Meadows *et al* 1972]. The market pricing mechanisms that adjust supply and demand of exchangeable commodities, and call forth technological improvements or substitutions when shortages threaten, continue to function quite well. The real threat to planetary habitability — even human survival — arises from the depletion of other exhaustible common property resources (e.g. the ozone layer and the nitrogen cycle) that are not divisible, not exchangeable, and unpriced. In this case, there is no market mechanism to call forth an automatic technological response.

The role of government, then, must be to take the place of the free market in this regard. For instance, the current pattern of dependence on "virgin" raw materials in preference to reclaimed or recycled materials is a consequence of the current pattern of relative prices. Specifically, it is a consequence of the fact that market-determined raw material prices are too low, to the extent that they do not reflect environmental externalities associated with extraction, processing, use and ultimate disposal.

The most promising area for revolutionary dematerialization technologies is in applications of micro-electronics and information processing. The most immediate — and virtually certain to occur — will be the "dewiring" of the telephone system and the electric power system. However, while other forces will encourage this trend in any case, it could be significantly accelerated by governmental action. A few years ago, the large-scale commercialization of photo-voltaic (PV) technology was problematic. The best known material for PV, gallium arsenide, has two drawbacks. It is difficult to manufacture (from extremely toxic intermediates) and gallium is fairly scarce. (There are no high quality ores). The most attractive candidate for low-cost systems — amorphous silicon — has not lived up to its promise, due to technical deficiencies. However, recently thin-film PV cells using cadmium telluride or copper indium diselenide with cadmium sulfide have become efficient enough and cheap enough to compete strongly with the older silicon cells. The more optimistic projections of manufacturing costs suggest that they will eventually become quite inexpensive, although there are still significant manufacturing problems to be overcome. Governments can speed up the process by providing more money for R&D, especially in the area of PV cell manufacturing.

Another way to bring down PV costs dramatically is to integrate PV technology directly into building materials. For example, thin film PV cells of microscopic thickness can be fabricated directly into windows. The electric power generated from window units could easily handle the needs of air-conditioning systems, which are needed primarily when the sunlight is at its most brilliant. The market for such systems could be easily stimulated by government action. It would be sufficient to simply require them to be installed in all new buildings. Larger and more secure markets would rapidly bring production costs down.

We can also expect a vast proliferation of "smart sensors" (including so-called "machine vision"). These devices will incorporate a variety of signal receptors, both passive and active, ranging from ultrasonic sound to ultraviolet light, not to mention particles, odors, etc. Microprocessors will be built into these sensors, and the sensors, themselves, will be built into virtually every appliance, machine and structure.[6] The sensors will facilitate automatic local adjustment and control of lighting, heating and airconditioning units, washing and cooking equipment, automobile speeds and vehicle spacing, etc. With local area networks (LAN's) they will facilitate truly effective home, office and automobile security systems capable of recognizing authorized users and activating countermeasures against intruders. In cars, when combined with cellular communications, they will permit automatic vehicle identification and location in real time (an effective deterrent to theft). They will also facilitate eventual

[6] Among the first practical examples are the self-focussing and self-adjusting cameras, that have been available for a number of years. Another is the point-of-sale bar-code readers that automatically feed price and quantity data into cash registers in stores.

automation of traffic systems, including speed control, parking control, priority rights for buses and emergency vehicles, and collection of road-use taxes in proportion to congestion. It need hardly be said that such systems have the potential of making automotive transportation much more fuel-economical, on the one hand, and making alternatives far more efficient and attractive, on the other.

Another potentially revolutionary development in the electronics/communications field is computer-assisted "virtual reality". Movies and TV are primitive forms of the idea, but more sophisticated versions now being developed are interactive and customized to the user. The computer feeds images, sounds and other sensations to the subject/user, based in part on the user's motor reactions — such as eye-blinks or finger twitches — as detected by "smart sensors". The potential for interactive entertainment, especially in simulated games or adventures, is obvious. In the future, this technology has the potential to substitute for a wide variety of energy/materials intensive entertainments and commercial services on a vast scale. Virtual-reality systems will make it possible for humans to "visit", via robot-proxy, remote and inaccessible places. Examples on earth include deep undersea exploration; maintenance or trouble-shooting inside radio-active containment vessels, water pipes, sewer pipes, gas pipes; fire-fighting; even combat operations. Off-earth operations such as exploration of the moon, Mars, Venus, the asteroids or comets, would require suitable high-bandwidth communications systems, plus some means of adjustment and compensation for the problem of time lag. But such systems — while not inexpensive — would be cheaper to build than life support systems, such as are now contemplated, for human pilots and crew.

There is one other field where revolutionary environment-friendly technologies may be just over the horizon. This is biotechnology. In agriculture, one can speculate on the possibility of biological control of pests, bio-engineered nitrogen fixation, bio-engineered new crops (drought resistant, etc.). There is some potential for biological recovery of heavy metals from mine wastes, industrial effluents, sewage or even from soils. It is unfortunate that short-sighted "environmentalists" have generally opposed biotechnology and thus hindered such developments.

Skipping Technological Generations in Developing Countries

Normally it would be hard to imagine how developing countries could skip a technological generation and acquire an advanced technology faster than the western world where these technologies are still overwhelmingly being developed. However, there is a lesson to be learned from the past. In Europe, North America and Japan the sequence of development in transportation was horse-drawn vehicles on crude unpaved roads, barges drawn by horses or mules in canals, steam-powered trains on railways, horse-drawn (later electric) electric trams for cities, internal combustion engine powered vehicles with rubber tires on paved roads, and airplanes. A number of developing countries have skipped one or several of these steps. There are almost no canals or railways in Latin America north of Argentina, but plenty of cars, trucks and aircraft. The same is true of Australia. Yet lack of canals or railways has hardly hindered the development of Australia.

In the case of telecommunications, the "standard" sequence was telegraph (serving the railways and using the railways right-of-way), followed by telephones linked by twisted wires, coaxial cables, microwave beams, satellites and optical fibers. Radio-telephones were introduced a century ago, for ship-to-shore communications. For nine decades the technology advanced but little. Suddenly, however, the entire telephone system seems poised to go "wireless".

It is interesting, in context, to note that the economic advantage of "wireless" telephony may well be greater in developing countries like India and China, or Russia, than it is in the U.S. or Europe. The reason is that it obviates the need for stringing telephone wires all over the countryside. Using modern wireless units a system can be put in place for villages at much lower cost than using the older technology.

A similar situation may hold for electric power. In the West, the sequence of development was to build central power stations, exploiting economies of scale to the maximum degree, and to send power over long distances via overhead transmission lines. Power plants have grown larger and larger, while transmission lines have gone to higher and higher voltages. Some HV lines today exceed 500,000 Volts (and a few are even higher). But overland power lines require rights-of-way and high towers, which are ugly and expensive. There is also some possibility that HV transmission lines may have subtle biological effects. Even discounting this, the system requires very large step-up and step-down transformers between the transmission lines and the local distribution network.

Two technological developments may change the economics and favor the developing world. First, aircraft-type gas turbines are now in production that can provide enough power for a village or small town at a tiny fraction of the capital cost of a large steam turbine. These turbines can burn low-BTU gas (from gasification of biomass, for instance). There is no longer any economic benefit from building a central generating plant to serve a large region by means of HV transmission lines when each village or town can have its own local generating plant. Second, individual houses (such as remote settlements, resorts, or farms too small to justify a gas turbine unit) can now utilize modern high efficiency windmills and/or photovoltaic units. There is really no need to connect every dwelling to a central system by means of copper wires.

Though gas turbines and PV systems are still much more expensive than conventional power plants per kwh produced, they can be a lot cheaper than conventional units in terms of providing electric power for essential purposes to remote villages. This, in turn, means that such villages can substitute electric motors for hand-powered or animal powered water pumps for irrigation. Electric power for cooking (via microwaves) would also obviate the need to collect fuel for this purpose, with associated adverse environmental impacts. Electric lights will be a very important adjunct of education for villagers. Finally, there is no substitute for electric power for purposes of telecommunication.

In fact, the "dewiring" of the electric power system may be the best hope that China, India, Indonesia and other countries of Asia will be able to enjoy the benefits of industrialization and electrification without building a large number of coal-fired power plants.

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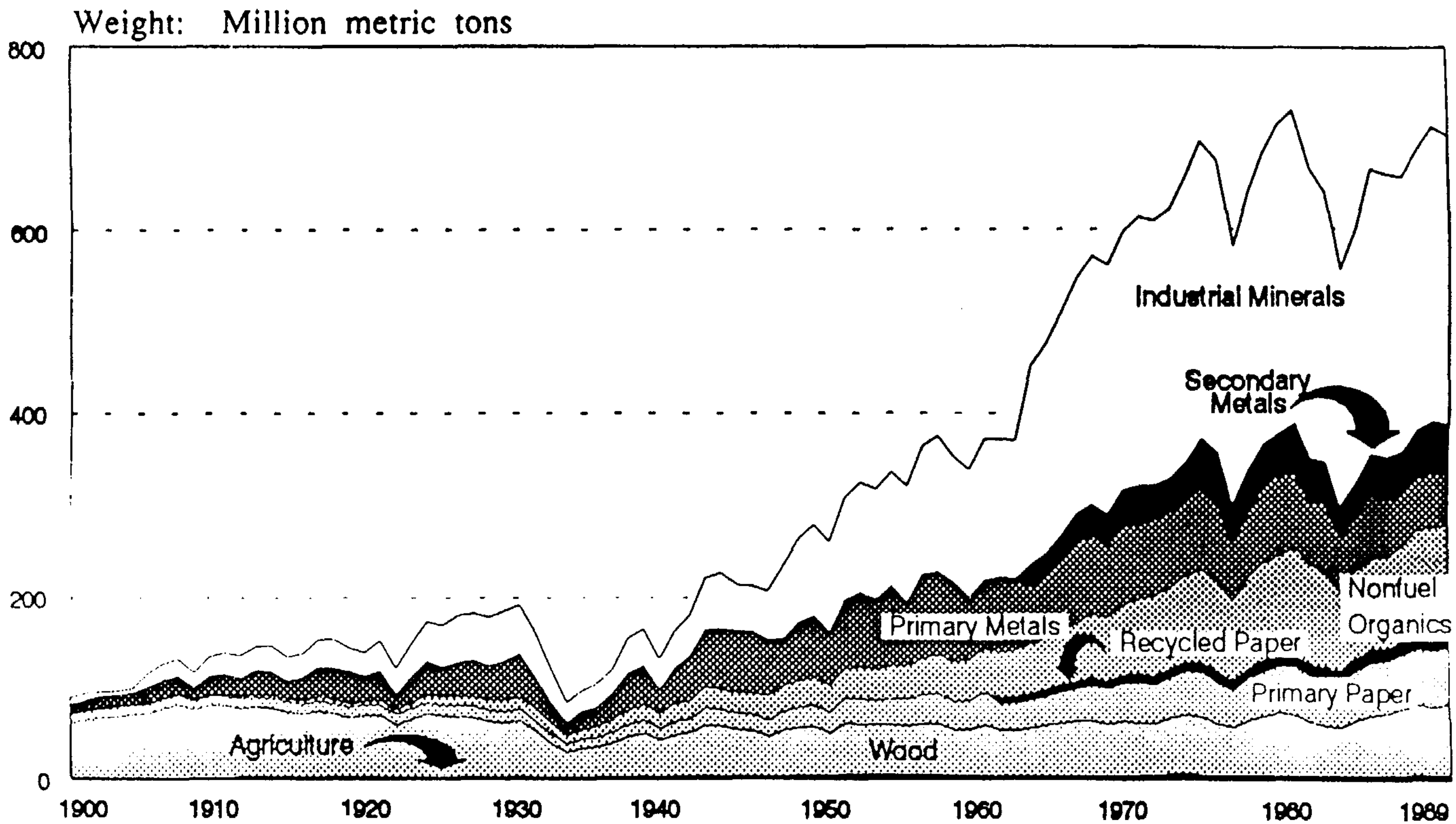


Figure 1: Total U.S. Consumption of Raw Materials (Excluding Stone, Sand & Gravel
Source: U.S. Bureau of Mines

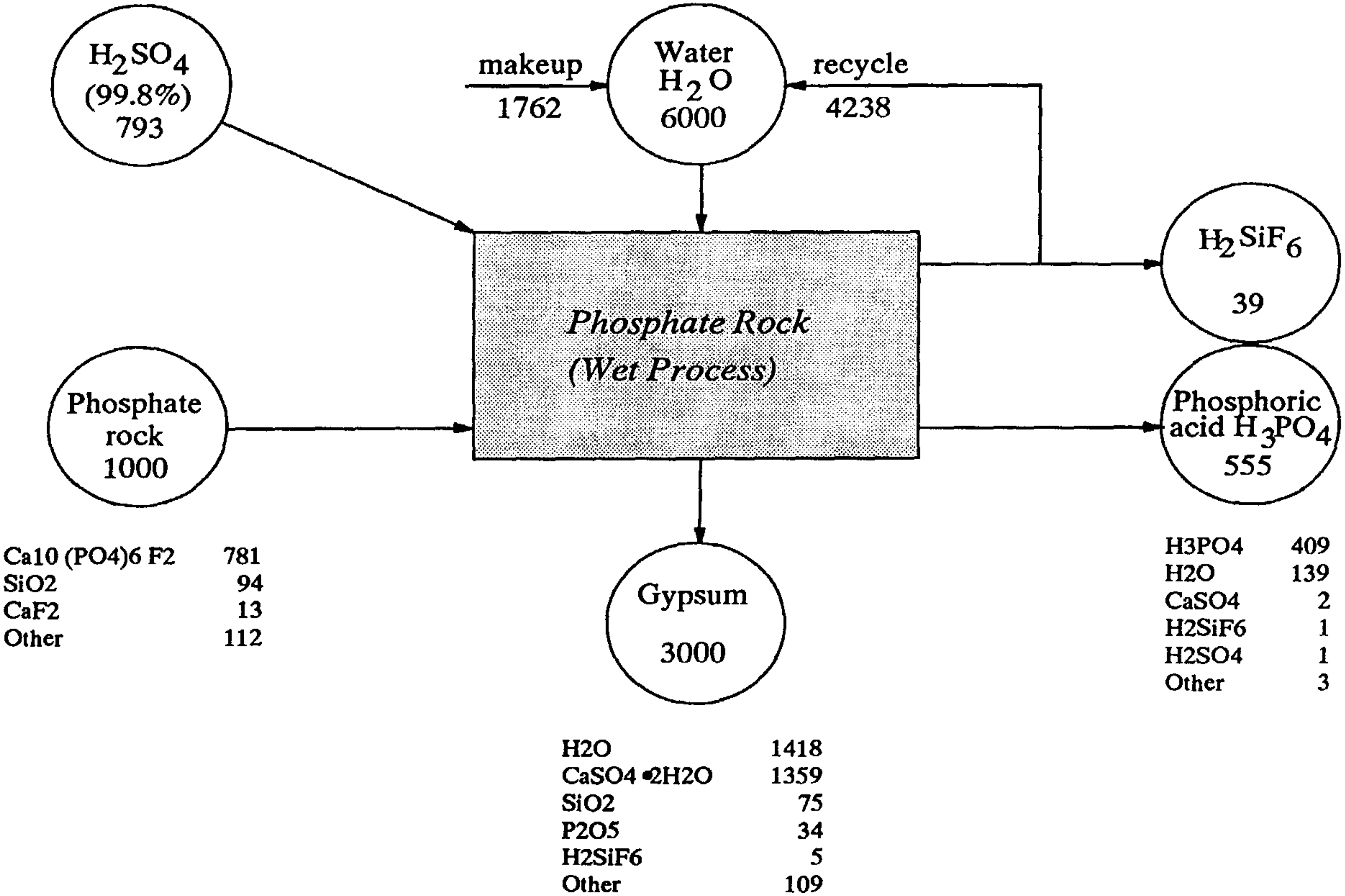


Figure 2: Materials Balance for Phosphate Rock Processing
Source: author

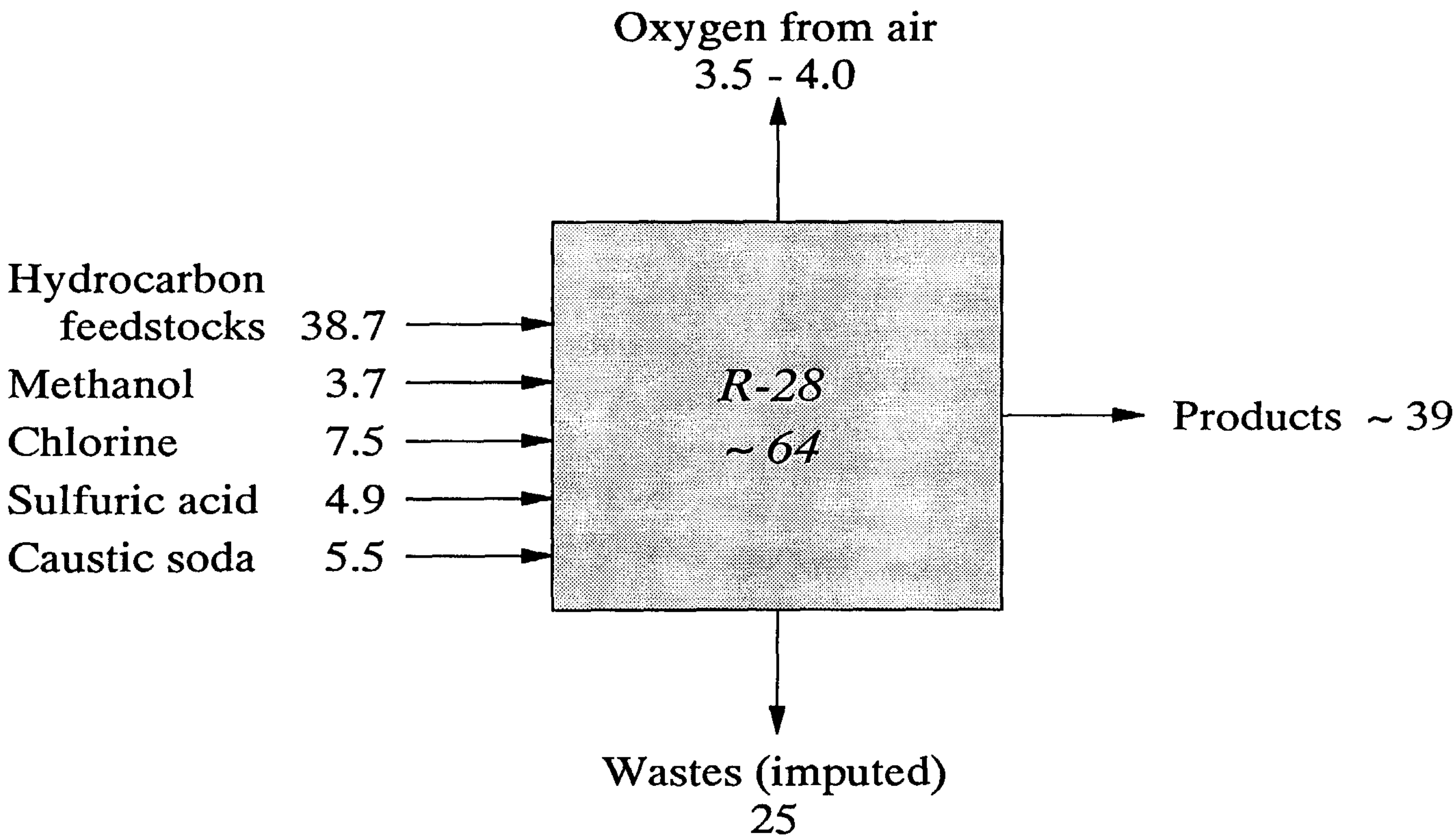


Figure 3: Materials Balance for R-28 (U.S.A. 1988, MMT)
Source: author

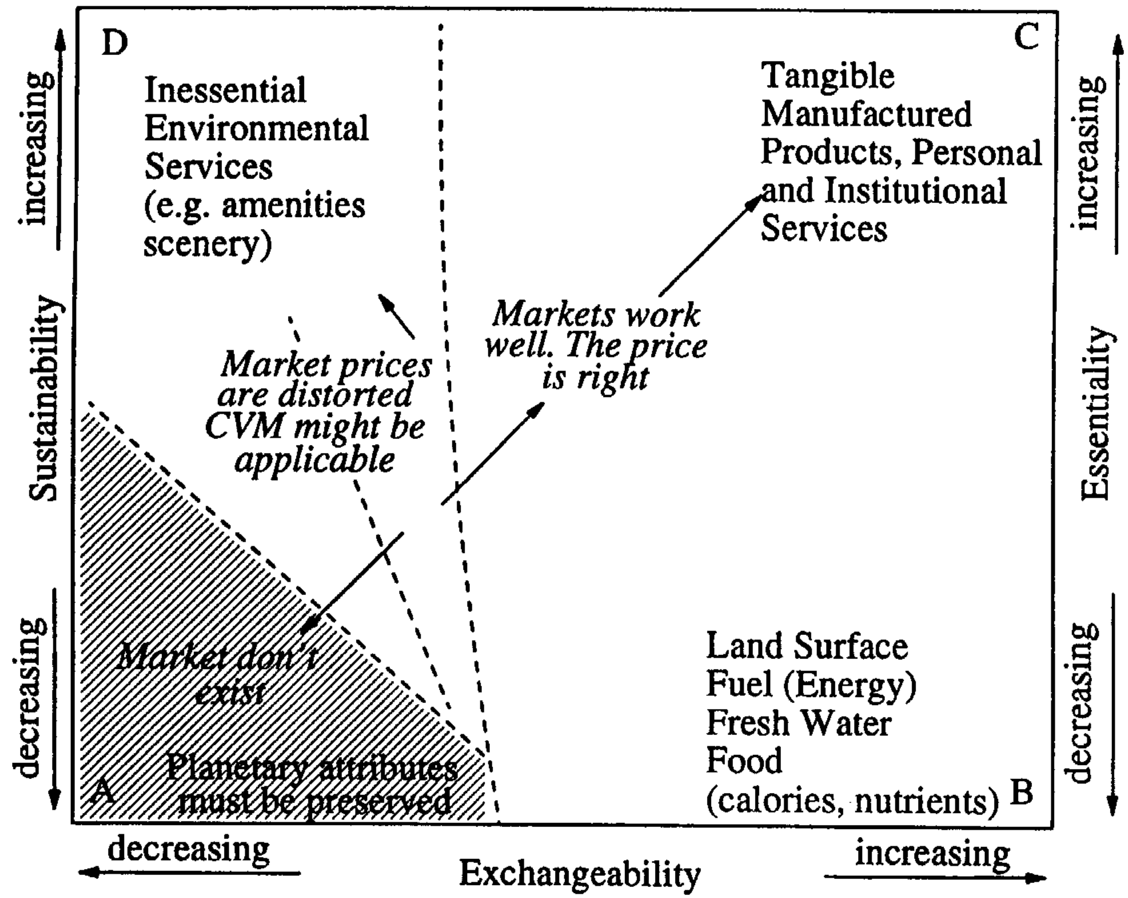


Figure 4: Applicability of Markets
Source: author

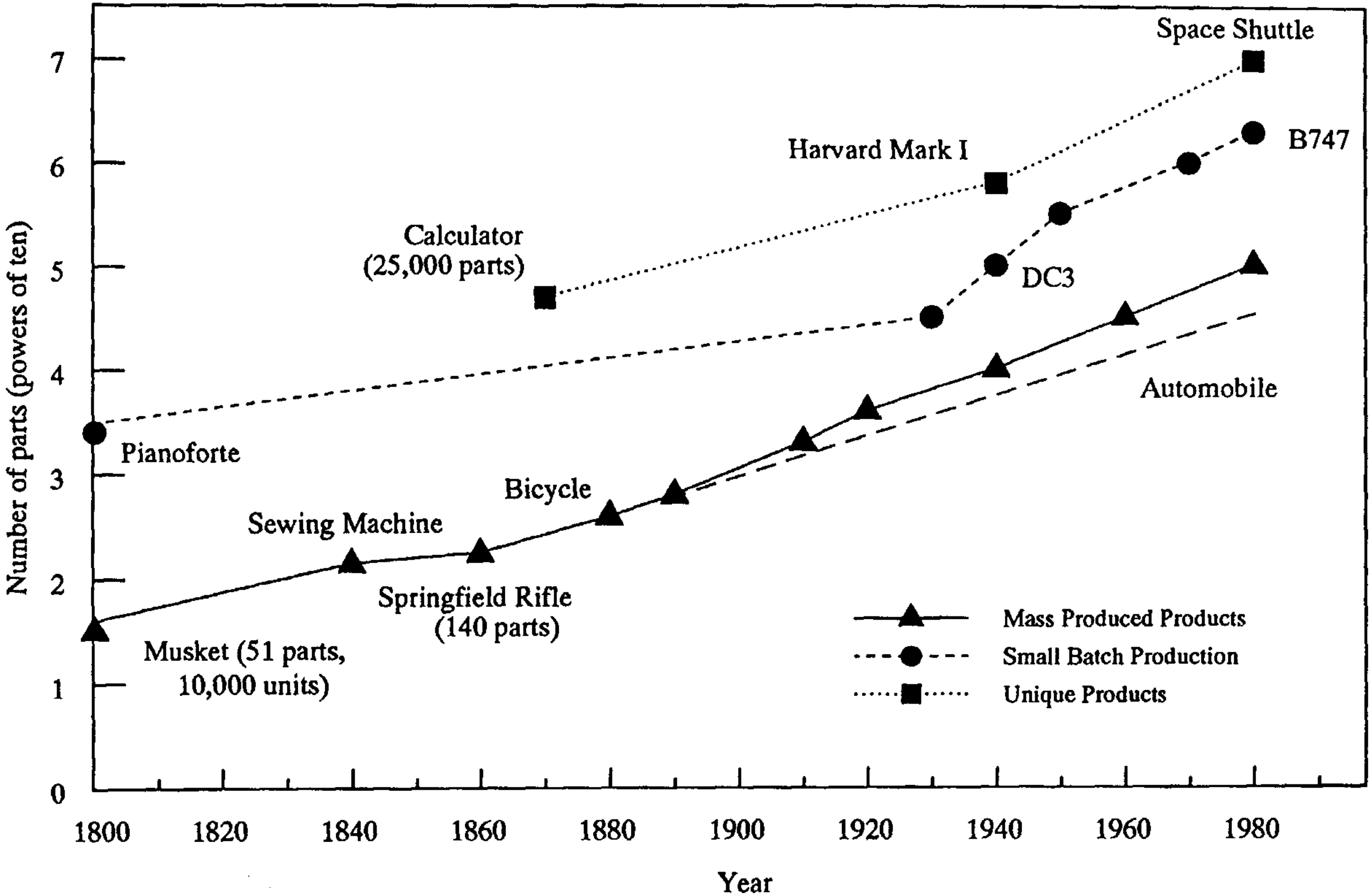


Figure 5: Complexity trends
Source: author

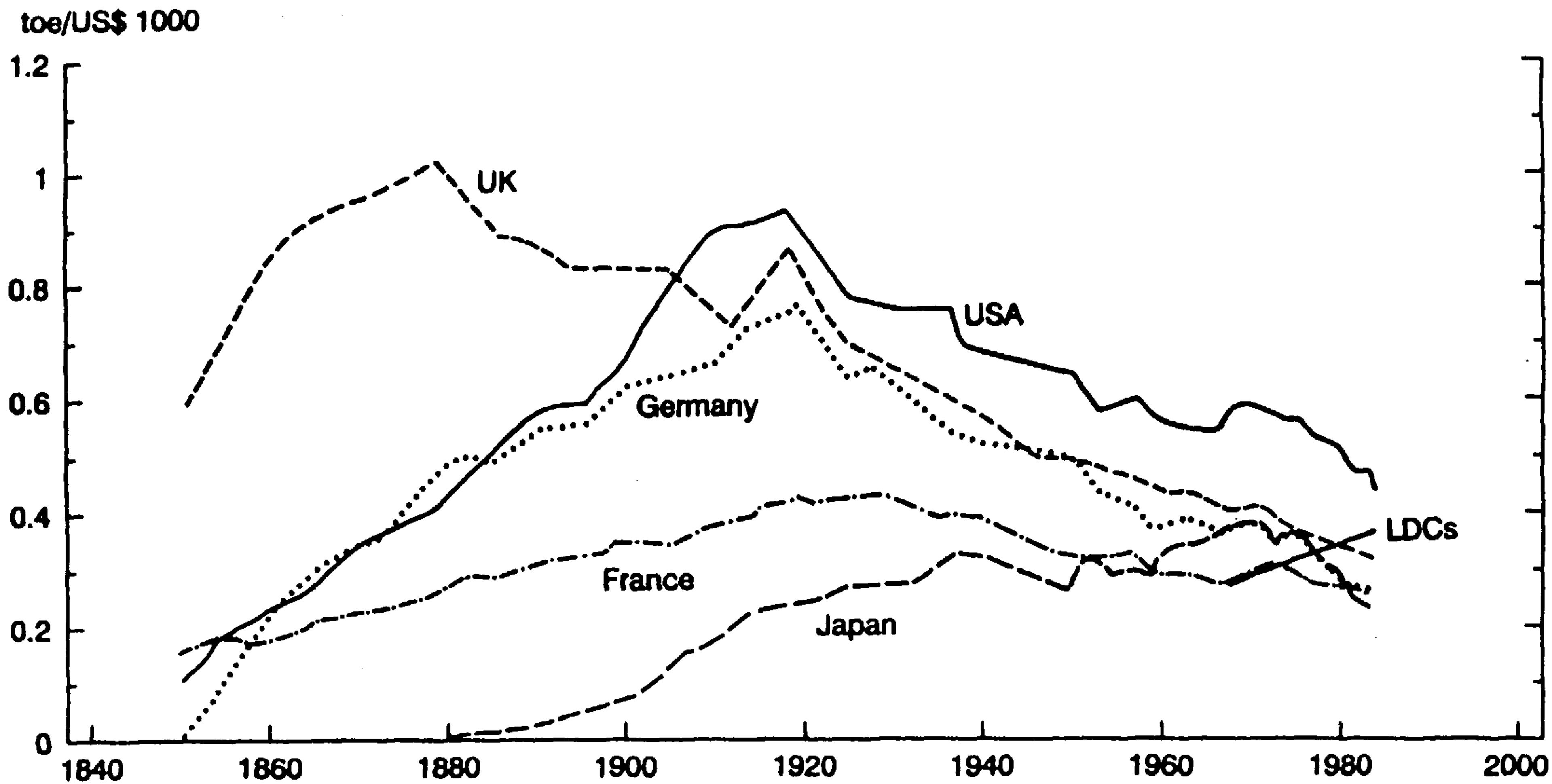


Figure 6: Energy/Productivity Relationships
Source: author

Power per Unit Weight, Mobile
Hp/lb

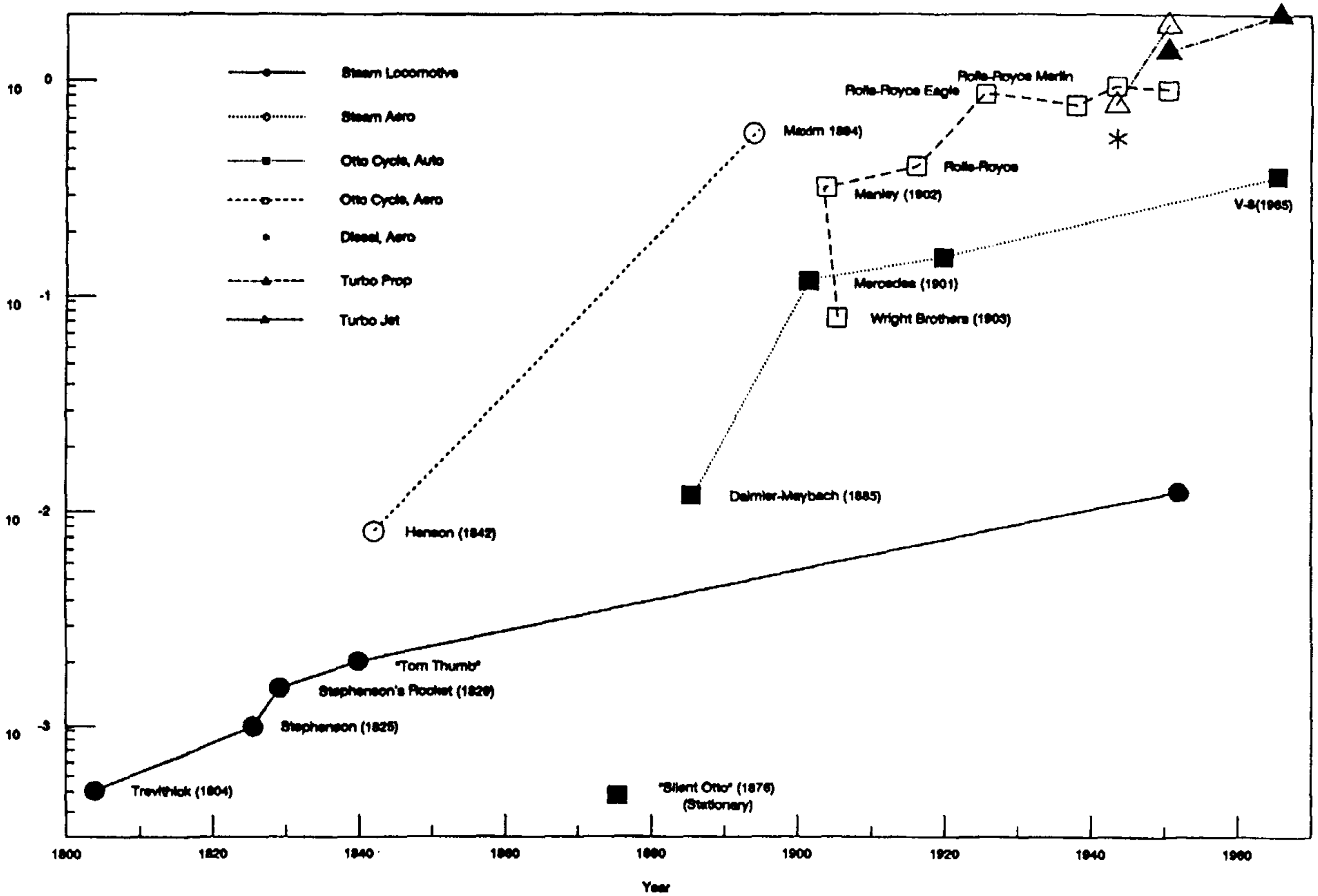
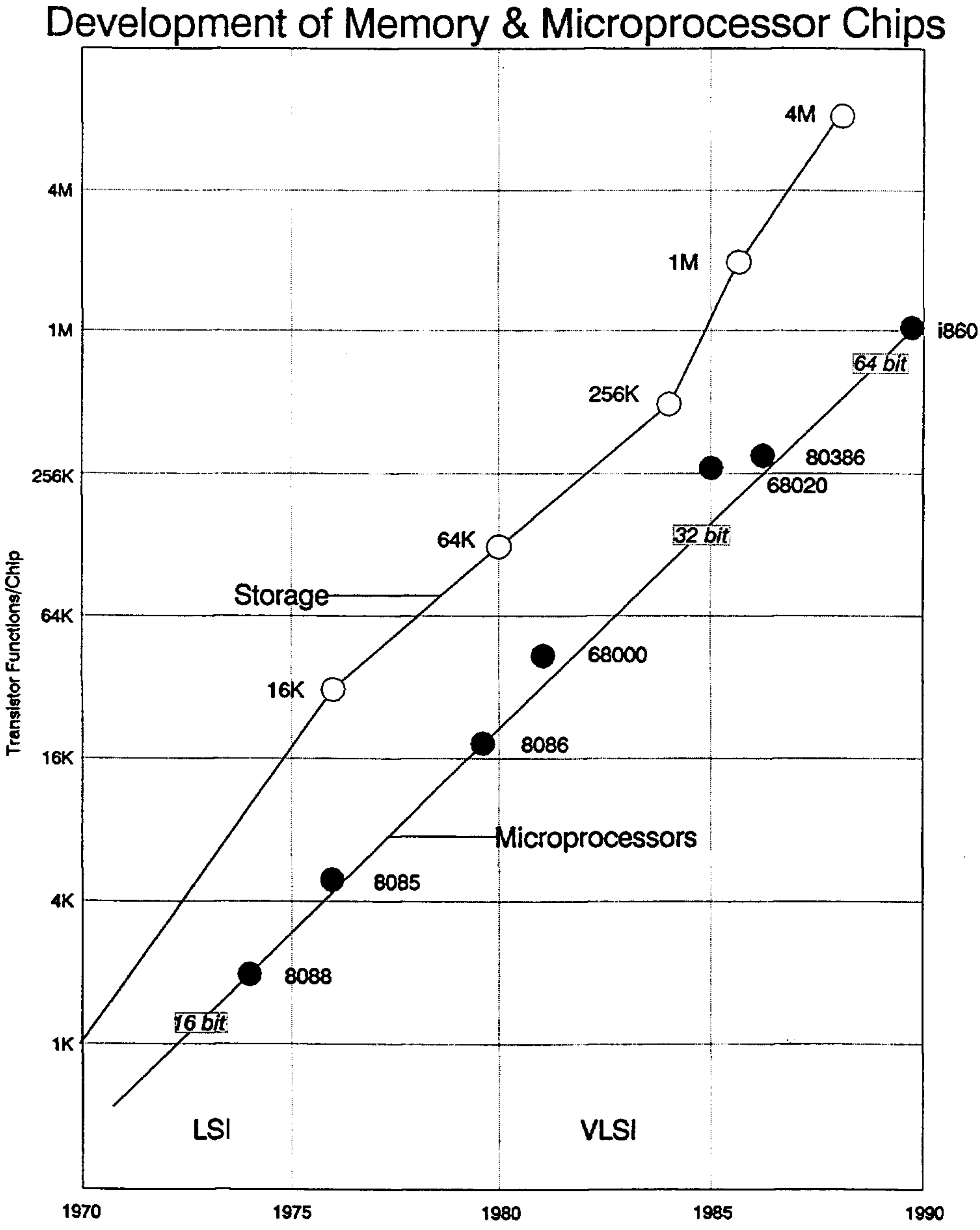
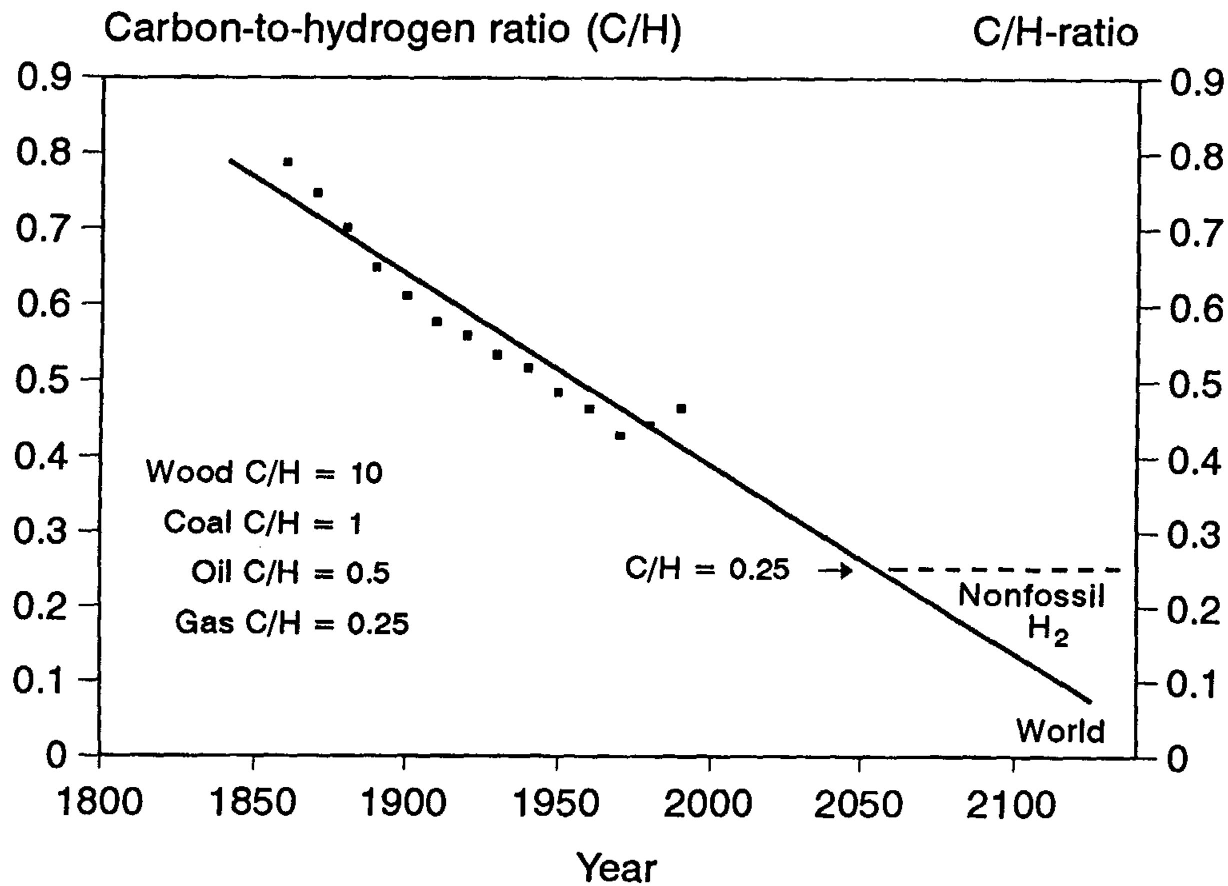


Figure 7: Power per Unit Weight, Mobile
Source: author

Figure 8



Adapted from *Bursky, Electronic Design, 1983*



SOURCE: ROGNER

Figure 9: Hydrogen/Carbon Ratio in Fuels

ELECTRIFICATION, U.S.

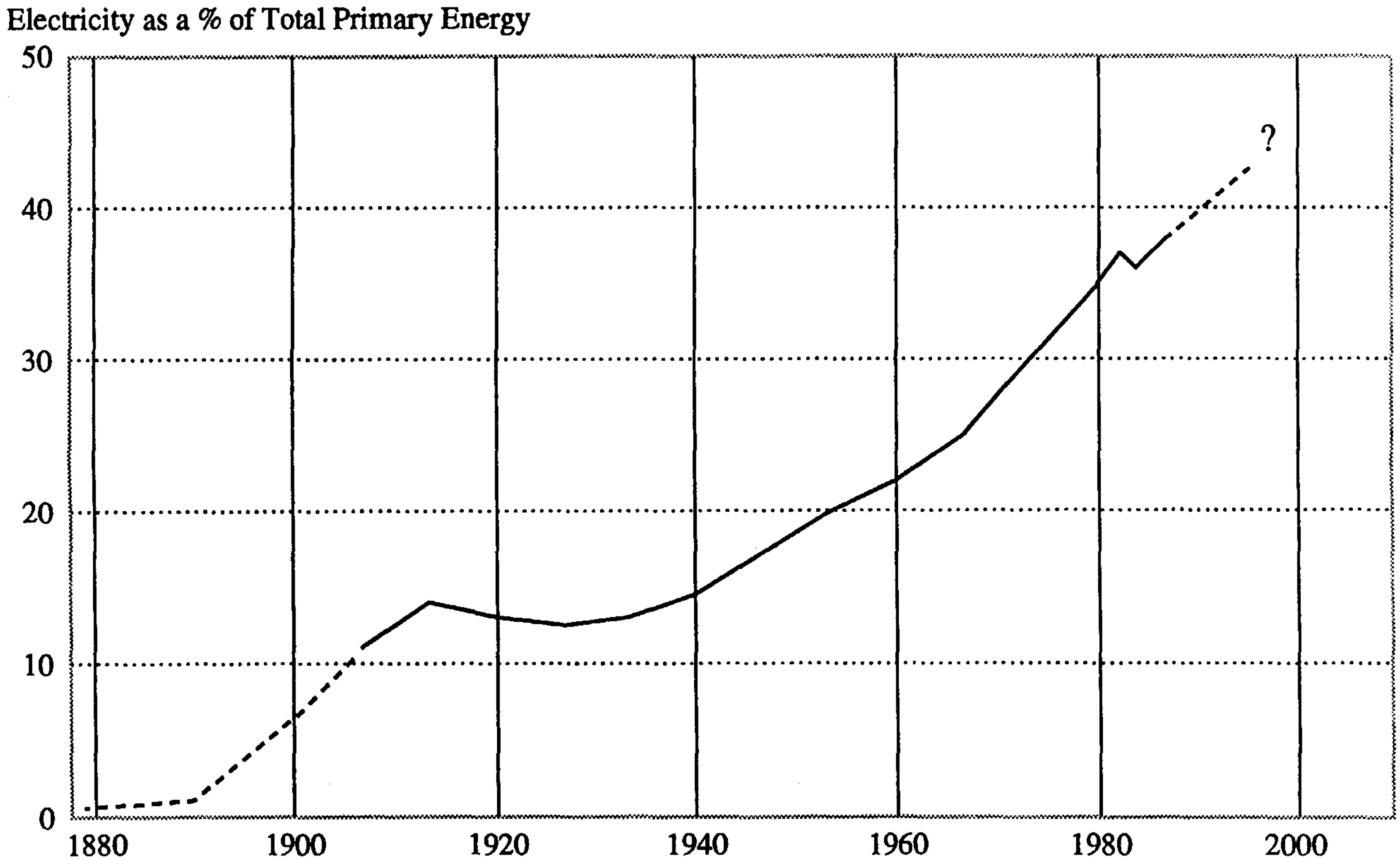


Figure 10: Electricity as a Fraction of Final Energy Use
Source: author