

IS THE US ECONOMY DEMATERIALIZING? MAIN INDICATORS AND DRIVERS

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Abstract

Dematerialization is a term that has become popular without significant analytic content. The simplest measures are inputs to the economy, namely the production and consumption of raw material commodities (including fuels). We have compiled the major commodity flows in the US economy since 1900, in both mass and exergy terms. Based on these data (and notwithstanding some impressions to the contrary) the US economy is not "dematerializing", to any degree that has environmental significance. Since 1900 it has exhibited a slow and modest long-term increase in materials consumption per capita, except during the depression and WW II. The trends in regard to resource productivity (GDP per unit of materials consumption) are moderately increasing, overall. We discuss some of the underlying driving forces, including declining ore grades, increasing recovery efficiency, increasing product complexity, and so on.

These commodity data exclude some massive indirect flows of unpriced materials, such as mine and agricultural wastes, that were never measured accurately and have been ignored until recently. On the other hand, the unpriced indirect material flows have much less environmental significance than is implied by the masses involved. Exergy is a measure that better reflects the potential for reactivity and environmental harm associated with mass flows. From this perspective, it is worthwhile discriminating between the materials used for construction of infrastructure, buildings and embodied in durable goods, on the one hand and materials that can be categorized as "consumable", on the other hand. The latter category includes food and feed, fuels, lubricants, soaps and detergents, solvents, fertilizers, and packaging materials. It is these dissipated materials that accounts for the bulk of harmful emissions to the environment. We argue that policy should focus *not* on reducing the total mass of materials consumed, but on reducing the need for consumables, especially intermediates.

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Background

Dematerialization is a popular environmental slogan these days. The notion that dematerialization is desirable follows directly from the idea that large mass flows are environmentally harmful as such [Schmidt-Bleek 1993a; Schmidt-Bleek 1993b; Schmidt-Bleek 1994; Adriaanse et al 1997]. It would follow almost automatically that less harm must follow from reduced mass flow. We argue that this is a misleading and essentially false proposition.

There is a widespread impression, even among sophisticated economists, that the economy of industrialized countries is well advanced along an inevitable process of dematerialization. Many examples have been presented to demonstrate the supposed trend towards dematerialization in industrial societies. The primary example, of course, is the computer chip. Undoubtedly the size and weight of computer chips, and products containing them, from radios and portable telephones to computers, are much less massive – and use less electric power – than their less powerful counterparts ten, twenty or thirty years ago. We will have more to say about this subsequently.

To a lesser extent, the same trend can be observed in a variety of other products. Bicycles made from aluminum or carbon-fiber frames are lighter than the older steel-framed units. Refrigerators are smaller and lighter, thanks to improved thermal insulation. Automobiles became lighter from 1975 to 1990, thanks to the CAFÉ standards (but prior to the great popularity of SUVs). Cans are thinner and lighter. Cold-weather clothing is lighter than in the past. Many products formerly made of metal are now made of plastic. And so forth.

Consider the following two quotes:

"Fiber-optics has replaced huge tonnages of copper wire, and advances in architectural and engineering design have made possible the construction of buildings with much greater floor space but significantly less physical material than the buildings erected just after World War II. *Accordingly, while the weight of current economic output is probably only modestly higher than it was a half century ago, value added, adjusted for price change, has risen well over threefold.*" Alan Greenspan, from speech at The Conference Board, NY, 10/16/96; cited in [Cairncross 1997]

or (based on the above)

"America's output, measured in tons, remains about as heavy as it was a century ago, even though real GDP, measured in value, is twenty times greater. The main reason for this striking shift from material goods to intangibles, described in a speech in 1996 by Alan Greenspan, chairman of the Federal Reserve Board, can be identified as the rising proportion of total cost of the "knowledge" content of goods and services, relative to materials and energy" [Cairncross 1997]

In fact, neither of these two eminent authorities has done sufficient homework. However that may be forgivable: the subject is much more complicated than it appears to be at first glance.¹ Some of the complexities are discussed in the next section. Subsequently we present the historical data on mass flows from three different perspectives, namely mass per capita and exergy per capita; then mass and exergy per unit of GDP; then embodied exergy per unit of mass. The material flows themselves are considered in five groupings, namely fossil fuels; agricultural products, construction materials and chemicals. Finally, we present some interesting conclusions.

Conventions and complications

Since GDP is a measure of economic activity in monetary units, it is literally impossible to weigh the GDP, as such. However, it is possible to do some other things. For instance, one might weigh the "final" products sold to end-users. However, this is not as simple as it might seem at first glance. Does the gasoline purchased by a farmer for his pickup truck count as an end-use or an intermediate use? Is a commuter's rail pass an end use? What about a business suit? There are many self employed persons and corresponding ambiguities, and no statistics on the allocation of physical flows between intermediate and end uses. (We return to the discussion of final vs. intermediate products later.)

It might be easier to weigh raw material inputs. But, here, too, we need to decide what is meant by a "raw material". The usual definition refers to primary commodities exchanged in markets (but obviously not all commodities). However this definition would exclude firewood self-gathered by the end-user, as well as vegetation grazed by sheep or cows and manure produced by those animals. (In India these would be major omissions).

If air and water are included as raw materials, as they should be from a purely physical perspective, the mass involved will be far larger than all other inputs combined. But those figures are unavailable in official statistics and would, in any case, be ambiguous. We would need to decide whether to include irrigation water and cooling water among these inputs. We also need to decide whether atmospheric nitrogen that does not participate in the combustion process should be counted as an input, or not. In practice, these numbers can be estimated roughly, but only for recent years, and probably not more precisely than plus or minus 50 percent.

A more 'reasonable' convention might be to include oxygen from the air insofar as it participates in combustion processes and animal respiration, but subtracting oxygen generated by photosynthesis in agriculture and forestry. The same convention, applied to air, would rule out nitrogen that is non-reactive. (Only a tiny percentage of atmospheric nitrogen throughput is 'fixed' by natural biological processes, or combustion processes, and this fraction can generally be neglected in a large-scale mass balance.) Similarly, we might try to include water only when it participates actively in a reaction, as in photosynthesis or when it combines with plaster-of-Paris or Portland cement. But then water driven off by dehydration processes should be subtracted. Water that *only* participates as a passive carrier of heat or a diluent of waste should probably not be counted, if only because there are no good statistics. This reasoning suggests that air and water should both be excluded from consideration.²

This convention would also exclude some of the 'hidden flows', such as earth — topsoil or subsoil — that is simply moved from one place to another by road-building or construction projects or surface erosion. These flows have been given considerable weight (!) by Schmidt-Bleek and others [Schmidt-Bleek 1993a; Schmidt-Bleek 1993b; Schmidt-Bleek 1994; Adriaanse et al 1997]. We think that displacement alone is not a sufficient argument for inclusion, although (if data were available) an argument could be made for counting erosion because of its double impact on agricultural land on the one hand and on siltation of lakes, river valleys and estuaries, on the other. Despite the poor data, the first major international study of mass flows did include erosion [Adriaanse et al 1997]. However, an argument for not including it is that there is no corresponding inflow, hence no way to use the mass balance condition for verification.

The case of material displaced by surface mining (overburden) is not quite so simple, however, since mine waste normally contains some chemically active minerals, such as pyrites that can oxidize when exposed to air and water. While the concentration of these contaminant minerals is low, the quantities are vast. Moreover, they are commonly piled in upland valleys where they result in acidification, mobilization of toxic metals, and drastically alter topography and stream flows. It seems defensible to include mine overburden as both part of an input to the economic system, as well as an unwanted output.

If air and water are excluded, but mining overburden, other minerals (like sand, gravel, clay and limestone) and crude metal ores are still included, one obtains a smaller but more justifiable set of numbers. A further convention is needed to decide how to deal with crude ores associated with imported metals. For instance, a hundred tons of platinum used each year in the US for industrial and automotive catalysts requires a hundred million tons of crude ore (more or less) must be dug up and processed in South Africa. In principle, we think it should probably be assigned to the consuming country.

The materials embodied in imported products — especially automobiles and electronic goods — raise a similar question. In principle, we think that not only the material content of the finished goods but the indirect material flows associated with their manufacture in other countries should be assigned to the consuming country. On the other hand, revenues earned by manufacturing goods for export are likely to be spent (on average, over time) on consumable imports. It is probably unavoidable, if theoretically unjustified, to assume that these inflows and outflows compensate, at least roughly. *Ad hoc* corrections might be possible in specific cases, such as South Africa, Chile, and some other African countries, where the indirect flows associated with exported mineral products such as diamonds, gold and copper concentrates vastly exceeds the indirect flows associated with imports. A detailed analysis based on international trade data would obviously complicate the analysis enormously and probably beyond any practical possibility of implementation in the near future.

There is another set of ambiguities, especially related to agriculture. For instance, should we include the grass consumed by cattle among the inputs? How shall we treat crop residues and manure that are recycled to the soil? How shall we treat manure that is not recycled? The most consistent rule, albeit not the easiest one to apply, is to draw the line at photo-synthetic products harvested directly by humans or harvested by animals whose products are consumed by humans. By this rule, plant parts that are physically removed, either by human farmers or by grazing

animals, are counted as 'inputs', regardless of what happens to them subsequently. On the other hand, plant parts remaining in or on the ground (roots, fallen leaves) are not counted. According to this rule, all plant parts that are harvested but not utilized, as well as animal wastes, are 'waste outputs'.

We cannot state a general all-encompassing rule for deciding what is 'in' and what is 'out', but the two primary criteria are common sense and data availability.

Exergy as an alternative measure

Exergy is an unfamiliar term, except to chemists or physicists. But it is really what non-technical people usually mean when they speak of *energy*. When people speak of energy consumption or energy production, it is really exergy that they mean. Notice that exergy can be used up, whereas energy is always conserved. The exergy embodied in a fuel can be equated approximately to the *heat of combustion* of that fuel.

However, exergy does have a formal definition in thermodynamics that is somewhat broader. Exergy is defined as the *maximum* amount of work that can be extracted from a subsystem as it approaches equilibrium reversibly with its surroundings. Thus a substance with little or no exergy content is almost indistinguishable from its surroundings, and conversely.

Combustion is an example of *chemical* exergy; where a substance reacts with oxygen rapidly and generates combustion products that subsequently diffuse and thus equilibrate with the atmosphere. Combustion process generate heat, which can do work via a Carnot cycle heat engine. Of course, oxidation need not be rapid. Rusting of iron is an example of slow oxidation. Heat is generated, but so slowly that it is not noticeable. But iron (like most other metals) will burn rapidly and liberate heat rapidly at a high enough temperature. Similarly, the respiration process in animals is another form of oxidation (which is why the energy – actually exergy – content of food is expressed in Calories.) There are several other kinds of exergy, including physical exergy (kinetic energy) and thermal exergy (heat). However for our purposes only chemical exergy need be considered.

There are some economically important processes that are essentially the reverse of combustion, in the sense that chemical exergy is concentrated and embodied in a target substance. Photosynthesis is an example. Carbo-thermic reduction of metal ores and ammonia synthesis are other examples. In the first case, exergy from the sun is captured and embodied in carbohydrates, which are combustible chemical substances. In the metals case, a metal oxide in contact with red hot carbon is converted to a pure metal plus carbon dioxide. The latter reaction is disguised combustion. In the ammonia case, natural gas plus air is converted to ammonia plus carbon dioxide by a series of catalytic processes at high temperatures and pressures, which also amount to disguised combustion.

However there are other processes that can do work (in principle). So when salt is dissolved in water, some heat is generated and work could be done if the heat were not rapidly diffused away. Desalination is the reverse of this diffusion process, and quite a lot of heat is required for the purpose. It follows that any useful material that is present in concentrations above the average in the air (if it is a gas) or the ocean (if it is soluble) or the earth's crust (if it is neither a gas or soluble) also embodies some exergy. Thus, pure rainwater contains some exergy as compared to

seawater, which has zero exergy by definition. Pure salt also contains some exergy for the same reason. Similarly pure oxygen or pure nitrogen contain some exergy, whereas the mixture that is air has zero exergy content, by definition. Finally, mine overburden has little or no exergy if it is chemically indistinguishable from the surrounding earth or rock.

The point of this rather long explanation is that all natural raw materials contain some exergy, insofar as they are chemically different from the air, water or earth, depending on whether the end product of all reactions is a gas, a liquid or soluble solid or an insoluble solid. By this test, the exergy embodied in a ton of sand is extremely small compared to the exergy embodied in a ton of coal. In effect, exergy is a measure of distance from equilibrium. This means that some chemical exergy is embodied in all material wastes. But of course the most dangerous wastes, environmentally speaking, are the ones with highest exergy content, meaning that they are chemically reactive.

Fuels, hydro-power, nuclear heat and products of photosynthesis (phytomass) are the major sources of exergy input to the economy. Most other materials have very little exergy in their original form, but gain exergy from fuels, as in metal reduction or ammonia synthesis. Nevertheless, the exergy content of materials is an interesting measure, especially in contrast to the traditional measure (mass).

Mass flows in the US economy, 1993³

Based roughly on the above conventions, a summary of the major mass flows in the US economy for 1993 is shown in **<<FIGURE 1 NEAR HERE>>** *Figure 1*. (We also included overburden and erosion, in this case, since estimates were available.) The mass balance principle was used to estimate a number of flows that could not be measured directly. In particular, we used the mass balance to calculate the amount of oxygen generated by photosynthesis in agriculture and forestry, the amount of atmospheric oxygen required to burn all the fossil fuels (and wood) and the amount of water vapor generated by the combustion process. (We used official estimates of carbon dioxide production from fuel combustion, and calculated the others as ratios, based on chemical reaction formulae).

It goes without saying that 'useful' outputs weigh a lot less than inputs. The difference constitutes production-related waste flows. But, the word 'useful' is also ambiguous. In economic terms, useful outputs would presumably be those with a well-defined market and market price. In general, lots of outputs are inputs for other 'downstream' products. Yet some of the physical outputs of the system — as defined by the foregoing conventions — must clearly be useful without having market prices. An obvious example of this would be forage and silage fed to animals on the farm. These are unpriced, but not unvalued intermediates. Manure generated and recycled by grazing animals on the farm is another obvious example; it is unpriced, but it would clearly be inappropriate to regard it as a waste. (In India this material is harvested, dried, and used as domestic fuel). On the other hand, animal manure generated in large industrialized feedlots *is* a waste. Finally, oxygen — a by-product of photosynthesis — is clearly valuable, albeit unpriced. The same is true of water vapor.

Raw agricultural products harvested in the US in 1993 amounted to 868 MMT, of which 457 MMT was crops and the rest was silage, hay and grass. Of this, 83 MMT (net) was exported, mostly for animal feeds. Animal products amounted to 119.5 MMT. The Food processing sector converted 374 MMT of harvested inputs (dry weight) to 286 MMT of salable products, of which 203 MMT was food consumed by Americans, 66 MMT was by-products animal feeds and food exports, and 14 MMT was a variety of non-food products including natural fibers, leather, tobacco and alcohol. Evidently 500 MMT, more or less, was 'lost' en route to the consumers, mostly as water vapor and CO₂ though other wastes were significant.

Consider forest products. Inputs (raw wood harvested) amounted to 520 MMT in 1993., not counting timber residues left in the forests (about 145 MMT). About 200 MMT of this weight was moisture. Finished dry wood products (lumber, plywood, particle board) weighed about 61 MMT. Finished paper products amounted to 83 MMT, which included some paper made from imported wood pulp from Canada and some recycled waste paper. The output weight also included 3.7 MMT of fillers and other chemicals embodied in the paper. Again, the difference between inputs and output weights was very large. Quite a lot was lignin wastes from the paper mills which are burned on site for energy recovery, but some of which still ends up as pollution. A lot of harvested wood (about 168 MMT, including paper mill wastes) was burned as fuel, producing about 230 MMT of CO₂ as a by-product. By our convention this must be counted as part of the weight of outputs.

Economists have tried to finesse these awkward complexities by creating a classification known as "final" goods, namely goods sold to "final" consumers in markets. This class of goods is reasonably well-defined. It is, presumably, what Greenspan and Cairncross had in mind when they spoke of "the weight" of the GNP. Even so-called "final goods" (except for food, beverages and medicinals) are not physically consumed. They are in a sense, producers of immaterial metabolic services. By this test, *all final outputs (not excepting food and beverages) are immaterial services and therefore weightless.*⁴ However, Greenspan and Cairncross were clearly talking about finished products, not ultimate services provided by those products. Products do have mass, as well as monetary value (counted in the GNP). The question, which we mentioned briefly at the beginning of the second section (on conventions) is: what products shall be counted as "final" and "useful" for purposes of weighing the GNP?

It might seem at first sight that intermediate products should also be weighed, inasmuch as they have economic value. However, on reflection, the value of intermediate products is already included in the value of the final goods. Similarly, the mass of final goods intermediates incorporates (part of) the mass of intermediates. The difference is the mass of wastes generated by the final stage of production. It can be argued that the mass of wastes is also, in some sense, part of the mass of the GNP, as produced, on the grounds that the wastes are direct consequences of the production process. However, we insist that the 'useful' materials should be separated conceptually (and in the statistics) from the 'wastes'. However, we agree with a reviewer that, with this convention, the mass of the final products does not really correspond with the GDP, and should not be defined as the mass of the GDP.

As a practical matter, it seems reasonable to start by counting the weight of finished materials, which is to say materials that are embodied in products, or

otherwise used, without further chemical transformation. Steel is an example. There is relatively little difference between the weight of raw steel produced (89 MMT in the US in 1993) and the weight of "finished" steel products. The small losses of steel in the rolling, casting and machining stages of production are almost entirely recycled within the steel industry.⁵ The same can be said of other "finished materials", from paper and plastics to glass and Portland cement: very little or none of the finished material is lost after the last stage of production, except as consumption or demolition wastes.

What of fuels and intermediate goods like ammonia, caustic soda, chlorine and sulfuric acid? Raw fuels are refined, of course, with some losses (such as ash), and some fuel consumption (around 10%) to drive the refineries. But refined fuels are converted, in the course of use, mainly to heat, mechanical power and combustion wastes. Fuels cannot be recycled. The mass of raw hydrocarbon fuel *inputs* was a little over 1600 MMT in 1993. It was mostly combined with atmospheric oxygen. The combustion of hydrocarbon fuels in the US, in 1993, generated around 5200 MMT of CO₂, the most important "greenhouse gas" [OECD/IEA 1995 p.39]. This may be a slight underestimate, since some of the hydrocarbons produced by refineries do not oxidize immediately (asphalt and plastics, for instance) but, except for what is buried in landfills, all hydrocarbons oxidize eventually.

Minerals such as salt, soda ash and phosphate rock, as well as petrochemical feedstocks, are converted to other chemicals. Some of these — mainly polymers — end in finished goods (like tires, carpets, packaging materials and pipes). Others are converted to wastes in the course of use. Examples include acids and alkalis, cleaning agents, detergents and solvents, pesticides and fertilizers. A rational accounting system should distinguish between dissipative intermediates, such as these, and non-dissipative materials embodied in finished durable goods that might (in principle) be repaired, re-used or remanufactured and thus kept in service for a longer period.

Another important distinction must be made, namely between 'potentially reactive' and 'inherently inert' materials. Most metals, paper, plastics and so on are in the 'reactive' category, insofar as they can oxidize or react with other environmental components. (Most of these, especially paper and plastics, can be burned for energy recovery). However, as a practical matter, these energy-rich materials are considerably outweighed by the inert materials utilized in structures, such as glass, brick and tile, concrete, plaster, gravel and stone. All of the latter group of materials are chemically inert, even though some of the manufacturing processes involve heating.⁶

Portland cement (made from limestone, clay and shale) is the single most important component of construction materials in terms of energy inputs and dollar value, but not in terms of weight (81.7 MMT) [USBuMines annual 1993, "Cement" Table 1]. Calcined gypsum products consumed in the US in 1993 amounted to 15.2 MMT [USBuMines annual 1993, "Gypsum" 1993, Table 1]. Brick and tile production accounted for 12.3 MMT of clay in 1993 [USBuMines annual 1993, "Clay" 1993]. Refractory products accounted for an additional 2.5 MMT of clay [*ibid*]. Glass production in the US was approximately 14 MMT of which only 4 MMT was flat (window) glass [USBuMines annual 1993, "Soda ash" 1993, Figure 1]. The total

mass of thermally processed building materials consumed in the US in 1993 was 125 MMT.

On the other hand, inert materials such as construction sand and gravel consumed in the US in 1993 (mainly aggregate for concrete) amounted to 870 MMT [USBuMines annual 1993, "Sand and Gravel", 1993, Table 1], while the total quantity of crushed stone – including other sand and gravel – produced and consumed was 1120 MMT [USBuMines annual 1993, "Crushed stone", 1993, Table 1]. Of this, about 110 MMT of raw limestone and dolomite was used as raw material in cement and quicklime (CaO) manufacturing. The rest of the sand, gravel and stone, including 1.2 MMT of "dimension stone" — such as marble and granite — was used as such, without further processing. Altogether, chemically inert structural materials consumed in the US in 1993 without thermal processing amounted to about 1870 MMT.

In contrast, the weight of all metals produced (and consumed) in the US in 1993 was less than 100 MMT. By far the greater part, especially of steel, was used for construction purposes or motor vehicles. The biggest consumer of copper (mostly as wire) is the construction industry, which accounted for 1.03 MMT in 1993; the motor vehicle industry consumed 270 kMT, while consumer durables (home appliances) used 250 kMT. The rest of the metals were mainly embodied in durable goods such as transportation equipment and other machines and appliances.

The total weight of materials consumed in the production of motor vehicles produced each year in the US amounted to about 27.8 MMT. Exact figures for other categories are difficult to obtain, however. The weight of all machinery, including electrical machinery and electronics, produced in the US can only be estimated on the basis of inputs (which, themselves, are approximate). We can account for about 12.3 MMT, mostly steel plus some aluminum; copper accounts for only 0.32 MMT.

Against these numbers, the weight of other consumer products is modest. For example, the weight of all textiles produced, including cotton, wool and all synthetics, amounts to around 5 MMT. Products of textiles, partly clothing and partly furnishings (including carpets) must be of the same order of magnitude.

Factors driving or inhibiting dematerialization

It is appropriate, now, to consider changes over time. Factors driving materials consumption per capita trends include declining ore grades (for metals), increasing efficiency of discovery, separation and recovery of valuable materials from ores, improved material properties (such as strength at high temperatures), and design improvements (such as miniaturization and longer lifetimes). Other factors inhibiting dematerialization include increasing purification requirements, shorter product life, and greater complexity of products, especially as it affects recycling.

Declining ore grades obviously generate more process waste (as well as overburden), other factors remaining equal. It might seem that this would lead to higher prices and thus, less use. However, so far, ore grades have decreased, but prices have fallen, not risen [Barnett and Morse 1962; Barnett 1979]. Increased efficiency of discovery and process technology probably account for this. In fact, a major message of this paper is that falling prices (together with rising personal income) have stimulated rising demand for most material products.

The history of iron and steel production over the past two centuries or more is a good illustration. In the mid-eighteenth century the iron was reduced from ore (an oxide) by contact with red hot charcoal, derived from controlled partial oxidation of wood. About 3 tons of charcoal were needed to produce a ton of iron, and as much as 5 tons of carbon in wood were required per ton of charcoal required. When coal first replaced wood, the coal/iron ratio was about 8 tons/ton, due to inefficient coking and low temperature blast furnaces. The introduction of air preheating (hot blast) in the 1830s cut the fuel requirements threefold. Today the average C/Fe for the industry is less than 0.6 tons of carbon (as coke) per ton of iron, which is approaching the theoretical limit of 0.44 tons/ton **<<FIGURE 2 NEAR HERE>>** (Figure 2). The quality of the pig iron produced in 1800 was essentially the same as the pig iron produced today, but the quantity of materials processed per ton of pig iron was vastly greater, as was the cost.

As costs fell, over time, the demand for iron and steel, per capita, grew even faster, largely due to new uses. This is one of the prime examples of the so-called 'rebound effect'. Iron and steel consumption per capita rose, in mass terms (discontinuously, to be sure) from the beginning of the industrial revolution until the 1950s and did not decline significantly until the late 1970s **<<FIGURE 3 NEAR HERE>>** (Figure 3). Aluminum is another example. Electric power requirements for electrolytic smelting have fallen by a factor of nearly 4 since the Hall-Heroult process was introduced in 1880 and by a factor of two since 1900. Meanwhile, per capita consumption grew steadily until around 1980, and has declined only slightly since then **<<FIGURE 4 NEAR HERE>>** (Figure 4).

Copper offers another case in point, complicated by significantly declining ore grades, as shown in **<<FIGURE 5 NEAR HERE>>** Figure 5. Nevertheless, prices have fallen in real terms since the 19th century, albeit very irregularly. From 1870 through 1918 copper prices averaged 50 cents/lb and ranged between 40 and 60 cents per lb (in 1967 \$). From 1919 through 1952 the average price was about 25 cents/lb, and ranged between roughly 20 cents and 30 cents per lb, except for a peak in 1929 and a trough (in 1932). From 1932 to 1970 copper prices increased fairly steadily, from 15 cents/lb to 50 cents/lb with an intervening peak in 1955-56. Since 1970, prices declined again quite sharply to below 25 cents/lb in 1984-86. There was another surge in the late 1980s and early '90s, followed by an even lower bottom in 1998-2000 similar to the prices in the mid-1930s. The long term trend appears to be down although there was a long period of generally rising prices (1920 through 1970) **<<FIGURE 6 NEAR HERE>>** (Figure 6). Meanwhile, consumption per capita has increased fourfold since 1900, ignoring wartime peaks and despite periods of rising prices, driven by steady electrification of the economy.

Other examples of dramatically increasing efficiency of chemical synthesis processes are illustrated in Figure 7. **<<FIGURE 7 NEAR HERE>>** However, thanks to price declines, per capita consumption of the major industrial chemical species, as a group, increased quite steadily until 1969 or so and has since fluctuated but increased slightly in aggregate terms (Figure 8). **<<FIGURE 8 NEAR HERE>>**

In the case of fossil fuels, significant gains in thermodynamic (as opposed to economic) efficiency on the production and processing side are largely confined to petroleum refining, as indicated by *Figure 9*, **<<FIGURE 9 NEAR HERE>>** which plots the historical trends in crude oil cracking and refining technology. The net result has been increased utilization of crude oil for purposes of propulsion vs. declining usage for other purposes such as illumination (kerosine lamps), cooking and space heating. Uses for lubrication and petrochemicals have also increased, although they are not plotted in the graph.

Per capita fuel usage is also affected by efficiency gains in energy services (work) performed, including steam engines and turbines (for electricity production), internal combustion engines for vehicular propulsion and heat utilization **<<FIGURE 10 NEAR HERE>>** (*Figure 10*). Nevertheless, despite efficiency gains, per capita fossil fuel consumption in mass terms has more than doubled since 1900 (see *Figure 21*, right scale).

As regards inert construction materials, including cement, gypsum, clay, stone, sand and gravel, thermodynamic efficiency gains on the construction side have been minor and largely limited to the cement industry. Gains – if any – on the consumption (end-use) side are difficult to measure, especially since there have been significant changes in the mix of materials (more steel, glass and plastics, less brick and plaster), and more prefabrication. Wood products are now used more efficiently than in 1900, as plywood and particle board have replaced simple lumber, for many purposes such as siding. Nevertheless, the mass of construction materials consumed per capita rose nearly six-fold from 1900 to its post-war peak in the mid 1960s. The bulge was a specific consequence of President Eisenhower's 41,000 mile interstate highway program. The program created in 1956 consumed an enormous amount of concrete and aggregate ("enough to build 80 Hoover dams or six sidewalks to the moon" [Yergin 1991] p. 553). The program was substantially complete by 1970. Yet there has been only a modest (<20%) decline since then (see *Figure 23*, right scale).

To complete the picture, gross biomass consumption per capita declined significantly (about 40%) from 1900 to its low point in the middle of the depression (*Figure 11*). **<<FIGURE 11 NEAR HERE>>** This probably reflects declining use of fuelwood for home heating and cooking, and less need for feed for horses and mules on farms, due to the increasing use of tractors after the 1930s. Since then, biomass consumption per capita has trended slightly upwards, reflecting increasing meat consumption, though it remains less than the 1900 level.

Although generalizations based on incomplete data are always open to question, it seems fairly clear that the most important factor opposing dematerialization is demand for new products and services, induced by declining prices and rising incomes. In fact, efficiency gains, in general, have been more than compensated by increasing demand (the so-called 'rebound effect').

Improvements in materials properties, such as strength-to-weight, have resulted in some dematerialization. **<<FIGURE 12 NEAR HERE>>** *Figure 12* indicates the extent of technical improvements, for the strongest materials, since historical times. However the very strong new lightweight materials, notably aluminum, titanium and composites, have found uses mainly in aircraft (**<<FIGURE 13 NEAR HERE>>** *ure 13*) and for extremely limited consumption items such as tennis rackets and golf clubs. Power to weight ratios of

the most advanced prime movers have increased by four orders of magnitude since 1800 and by tenfold since 1900 (*Figure 14*). <<**FIGURE 14 NEAR HERE**>> However, these gains have resulted mainly from design innovations (such as the diesel engine and the gas turbine) made possible by the availability of better alloys and precision manufacturing techniques. They have made bigger power units possible and contributed mainly to increased use of electricity generation and propulsion power, as already indicated.

Similarly, very dramatic improvements in telecommunications technology have increased telecommunications channel capacity by at least eight orders of magnitude from 1800 to 1980 [Martin 1971], when glass fibers began to replace copper wires. Channel capacity has increased by several more orders since then. The mass of a single equivalent telephone circuit has fallen from 100 kg/km in 1914 to around .005 kg/km now (*Figure 15*). <<**FIGURE 15 NEAR HERE**>>

The substitution of copper by glass optical fibers cannot be detected in the aggregate data. The weight of refined copper consumed in the US in 1993 was about 1.8 MMT of which just 504 KMT (0.5 MMT) was destined for wire manufacturing. Thus, while Alan Greenspan may be right that fiber optics have replaced "huge tonnages" of copper wire, the adjective "huge" must be understood in a comparative sense. Optical fiber usage for telecommunications has increased sharply, displacing some copper wire. However, although glass fibers can carry far more information per unit mass than copper, the amount of copper displaced cannot be more than a few hundred thousand tons at the very most. So glass fiber has replaced a small part of the demand for copper wire, but probably not (yet) enough to affect the tonnage per capita or tonnage/GDP trend for copper, and certainly not enough to affect the overall trend.

The final example of (apparent) dematerialization resulting from technological improvements in design is the computer chip. Since Moore's Law was first stated in 1965, the number of circuit elements per square cm. of chip surface has doubled every 18 months, with astonishing regularity. However demand for chips – and computers to contain them – has also increased even faster.

The weight of an electronic computer c. 1955 (as now) consisted mostly of peripherals. The first commercial computer made by IBM, the model 701 (1953), occupied — with its peripherals, such as DC power supply, tape drives, card readers and printers — a floor space of at least 40 square meters, not counting space required for special air-conditioning units. The machine itself, occupied a volume of at least 6 cubic meters and contained several thousand vacuum tubes (for logic circuitry) and cathode ray tubes (for memory), not to mention steel racks. By 1955 there were probably 20 such machines in the US (including the competing UNIVAC units) and, including peripherals, each one probably weighed as much as a car, or around one metric ton, if not more.

Now jump to the present. Domestic shipments of personal computers (PCs) in 2000 were about 50 million units. These were mostly lap-top and desk-top units. The average weight of each desktop unit is over 10 kg. (of which the monitor accounts for something like half, while laptops average something like 3-4 kg. So, at 6-7 kg per unit, the overall mass of small computers shipped in the US in the year 2000 — disregarding workstations, 'mainframes' and supercomputers — must have been around 300 million kg or 1 kg/capita. (The mass of silicon chips contained therein was much smaller, probably less than 1000 metric tons). Other types of

computers, such as servers, though fewer in number, are also bigger and heavier than PCs. The mass of PCs and associated hardware produced and sold annually in the US is of the order of 2 kg per capita, and this does not include the rather large indirect use of materials for processing ultra-pure silicon, wafers and chips (see Appendix). The point is that the alleged 'dematerialization' in this case is mostly mythical: computers are individually smaller but their numbers are enormously greater than was the case forty years ago, and aggregate material consumption is up, not down.

To summarize briefly, there is little evidence of per capita dematerialization of the US economy. On the contrary, increased demand seems to over-compensate for efficiency gains in every case we have investigated.

Trends in exergy/capita, mass/GDP and exergy/GDP

<<FIGURES 16-20 NEAR HERE>>

Up to now we have considered mass of materials consumed per capita. There are three other measures of possible interest, however, namely exergy/capita, mass/GDP and exergy/GDP. For instance, though exergy consumption is proportional to mass, for a given material, this is not necessarily true for groups of materials (e.g. construction materials or fuels) due to changes in the mix or composition of the group. The differences, as shown in *Figures 16-19*, for fuels, metals, construction materials and chemicals, offer some interesting insights. (In the case of biomass exergy and mass are essentially proportional). *Figure 20* shows mass and exergy per unit GDP for the total of all the materials considered, including biomass.

It is noteworthy that there has been a modest dematerialization of energy carriers since 1900. That is to say, the mass/exergy ratio for primary fuels consumed in the US has declined from 0.042 metric tons per teraJoule (tJ) in 1900 to 0.03 metric tons/tJ in 1995. This is an overall decline of 28 percent, due primarily to the increased use of natural gas and less use of coal. But actually the minimum point was reached in the decade 1965-1975 (0.028 metric tons/tJ). The trend has been rising since that time as coal has increased its share of the electric power generation market since the "energy crisis" of 1973-74.

The pattern for steel is quite similar to that for fuels. The peak in production per unit of GDP occurred in 1920, at about 75 metric tons/\$million. There were subsequent (lower) peaks in 1940, 1950 and 1955, followed by a sustained decline. Steel has lost ground to many other structural materials, including aluminum and concrete. Aluminum production, on the contrary, exhibits a sustained and monotonic *increase* in the tonnage/GDP ratio from 1900 through 1970, largely due to the increasing importance of air transportation and the use of aluminum cans for beverages. There was a small decrease in 1975 followed by another increase in 1980. Both peaks were about 1.5 metric tons/\$million. However since then, the mass/GDP ratio for aluminum has fallen to 1.2 metric tons/\$million, probably because two of the main existing aluminum markets were saturated by then and because of competition by plastics, mainly PVC, in the building sector.

As might be expected, plastics exhibit the most dramatic increase, from virtually zero in 1900 to about 6.6 metric tons/\$million in 1995. For the most part, plastics have been substituting for other materials, including steel, aluminum, lumber, and paper.

<<**FIGURES 21-25 NEAR HERE**>> Trends in mass/GDP and exergy/GDP diverge significantly from trends in mass/capita and exergy/capita. The per GDP trends tend to exhibit declines (albeit with some exceptions for specific materials during certain periods), but most of the per capita trends show increases, (again, with a few limited exceptions) as shown in *Figures 21-24* and summarized in *Figure 25*. This reflects the fact that GDP has increased faster than mass (or exergy) consumption. This follows, in turn, from the overall shift from products to services in the economy.

For instance there has been a steady long term decline in fossil fuel exergy/GDP (tJ/ \$ million) in 1987 dollars. This indicator was about 27 tJ/\$million in 1900, peaked at 33 tJ/\$million around 1920 and has declined more or less monotonically since then to 13 tJ/\$million in 1995, except for a sharp but temporary drop below trend for World War II and a slight rise during the early 1970s due to the embargo and its aftermath. Combining mass/exergy and exergy/GDP the maximum occurred in 1920 (1.25 metric tons/\$million). This indicator had dropped to approximately 0.55 metric tons/\$million by 1960 and around 0.4 metric tons/\$million by 1990, and slightly lower in 1995. The recent rate of decline has been around 0.8 percent/per annum.

Cement consumption per unit GDP has fallen monotonically since 1955 (38 metric tons/\$million) to 18 metric tons/\$million in 1995. Curiously, the gypsum/GDP ratio appears to have reached a postwar minimum in 1975, since which it has risen slowly but steadily. The tonnage/GDP ratio for bricks has declined more or less continuously on average, despite temporary fluctuations.

Lumber and paper exhibit opposite trends in relation to GDP. For lumber the tonnage/GDP trend has been steadily down since 1905, except for a slight rise from 1945 to 1950. This clearly reflects a substitution of other building materials for wood. For paper, however, the trend was steadily upward from 1900 through 1960 (except for 1945) but since then it has fallen slightly, with a recent increase. The pattern for rubber is somewhat similar to that for paper, rising to a peak tonnage/GDP ratio in 1960. Since then the ratio has declined quite sharply, however, from a maximum of 0.9 metric tons/\$million to a recent level of around 0.42 metric tons/\$million.

Two examples of non-structural materials are sulfur and copper. Sulfur, which is almost entirely used to produce sulfuric acid — is a well-known indicator of the chemical industry, but roughly half of the total output currently is used for the processing of phosphate rock to make super-phosphate. In this case the tonnage/GDP ratio rose sharply to a high in 1930. Thereafter the ratio fluctuated with a lower peak in 1940, a higher one in 1950 and another in 1970. Since then the ratio has declined fairly steadily from 3.5 metric tons/\$million to around 2 metric tons/\$million. This decline probably reflects saturation in the phosphate fertilizer market.

The tonnage/GDP ratio for copper production rose modestly from 1.3 metric tons/\$million in 1900 to about 1.9 metric tons/\$million in 1925 and 1930, and, after a sharp dip in the 1930s, it reached almost the same level in 1940. Then the trend has been sharply down to about 0.5 metric tons/\$million in 1980. Since then the ratio has fluctuated at or slightly below that level. The major decline from 1940 through 1980 reflects reduced consumption of brass (replaced by other cheaper materials), substitution of PVC pipe for copper pipe and replacement of some copper wire by

aluminum wire. The latter substitution proved abortive (for safety reasons) and copper has made a comeback.

Obviously some substitution has occurred, especially of plastics for metals and some structural materials. This tendency has reduced the mass of finished goods, to some degree, but not the potential hazards of process wastes. Chemical wastes are, on average, more reactive and hence more likely to be hazardous than other wastes.

Further remarks on dematerialization

Referring again to larger question raised by the comments of Mr. Greenspan and Ms. Cairncross, it is difficult to decide exactly what categories of 'final' products should be included in a meaningful comparison between (say) 1900, 1950 and 2000. To mention a few contrary examples, cars and houses are much bigger than they were then, and there are more of each. Moreover, current trends are still up.

Similarly, per capita consumption of rail transport in 1900 was considerably higher than today, but the reverse is true for motor vehicles and air transport. More important, the fuel consumed per capita for all transportation purposes has increased enormously in the past century, and in the last half century. Similarly, the fuel consumed to generate electric power has increased enormously. A century ago, electric power was only available in big cities and it was still an expensive luxury. Today it is a necessity. Obviously there have been substantial improvements in the efficiency and power/weight ratios of gasoline engines, gas turbines and electric power generation. But these and similar technological contributions to dematerialization have been far outstripped by the increased demand.⁷

Of course, apart from fuels and food, the total mass of materials consumed by the economy was — and still is — dominated by construction materials, especially sand, gravel and crushed stone. It is certainly true, as Greenspan notes, that technological improvements in the building sector permit some increase in the available floor space per unit of mass input. But, again, these efficiency gains are minor compared to the increased demand for floor space. So, even in this case, the quantity of building materials consumed per capita in the US has increased significantly in the last century, even if not per dollar of GDP.

In terms of mass per capita, the US economy is not dematerializing at all. There are two countervailing trends that appear to explain this result. One is the phenomenon known as the 'rebound effect', which is the fundamental growth mechanism that operates in the economic system. In brief, increased efficiency of production or usage leads to reduced costs and greater demand. The latter more than compensates for the efficiency gains. The other countervailing phenomenon is increased complexity. Simply stated, as functionality increases (e.g. computer chips become smaller and more powerful) the manufacturing process becomes more and more complex. The ratio of indirect material consumption to material actually embodied in the product is extremely large, which is, in itself, a new phenomenon.

This situation is in marked contrast with conventional metal or plastic products. Stone, glass, clay and concrete products generate very little waste during the quarrying, mining and processing of the materials, and even less is lost during construction. Forest products are also used quite efficiently: wood that is not used directly as lumber is generally converted into fiberboard or paper. Even the wastes

are burned as fuel. In the case of paper, most of the waste is at the consumption end. Only in the case of metals is the waste mass during mining, concentration and smelting significantly greater than the mass of the refined product. (This is especially true for copper and even more so for the precious metals.) However, from that point on in the manufacturing process, losses are small and mostly recovered. Again, it is mainly in the final consumption stage that significant unrecoverable losses do occur.

It is true that the economy is gradually 'dematerializing' in terms of mass/GDP. The overall decline from 1905 to 1995 is almost exactly a factor of 3. Since 1950 the decline is a factor of 2. However, this measure is not particularly relevant, especially as long as actual mass consumption per capita is not decreasing.

Summary and final comments

The decline in aggregate tonnage of processed materials per unit of GDP, summarized in *Figure 20* is consistent with (modestly) increasing resource productivity. It is also consistent with the fact that some of the materials produced today are worth more, in real terms, than a half century or a century ago (although this would not necessarily be the case for most fuels or for tonnage materials like lumber, cement, bricks or even structural steel). Quality and performance have improved in many areas. For instance, within the iron/steel category, the use of cast iron is now largely limited to automobile engines, and low grade structural steels are being replaced in many applications by higher grade steels that can be used in significantly smaller quantities. This is particularly evident in the case of rolled sheet steels for cans and automobile bodies, both of which are significantly thinner and lighter than they were a generation ago. It is fair to say that more "information" is embodied in (some) materials, and products, made nowadays than was the case in the past.

On the other hand, it is clear that the total mass of materials processed (and wasted), both per capita (*Figure 25*) and in total **<<FIGURE 26 NEAR HERE>>** (*Figure 26*), have increased considerably over that same time span. The use of structural materials in housing has increased because, despite modest improvements in performance. Each American occupies more floor space and consequently requires a greater quantity of walls, floors, roofing, plumbing, carpets and furniture. This fact is reflected in the data.

The use of dissipative household consumables, such as fuels, detergents, bleaches, solvents, refrigerants, household pesticides, cosmetics, and packaging materials has increased even more dramatically, if anything. Within industry (and agriculture), the use of intermediates, such as explosives, fertilizers, herbicides and insecticides, drilling fluids, flotation agents, flocculents, industrial acids, catalysts, drying agents, water and waste treatment chemicals and so on has undoubtedly grown faster than the total throughput. However, the quantitative details are not easily documented at this point in time.

Returning to the main theme of this paper, recent discussions of the implications of sustainable development imply that per capita, and total, consumption of materials must be reduced in the industrialized world (e.g. by "factor 10"[Factor Ten 1994 and 1997] or "factor 4" [von Weizsäcker et al 1994; von Weizsäcker et al 1998]), in order to allow some room for absolute growth by the

developing countries without overloading planetary waste assimilative capacity. The underlying imperative is clear.

However, the quoted comments of Greenspan and Cairncross (among many other economists) suggest that this dematerialization process is already happening spontaneously. The intended implication is that governmental intervention to accelerate the process is unnecessary.

On the contrary, our data strongly suggest the opposite conclusion. In the first place, the optimists have overstated the extent of on-going dematerialization. The weakly favorable trend in resource productivity in a few sectors is not nearly enough to compensate for increasing consumption per capita. It follows that major policy changes will be needed to bring about the needed reductions in materials/energy intensity.

Endnotes

1. A more academic source of background material can be found in an excellent literature survey in the *Journal of Industrial Ecology* [Cleveland and Ruth 1997]. In particular, it listed and compared 41 relevant studies, on topics including intensity of materials use (the environmental Kuznets curve, or EKC), long wave theory, materials use decomposition analysis and related I-O studies. These studies varied widely as to country or country grouping, time period covered, materials, degree of aggregation, data analysis method used, and implications drawn.
2. Other studies of mass flows have generally arrived at the same decision, i.e. to exclude air and water flows [Adriaanse et al 1997; Stahmer et al 1998; Gravgard-Pedersen, 1999; WRI 2000].
3. All of the detailed production and consumption statistics in the following paragraphs were derived by an extensive sectoral analysis of mass flows in the US economy for 1993. The details are given in [Ayres and Ayres 1998].
4. It can be argued that food and beverages are also service-carriers, inasmuch as they pass through the body and become wastes almost immediately, except for the tiny fraction that is retained in body mass. Even that is returned to the environment at the end of life, except for the annual incremental increase in the mass of the human population..
5. Actually 51 MMT of the 89 MMT of steel produced in the US in 1993 was recycled scrap. Domestic pig iron inputs were only 48 MMT. (The two input streams add up to 99 MMT; the weight difference consists mostly of slag and CO₂).
6. Glass is manufactured by a thermal process from a mixture of silica (sand), magnesia, kaolin and soda ash (sodium carbonate) plus traces of other metal oxides. Carbon dioxide is released. Portland cement is made by heating (calcining) a mixture of crushed limestone, clay, gypsum and other silicate minerals. Carbon dioxide is released. Concrete is made from cement, sand and other fillers, with added water. Brick and ceramic tiles are made from clay by heating to drive off water. Plaster is produced from natural gypsum by heating to drive off water, but the material is rehydrated (as in the case of portland cement) to solidify.
7. The offsetting effects of economic growth — sometimes called the "rebound effect" — have been documented by a number of authors, e.g. [Key and Schlabach 1986; Wernick 1994; Janicke et al 1997].

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APPENDIX

The fabrication of computer chips is undoubtedly the most complex process in industry. Consider a day's production in a representative modern plant (c. 1998). The raw material input for this process consists of approximately 700 8-inch wafers of ultra-pure silicon metal, with a total mass of 14.2 kg. Each wafer has a thickness of 0.76 mm and a cubic volume of 8.55 cm³.

The fabrication process begins with cleaning, by means of an acid bath. The next step is doping, by molecular diffusion. Typical dopants are silane, dichlorosilane, phosphine, arsine, or diborane. This step is followed by surface oxidation or epitaxy (using pure oxygen) and/or vapor deposition of a thin photo-resist film, either positive or negative. Next comes photolithography, which 'exposes' the film to light in a complex pattern representing the circuitry. This is followed by an etching acid bath, which removes either the exposed (light sensitive) or unexposed (insensitive) portion of the film, leaving the remainder. The doping-epitaxy or film deposition--photolithography -- etching sequence may be repeated many times, leaving successive layers of circuitry alternating with layers of non-conducting oxides. Finally there is a metalization and passivation step before the wafer is tested and cut into individual chips.

Acids (HF, HCL, HNO₃ and H₂SO₄) and solvents are used at several stages in the sequence. Bases (mainly ammonia and caustic soda) are used to control pH and to neutralize acid wastes. Finally, very large amounts of neutral gases (mainly nitrogen, but also some argon and helium) are used as vapor carriers, and even larger amounts of purified water and air are used for a variety of purposes.

The process chemicals used in this plant, per day (not including air) are as follows, in kg:

Gases (mostly nitrogen)	102 826
Dopants	2.15
Etchants (dry)	52.2
Acids & bases	5 372
Solvents & developers	3 274
Water (liquid)	3 648 000
Water (vapor)	81 600
Total	3 841 141
Total, excluding water	228 661

It is easy to verify that for each kilogram of silicon wafer input 161 kg of other chemicals, not including air or water, are used and discarded. The yield of the process is less than 100%, so, for each kilogram of usable silicon chips from the process at least 200 kg of chemicals (dry weight) are consumed and discarded.

Now it is of some interest to consider exergies. The exergy embodied in pure silicon metal is 30.43 mJ/kg, although the process of reduction from silica and purification to electronic grade (99.9999% pure) is very energy intensive (about 234 mJ/kg). The exergy embodied in fabrication process input chemicals, however, is approximately 788 mJ per kg of silicon processed, if water is not counted. (I should acknowledge that I could not calculate the exergies of all of the organic chemicals used, some of which are very obscure. It was necessary to make some approximations, resulting in an overall uncertainty of the order of 10% or so.) If the

exergy of ultra-pure water is included, the total exergy embodied in the inputs is much larger – 2100 mJ/kg, or roughly 70 times the exergy embodied in the silicon itself. The surprise is that, because so much is required, ultra-pure water accounts for almost two thirds of the exergy inputs to the process. (Seawater is an environmental sink, with an exergy of zero, by definition, but pure fresh water has a small but non-zero exergy.)

But that is not the whole story either. If, in the spirit of LCA, we also take into account the exergy inputs to the processes of manufacturing the major bulk chemicals. Again, I do not have manufacturing data for the solvents and photo-resists, so the totals above are significantly underestimated. Nevertheless, it is interesting to note that utility energy (roughly equivalent to exergy) used indirectly in manufacturing bulk chemicals amounts to at least a further 7000 mJ/kg, mostly attributable to the energy (exergy) required to separate nitrogen from oxygen in air!

In short, the micro-electronic products that are commonly cited as examples of dematerialization are really illustrations of quite a different and less favorable trend, namely a sharply increasing ratio of process wastes to finished goods.

Figure 1: The US economic system as a whole from a mass flow perspective (1993 in MMT)

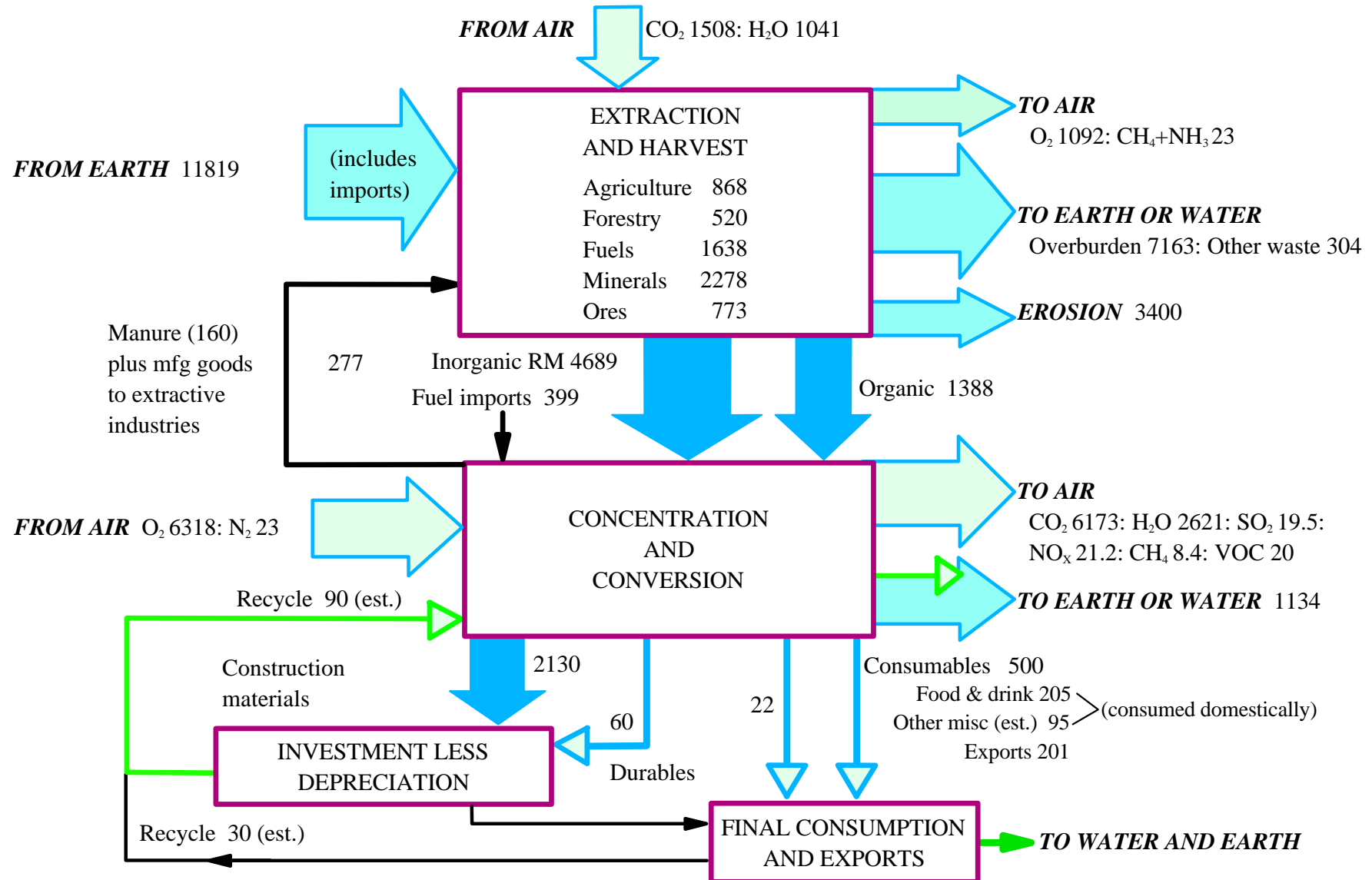


Figure 2: Iron/steel production; C, Fe input per ton C, Fe output

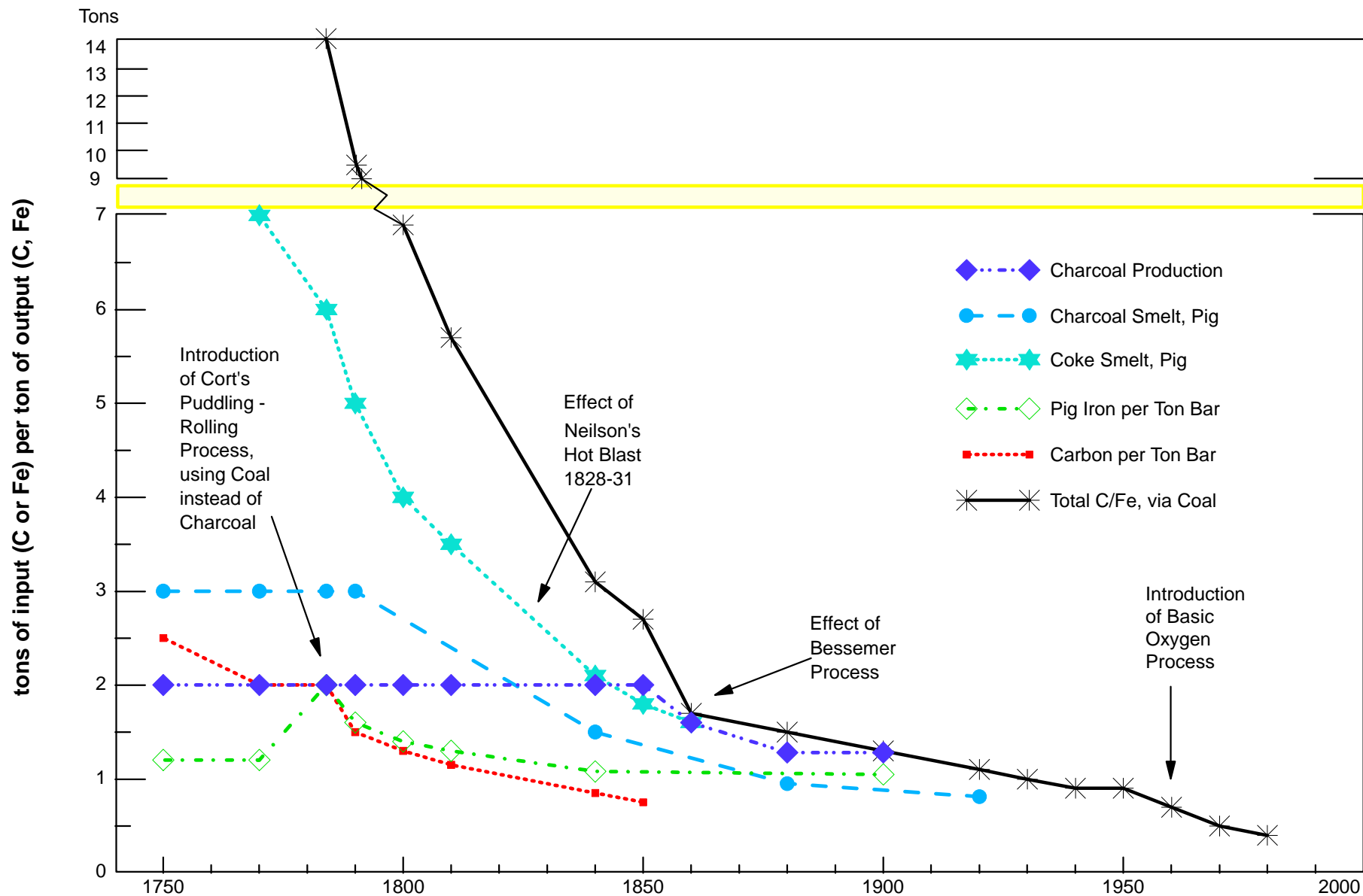


Figure 3: Iron and steel consumption; mass/capita (USA 1900-1998)

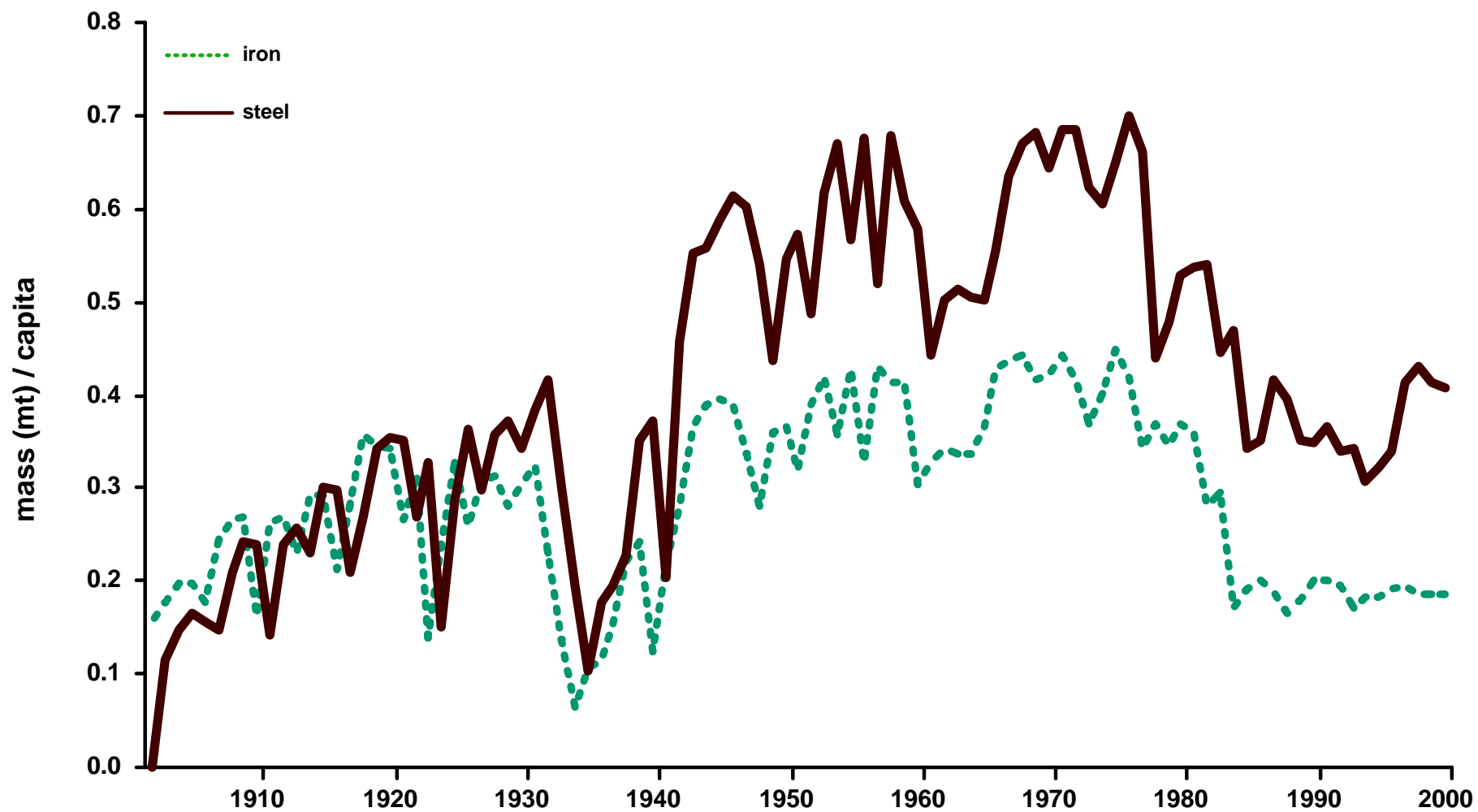


Figure 4: Aluminum consumption; mass/capita; (USA 1900-1998)

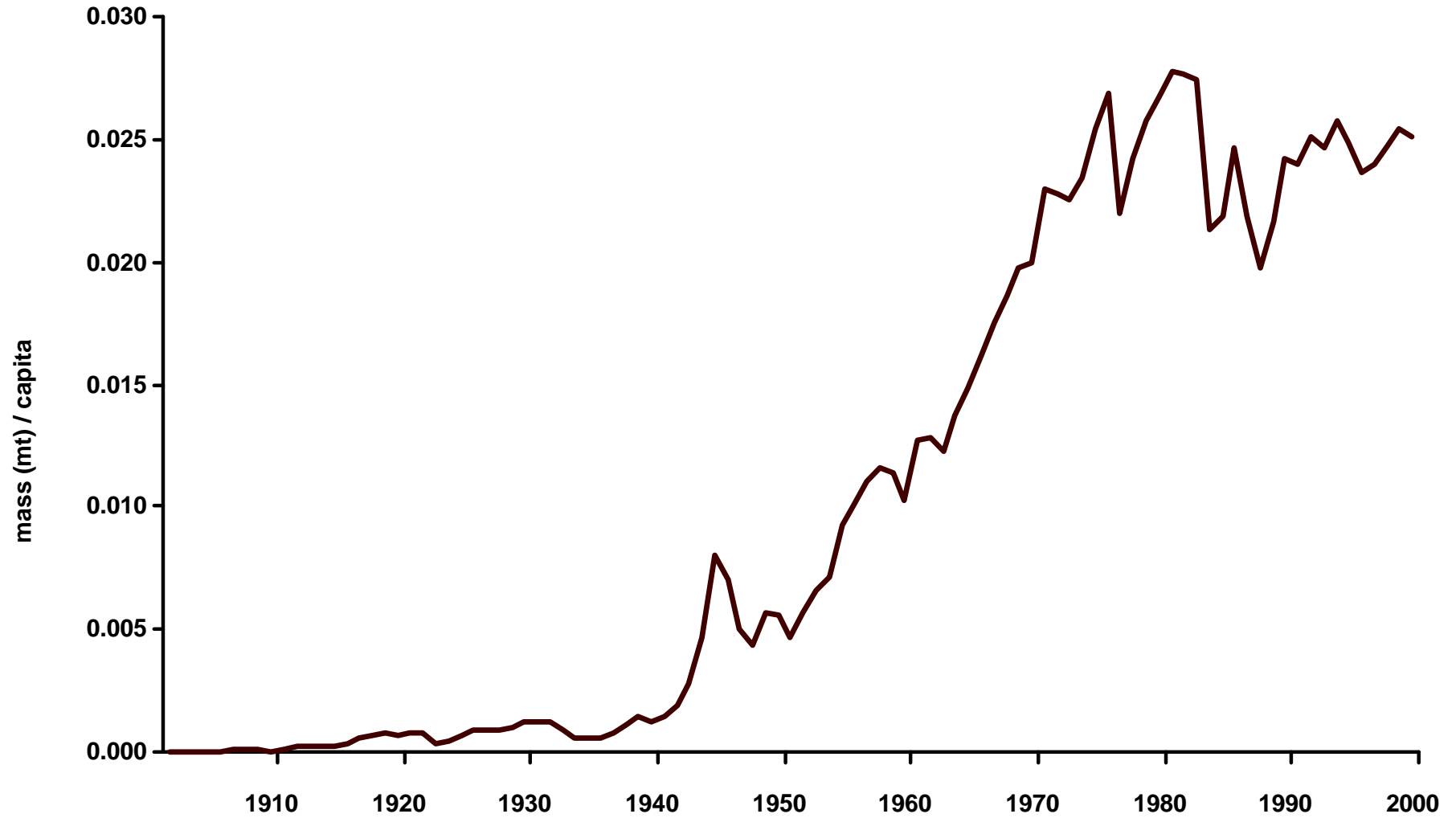
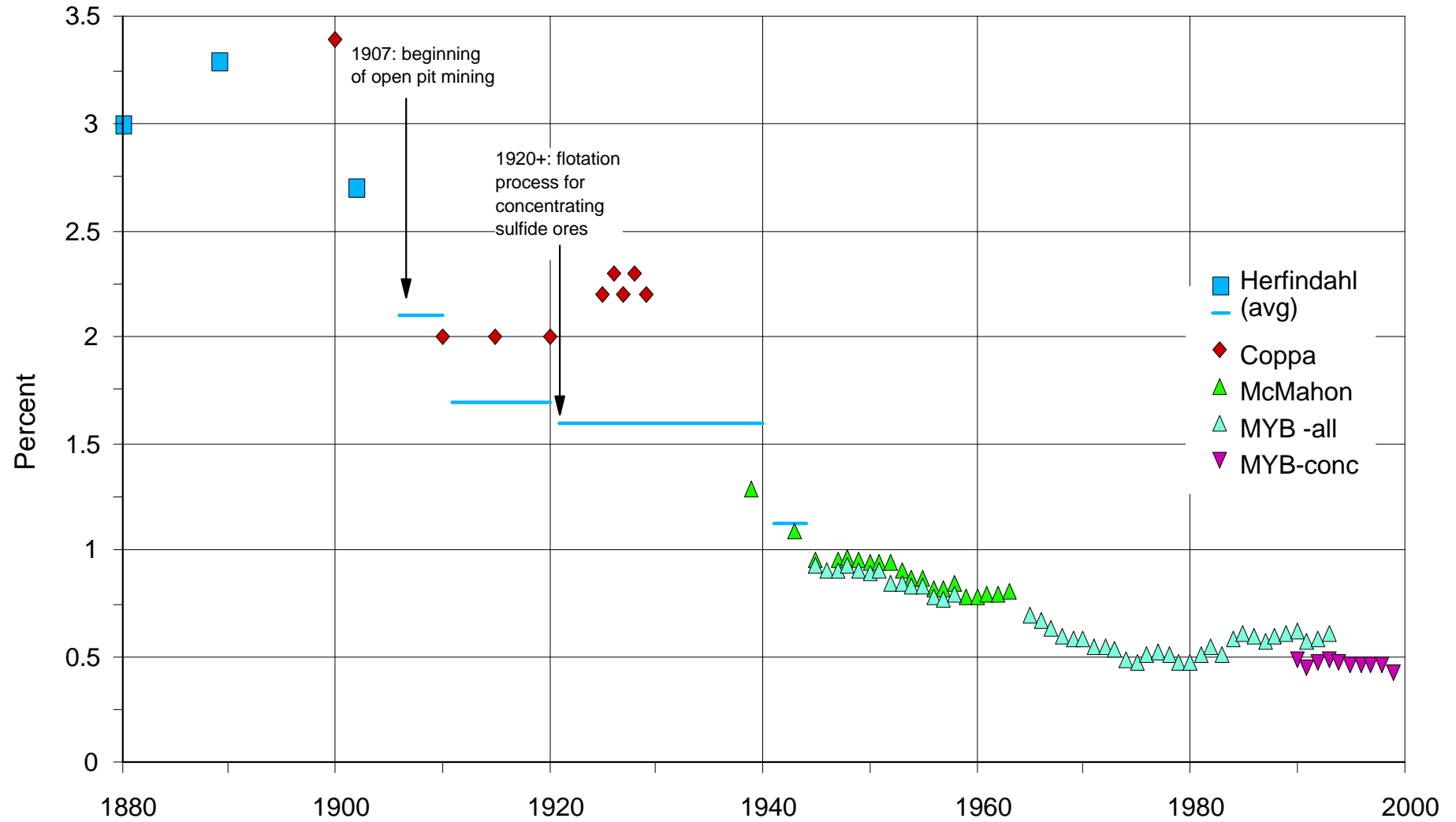


Figure 5: US copper ore grade percent, 1880-2000



Sources: USBuMines annual (=MYB); McMahon 1965; Herfindahl 1967; Coppa 1972

**Figure 6: Price of copper on the New York market, 1870 - 2000
(cents per pound in current and constant 1987 US dollars)**

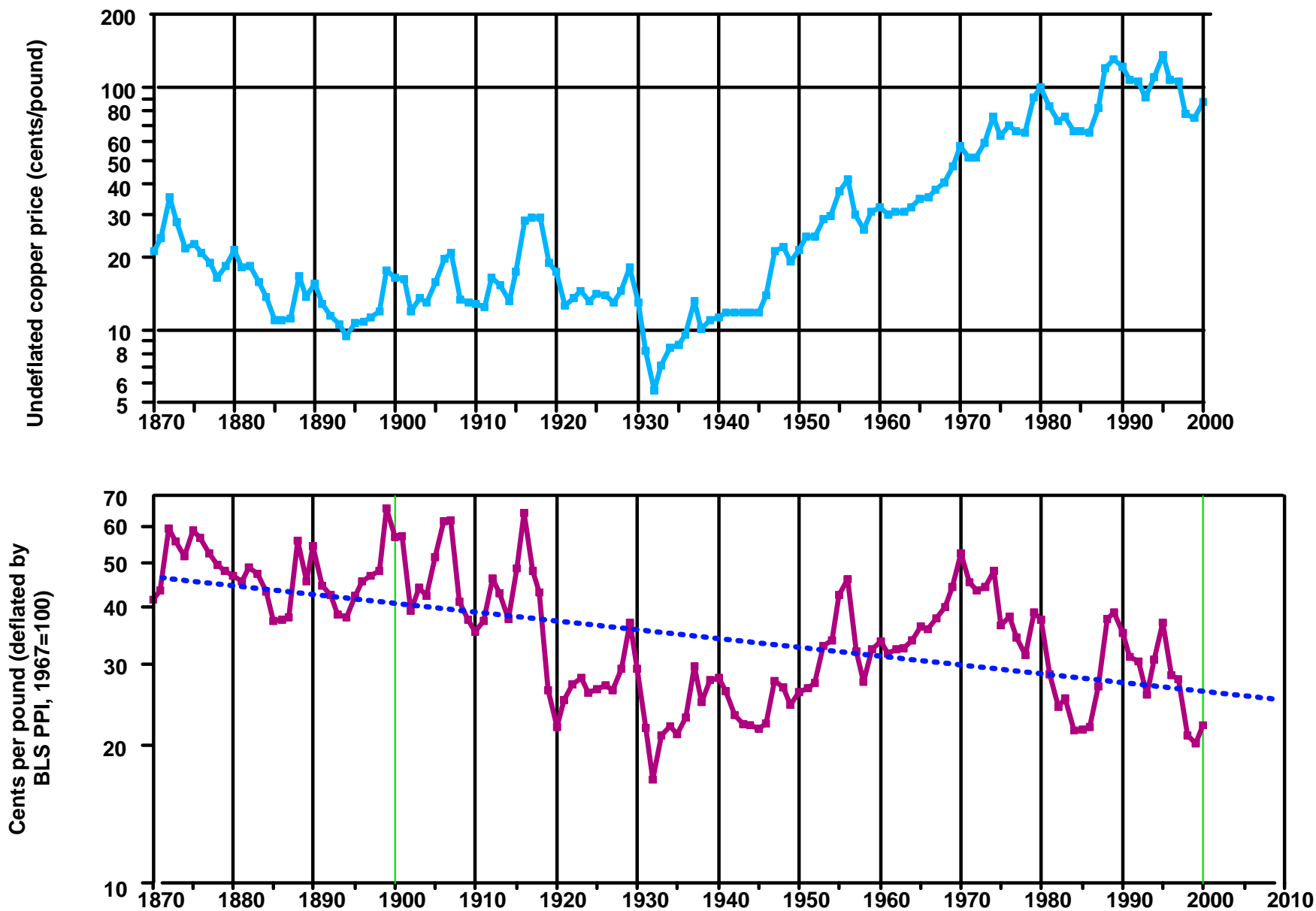


Figure 7: Exergy consumption by industrial processes; USA 1880-2000

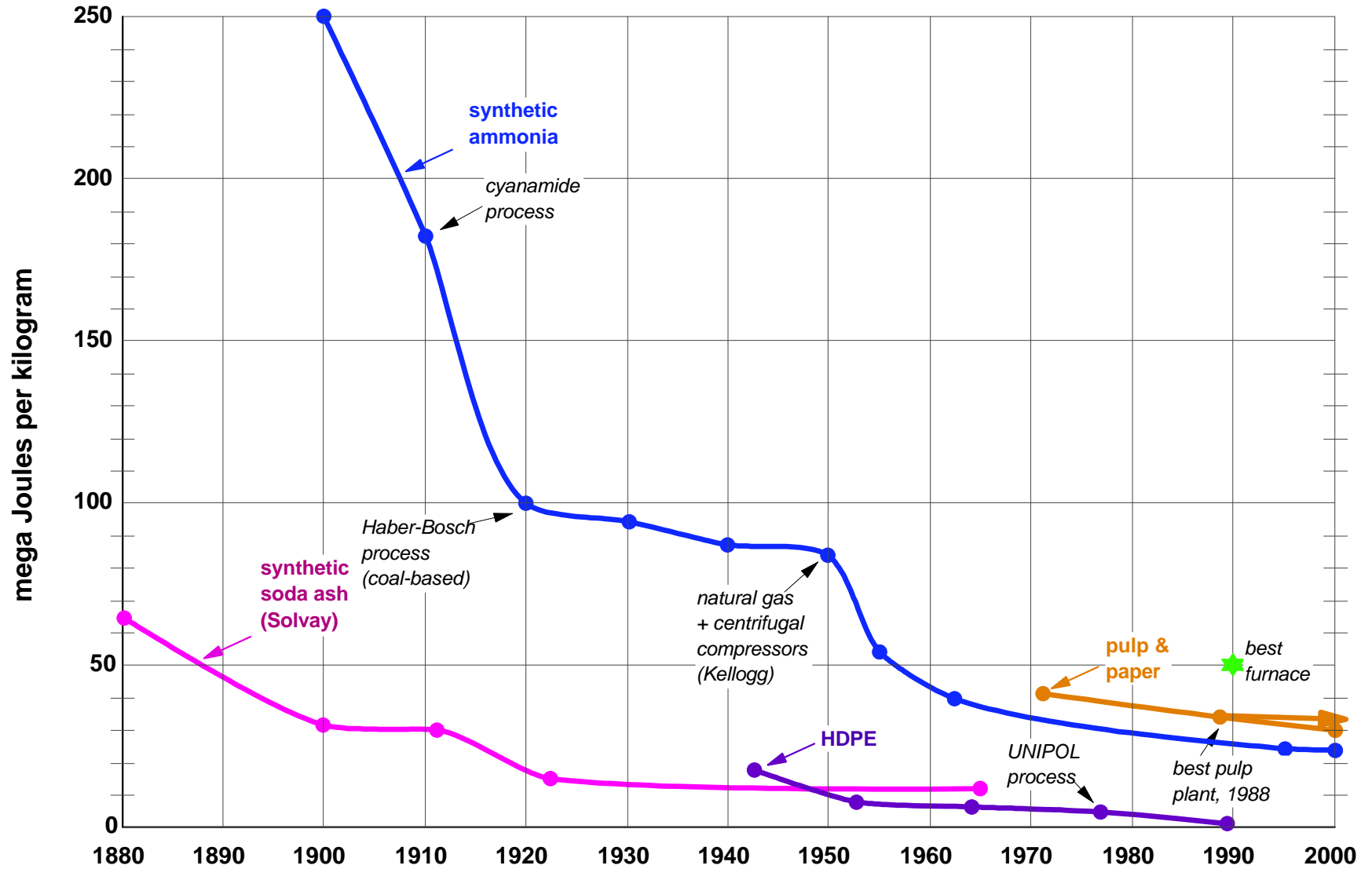


Figure 8: Organic and inorganic chemical consumption; mass/capita (USA 1900-1998)

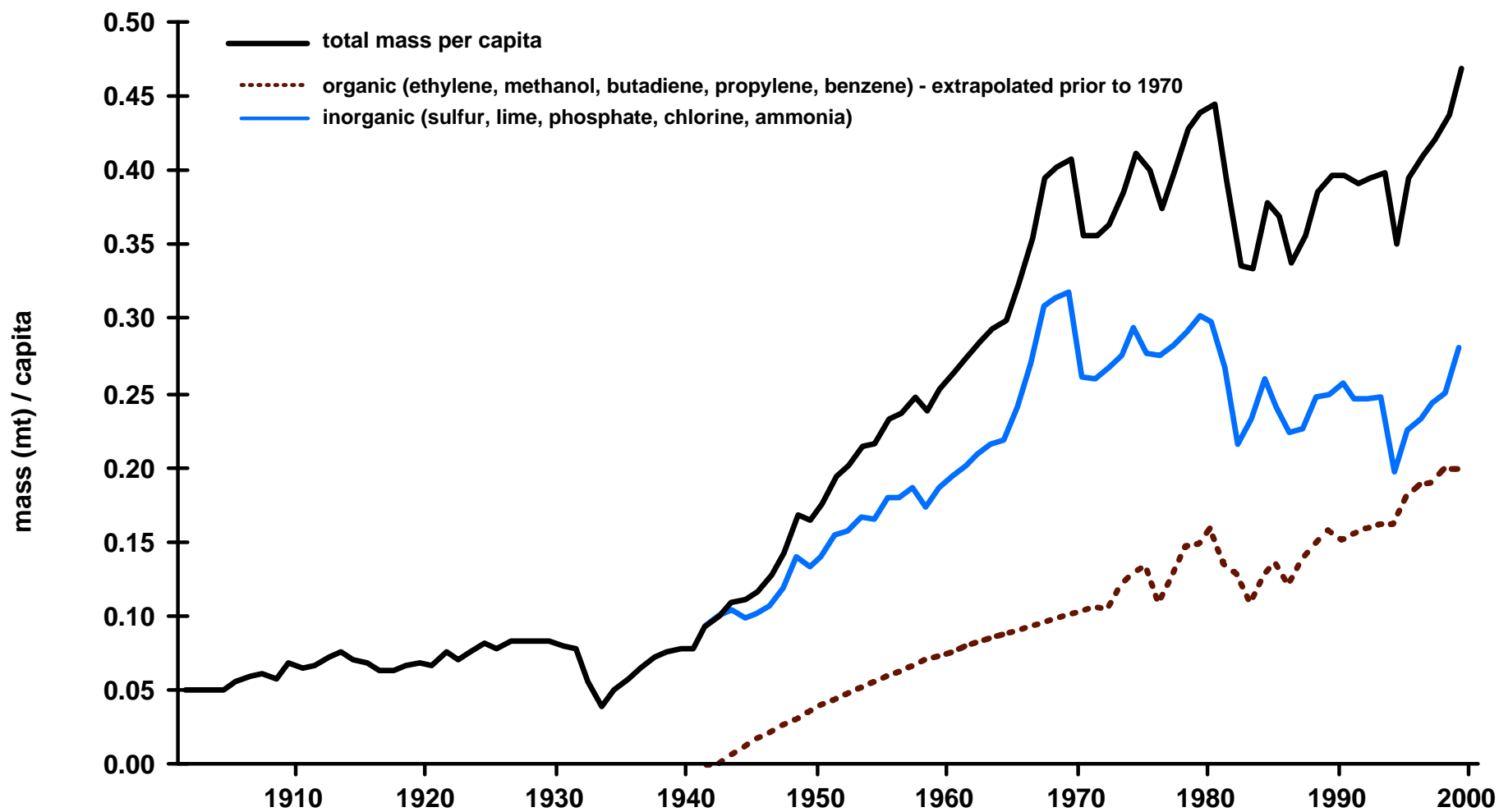


Figure 9: Petroleum utilization efficiency; % as fuel for prime movers

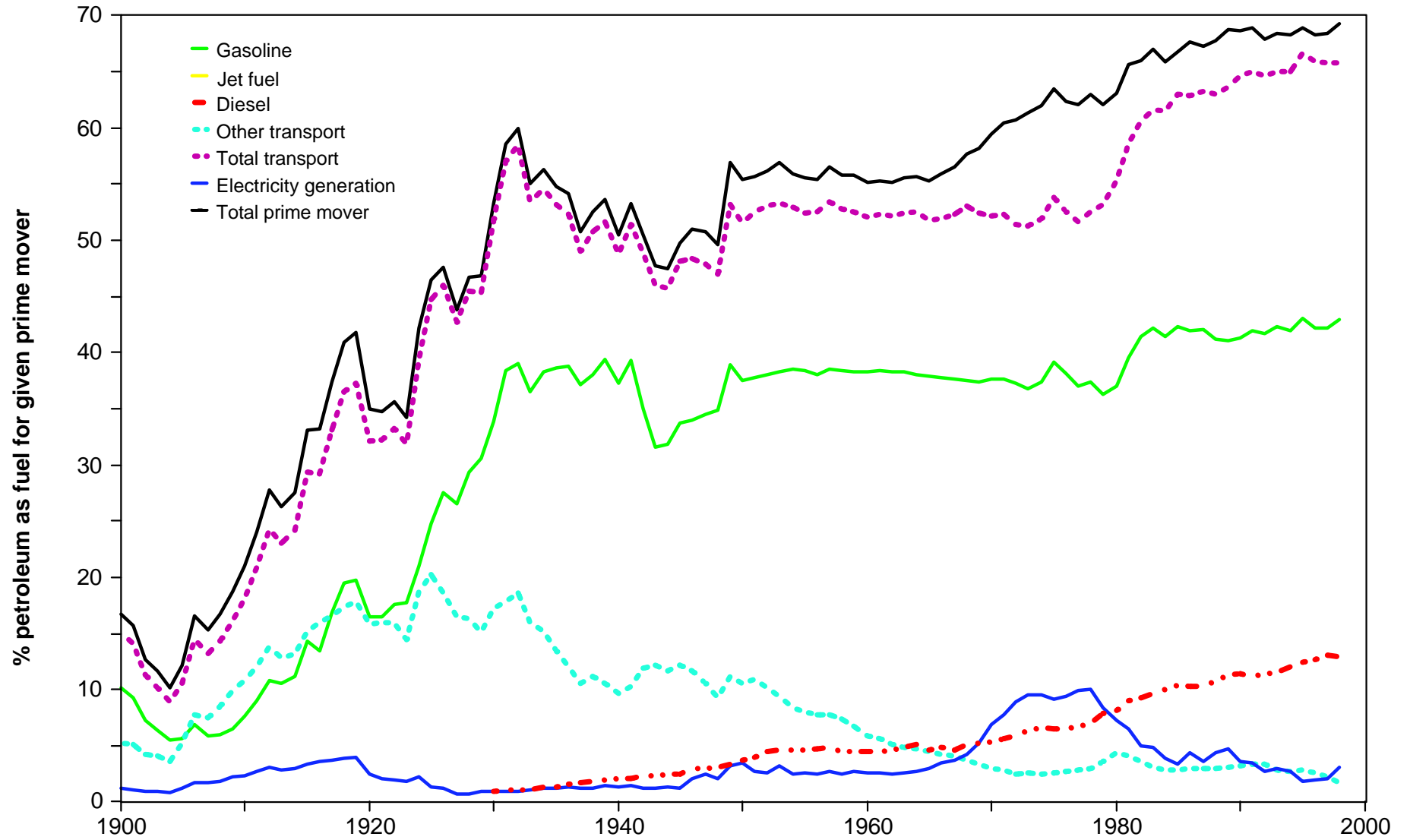


Figure 10: Energy (exergy) conversion efficiencies, USA 1900-1998

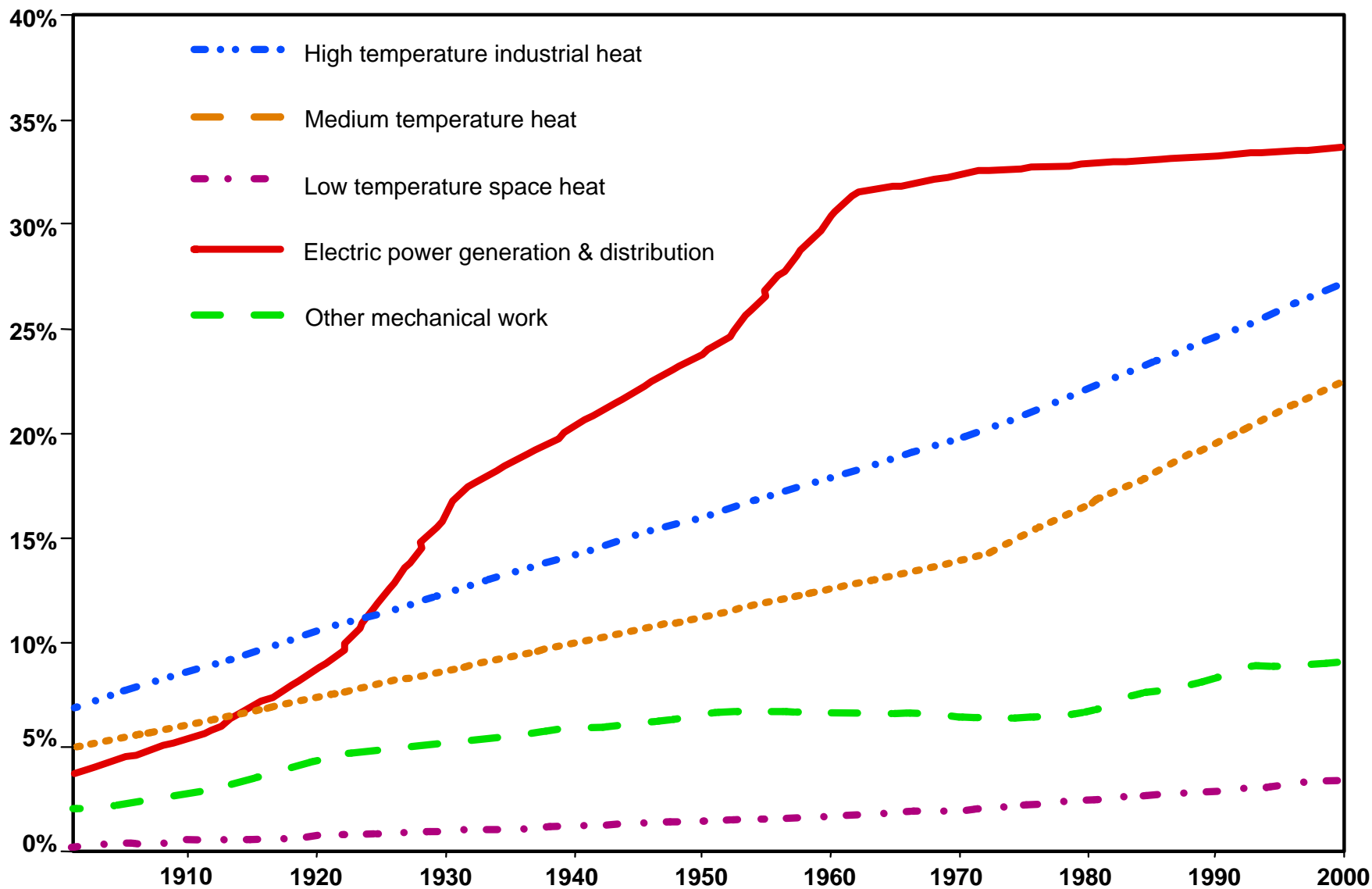


Figure 11: Biomass consumption; mass/capita (USA 1900-1998)

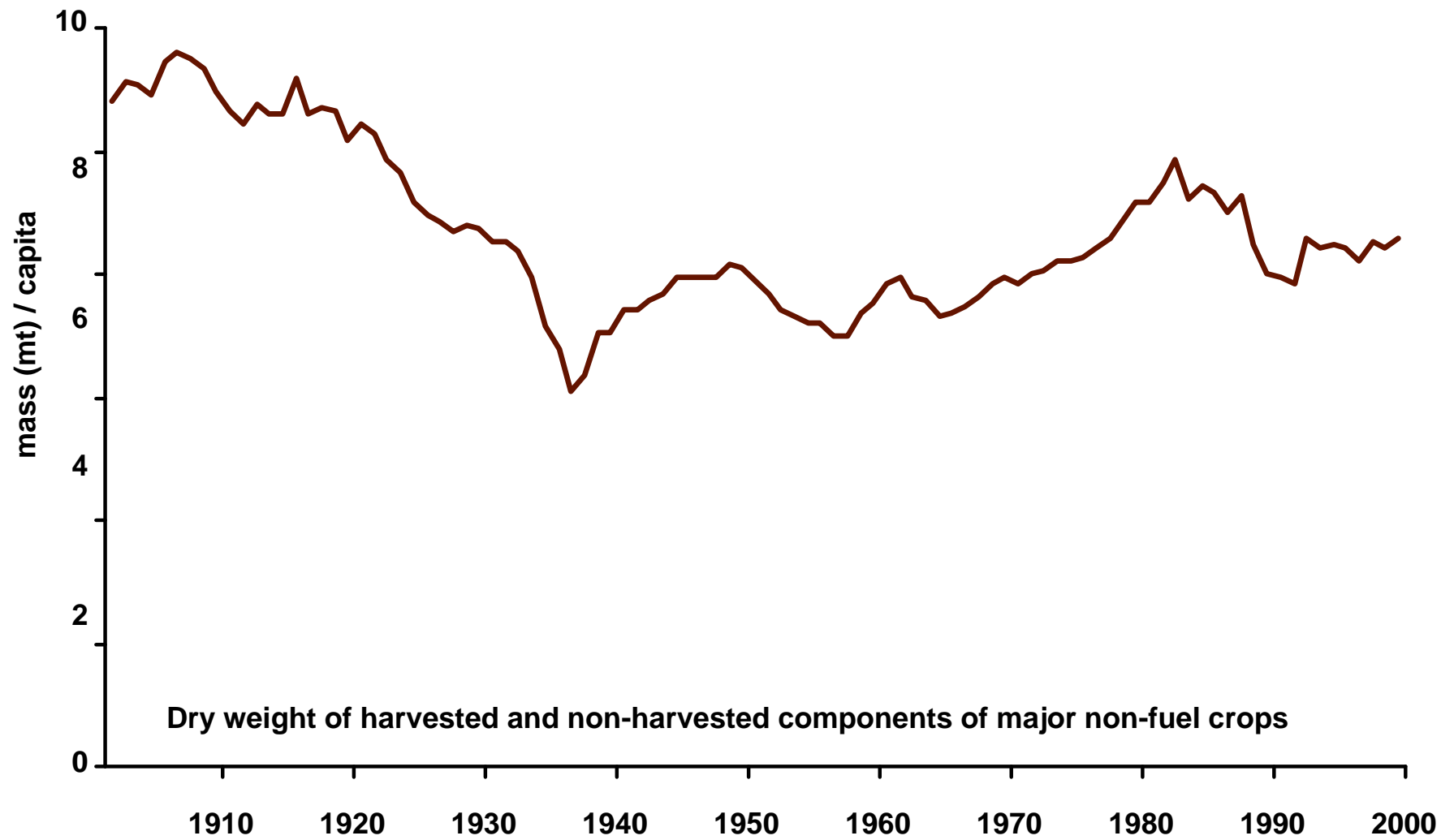
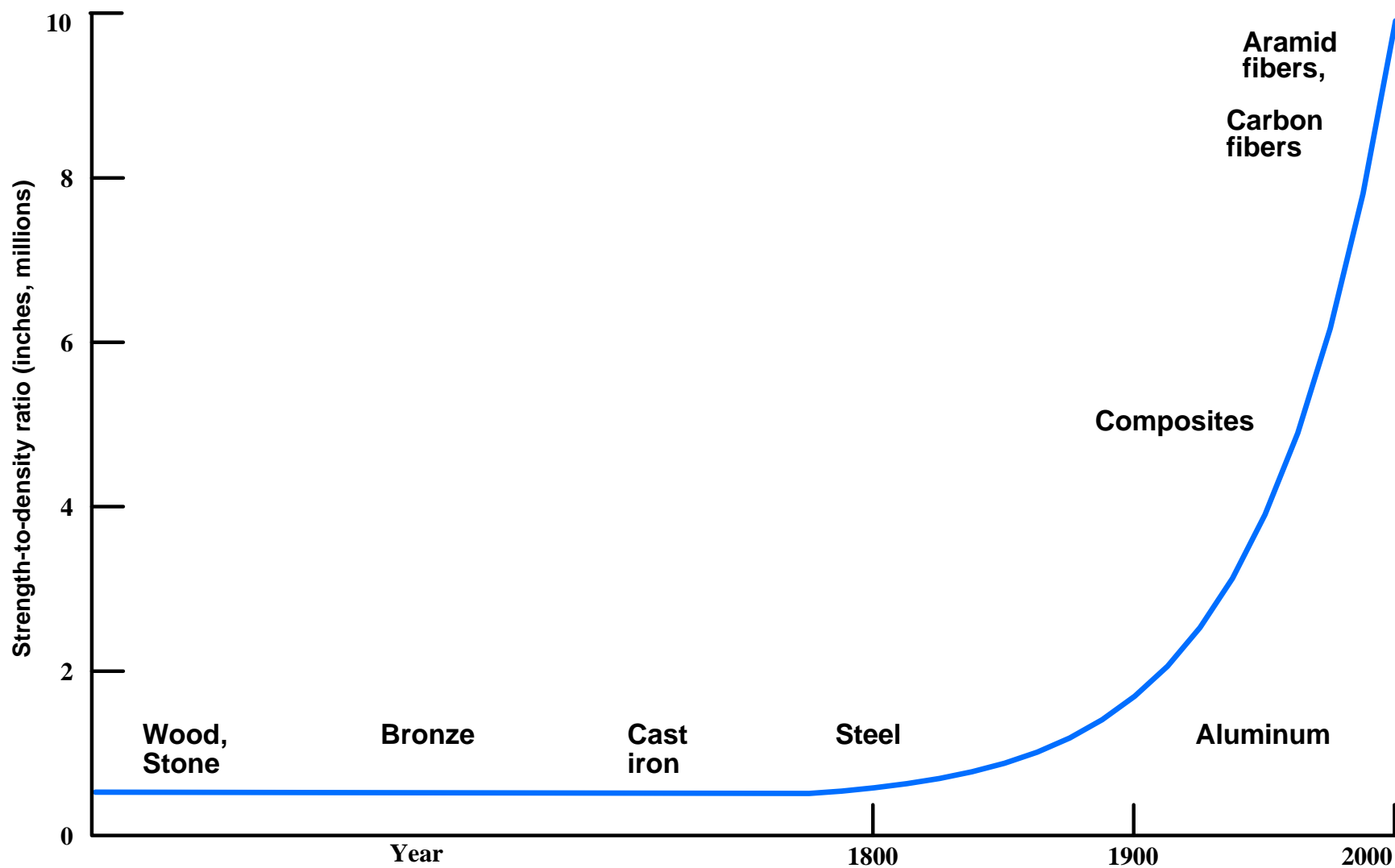
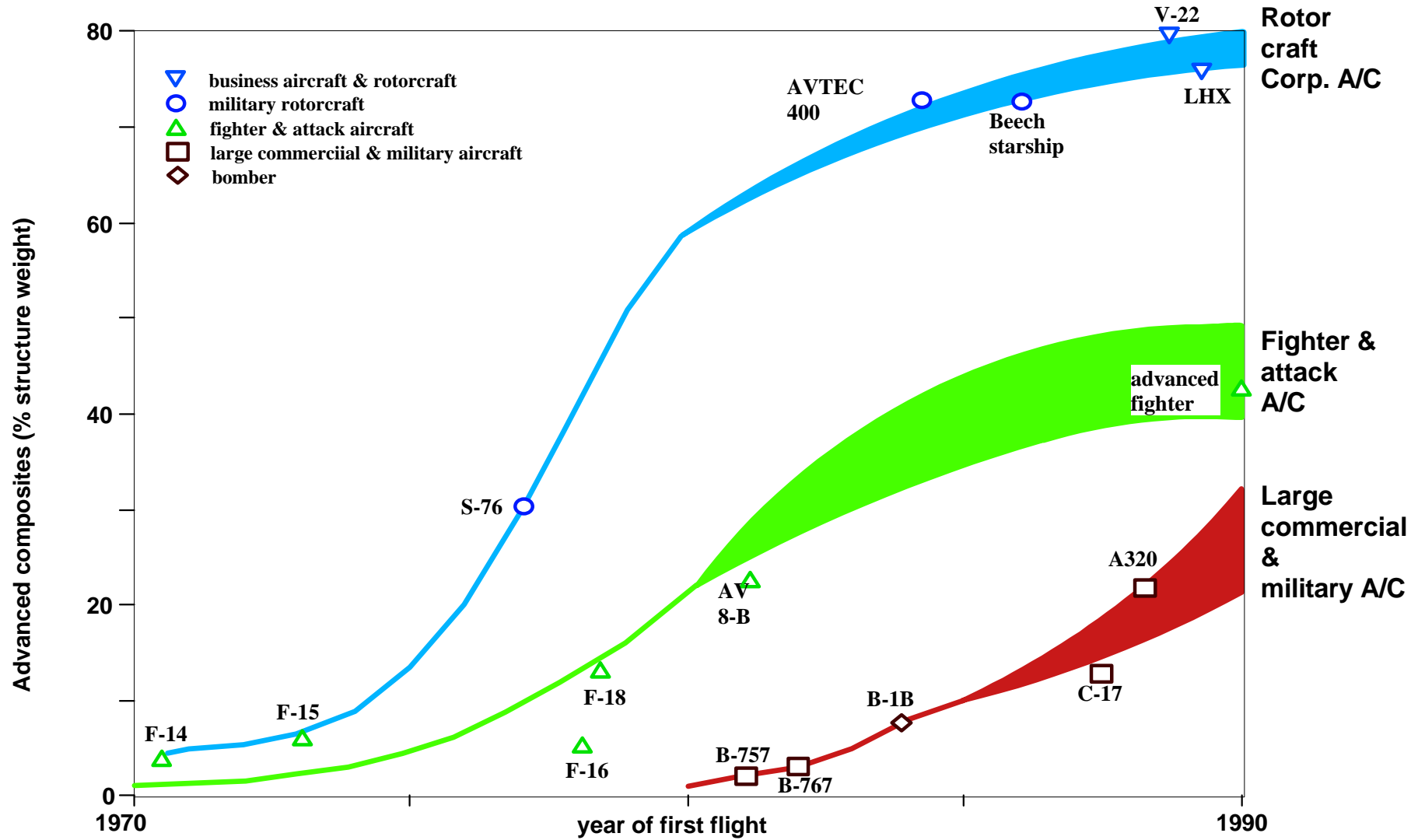


Figure 12: Progress in materials strength/density ratio showing a 50-fold increase



Source: *Materials Science & Engineering for the 1990s*

Figure 13: Timetable for composites in aircraft



Source: Grumman Aircraft Systems Division

Figure 14: Power per unit weight (mobile)

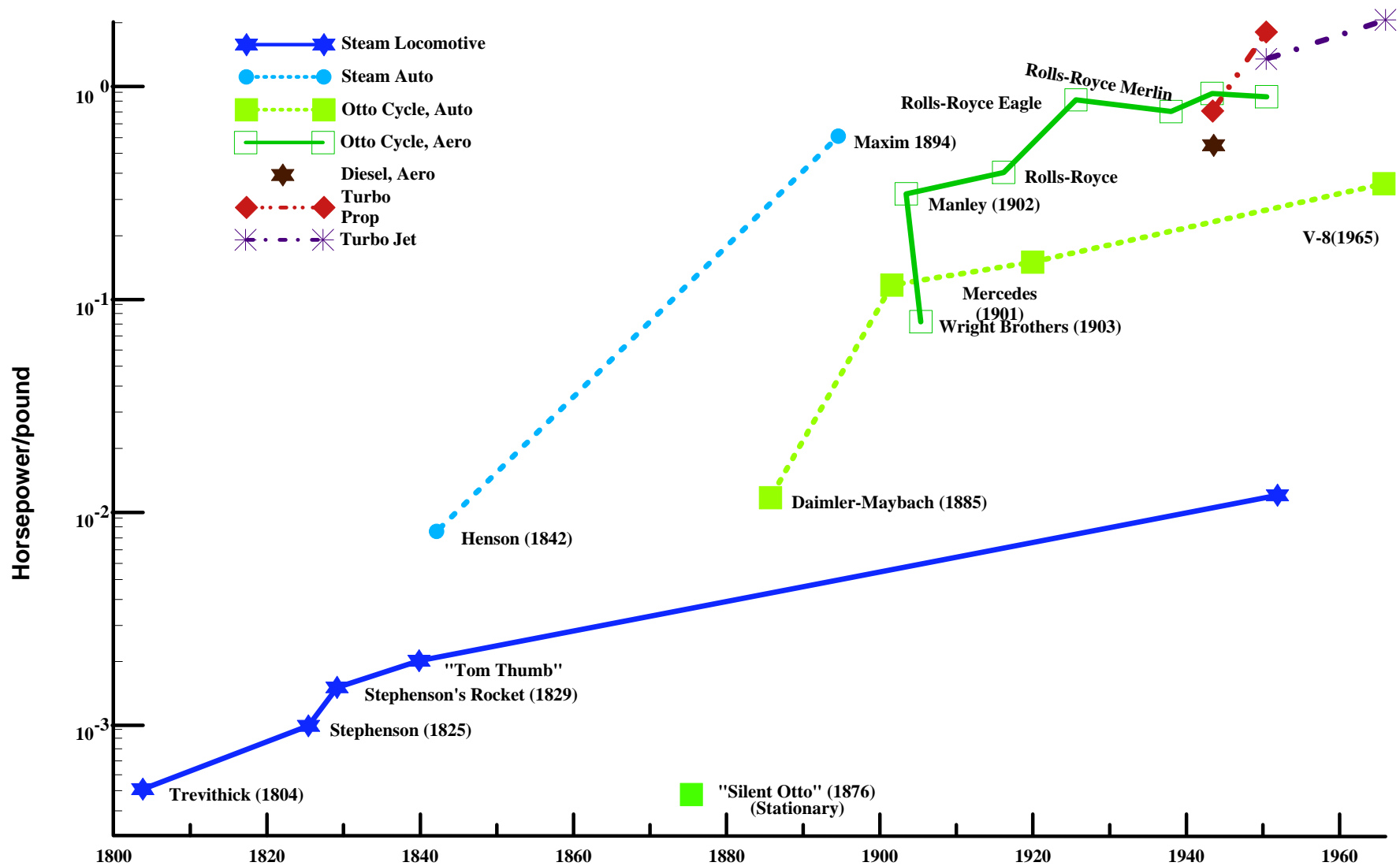


Figure 15: Reducing material consumption in long-distance telecommunication cables

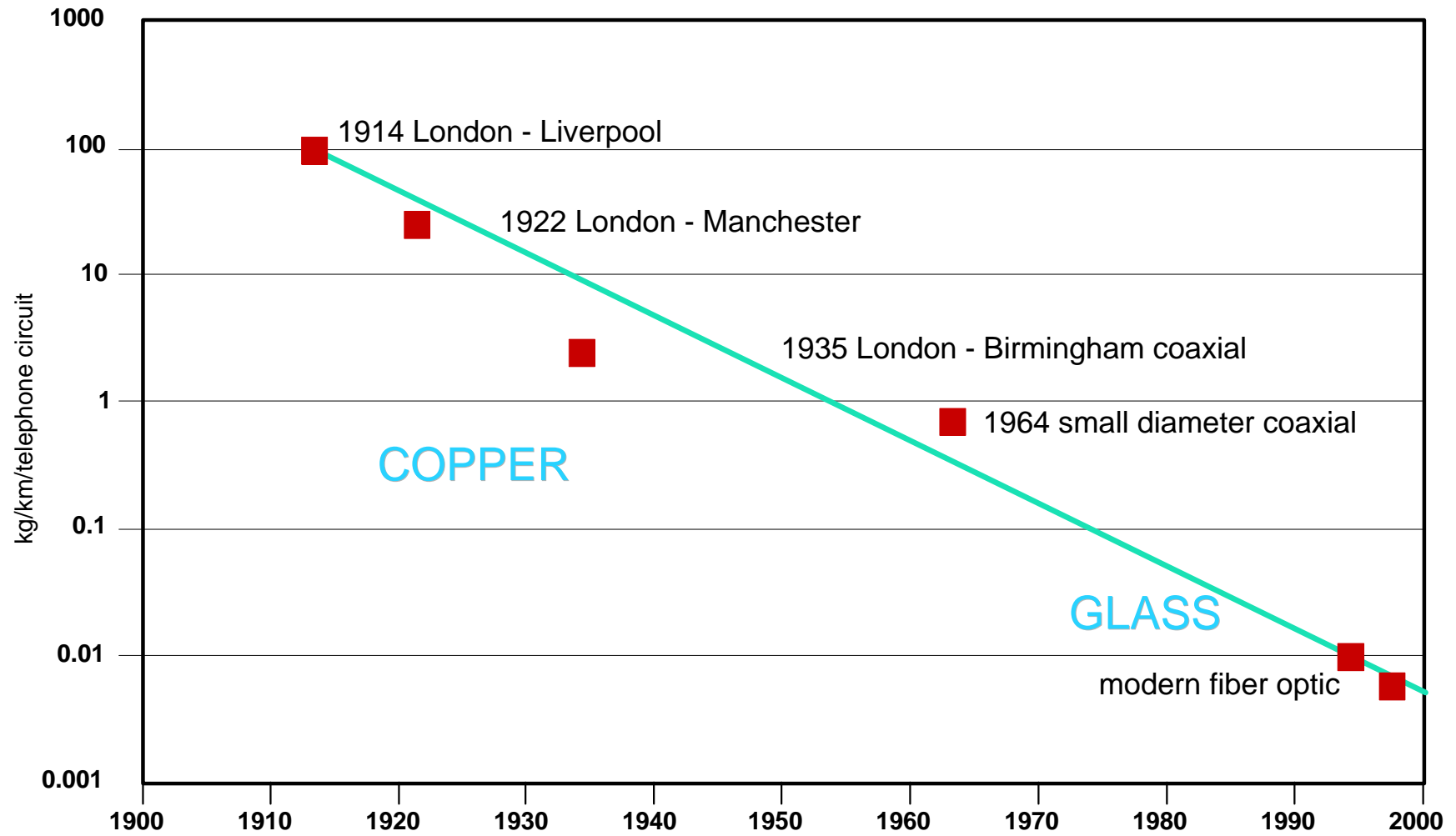


Figure 16: Fossil fuel consumption; mass/GDP vs. exergy/GDP (USA 1900-1998)

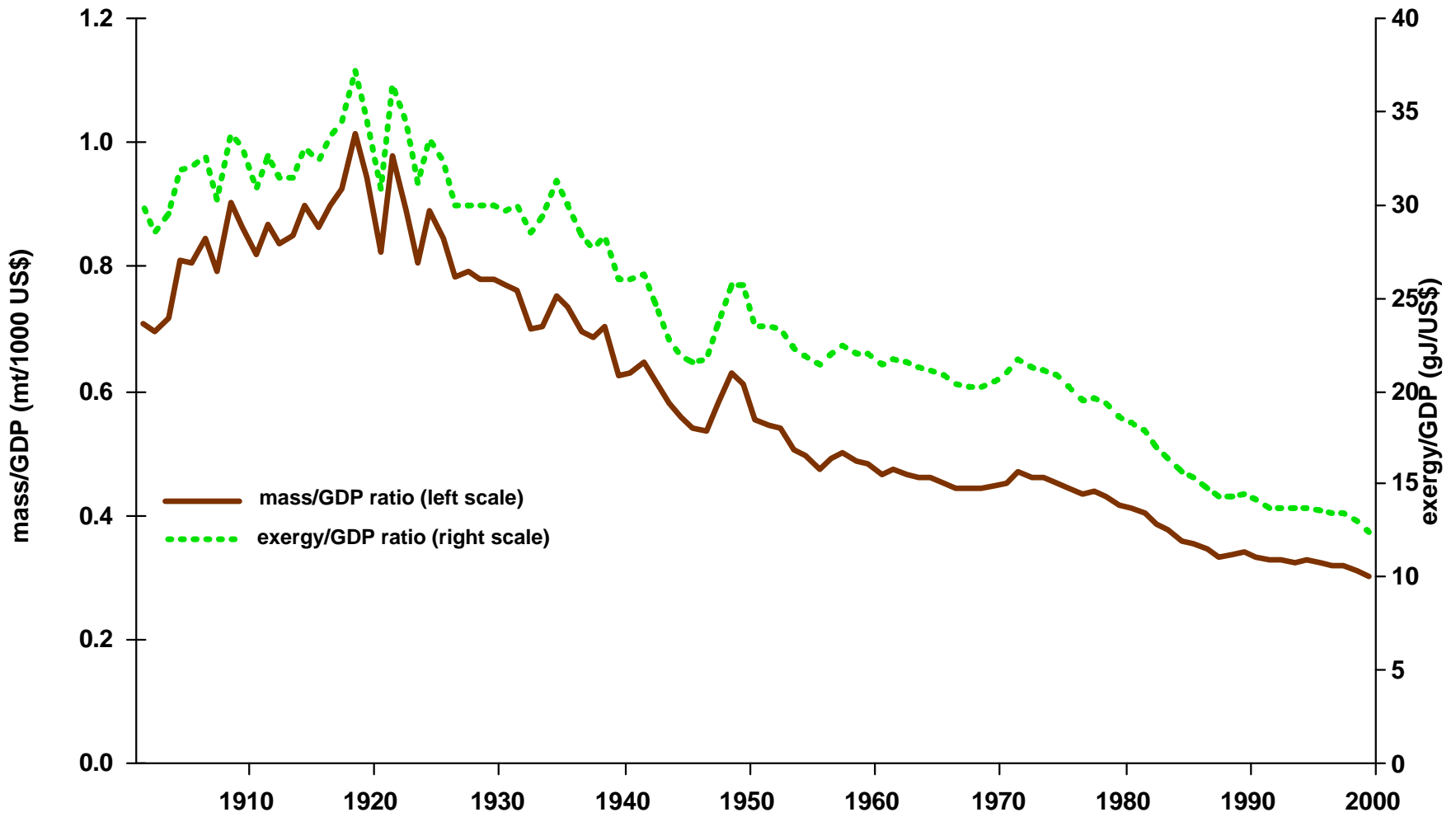


Figure 17: Metals consumption; mass/GDP vs. exergy/GDP (USA 1900-1998)

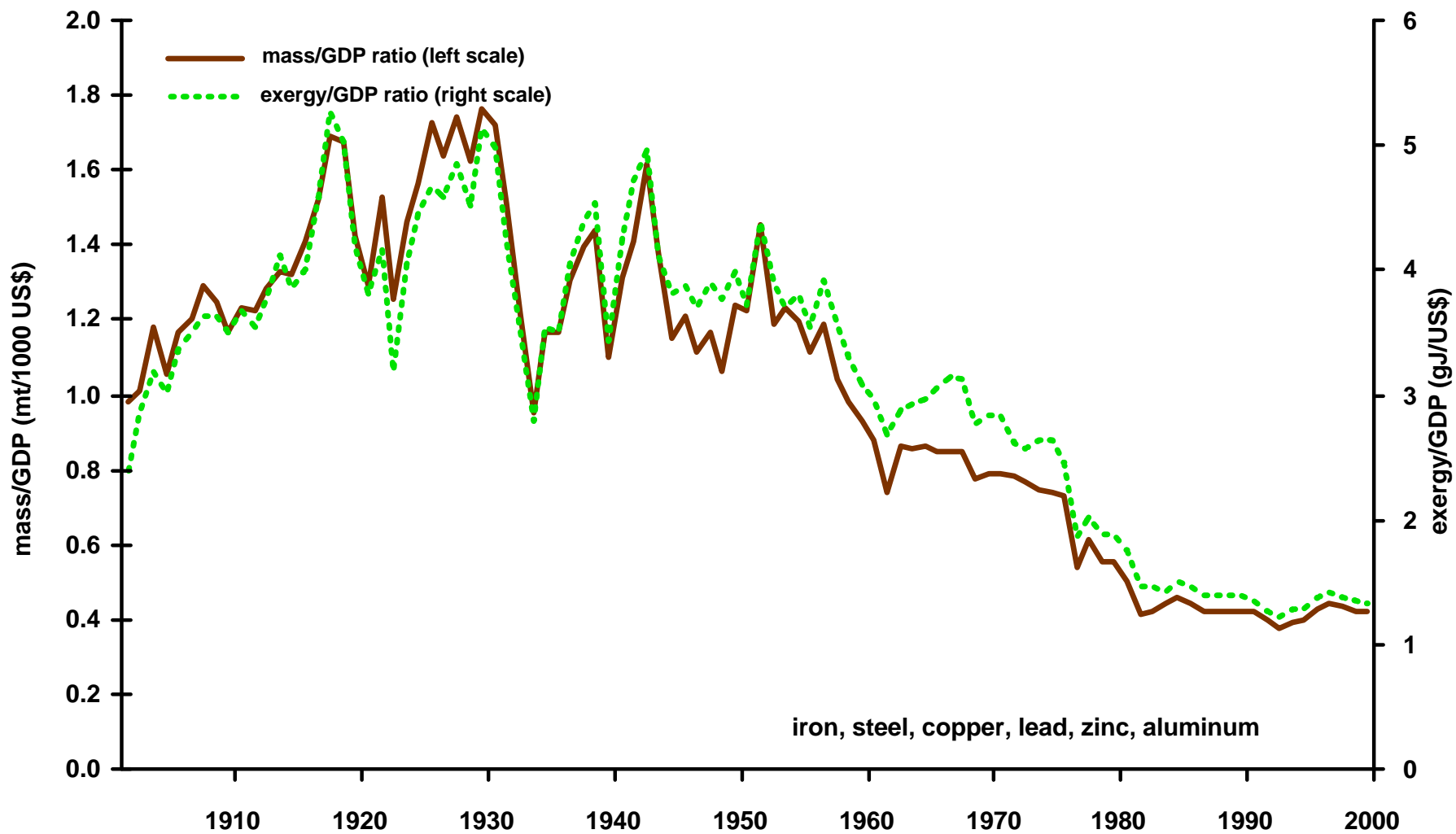


Figure 18: Construction materials consumption: mass/GDP vs. exergy/GDP (USA 1900-1998)

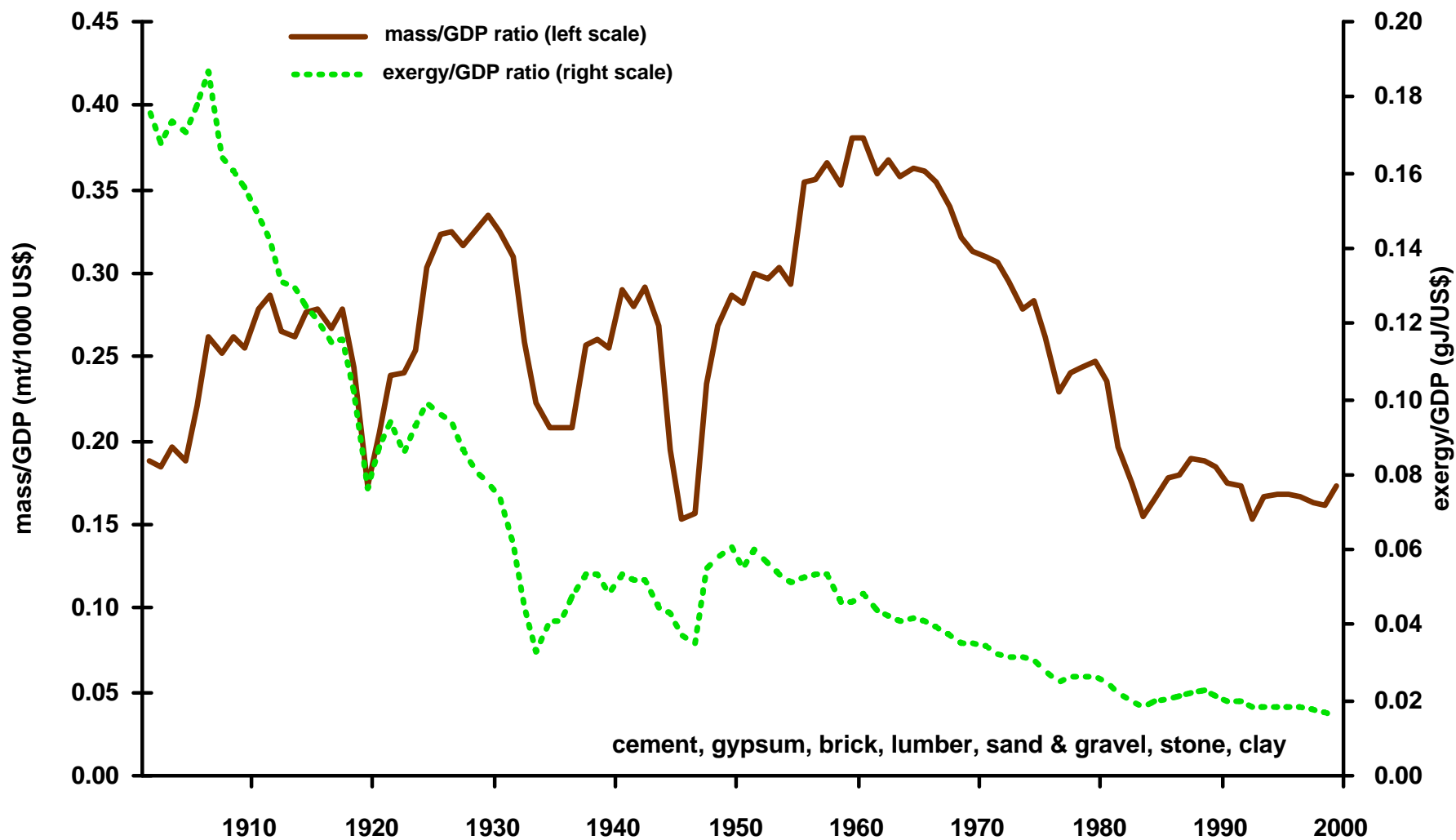
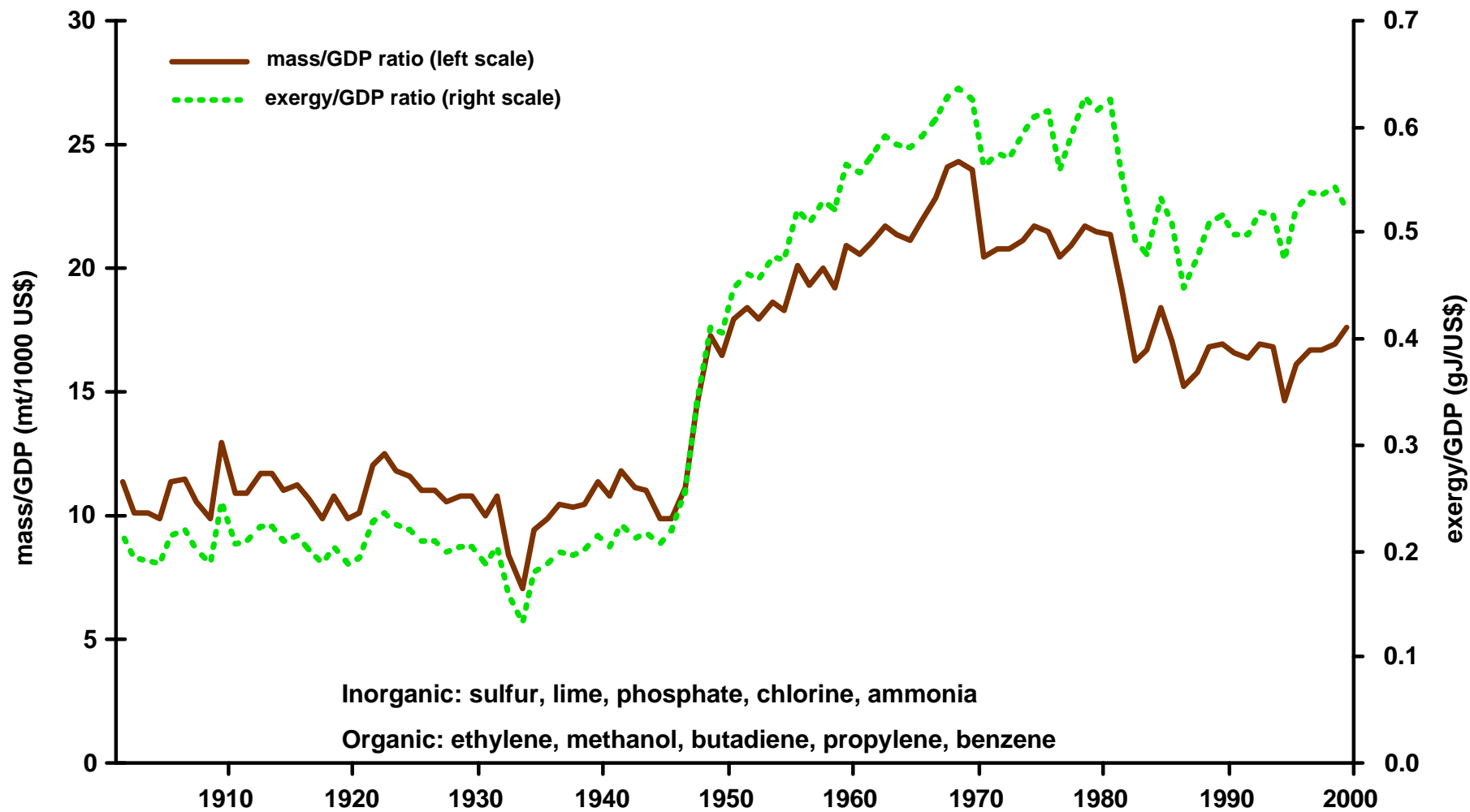


Figure 19: Chemicals consumption: mass/GDP vs. exergy/GDP (USA 1900-1998)



**Figure 20: Total* fuels, metals, construction, chemicals & biomass:
mass/GDP and exergy/GDP (USA 1900-1998)**

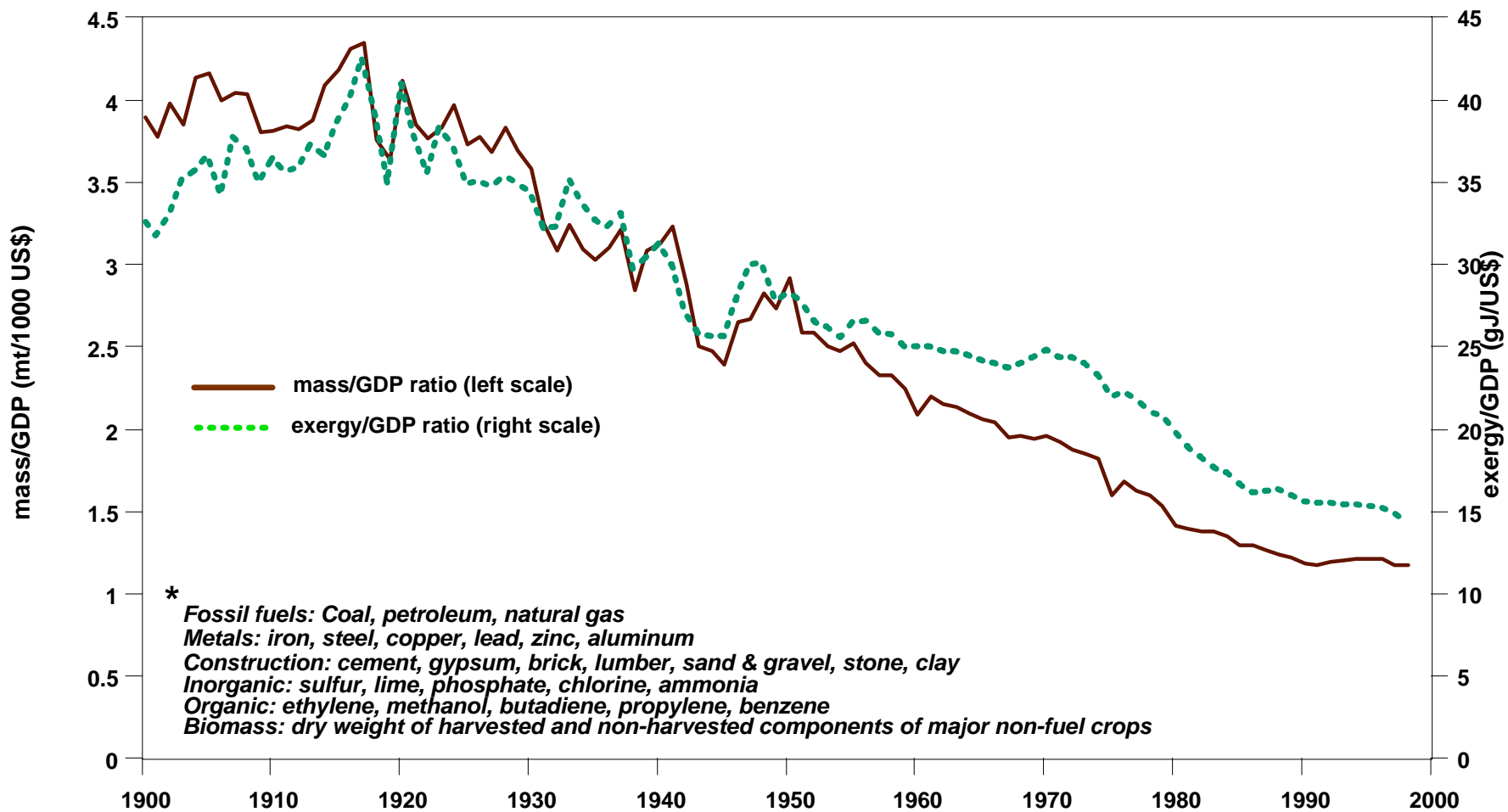


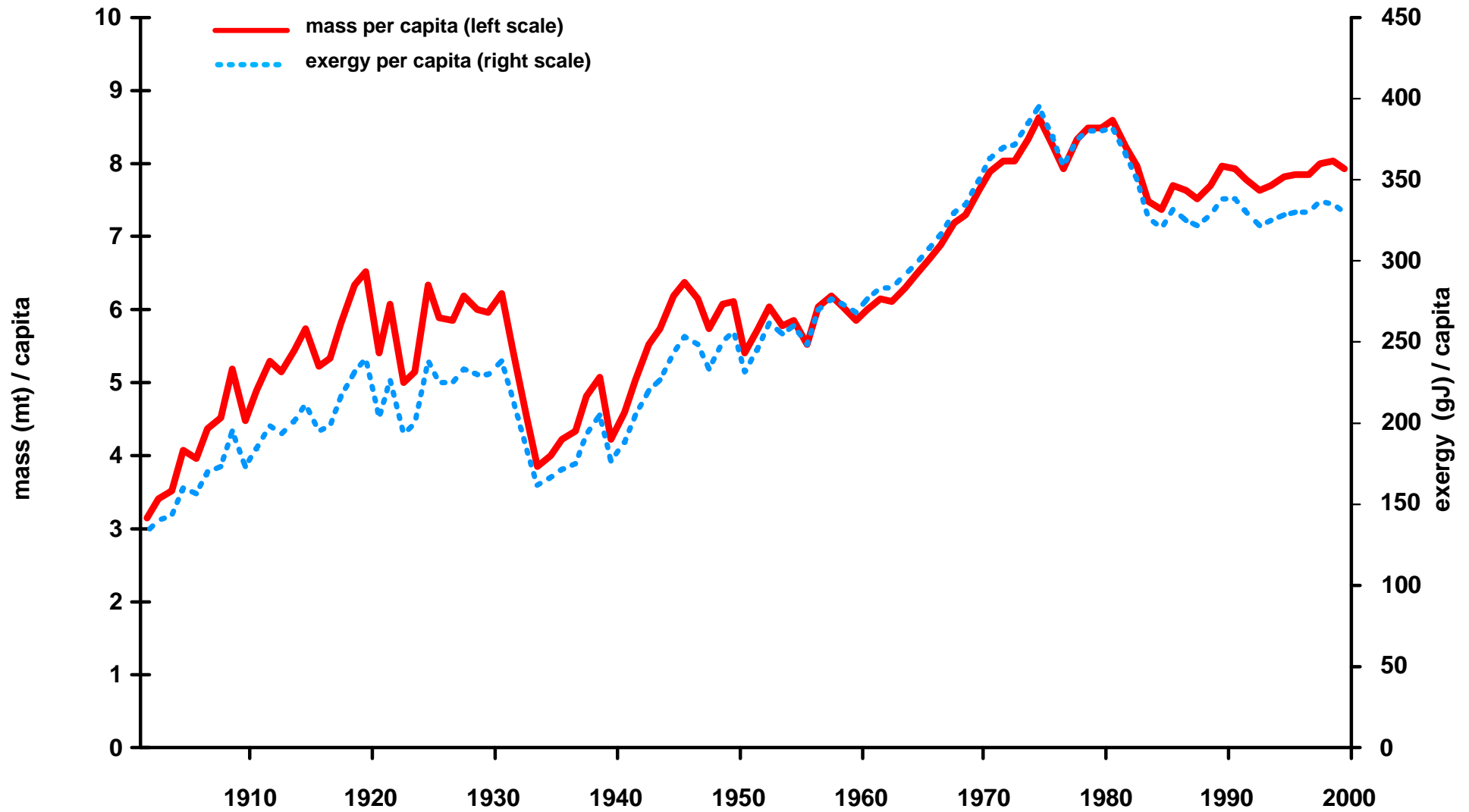
Figure 21: Fossil fuel consumption; mass/capita vs. exergy/capita (USA 1900-1998)

Figure 22: Metals consumption; mass/capita vs. exergy/capita (USA 1900-1998)

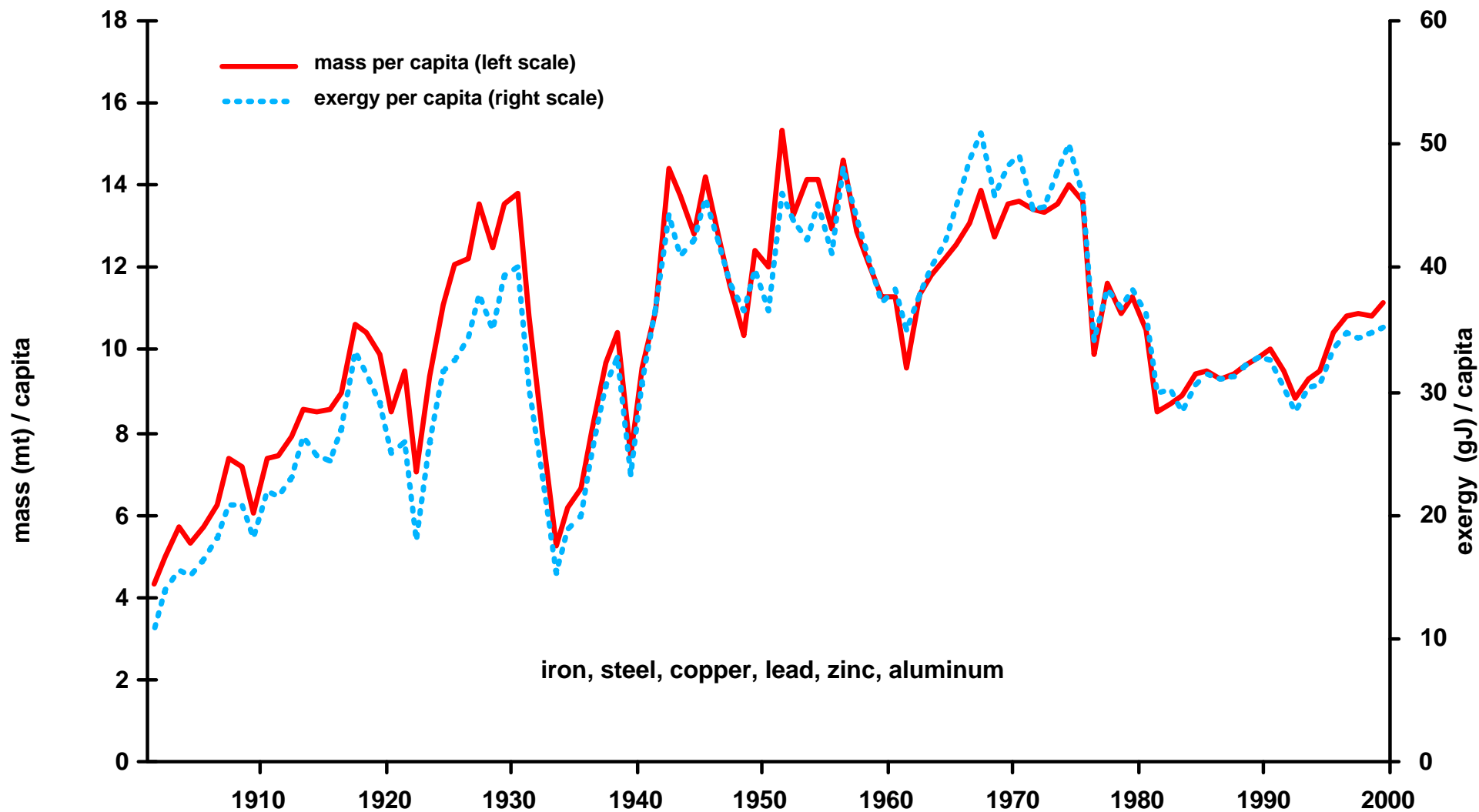


Figure 23: Construction materials consumption; mass/capita vs. exergy/capita (USA 1900-1998)

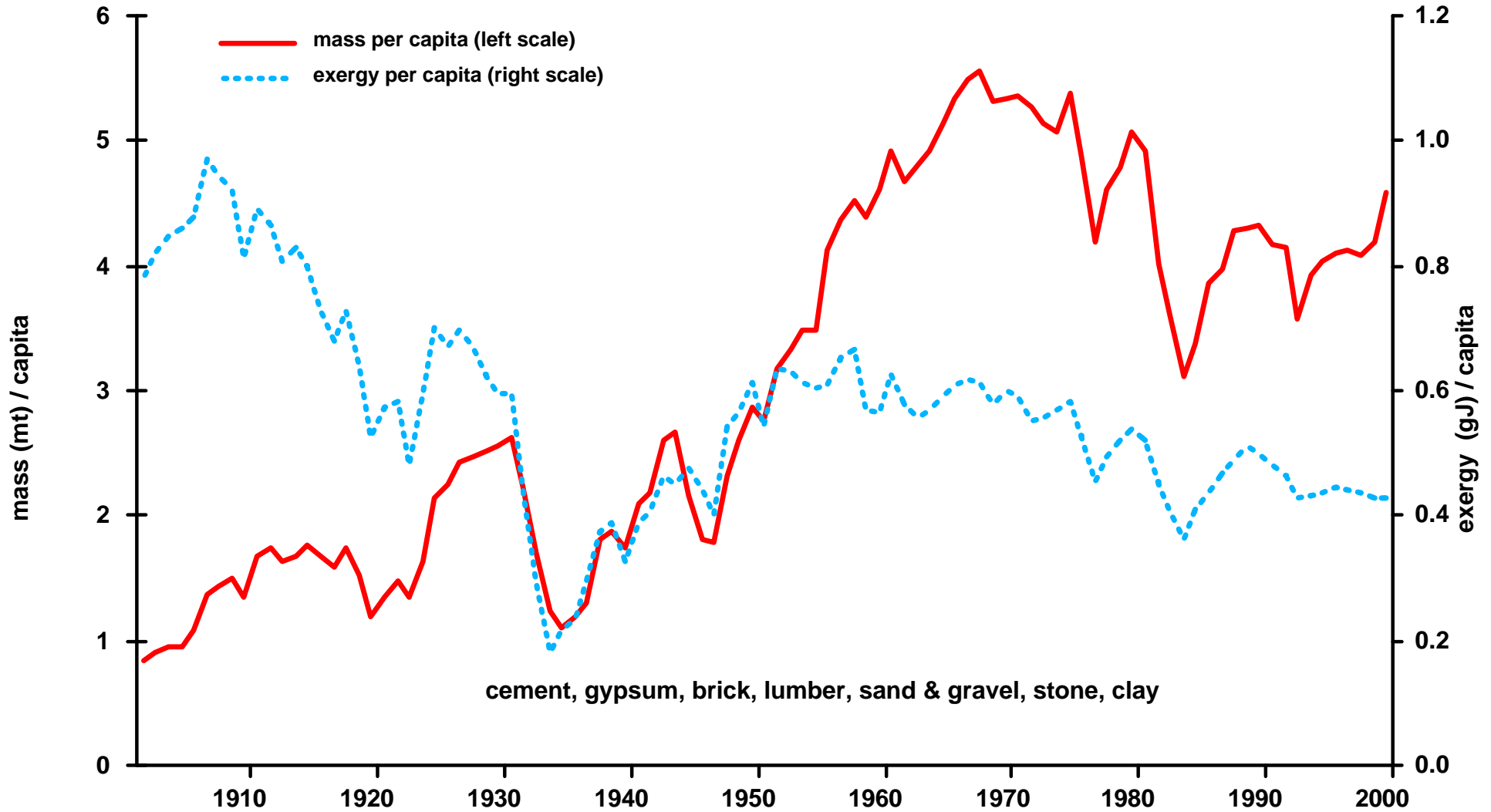


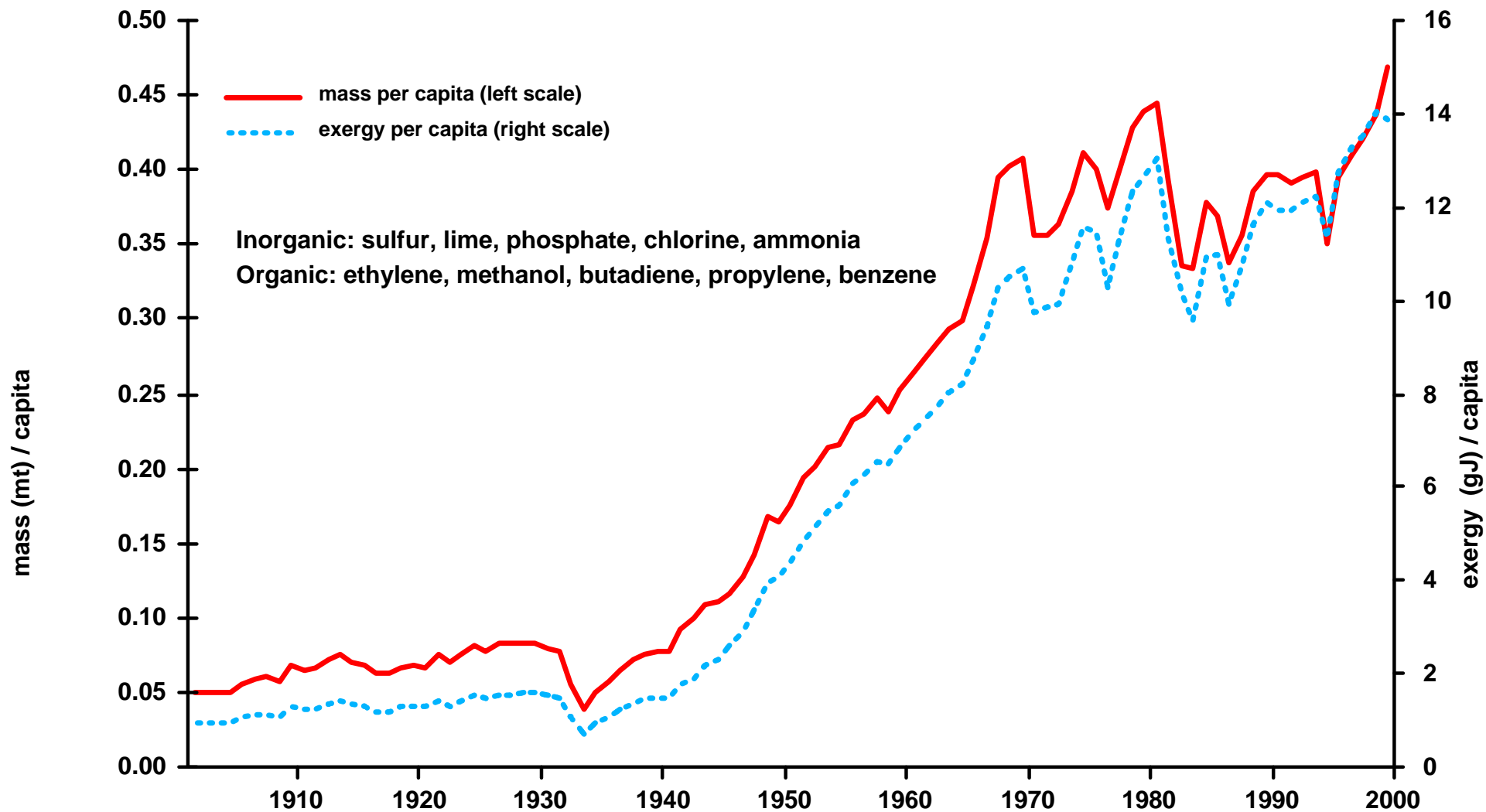
Figure 24: Chemicals consumption; mass/capita vs. exergy/capita (USA 1900-1998)

Figure 25: Total* mass/capita and exergy/capita (USA 1900-1998)

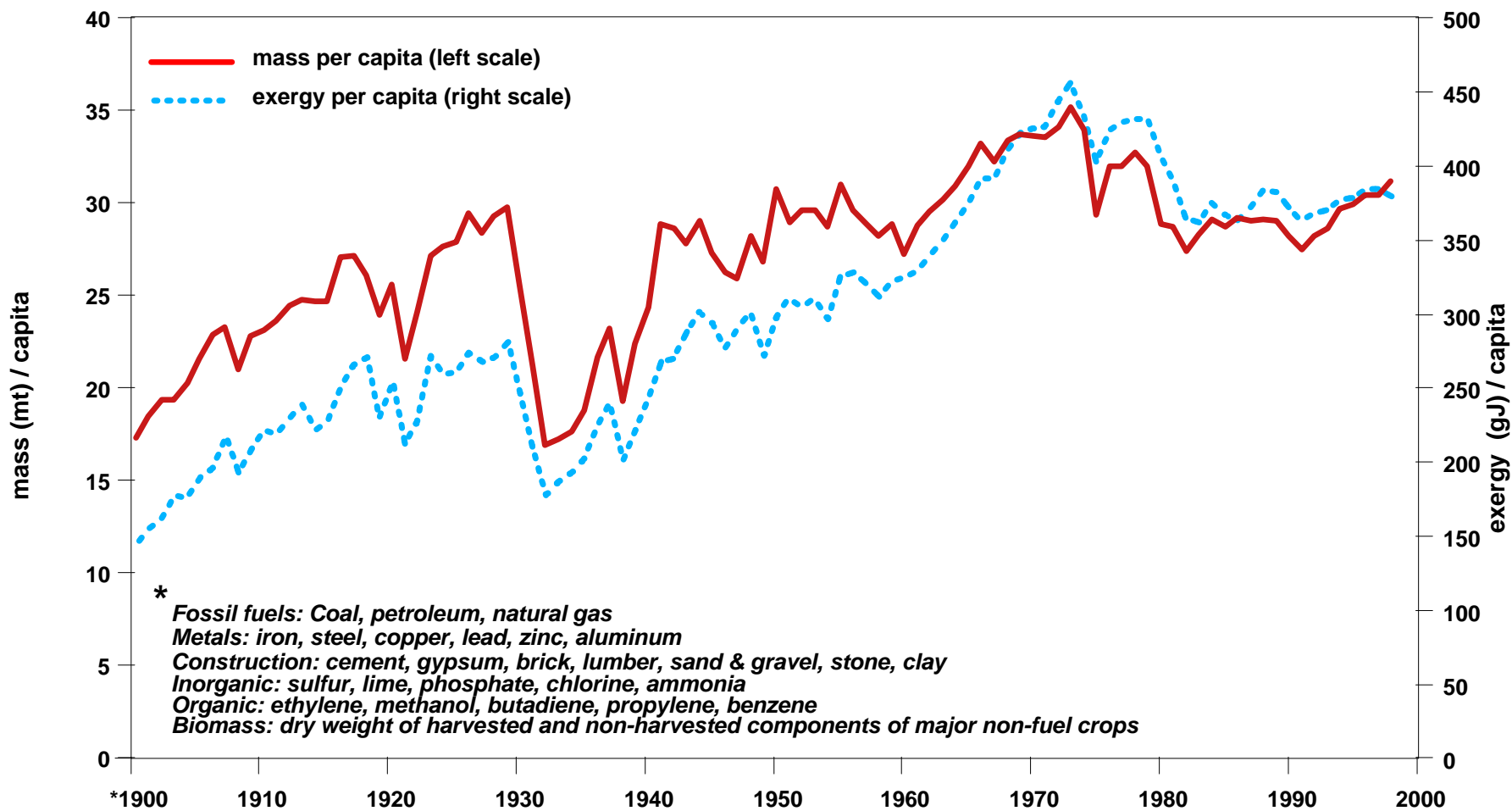


Figure 26: Total* consumption mass (USA 1900-1998)

