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ANALYSIS

# Sustainability economics: Where do we stand?

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ABSTRACT

Environmental economics, which is a branch of resource economics – the environment as a scarce resource – is essentially about market failures, the costs of pollution and pollution abatement, and the economics of regulation. Sustainability economics includes the problem of maintaining economic growth, while reducing pollution and/or its impacts, with special attention to the linked problems of energy supply (not to mention the supply other exhaustible resources), climate change and – most urgently – fossil fuel consumption. There is a need for integration of resource and environmental economics under a new rubric, sustainability economics.

## 1. Market failures and the cost of pollution

Economists in the first two thirds of the twentieth century were primarily concerned with problems of unemployment, investment, growth and fiscal policy. However the importance of land as a resource was recognized as primary by the French physiocrats, and again by Malthus (Malthus, 1946) in the 18th century and by John Stuart Mill in the 19th century (Mill, 1848). The Journal of Land Economics was founded in 1925. The possible implications of exhaustion of coal, the major energy resource of 19th century Britain was explored by Jevons in the 19th century and many other since then (Jevons, 1866). The mathematical theory of depreciation as applied to exhaustible resources began with the work of Harold Hotelling (Hotelling, 1925, 1931), and modern resource economics took off from there.

Broader economic considerations, such as the problem of externalities in welfare theory goes back at least to Pigou (Pigou, 1920). This issue received new impetus from the theoretical work of Mishan (Mishan, 1967) and Kneese et al (Ayres et al., 1970) on externalities. Boulding and Mishan were also among the first to call attention to the environmental costs of economic growth (Boulding, 1966; Mishan, 1967). However, mainstream economists were slow to recognize the implications of the fact that materials extracted from the earth and utilized for economic purposes are not literally 'consumed', but become waste residuals that do not disappear and may cause environmental damage and result in unpaid social costs (Ayres and Kneese, 1969). Another economic aspect of the competitive quest for scarce resources was emphasized by Garrett Hardin's famous paper "The tragedy of the Commons" (Hardin, 1968).[1]

Environmental economics finally emerged as a recognized branch of the discipline around 1970 when the deteriorating state of the human environment began to achieve headline status. "Earthday" in 1970 marked the creation of the Environmental Protection Agency (EPA) in the U.S. and comparable agencies in other western countries. This was followed quickly by the publication of One Earth by René Dubos and Barbara Ward (Ward and Dubos, 1972), and the UN Stockholm Conference in 1972. The Stockholm conference resulted in the institutionalization of environmental concerns at the international level through the creation of an Environmental Directorate at the OECD and a new UN agency, UNEP. Fig. 1 indicates the number of new environmental regulations introduced in Germany, which exploded starting in the late 1960s. The first professional journal in the field, the Journal of Environmental Economics and Management (Academic Press) appeared soon after.

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[1] This idea led naturally to the idea of a stationary or steady-state economy (Ayres and Kneese, 1971; Daly, 1973)and of course "limits to growth" (Meadows et al., 1972).

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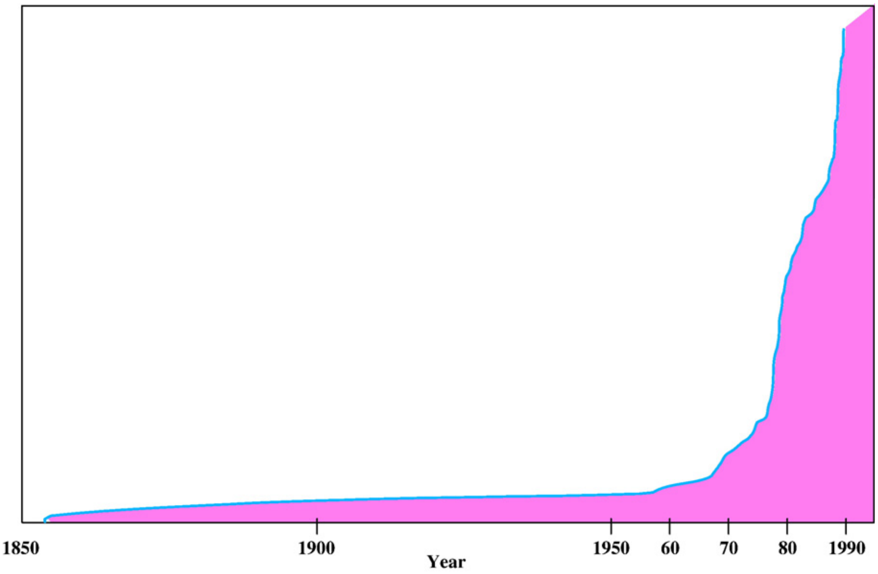

Fig. 1 – Increasing burden of “top down” regulation cumulative environmental laws enacted in Germany.

The most urgent and visible environmental problems of the first seven decades of the twentieth century were local in nature: they included arsenic from copper smelters, cadmium from zinc metallurgy, asbestos, tailpipe emissions from automobiles (and “smog”), carbon monoxide, nitrogen oxides and sulfur dioxide and particulate emissions from coal-burning power plants and industrial boilers, lead emissions from gasoline and water pipes in old buildings, PCBs, mercury, untreated sewage and industrial wastewater, and old industrial dump-sites with toxic wastes. It was necessary to change the public perception – a hangover from the Great Depression – that smoke from factory chimneys was a good thing, because it meant jobs. Substantial investment was needed to clean up old messes and to enforce measures to treat or reduce waste emissions from existing activities. Hence, the initial approach to environmental protection at the practical level was largely limited to what has been termed “end of pipe” treatment of wastes and pollutants.

Water pollution was recognized as a health problem long ago, albeit the role of untreated sewage was not understood until near the end of the 19th century. Chlorination and sewage treatment were on the (local) political agenda by then, but economists were not much interested. Smoke control by means of electrostatic precipitators (ESP) was the first serious attack on atmospheric pollution. (The technology was introduced at the beginning of the twentieth century and was already in fairly general use by 1960.) Carbon monoxide and other emissions from coke ovens and blast furnaces were another early target, partly because they represented inefficient use of the expensive coke. The problem of smoke (particulates) and sulfur dioxide emissions from coal combustion, mainly in power plants, were addressed by installing

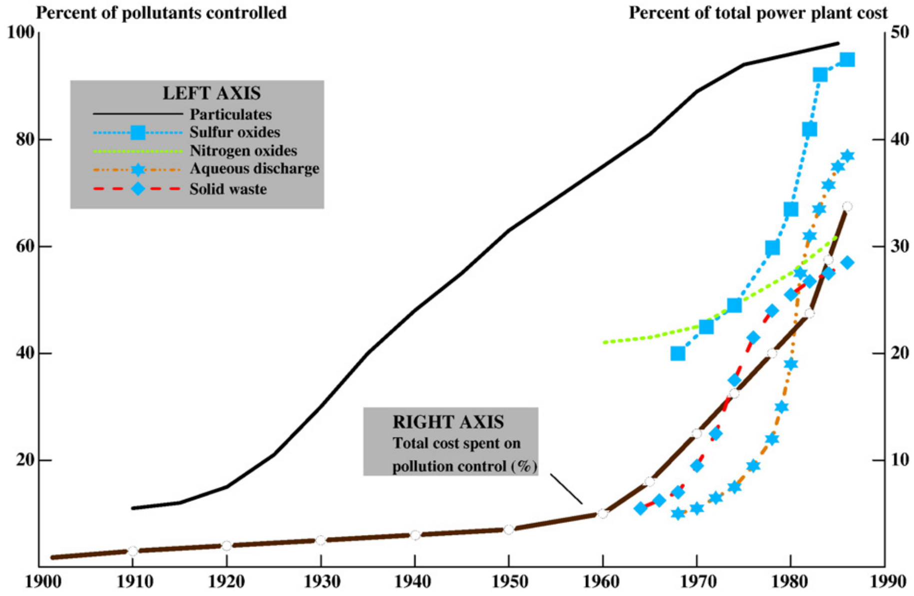

Fig. 2 – Pollution control costs in the US.

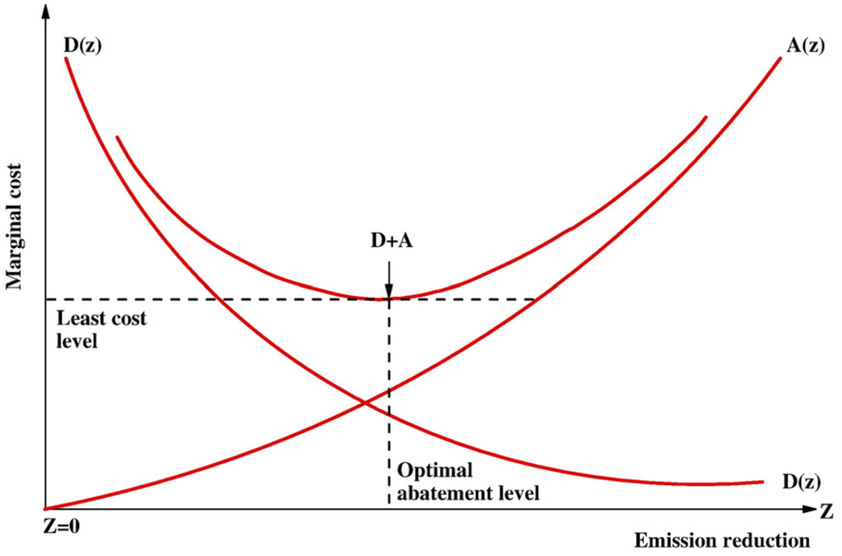

**Fig. 3 – Emission reduction vs marginal cost.**

ESP and flue gas desulfurization (FGD) units on the stacks. But, ESP consumes several percent of the electric power produced by a power plant; while FGD requires substantial quantities of limestone or lime as inputs. Both technologies involve significant energy consumption plus capital costs that added to the price of steel, cement and electric power, as indicated by Fig. 2.

Next came regulatory requirements on automobile manufacturers to include catalytic "convertors" to reduce harmful engine exhaust components such as carbon monoxide, unburned hydrocarbons and nitrogen oxides. These regulations and the controls have been effective in reducing sulfur dioxide (and, later, nitrogen oxide emissions). They also added several hundred dollars – something like 5% – to the price of each car. The same tendency for costs to increase non-linearly holds for sewage treatment plants, incinerators and toxic waste disposal facilities. Only in the case of waste incineration was there any potential for resource recovery or savings, and this potential has seldom been realized in practice due to persistent engineering problems. Economists began to notice.

Then after considerable debate (and a lawsuit under the Clean Air Act), it was decided in 1973 to eliminate the use of tetraethyl lead as an additive to motor fuel in the US. This was partly to prevent the catalytic convertors from being "poisoned", but mostly because of demonstrable health hazards. The ban on lead cut the octane number of gasoline and increased the cost of petroleum refining by at least 10% It also forced auto manufacturers to reduce compression ratios from 11 to 8 or 9, thus increasing automobile fuel consumption. However (US) tetraethyl lead consumption was essentially eliminated by the mid-1980's and ambient air concentrations of lead dropped in parallel.

In recent decades particulate emissions have also significantly decreased in the industrial world, although the main reason for this is the widespread substitution of natural gas for coal in most small scale uses, especially home heating. Sulfur dioxide emissions appear to have leveled off, or even decreased slightly. But the potential for abatement of NOx in combustion products is quite limited, and total NOx emissions have been continuing to increase, despite significant (and costly) efforts to reduce them. Progress in reducing localized air and water pollution has been made since 1970, but rarely without significant added cost.[2]

In fact, the cost of pollution control became the central theme of environmental economics in the late 1960s and '70s. Perhaps the key insight from those years was that, if environmental damage can be quantified in monetary terms, then the *benefits* of pollution control can be expressed as an increasing function of the degree of control, but the *marginal benefits* decline toward zero. Meanwhile it is easily demonstrated that both the *cost* and the *marginal cost* of control tends to increase as the degree of control approaches 100%. It follows that there is always an optimum point where the marginal cost of control is equal to the marginal benefit, and further reductions of emissions cost more than they are worth e.g. (Kneese and Bower, 1972). This is shown schematically in Fig. 3. It follows from this simple insight that popular ideas like "zero emissions" make as little sense economically as they do in physical terms.

Many environmentalists still have difficulty with this conclusion. They argue that environmental harm, and especially human life, cannot be evaluated in monetary terms and that human life, in particular should have infinite value. It seems to follow that the benefits of pollution elimination are beyond price. However, measures to abate or compensate for environmental damages do have real monetary costs, and available funds are always limited. It is not possible to spend money for any purpose without limit. Consequently choices must be made and benefit-cost analysis – despite its weaknesses – has become a standard tool of government.

The next question for economists was: how should the external costs be allocated? This aspect of the cost problem has been addressed as the "polluter pays" principle (PPP), emphasized in many of the international discussions, especially at the Rio Conference (UNEP) in 1992. In principle, it

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[2] The pulp and paper industry is a possible exception, in that the most advanced mills have found ways to reduce water, chemical and fuel consumption drastically by internal recycling. However, it is unclear whether these innovations were actually profitable.

seems clear that the polluter should pay for the environmental harms attributable to pollution. But of course the costs will be passed on to consumers whenever producers are able to do so, especially in oligopolistic industries.[3]

In practice, the 'top down' regulation by government agencies has become increasingly complex and burdensome, albeit necessary. Moreover, the rate of environmental improvement has declined, probably because the most cost-effective improvements have been made. By the mid-1980s the inherent limitations of this 'end-of-pipe' approach began to become clear, especially in regard to regional and global problems such as soil acidification and/or toxification, coastal eutrophication, ozone depletion and "greenhouse" warming. These problems are all attributable to emissions that are either increasingly costly (SOx, NOx, CFCs, heavy metals) or nearly impossible ($CO_2$) to remove from waste streams.[4]

Another useful insight from neoclassical analysis resulted from a controversy on limits following publication of Georgescu-Roegen's book "The Entropy Law and the Economic Process" ; (Georgescu-Roegen, 1971) and the more popular "Limits to Growth" in 1972 (Meadows et al., 1972). Mainstream economists took the contrary position in a series of papers e.g. (Solow, 1974a,b; Dasgupta and Heal, 1974; Stiglitz, 1974, 1979). These papers addressed the question: does increasing physical scarcity imply increasing economic scarcity? They all assumed that resources are privately owned and traded in efficient markets, including forward markets between generations. They also assumed continuing exogenous technological improvements, allowing economic growth to continue despite diminishing returns to investment. Many of these assumptions have been challenged, of course, especially in this journal.

The major insight from these papers was that, subject to the underlying assumptions (perfect competition, perfect information, etc.) the answer to the question that was posed depends on whether the elasticity of substitution between the resource and capital (including human capital) is large enough. The immediate implication was that worries about impending resource exhaustion were probably overblown. Powerful – if anecdotal – support soon appeared e.g.(Goeller and Weinberg, 1976; Kahn et al., 1976; Kahn, 1984). Econometric support for the 'unlimited substitution view was also found by some researchers, such as Weitzman (Weitzman, 1997, 1999). In principle, it has been widely accepted by economists that scarcity is not an immediate problem and that capital may be substituted for most physical resources, at least up to some point that might be quite far in the future.[5]

A second important insight from these studies and others in that period was that exhaustible resources may actually pose less serious problems than so-called 'renewables' e.g. (Wilson, 1989; La Riviere, 1989; Postel, 1989; Wang, 1989; Frederick and Gleick, 1990; Gleick, 1992; Ayres, 1993b; Raskin et al., 1994; Heywood and Watson, 1995; Gowdy, 1997). The reason is that most renewables, including air, fresh water, favorable climate and biodiversity (especially in tropical forests), are public goods, not traded in markets. Hence environmental damage has the character of an externality and – lacking market mechanisms to assure that the "polluter pays" – regulatory means of abatement or compensation are needed. Moreover, a further insight is that, absent adequate resource policy, technological change is likely to accelerate the rate of environmental degradation e.g. (Smulders, 1998, 2000).

Global problems like ozone depletion and climate warming are examples of public goods (or bads) that cannot even be addressed at the local or national level. One partial success story has been the reduction and hopefully total elimination of certain chloro-fluorocarbons (CFCs) that were formerly used very extensively as propellants for aerosol sprays, industrial solvents and – especially – as refrigerants. The ban on using CFCs in aerosols was enforced first in the US, starting in 1974, because the cost of switching to substitute propellants was relatively trivial. It was extended to refrigerants when feasible alternatives had been developed and 'globalized' at the Montreal convention in 1987. Unfortunately, there was a loophole in the Montreal Protocol, which allowed developing countries, notably China and India to continue to manufacture one of the CFCs (CFC-22) for refrigerators and air-conditioners, until 2016. It seems that production of this chemical – especially by China – has accelerated by many orders of magnitude since 1987. This has seriously undermined international efforts to reduce ozone depletion, as well as contributing significantly to climate warming. CFCs are thousands of times more potent than carbon dioxide and the other so-called greenhouse gases (GHGs).

In any case, at the global level there has been virtually no progress in reducing most greenhouse gases, especially carbon dioxide. The Kyoto Protocol is only a small first step, with primarily symbolic significance.

## 2. Emissions reduction and economic growth

The possibility that pollution would inhibit economic growth directly (albeit in unspecified ways) was suggested in the report to the Club of Rome entitled "Limits to Growth" by Meadows et al (Meadows et al., 1972). However, except for supposed scarcity problems, specific mechanisms for this supposed feedback effect were not discussed in that report, and have not been discussed subsequently *except* insofar as the costs of government mandated pollution control or treatment affect the prices of goods. The cost issue was noted in the previous section. In other words, the current state of economic and environmental science did not (and still does not), encompass more subtle indirect impacts of pollution on economic growth, at least in the industrial world.

The first major recognition of the issue at the official international level was the creation by the UN General Assembly in 1985 of the Commission for Sustainable Development, chaired by the Prime Minister of Norway, Mrs

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[3] In a competitive free market, this also depends on the elasticities of demand and supply. If the elasticity of demand is large enough, costs are likely to be borne by producers (through reduced profits), whereas if demand is inelastic, consumers will pay. Costs can be passed on to consumers as fees, in some cases, such as sewer or refuse collection services.

[4] The notion of removing and sequestering carbon dioxide from power plant flue gases has been given serious consideration in recent years, but while is technically feasible for large coal or gas fired electric power plants, it will be very costly and is not applicable to any of the smaller combustion sources such as motor vehicles.

[5] The evidence that has emerged in recent years, especially with regard to oil and gas depletion, is much less supportive of the optimistic view.

Brundtland. The commission's report "Our Common Future" tried to make the case that environmental protection is an essential element of economic development because the environment is an essential "factor of production" and source of important welfare services to people, even more so in poor countries than in wealthy countries (Brundtland, 1987). Here the impact mechanism was also not spelled out, but it presumably was intended to include such things as acidification, eutrophication, loss of bio-diversity and climate change.

The Brundtland Report popularized the notion of long-term 'sustainable development', which has since become a cliché in some circles. (In fact, the term has been twisted by many interest groups, including organizations focused on economic development, to mean something close to the opposite of its original intent, i.e. continuous development). One widely accepted prerequisite of long-term ecological sustainability, however, is the reduction of anthropogenic pressures on the environment. These pressures arise primarily from extraction and processing of natural resources and using the environment as a sink for the disposal of waste effluents and 'garbojunk'. The Brundtland Report did note the "continuing dilemma" of dependence on fossil fuels (*op cit* pp 174–177) as well as the loss of bio-diversity. The recent literature on sustainable development has been reviewed in a special issue of this journal (vol. 63 no.4).

## 3. Resource and environmental implications of economic growth

The impact of economic growth on the environment has received considerable recent attention in the literature. There are some who emphasize the positive aspects, notably Julian Simon (Simon, 1980, 1981) and, more recently, Lomborg (Lomborg, 2004, 2001). These writers (and others of their persuasion) argue that economic growth is neutral or even good for the environment because technological substitution will quickly solve any problems and the alleged problems are all grossly exaggerated. I cannot take these arguments very seriously, though media organs such as The Economist and Wall Street Journal are great admirers.

But there are other more optimists from a different perspective. One of the 'stylized facts' of long term economic growth and development, that attracted renewed attention in the 80's and 90's, is the so-called 'Environmental Kuznets' Curve (EKC), based on the E/GDP ratio. [6] Some development economists, especially at the World Bank, have elaborated an argument to the effect that environmental pollution reduction is a 'superior good' and that it will occur automatically as poor countries grow richer. The general idea is that increased wealth (i.e. GDP per capita) allows countries to afford more environmental protection. It is supported by empirical evidence that certain types of pollution tend to be worse in poor countries. This correlation applies especially to sulfur oxides and particulates, as well as all sorts of waterborne pollutants, but not for $CO_2$. However the likely explanation for at least part of the apparent correlation is that poor countries necessarily utilize poorer quality fuels, such as charcoal, and use them inefficiently.

On the other hand, it is true that more industrialized countries are more likely to construct water and sewage treatment facilities and mandate the installation of equipment such as electrostatic precipitators (ESP) and flue gas desulfurization. It is also evident that the limited successes that have been achieved since the 1960s are almost exclusively to be found in the richest countries, especially the US, Japan and Western Europe.

It has to be said that the EKC argument can be – and has been – used to justify perverse development strategies. The most worrisome is the argument by some conservatives to put wealth creation at the top of the priority list, while deferring serious and presumably costly attempts to control or regulate Greenhouse Gas (GHG) emissions until a future generation which will (hopefully) by much richer and hence more able to afford such investments. The perverse implication for industry, of course, is that development aid to poor countries can continue to focus on infrastructure for raw material extraction and need not include provisions for environmental protection in an "under-polluted" environment, a crude justification of past practices. Moreover, it is an empirical fact – known in some quarters as the 'curse of oil' – that resource exporters have, almost without exception, failed to develop economically.[7] In most cases it appears that most of the oil or gas wealth is siphoned off by the international mining/drilling firms (especially oil companies) and/or by corrupt officials.

Nevertheless, it is also a fact that a number of developing countries depend upon the export of raw materials, ranging from petroleum to uranium, chrome, copper or gold, for much of their national income. Hence serious attempts by countries in the industrialized West to reduce their consumption of such materials – by energy conservation or accelerated 'dematerialization' – would have adverse economic impacts on those exporters. It is no accident that the middle-eastern oil exporters and Australia were the strongest opponents (apart from the US) of the Kyoto Protocol. Moreover, it is clear that rigorous environmental protection in a country like China or India will involve significantly increased costs of production, either for domestic consumption or export, and, hence, constitute a drag on economic growth.

More recently, the notion of "sustainable consumption" has emerged, to reflect the recognition that consumption of physical materials and energy derived from non-renewable fuels cannot exceed some finite limits imposed by the carrying capacity of the Earth. The biosphere can only absorb a limited amount of

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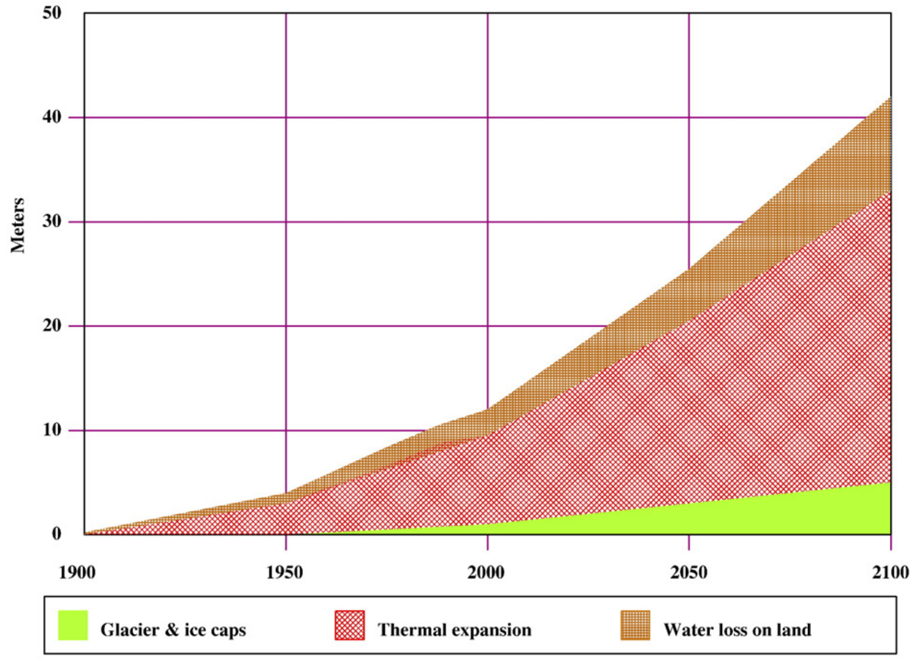
[6] For early work see (Kuznets, 1930, 1963). The history energy consumption per unit of GNP for the U.S. was first calculated in detail by (Schurr and Netschert, 1960), based on Kuznets' estimates of GNP for the years before 1910 and Kuznets–Kendrick's estimates of GNP in 1929 prices (Kendrick, 1961), updated in terms of 1958 prices by the Bureau of Economic Analysis (BEA) for later years, based on National Income and Products Accounts of the United States 1929–1965(Bureau of Economic Analysis, 1965). For the more recent work involving the so-called Environmental Kuznets Curve (EKC), see (World Bank, 1992; Selden and Song, 1994; Beckerman, 1995; Grossman and Krueger, 1995; Stern et al., 1996). The empirical evidence casting doubt on the EKC hypothesis has recently been summarized by Stern (Stern, 2004).

[7] The only exceptions in recent years have been the countries benefitting from North Sea oil and gas, especially Norway, Great Britain and the Netherlands. All of these countries were already industrialized before the resource bonanza was discovered.

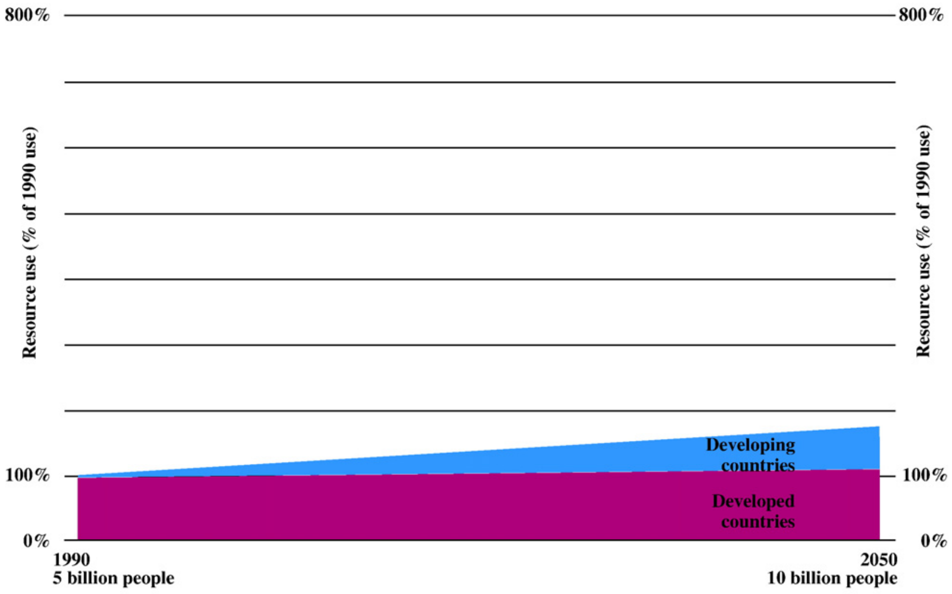


*Source: AQUA, GLOBO Report Series 6, RIVM*

Fig. 4 – Historical and projected global sea level rise: 1900–2100.

waste products (including, but not limited to $CO_2$) associated with the extraction, processing and disposal of materials. For a recent survey of this literature see Jackson (Jackson, 2007).

There are indications that some limits are not far away. In fact, given the slow response of complex systems to perturbations, it is possible that the long-term carrying capacity of the Earth/biosphere have already been exceeded, at least in some regions and biomes. Biodiversity is unquestionably and ever more rapidly decreasing, especially in the tropics. Moreover, it is now clear to all but the self-deluded that the global climate has already started to change and that the process is accelerating. These changes will affect all countries, the poorest most of all. Recent experience with increasingly powerful storms illustrates the point: poor countries like Sri Lanka, Bangladesh, Indonesia and the Philippines are much less able to prevent or recover from floods and landslides than Western Europe or the US. Sea level rise (Fig. 4) will affect countries like the Maldives, Bangladesh, Indonesia, Viet Nam, thee Philippines, China and



*Source: [FOTE undated]*

Fig. 5 – Effects of predicted population growth on worldwide use of resources if current consumption and production patterns are maintained (1990 = 100%).

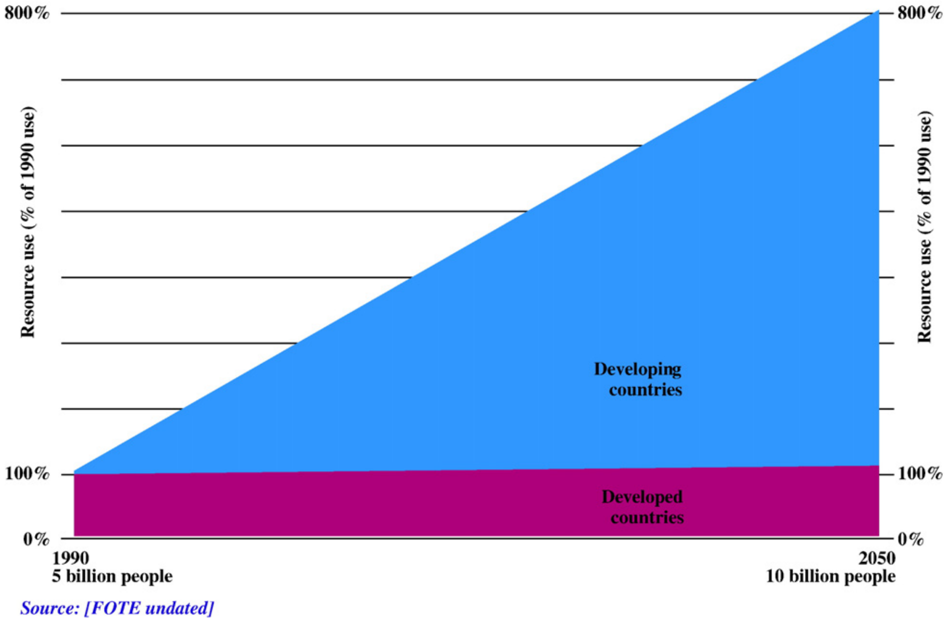


**Fig. 6 – Effects of predicted population growth on worldwide use of resource if consumption figures worldwide were equal to those of developed countries (1990 = 100%).**

the Nile Delta far more severely than Europe or North America. (Although Florida, Louisiana and coastal barrier islands including Long Island are also at risk.)

Yet global GHG abatement efforts (such as the Kyoto protocol) are still derisory and climate stabilization will be very difficult, if not impossible, to attain without international cooperation and agreement that is hard to imagine in a world where 'beggar thy neighbor" is the rule.

Apart from direct costs of pollution control and treatment, the impact of economic growth on the environment is linked to increased extraction and consumption of all kinds of materials, but especially fossil fuels. Consider first the sort of increase in materials use that would occur if only population growth occurs, with current development levels and resource consumption patterns (as between industrialized and less developed countries), as indicated in Fig. 5. Economic development – in the sense of increasing GDP – is the highest priority of every country in the world, including the countries that area already 'rich'. And the rate of economic growth in Asia, especially, has accelerated in recent decades. There is little chance of a 'no-growth' scenario like Fig. 5, and few would advocate it. However, economic development in the developing countries over the next half century at recent growth rates, combined with unavoidable population growth, will inevitably require massive increases in the consumption of natural resources, more like (Fig. 6).

## 4. Economic growth and material flows

Even if this kind of GNP growth were feasible from an economic perspective (which is doubtful) it would be inconsistent with ecological sustainability. As this journal has emphasized, the links between production, consumption and the natural world are vitally important to any consideration of long-term sustainability (Ayres and Kneese, 1969; D'Arge and Kogiku, 1973; Boulding, 1978; Ayres, 1989; Cleveland, 1991; Costanza, 1991a; Common and Perrings, 1992; Ayres, 1993a; Allen, 1994; Ayres, 1994a; Goodland and Daly, 1996; Raskin et al., 1998; Rees, 1999). Since human activity now competes with natural processes in terms of materials fluxes, especially with regard to the most toxic metals (arsenic, cadmium, lead, mercury, etc.) and the most environmentally harmful chemicals (e.g. pesticides, chlorinated hydrocarbons), it is not too much of an exaggeration to say that most environmental problems are attributable to materials consumption and disposal. The inconvenient truth is that material inputs become waste outputs. *Every raw material extracted from the environment is a potential waste, and most become actual wastes within a few months*. Only a tiny fraction are incorporated into durable goods, and still less is recycled (or suitable for recycling). Very few durables, apart from structures, survive more than a few years.

Thus, notwithstanding the optimism of World Bank economists, it is contrary to common sense and experience to assume that increasing wealth will automatically reduce pollution, especially the emissions of greenhouse gases (GHGs).[8] All economic activity is based on material goods, and virtually all activities are driven by expenditures of energy (actually, *exergy*, as explained later.) Fig. 7 indicates the scale of the material flows in a real economy. All raw materials extracted from nature eventually return to nature as wastes and pollutants, some of which are harmful in (initially) unsuspected ways (Kneese et al., 1970).

This linkage constitutes a very real constraint to economic growth, even if the limit is somewhat subtler than the scarcity problems simplistically portrayed in the first Report to the Club

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[8] Indeed there is an influential group of economists who argue that increasing efficiency will result in increased demand (and emissions) via the so-called "rebound effect" (Khazzoom, 1987; Brookes, 1990, 1992; Saunders, 1992).

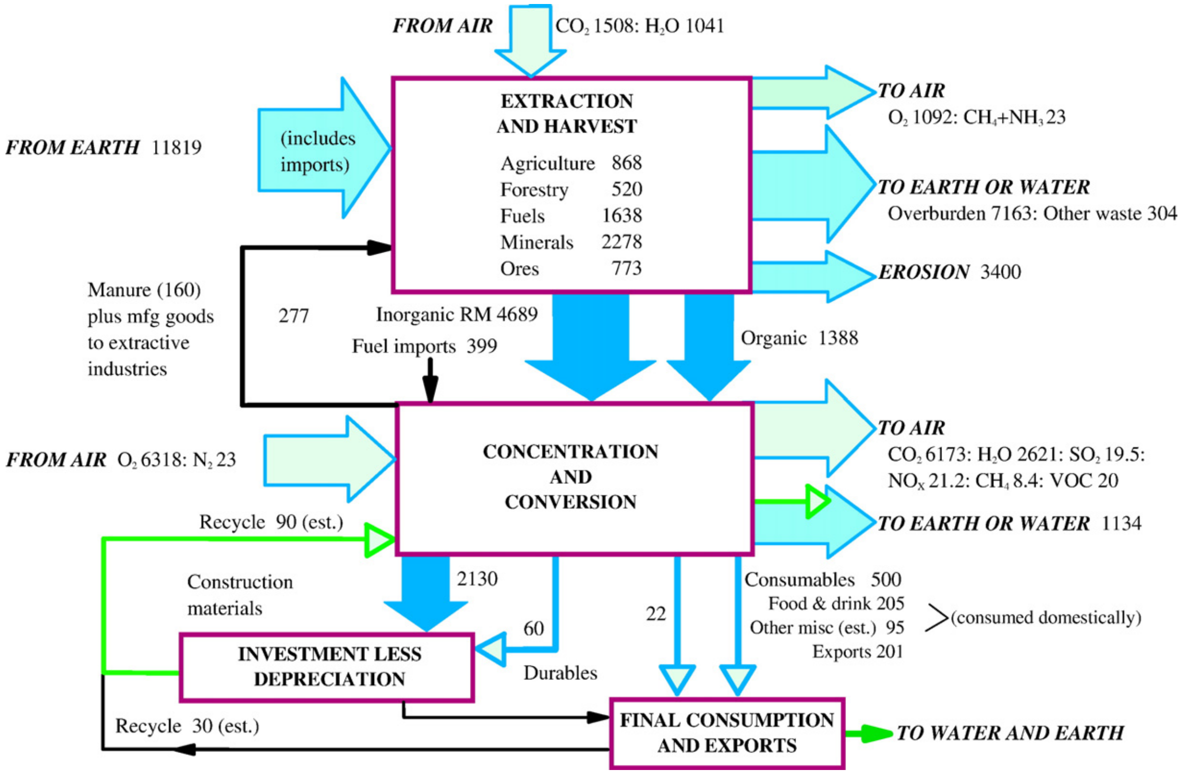

**Fig. 7 – The US economic system as a whole from a mass flow perspective (1993 in MMT).**

of Rome (Meadows et al., 1972) and derided by its critics (Nordhaus, 1973b; Solow, 1973, 1974a,b). Nevertheless some environmentalists, e.g. at the Wuppertal Institute, have proposed that the total worldwide consumption of all minerals as well as fossil fuels should be stabilized (Schmidt-Bleek, 1992; Schmidt-Bleek, 1994). But allowing for inevitable global population growth, which will certainly increase by around 50% in the next 50 years, and allowing for economic growth in the non-industrialized countries, especially China, South Asia, and Africa, stabilization at the global level can only be achieved by sharp *reductions* in the consumption of materials in the industrialized West. One recent book suggests a reduction factor of four (von Weizsaecker, Lovins, and Lovins, 1994). Others, like Schmidt-Bleek suggest the need for an even more dramatic ten-fold reduction (Factor Ten Club, 1994 and 1997). In short, we must aim for a pattern of economic growth that is consistent with a materials consumption scenario like Fig. 8.

Whether the appropriate divisor is four or ten does not matter so much as the fact that any reduction at all means a major “U-turn” in both economic development and environmental strategy (Ayres, 1996, 1998). But, the question is: what (if any) are the feasible ways and means of achieving this sort of outcome? End of pipe treatment is an essential first step but it cannot achieve the necessary reductions, especially of GHGs. In recognition of this fact a new ‘bottom up’ way of thinking about emissions reduction began to emerge in the mid-1980s. It has been variously called “source reduction”, “waste reduction”, “cleaner production”, “low-waste” (or “non-waste”) technology, “design-for-environment” or DFE, “dematerialization”, “industrial ecology”, “eco-efficiency” and (in China) ‘circular economy’.

There are significant differences among these approaches. For instance, “waste reduction” emphasizes energy conservation and materials utilization efficiency. “Cleaner production” emphasizes technical change that reduces emissions at the source, such as the (classic) example of substituting water soluble paints and cleaning agents for coatings and cleaning agents requiring volatile hydrocarbons or chloro-fluorocarbons. DFE emphasizes the potential for reducing wastes by making products more repairable, more remanufacturable, or more recyclable. “Dematerialization” is focused on reducing the mass of materials used in production, by miniaturization or substitution of services for products. Industrial ecology emphasizes the potential for recycling wastes from one industry as feed-stocks to another, in analogy to the carbon–oxygen cycle. (Oxygen is a waste product of photosynthesis, while carbon dioxide is a waste product of animal respiration). “Eco-efficiency” differs from the others in that it is being developed and presented explicitly by businessmen – notably the World Business Council for Sustainable Development, or WBCSD – as a strategy for business (Schmidheiny, 1992; Fussler, 1996). Whereas the other approaches are typically defined by an outcome, eco-efficiency is a concept more firmly based on a business perspective. A business cannot survive without making a profit. This implies that a basic business approach is to increase the value-added to customers *per unit of materials/energy input*. This means that for every increment of added cost, value to customers must increase as much or more.

Proponents of eco-efficiency like Fussler (ibid) or Lovins (Lovins et al., 1981; Lovins and Lovins, 1991) argue that there are many “win-win” opportunities for value creation that are

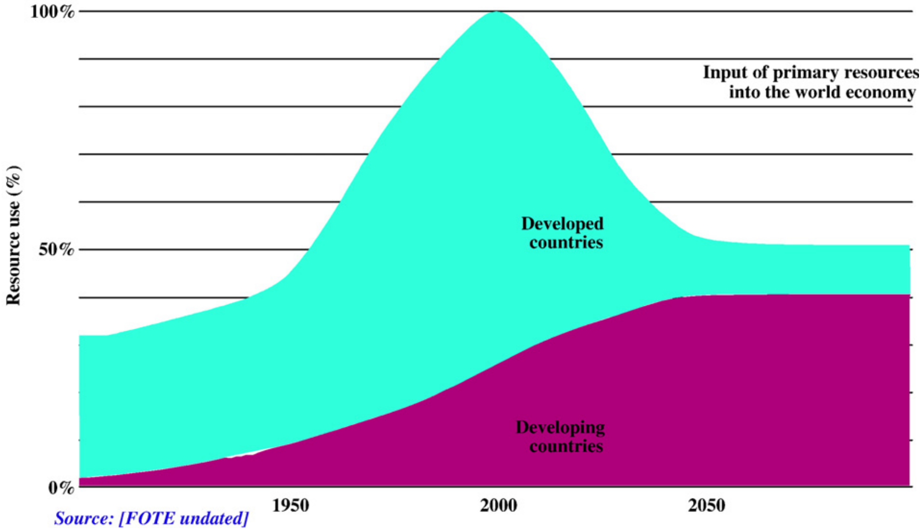

**Fig. 8 – Sustainable development path.**

also environmentally friendly. Some firms have introduced slogans expressing this idea, such as PPP for Pollution Prevention Pays (3-M Corp.) and WRAP for Waste Reduction Always Pays (Dow Chemical Co.) Unfortunately, these slogans cannot be taken too literally. Most economists are extremely skeptical about claims of numerous "win-win" possibilities because, in the ideal neo-classical world of competitive free markets with no or low entry barriers, if the opportunity were real, it would be exploited by some entrepreneur. In the view of mainstream economists, at least, the reality is that gains from pollution prevention and waste reduction are most likely to be illusory (because of 'hidden costs') and more costly than profitable (Jaffe and Stavins, 1994; Goulder, 1995). This is becoming a somewhat contentious issue.[9]

To be sure, real markets are not nearly as free and competitive as the ideal, thanks to legal monopolies and oligopolies, economies of scale, government regulations, labor agreements, protective tariffs and other anti-competitive arrangements. This being so, the 'free market' as it operates now, does not exhibit the optimal set of technologies. Established firms in oligopolistic markets have enormous cost advantages in terms of economies of scale and experience, as well as favorable treatment from regulators, making them very hard to displace. Many examples of regulatory and other barriers have been documented, e.g. for electric motors (De Almeida, 1998), lighting (DeCanio, 1998) and wind and solar power (Del Rio and Unruh, 2007). New entrants often face very high entry barriers. Hence it may be possible, *in principle*, to cut costs and pollution at the same time in some sectors, as illustrated schematically in Fig. 9 although it is rarely accomplished in practice.

The existence of potential "win–win" situations, or "double dividends" (or "free lunches") is not just imaginary. "Least cost" studies suggest evidence of very significant opportunities for savings that have been neglected at the national level (Sant and Carhart, 1981; Lovins et al., 1981; Lovins and Lovins, 1991; Morris et al., 1990; von Weizsaecker, Lovins, and Lovins, 1998; Intergovernmental Panel on Climate Change (IPCC) 1996). At the sectoral or firm level there are even more convincing examples.[10] Significant opportunities for savings in the field of electric power generation have been estimated, e.g.(Mills, Wilson, and Johansson, 1991). Recent studies suggest even more dramatic savings potential, simply by wider use of the technology known as decentralized combined heat and power (DCHP), viz. (Casten, 1998; Casten and Ayres, 2007). This would prove very attractive to entrepreneurs if the laws regulating electric power generation, and giving incumbents a legal monopoly over distribution, were suitably modified.

While there is ample evidence that the economy in general, and the energy system in particular, are not in equilibrium and not optimized, neo-classical economics does not really recognize that possibility. Virtually all large scale economic forecasting models utilize an approach called "optimal path" analysis which assumes that growth is driven by an exogenous force called "total factor productivity" while remaining in a state of economic equilibrium. The latter is achieved by utilizing "computable general equilibrium" (CGE) models.[11] This assumption of growth in equilibrium is convenient because nobody knows how to calculate growth trajectories for an economic system that is not in equilibrium. However, in reality the

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[9] In particular, there has been a considerable controversy over the so-called 'Porter hypothesis' (Porter and van der Linde, 1995).

[10] A list of examples supported by empirical data include a remarkable ten year experiment at Dow Chemical Co (Nelson, 1989; Ayres, 1994b). The negative cost savings at British Petroleum have been documented (Browne, 2004); and 51 case studies prepared for the EPA (Laitner and Finman, 2000).

[11] The methodology was introduced to economics in the 1960s as an application of a theory from dynamics, known as optimal controls, developed mainly by Russian mathematicians (Pontryagin et al., 1962). Applications in the economics literature are numerous, especially to growth theory and resource depletion: for example (Radner, 1961; Koopmans, 1965), (Gale, 1967), (Arrow, 1968; Dorfman, 1969), (Intriligator, 1971; Dasgupta and Heal, 1974), (Stiglitz, 1974), (Kamien and Schwartz, 1978), (McKenzie, 1981), (Newbery and Stiglitz, 1982; Eriksson et al., 1984), (Ayres, 1988) and (Ruth, 2002). An important exception is the Imaclim model developed by R. Crassous, J. C. Hourcade and their colleagues (Crassous et al., 2006a,b).

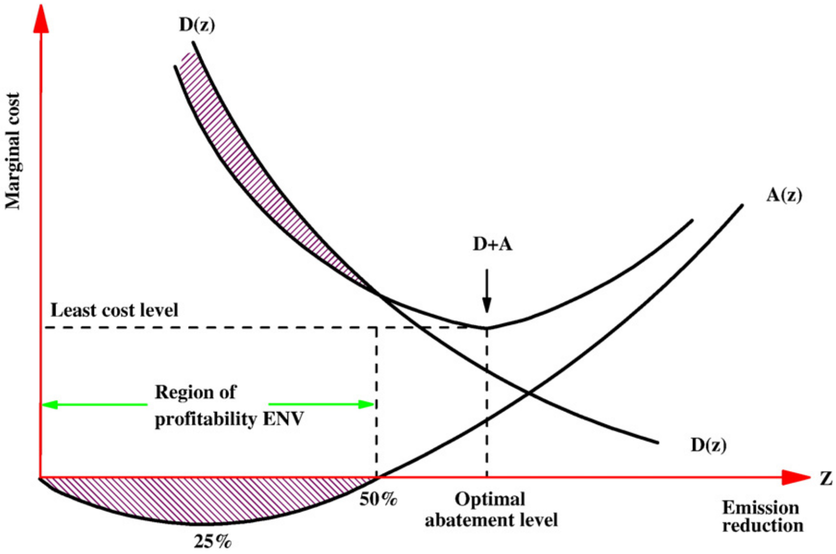

**Fig. 9 – Emission reduction vs marginal cost.**

economy is never in equilibrium (see (Kaldor, 1971; Kaldor, 1972; Kornai, 1973)), so that simplification is somewhat like looking for a lost key under the streetlight, or assuming a spherical cow.

## 5. Sustainability implications of economic growth

Unfortunately, radical dematerialization is not a likely consequence of either end-of-pipe waste treatment, or of a systematic search for "win-win" opportunities to use resources more efficiently while producing the same products as before. The problem is that economic growth along its current trajectory demands more – and more – material products.

For instance, consider the private automobile. Worldwide demand continues to grow, not only in absolute terms, but faster than population growth. In other words, the number of automobiles per thousand human beings is growing also. This trend is good news *if* you are an automobile manufacturer like Ford or GM with large investments in plant and equipment, and (of course) you are seeking to increase revenues and profits. It is equally good news if you are in the oil business, like Exxon, Shell or BP, with large investments in tankers, refineries, pipelines and so on.

However these trends are very bad news if you start to think about the global environmental impact. It is easy to see that there are widespread implications for highway construction, loss of valuable farmland, petroleum consumption, air pollution, and so on. Such calculations, and questions, are essential aspects of the "life cycle" perspective. But they are not normally part of a corporate manager's portfolio of concerns. Even if the CEO (of General Motors or Exxon-Mobil for instance) recognizes the problem, a life cycle analysis offer little or no guidance as to how an individual firm should behave. This is because the incentives for the CEO and other managers of the firm require them to seek bigger markets for their product, or to make bigger and more costly products, even though the end result – if they succeed – will be disastrous for everybody.

Consumers and workers also depend upon growth, because public services, including social security, are funded by taxes, not by savings. Without economic growth the tax revenues will not grow fast enough to satisfy the demand for pensions and health services that have been promised to a growing population of retirees. The fraction of non-working hours as compared to working hours, increases rapidly as birth-rates decline and life expectancy increases. For this reason alone, governments of the richer democracies are addicted to growth.

In short, none of the important economic actors, whether government leaders or private sector executives, has an incentive compatible with a 'no growth' policy. No economic growth is evidently not a politically viable proposition for a democracy, at least in a world with enormous gaps between poverty and wealth. But 'no growth' is an imperative as regards extractive materials, energy and pollution emissions because economic activity is based on a material foundation.

The prospect of physical resource depletion – probably beginning with petroleum (and natural gas soon after) – adds a further complication. The dates of 'peak oil' output are a matter of dispute, but there is no doubt that it will happen, whether in five or twenty-five years. There is also no doubt that the gap between supply and demand for light oil can eventually be met at some price by some combination of alternatives, including heavy oils, tar sands, shale, coal liquefaction, or bio-fuels. However every one of these options involves higher costs and lower energy-return-on-investment (EROI).[12] The clear implication of lower EROI is that (1) either more energy must be expended in producing the same amount of exergy or useful work, leaving less for other consumptive purposes, or (2) overall extraction of primary

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[12] See article in the Encyclopedia of Energy (Cleveland, 2004); also www.lesjones.com/posts/003223.shtml.

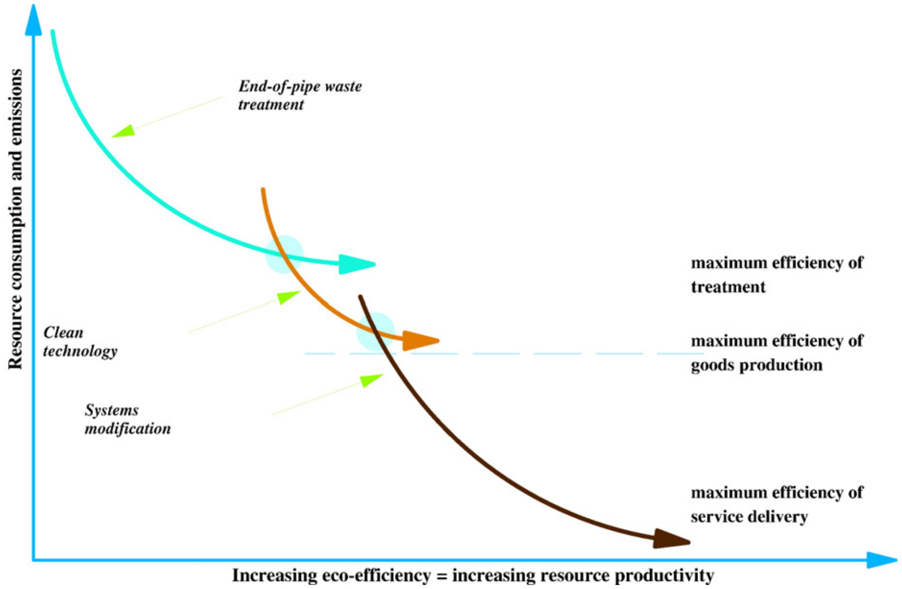

**Fig. 10 – Towards the spaceship economy: three stages in eco-efficiency.**

fuels or biomass to support economic growth must increase even faster than it has in the past.

Evidently a new and radically different development trajectory is needed. Some would call it a new paradigm. Our historical emphasis on the use of fossil fuels to increase labor and capital productivity is no longer appropriate. We must concentrate, in the future, on increasing *resource productivity*. In effect, goods must be converted as much as possible into services, and services must be delivered with the minimum possible requirement for material and energy inputs. The changes involved will not be marginal.

Let me summarize up to this point with another diagram Fig. 10. This figure shows schematically the limits of eco-efficiency as applied to the manufacturing economy, *vis a vis* a pure service economy. It is convenient and evocative to label the latter as the “spaceship” – or “zero-emissions” – economy, inasmuch as it is an economy in which all materials that are intrinsically scarce must be recovered, repaired, reused, re-manufactured or – as a last resort – recycled. In the ultimate spaceship (or circular) economy the material cycle would have to be closed, or nearly so. On the other hand, such an economy must be extremely energy-(exergy)-intensive. Are there enough non-polluting sources of energy? The answer is probably ‘yes’ at least in the long run. Nuclear fusion power, or photovoltaic power generated on the moon and sent to earth by microwave could add significantly to current options. But a very important preliminary question now arises: can radical de-materialization by sharply increasing resource productivity be accomplished without sacrificing economic growth and material comfort?

This is another contentious but essential question. As I have noted already, mainstream neoclassical economists do not accept the idea that there is a strong causal link between growth and energy consumption. The lack of such a link implies that energy consumption may be cut drastically without adversely affecting economic growth. This skepticism is a consequence of some of the convenient – but not necessarily factual – assumptions underlying standard economic models. The last section returns to this issue.

## 6. Bio-economics: weak vs. strong sustainability

The need for integrating ecological and environmental processes in the economic models – they are already integrated in the real economy – has been recognized by some scholars for many years, certainly since Boulding (Boulding, 1978). The creation of this journal can be regarded as evidence of the spread of ‘eco-sensibility’ among a few economists, viz. (Costanza, 1991b,c; Toman, 1994; Toman and Crosson, 1991; Common and Perrings, 1992; Ayres, 1993b; Goodland and Daly, 1996). One key insight that has emerged is that there are a number of services of nature that *cannot*, even in principle, be replaced by man-made capital or human labor. This is the essence of what is meant by “strong sustainability” as elaborated by a number of authors, including (Guts, 1996; Gowdy and O'Hara, 1997; Goodland, 1999; Ayres et al., 2001; Ayres, 2001; Pezzey and Toman, 2002; Neumayer, 2003).

Yet strong sustainability is a controversial position, inasmuch as it has been explicitly contradicted by a number of reputable mainstream economists, who argue that human ingenuity and man-made capital can indeed replace virtually all such services. Eminent economists on this side of the argument include Solow (Solow, 1992) and Pearce (Pearce, 1997), and probably Julian Simon (though he did not discuss the topic explicitly) (Simon, 1981). The key question, then is: what are the possibilities and limits of substitutability, not only between capital, labor and energy but also between different economic activities ranging from shelter to food and communication, and between human labor and man-made capital and other services of nature, from fresh water and clean air to topsoil and bio-diversity. There is some room for dispute as to the possibilities for substitution in the very long run, but very little doubt that substitutability between sectors as well as between factors, is extremely limited in the short to medium term (Ayres, 2006).

The plain implication of this fact is that production function models of the single sector, single product variety – whether Cobb–Douglas, CES or trans-log – cannot adequately reflect the problems of scarcity. Any production function of two or three variables that satisfies the usual conditions, (constant returns, maximization, integrability and equilibrium) must allow any combination of the variables, and consequently it must admit perfect substitution among them. Non-substitutability can only be expressed by an Input-Output type of model, and such models are normally static. They can be made dynamic, in practice, only by attaching a macro-driver that determines future demand. But of course technological progress and innovation must be exogenous to such a model. Moreover, there are no financial transactions among natural services, so the only medium of exchange common to all sectors must be exergy.

The flow of energy among natural systems has been studied by many authors, at least since the pioneering work of Lotka (Lotka, 1950) and more recently Odum, Ulanowicz and others (Odum, 1973, 1986; Ulanowicz, 1986). Given the difficulties, it is not surprising that the possibility of introducing the services of nature explicitly in a formal I-O framework has not been developed very far. I only know of one early attempt (Crocker and Tschirhart, 1992).

## 7. Need for a new energy-economic paradigm

A macro-economic perspective can help to clarify the deeper question at issue here. The starting point may as well be the relationship between economic activity and the larger physical–biological environment in which it is embedded. At one time economics textbooks were inclined to conceptualize economic activity as a closed loop between abstract production, abstract consumption and investment. The system thus described is supposed to be self-organized and capable of growth, but such that every product is produced from other products within the system e.g.(von Neumann, 1945; Sraffa, 1960). In this paradigm growth is assumed to occur without any inputs of energy or materials from outside the system. As pointed out long ago by Georgescu–Roegen, this model economy is an immaterial perpetual motion machine, in violation of both of the laws of thermodynamics (Georgescu-Roegen, 1971). Readers of this journal generally agree with that critique.

The connection with real material objects and the physical world from which materials are extracted, processed, made into products and finally disposed of, was never considered to be an essential aspect of mainstream neo-classical economics until forty years ago (Kneese, Ayres, and d'Arge, 1970; Nordhaus, 1973a; Jorgenson and Houthakker, 1973; Dasgupta and Heal, 1974; Solow, 1974a; Allen et al., 1976; Allen, 1979). Even now, the essentiality (i.e. non-substitutability) of energy (exergy) as a factor of production is ignored in the great majority of economics textbooks and research papers. However, it must be acknowledged that most environmental economists are well aware of the importance of materials and energy in the economic system, while generally assuming that these inputs are "produced" by applying capital and labor to natural resources.[13]

In contrast to the closed perpetual motion machine described above, the real economy is essentially a large-scale materials processing system, largely powered (for the present) by machines using fossil fuels that were created and stored in the earth's crust hundreds of millions of years ago. Virtually none of the materials consumed by the economy are recycled at present. The basic engine of economic growth in a mass-production manufacturing economy is the positive feedback cycle, shown in Fig. 11. In brief, the impetus to growth arises from the fact that demand for a product tends to increase as (real) prices fall. This phenomenon is called the 'price elasticity' of demand. Falling prices, in turn, result from exploiting economies of scale in manufacturing. Thus, firms can reduce costs, cut prices, increase sales and maximize profits (and grow) by increasing the scale of production. So ever greater consumption of resources is, *ipso facto*, a driver of growth in this paradigm: consumption (leading to investment and technological progress) drives growth, just as growth and technological progress drives consumption.

In effect, a new growth engine is needed, based on non-polluting energy sources and selling non-material services, not material products. One of the progenitors of the idea of "products as service" is Michael Braungart, founder of the Environmental Protection Encouragement Agency (EPEA) in Hamburg, Germany. Braungart calls his scheme the "Intelligent Product System" or IPS (Braungart et al., 1990; Braungart and Engelfried, 1992). The system recognizes three types of products. The first type is *consumables*, which are either literally consumed or are biodegradable. The second category is *durables*, which are not sold but rented or licensed, but remain the responsibility of the maker. The third category consists of *unsalables*. The latter are toxic materials that should not be sold but must always belong to the original maker and must be stored in licensed storage facilities operated for the purpose by regulated public utilities.

One of the advantages of an economy based on services is that it is inherently more labor-intensive than the mass-production manufacturing and "throw-away" economy. Treating products as capital goods will create more jobs because repair, renovation, disassembly and remanufacturing are inherently more labor-intensive than original equipment manufacturing (Stahel and Reday-Mulvey, 1981) (Stahel, 1982). The reason is simple and straightforward: these activities are much less able to exploit economies of scale or learning-by-doing precisely because they are less repetitive and standardized. For workers they will be more interesting and will require higher levels of skill.

But what seems like an advantage in terms of job creation (especially from a European perspective) is a disadvantage from the perspective of labor productivity. The Salter cycle growth mechanism depends on economies of scale, which are much less applicable to services as such, than to products. A fundamentally different economic mechanism is needed to reduce service costs as such. One mechanism that is common

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[13] I am reminded of the Aristotelian physics where every compound was assumed to consist of some combination of the four elements, fire, water, earth and air.

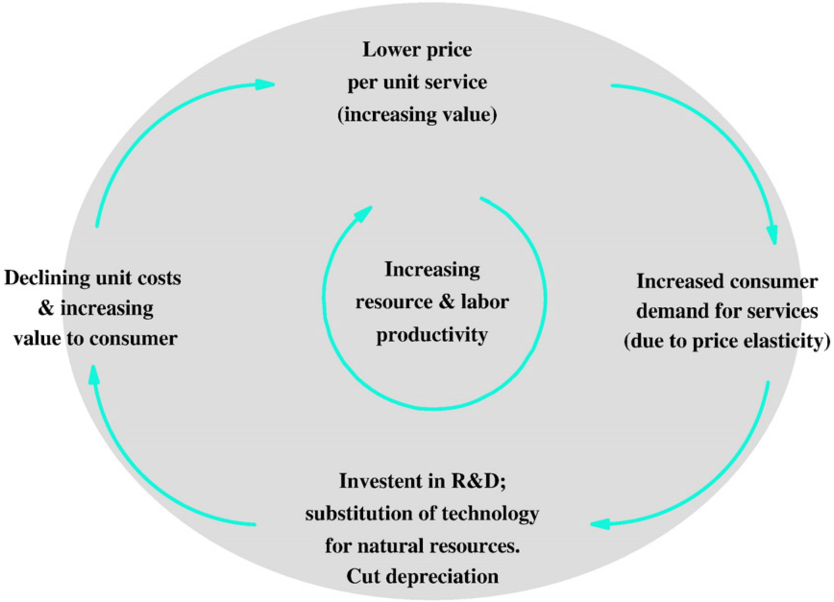

**Fig. 11 – Feedback cycle ("new" growth engine).**

to both situations is "learning-by-doing". Another mechanism for cost reduction in the service sector, now beginning to take hold, is information technology (IT). But insofar as IT, as applied to the service sector, is productivity enhancing it is also inherently job reducing, almost by definition. It can, however, help compensate for the higher costs arising from product life extension. Thus another, and increasingly important, mechanism for cost-reduction – or increased value-added – is R&D applied to the delivery of services.

Recall, once again, the long-term goal of "zero emissions" advocated by many environmentalists. Is this merely a theoretical end-point many thousands of years in the future? Or is there a plausible scenario that could get us to a reasonable approximation of the zero-emissions world within a couple of generations? I believe there is such a scenario, viz. the solar hydrogen-plus-conservation economy, although the short name does not give sufficient emphasis to the equally important future roles of wind, tidal power, biomass, photovoltaic (PV) electricity, materials recycling, ultra-light electric vehicles, and possibly nuclear electricity. Nor does it give sufficient emphasis to the shift from "throw-away product orientation" to "lifetime service orientation" (IPS) in the manufacturing sector. Another name for the scenario could be "the spaceship economy".

However it is named, I believe this scenario is inevitable in the long run, if the world does not explode into resource wars and anarchy (Klare, 2001). Of course the specific details, the regulatory incentives, the funding sources, and the timing remain quite uncertain. Progress depends in large part on technical synergies and "learning". The role of government in accelerating, or inhibiting, this technological development is also vital. But, in view of limited space, I cannot discuss either the technology or the economics in greater detail here.

To conclude: the driver of change – the imperative – is the cumulative environmental burden arising from fossil fuel use (and resulting emissions) and the higher costs that will result.[14] This burden is inconsistent with economic growth – hence unsustainable – in the long run. I trust this fact will be generally recognized as such within a decade or two at most. More specifically, it is becoming clear that cost-effective zero-emissions substitutes for fossil energy in general, and motor fuel, in particular, are needed. Hydrogen is one answer (there may be others). There are no physical laws standing in the way. The major barriers are indifference, initial costs and vested interests.

My core argument is that this combination of technological potential and demonstrated demand (reflecting a societal need) could trigger an industrial revolution of the first magnitude. Surprisingly, perhaps, none of the standard energy-economic forecasting models[15] predict such a burst of creative activity. The reason they do not may be that most energy forecasting

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[14] There are still some who believe that nuclear power is an acceptable substitute. I do not agree. Nuclear power has always been underpriced because of government financing of the R&D and special exemptions from liability. However the real problem is that costs of safe disposal of nuclear wastes were never taken into account and these costs cannot, even now, be estimated accurately or capped because no acceptable disposal technology has yet been demonstrated. Moreover, the increasingly urgent need to minimize the spread of nuclear weapons constitutes a further disincentive to future dependence on this dangerous technology. Finally, despite hundreds of billions of dollars of investment in R&D over the past four decades, there has been little progress in cost reduction. By contrast, the cost of PV power has fallen dramatically and continues to fall as the technology and scale of production advances.

[15] The best-known energy optimization models are ETA-MACRO [Manne, 1977], MARKAL [Fishbone et al., 1983], EFOM [Van der Voort et al., 1985], and MESSAGE [Messner and Strubegger, 1994]. ETA-MACRO was the first energy optimization model to be linked with a macroeconomic forecasting module. Other such combinations include MARKAL-MACRO, which uses the same economy module as ETA-MACRO and ETSAP, which also uses MARKAL [Kram, 1993].

models assume that economic growth driven by technological progress will continue automatically and indefinitely without cost or investment.[16] They also assume that energy supply is not a constraint on growth because rising prices will assure continued supply, at reasonable costs, whether in terms of new discoveries or new technologies (Energy Information Administration (EIA) 2004; International Energy Agency, 2004). And finally, they assume that the price of energy will have little if any impact on growth. All three of these assumptions are derived from standard neoclassical economic theory. But all three are dangerously out of touch with reality.

The fundamental problem is that neo-classical economic theory has no role for physical materials, energy or the laws of thermodynamics. Energy and materials exist in the theory as outputs – products and services – but not as inputs or drivers. It is fundamentally a theory about relationships between immaterial abstractions. Moreover, standard theory assumes that scarcity does not exist in reality, because any threat of scarcity is automatically compensated by rising prices that induce reduced demand and increased supply or substitution. One implausible consequence of this theory is that energy consumption can be reduced arbitrarily with no implication or consequence for economic growth. Future growth is simply assumed to be automatic, cost-free and independent of future energy costs. Thus the standard neoclassical economic theory is, in effect, "dematerialized". It needs to be "rematerialized"in the sense of incorporating the laws of thermodynamics as real constraints on possible outcomes.

Some of the evidence for these statements is incorporated in Appendices A and B which are posted on *Ecological Economics*' website.

## 8. Conclusion: towards sustainability economics

The economics of sustainability encompasses important insights from several fields of science, from thermodynamics to geology, ecology to economics, psychology and political science. Economics as the science of resource allocation, occupies the central position, in some sense. But the resources applicable to sustainability economics range from minerals to species, and from solar energy to geological and hydrological processes, as well as man-made capital and human intelligence. The core insight of classical economics, from the time of Adam Smith, was the important role of markets acting as the 'invisible hand' to regulate supply and demand, and the role of savings and investment as a driver of growth. But classical economics recognized the importance of the natural resources as land and only insofar as it produced crops for food and feed. Yet Thomas Malthus correctly foresaw more than two centuries ago the fact that natural resources have limits, though he was ludicrously wrong about the magnitudes and the immediacy of the problem.

Crucial insights of environmental economics pertain largely to the limitations of the marketplace, notably the pervasiveness of wastes and pollutants, and the necessity of enforcing a "polluter-pays-principle" or a second-best approach in the form of government regulation. The need to balance benefits and costs of pollutant treatment and abatement has been a key insight. Another was the importance of private ownership as a precondition of conservation. The fact that some resources cannot be privately owned, or can be owned only in common, has emerged as a major theme. Of course land and minerals – including fossil fuels – can be owned, but sunlight, air, flowing water and bio-diversity cannot be privatized and consequently are subject to abuse.

The critical insights of geology were that natural resources are distributed in the earth's crust according to something like a log-normal pattern, characterized by relatively small amounts of very high quality but larger amounts of progressively lower quality. It follows that extraction rates of a particular resource will tend to accelerate at first (as costs drop due to economies of scale and increasing demand) but – as in the case of petroleum and natural gas – that a time of peak output (a so-called 'Hubbert peak') will come, followed by an inevitable decline (Deffeyes, 2001).

Important insights of resource economics start with the strategy of exploitation starting with the highest quality and easiest to extract. More subtle insights pertain largely to the issue of inter-generational allocation and discounting, since high quality resources consumed in the present will not be available in the future. But resources extracted and utilized in the present do not only contribute to current enjoyment, but also to the creation of man-made capital and "human capital" that will permit more effective strategies for the discovery and exploitation of lower quality resources, or the substitution of others.

The importance of 'human capital' – or technology – as drivers of growth and as a source of substitutes for natural resources is yet another insight of recent decades.

Finally, it is only now being realized that all of these insights from different fields of science converge on the role of energy, primarily from fossil fuels, in the economic system, and the importance of energy-related pollutants as causes of environmental damage. All of these critical insights are relevant to sustainability economics.

## Appendix A. Energy, exergy, work and power

Energy is a conserved quantity. It cannot be 'consumed' or 'used up', as such. However it can (and does) become less able to perform useful work. Potentially useful work, or availability is quantifiable. By general agreement among physical scientists this quantity is now denoted *exergy*, namely the fraction of total energy that is available to perform work. (This fraction is also what most people really mean when they speak of energy.) Exergy is not conserved.

*Exergy*. There are four components of exergy, each with a corresponding type of work (Szargut et al., 1988). They are as follows: (I) *kinetic* energy associated with relative motion. Mechanical work associated with motion is exemplified by the action of a water wheel or windmill. Next, (ii) *potential field* exergy is associated with gravitational or electromagnetic field differentials. Work must be done on a mass to escape from a gravitational field or, on a charged particle, to overcome an

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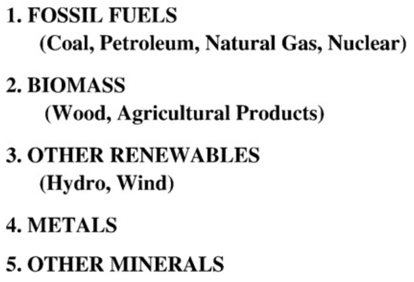
[16] A reviewer has pointed out that many theoretical and applied models (such as ETA-MACRO) actually do actually converge to long-run stationary states with constant consumption and zero net investment. This is due to declining returns to capital, which is built into the standard Solow growth model. Unbounded growth is still possible (due to continuous technological progress) but not necessary.

electrical field. The third category (iii) is *thermal* exergy (from pressure or temperature differentials). A heat engine exemplifies the conversion to work. Finally, (iv) *chemical* exergy arises from differences in chemical potential, associated with composition. Exergy types of interest are summarized in Fig. A-1.



1. FOSSIL FUELS
   (Coal, Petroleum, Natural Gas, Nuclear)
2. BIOMASS
   (Wood, Agricultural Products)
3. OTHER RENEWABLES
   (Hydro, Wind)
4. METALS
5. OTHER MINERALS

**Fig. A-1 – Exergy types.**

The exergy content of organic materials – fossil fuels, food, animal feed and other organics (wood, cotton, etc.) – is closely related to enthalpy (potential heat of oxidation) and can be calculated in a straightforward manner by multiplying mass quantities by the coefficients taken from the following Table A-1:

**Table A-1 – Typical chemical exergy content of some fuels**

| Fuel | Energy coefficient | Net heat value [KJ/kg] | Chemical energy [KJ/kg] |
|---|---|---|---|
| Coat | 1.088 | 21,680 | 23,687.84 |
| Coke | 1.06 | 28,300 | 29,998 |
| Fuel oil | 1.073 | 39,500 | 42,383.5 |
| Natural gas | 1.04 | 44,000 | 45,760 |
| Diesel gas | 1.07 | 39,500 | 42,265 |
| Fuelwood | 1.15 | 15,320 | 17,641 |

Data source: expanded from (Szargut et al., 1998).

The "other" category includes water power, nuclear power, wind power and solar power, expressed in terms of exergy input. For industrial minerals and metal ores the calculation is a little less straightforward, but not difficult (Szargut, Morris, and Steward, 1988). However, as a practical matter the only inorganic element that makes a significant contribution at the national level is sulfur, either in native form or in the form of sulfide minerals. Exergy inputs (including harvested food and feed crops) per unit of GDP for the US and Japan are plotted since 1900 in Fig. A-2. It is noteworthy that the trend for Japan is consistently less than half that for the US, meaning that Japan gets more than twice the GDP per unit of exergy input than does the US. It is also noticeable that the trend for Japan is monotonically down, whereas the US exhibits a (small) increase from 1900 to the early 1920s, after which the trend is also declining. Exergy inputs to the US economy since 1900 by type are shown, in percentage terms, in Fig. A-3. The relative importance of biomass (close to 40% of the total in 1900) has declined significantly, to about 25% in 2000. Fossil fuels have increased in relative importance during the period by roughly the same amount. Allocation to end uses, by type, are shown in percentage terms in Fig. A-4.

*Work* is usually defined as a force operating over a distance. For instance, the work done by a horse to lift a weight against gravity depends on the weight and the distance lifted. The work done by a piston to compress air or a gas depends on the force needed to overcome resistance, and the distance traveled by the piston. This is how the idea is usually explained in textbooks. However, it is important to note that work has the same units as energy and exergy, whence the ratio of work performed to exergy supplied is a pure, dimensionless number, between zero and unity, called *efficiency*.

It is convenient at this point to introduce the notion of 'quasi-work' not involving kinetic energy of motion. This refers to driving an endothermic chemical process or moving heat from one place to another across some thermal barrier. (Metal smelting is an example of the first; space heating or water heating is an example of the second.) Electricity can be regarded as 'pure' work, since it can perform either mechanical or chemical work with virtually no loss i.e. with very high efficiency. It is also convenient to distinguish primary and secondary work, where the latter is work done by electrical devices or machines. In all of these cases the physical units of work are the same as the units of energy or exergy.

Work (and quasi-work) can be estimated quantitatively by multiplying exergy inputs by an appropriate conversion efficiency. It is important to bear in mind that efficiencies vary greatly among types of work performed. Mechanical and electrical efficiencies tend to be significantly higher than thermal process efficiencies.

*Power* is the rate at which work is performed; it is work per unit time or the time derivative of work. Hence the integral of power output over time is equal to total work performed. In mechanical and electrical engineering power, measured in units of horsepower or kilowatts is more familiar than work (kilojoules or kilowatt-hours).

For purposes of empirical estimation of conversion efficiency, it is helpful to distinguish between two categories of fuel use. The first category is fuel used to do mechanical work, which means fuel driving so-called 'prime movers', including all kinds of internal and external combustion engines, from steam turbines to jet engines. (Electric motors are not included in this category, because electricity is essentially equivalent to mechanical work, as already noted. Electric power is mostly generated by a prime mover of some other sort). The second category is fuel used to generate heat *as such*, either for industry (process heat and chemical energy) or for space heat and other uses such as hot water for washing and cooking heat for residential and/or commercial users.

Historical statistics have never been compiled by official government agencies to distinguish between these two categories of fuel use, but detailed estimates for the period 1900–1998 have been compiled and published for the US (Ayres et al., 2003).

It is possible to estimate human and animal contributions to mechanical work crudely on the basis of food or feed intake, times a biological conversion efficiency adjusted for the fraction of time spent doing physical (muscle) work. However, since human labor is treated independently in economic analysis – and since human muscle power is no longer an important component of human labor in the industrial world as compared to eye-hand coordination and brainwork – we neglect it hereafter. (The magnitudes would be trivial in any case). However

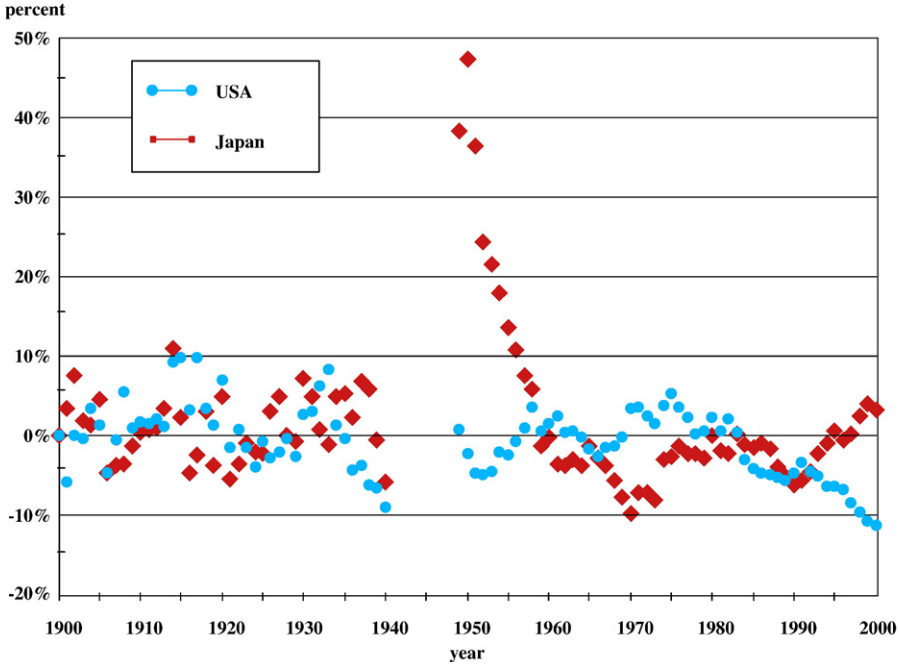


Fig. A-2 – Exergy to GDP ratio, US and Japan 1900–2000 excluding 1941–1947.

work done by animals, especially on farms, was still important at the beginning of the 20th century and remained significant until mid-century until trucks and tractors displaced horses and mules. Recent estimates by several authors converge on 4% efficiency or 25 U of feed per unit of work (Gruebler, 1998), Box 7.1 p.321 and references cited therein]. Higher precision is probably unnecessary for the quantitative estimates in the US case because the magnitude of animal work is relatively small compared to inanimate power sources. In any case, animal conversion efficiency does not change significantly over time.

This is not true of other types of energy conversion systems, of course. However official historical time series do not exist, except in the case of electric power generation, but crude estimates, for the US case, have been prepared, as shown in Table A-2 below (Ayres et al., 2003).

Electric power generation and electrical work performed (e.g. by motors or electric light) are the most efficient, while space heating and domestic cooking and hot water are the least efficient. The derivation of efficiency estimates over time (Table A-2) and Fig. A-5 is too complex to summarize here (see

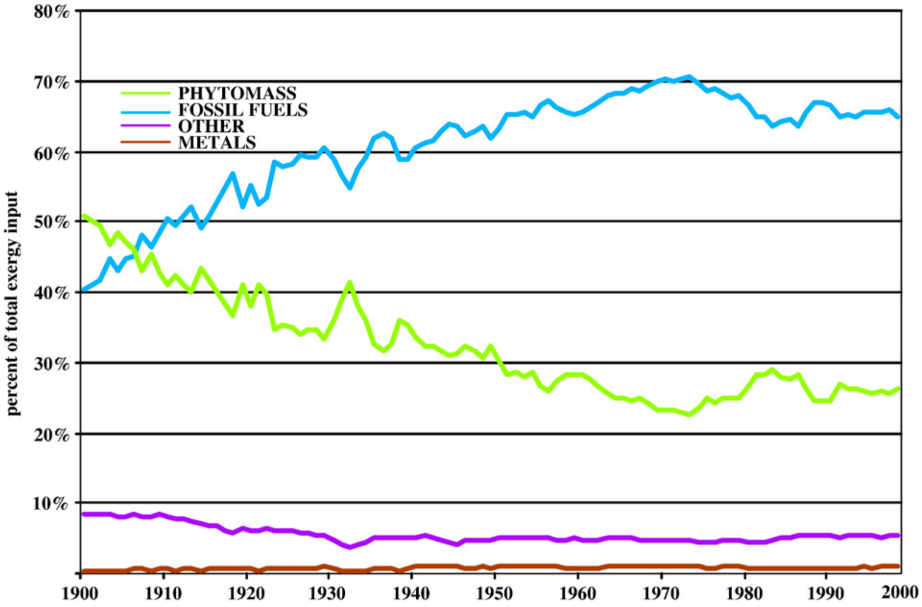


Fig. A-3 – Exergy inputs to the US economy by type: 1900–1998.

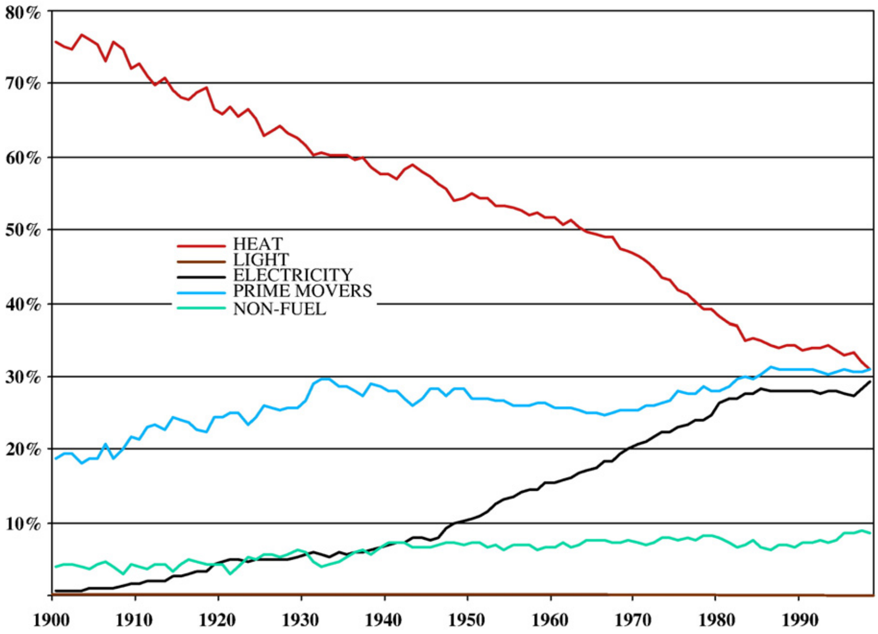


**Fig. A-4 – Percent of fossil fuel exergy consumed by type of enduse, USA 1900–1998.**

(Ayres et al., 2003)). The efficiency of electric power use by motors, lights, electrolytic cells, electric furnaces and other applications varies considerably from application to application. But overall efficiency has remained surprisingly close to 50% since 1900, since increasing efficiency for some uses (such as lighting) has been compensated by increases in the demand for low efficiency uses such as space heating (Fig. A-6). For details we refer the reader to an earlier publication (Ayres et al., 2005).

Aggregate work/GDP output by the US and Japan are plotted in Fig. A-7. It is noteworthy that this ratio rises consistently for both countries before peaking in the early 1970s. The 1973–74 peak coincides with the price spike associated with the so-called ‘energy crisis, triggered by the Arab oil embargo of 1973. Exergy-to-work efficiency ratios are plotted in Fig. A-8. It is not surprising that the Japanese economy is considerably more efficient than the US economy, but it is perhaps surprising, at first sight, that the difference is so great. The decline after 1970 reflects the exhaustion of hydroelectric sites and increasing demand for less efficient technologies such as personal automobiles.

## Appendix B. Analysis

### B.1. *Introduction*

The purpose of this Appendix is to summarize an extensive econometric analysis supporting the hypothesis that energy delivered as *useful work* (in the thermodynamic sense) is one of the three major factors of production in modern industrialized economies. Indeed, useful work has largely displaced unskilled labor as a factor of production in the US and Japan, since the beginning of the twentieth century. More extended treatments of these issues are dealt with in prior publications (Ayres et al., 2003, 2005; Ayres and Warr, 2005; Warr and Ayres, 2006).

### B.2. *Growth equations*

We conceptualize the economic system as a multi-sector chain of linked processing stages, starting with resource extraction, reduction, refining, conversion, production of

**Table A-2 – Average exergy efficiency of performing useful work, percent**

| Year | Electrical generation and distribution | Electrical work | Other mechanical work | High temperature industrial heat (steel) | Low temperature space heat 1900 |
|---|---|---|---|---|---|
| 1900 | 3.8 | 52 | 3 | 7 | 0.25 |
| 1910 | 5.7 | 51 | 4.4 | 9 | 0.4 |
| 1920 | 9.2 | 55 | 7 | 11 | 0.6 |
| 1930 | 17.3 | 55 | 8 | 13 | 0.8 |
| 1940 | 20.8 | 56 | 9 | 15 | 1.0 |
| 1950 | 24.3 | 55 | 9 | 16 | 1.2 |
| 1960 | 31.3 | 56 | 9 | 18 | 1.5 |
| 1970 | 32.5 | 57 | 8 | 20 | 2.0 |
| 1980 | 32.9 | 58 | 10.5 | 23 | 2.5 |
| 1990 | 33.3 | 58 | 13.9 | 25 | 3.0 |

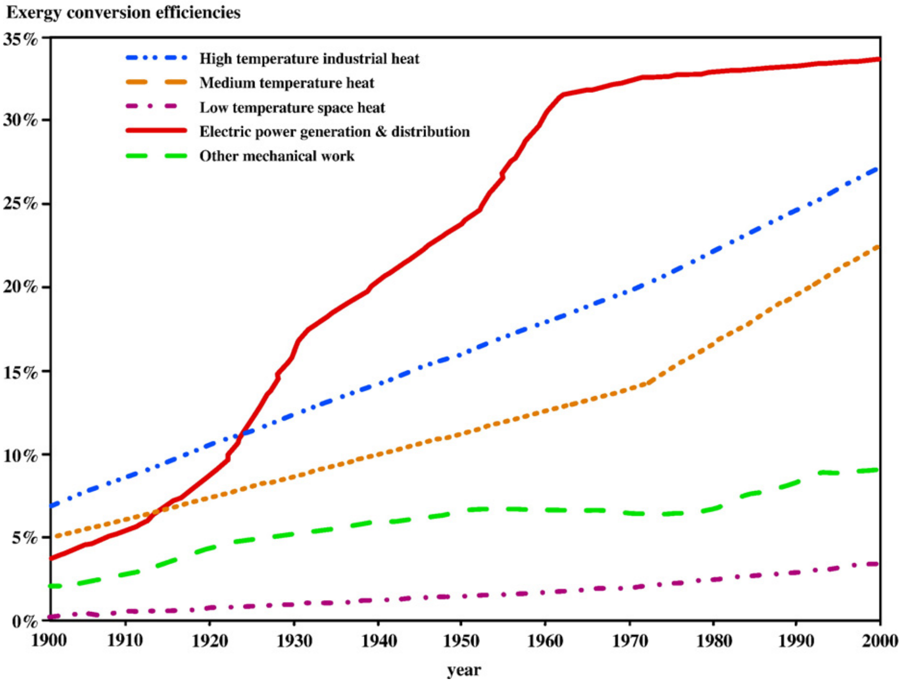


**Fig. A-5 – Energy (exergy) conversion efficiencies, USA 1900–1998.**

finished goods and services (including capital goods), final consumption (and disposal of wastes). Each stage has physical inputs and physical outputs that pass to the next stage (Fig. A-9). At each stage of processing value is added and useful information is embodied in the products, while low value, high entropy, low information wastes are separated and disposed of.[17] Global entropy increases at every step, of course, but the value-added process tends to reduce the entropy of useful products, while increasing the entropy of the wastes. An adequate description of the economic system, viewed in this way, must include all materials and energy flows, and information flows, as well as money flows. These flows and conversion processes between them, are governed by the first and second laws of thermodynamics, as well as by monetary accounting balances.

The quantitative results reported hereafter are based on a two sector, three-factor production function $Y(K, L, E, t)$ where $K$ is a measure of capital stock, $L$ is labor supply, $E$ is a variable related to energy (defined later) and $t$ is time. All variables are indexed to unity in the starting year (1900). The growth equation is the total (logarithmic) time derivative of the production function, viz

$$\frac{dy}{Y} = \alpha\frac{\partial K}{K} + \beta\frac{\partial L}{L} + \gamma\frac{\partial E}{E} + \delta\frac{\partial A}{A} \tag{1}$$

The last term reflects the possibility that some part of the growth cannot be explained in terms of $K$, $L$, $E$ and is therefore a function of time alone. This term, originally identified with technical progress, is now called total factor productivity or TFP. It cannot be accounted for within a single sector model (because a single sector model produces only a single composite product), whence it must be regarded as exogenous.

The four output elasticities $\alpha, \beta, \gamma, \delta$ are defined below, where $\delta$ can be thought of as the elasticity of "innovation" (or "creativity"in Kuemmel's words). Assuming constant returns to scale:

$$\alpha(K, L, E) = \frac{K}{Y}\frac{\partial Y}{\partial K} \tag{2}$$

$$\beta(K, L, E) = \frac{L}{Y}\frac{\partial Y}{\partial L} \tag{3}$$

$$\gamma(k, L, E) = 1 - \alpha - \beta \tag{4}$$

$$\partial(t) = \frac{t - t_0}{t}\frac{\partial Y}{\partial t} \tag{5}$$

The integrability conditions imply that the second-order mixed derivatives of the production function $Y$ with respect to all factors $K$, $L$, $E$ must be equal (Kuemmel, 1980). It follows that

$$K\frac{\partial\alpha}{\partial K} + L\frac{\partial\alpha}{\partial L} + E\frac{\partial\alpha}{\partial E} = 0 \tag{6}$$

$$K\frac{\partial\beta}{\partial K} + L\frac{\partial\beta}{\partial L} + E\frac{\partial\beta}{\partial E} = 0 \tag{7}$$

$$L\frac{\partial\alpha}{\partial L} = K\frac{\partial\beta}{\partial K} \tag{8}$$

---

[17] The language here is suggestive of an energy (or information) theory of value. Unfortunately, perhaps, the term 'value added' is so thoroughly established in economics that it cannot reasonably be avoided. In any case, we are not espousing the discredited energy theory of value. For a more thorough discussion of the economy as a self-organized system of concentrating 'useful information' see (Ayres, 1994) chapter 8.

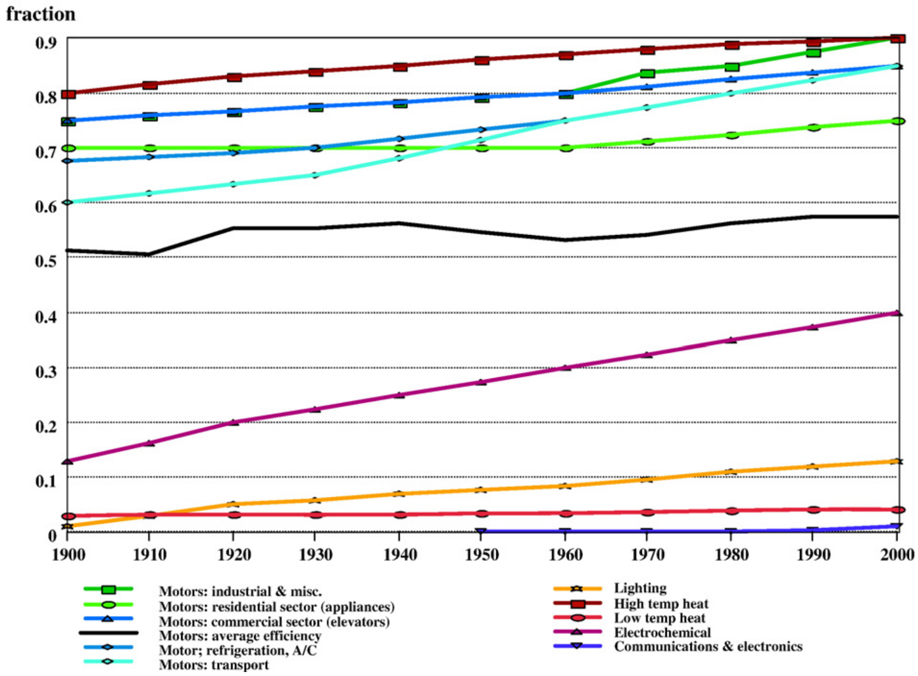


**Fig. A-6 – Efficiencies in performance; secondary work from electricity by function; US 1900–2000.**

The most general solutions to these three equations are:

$$\alpha = a\left(\frac{L}{K}, \frac{E}{K}\right) \tag{9}$$

$$\beta = \int \frac{L}{K}\frac{\partial \alpha}{\partial L} + J\frac{L}{E} \tag{10}$$

The simplest (trivial) solutions are constants: $\alpha=\alpha_0$, $\beta=\beta_0$ and $\gamma=1-\alpha-\beta$. We consider other solutions of the above equations later. For the single sector two factor case, omitting the energy variable ($\gamma=1$), one obtain the usual Cobb–Douglas form

$$Y = A(t)K^{\alpha}L^{\beta} \tag{11}$$

This is the conventional growth model with output elasticities equal to cost (payment) shares for capital and labor, respectively, in the national accounts. The usual parametric choices are $\alpha_0=0.3$ and $\beta_0=0.7$, respectively, and $\alpha_0+\beta_0=1$. $A(t)$ is the 'Solow residual', i.e. the growth component that is not

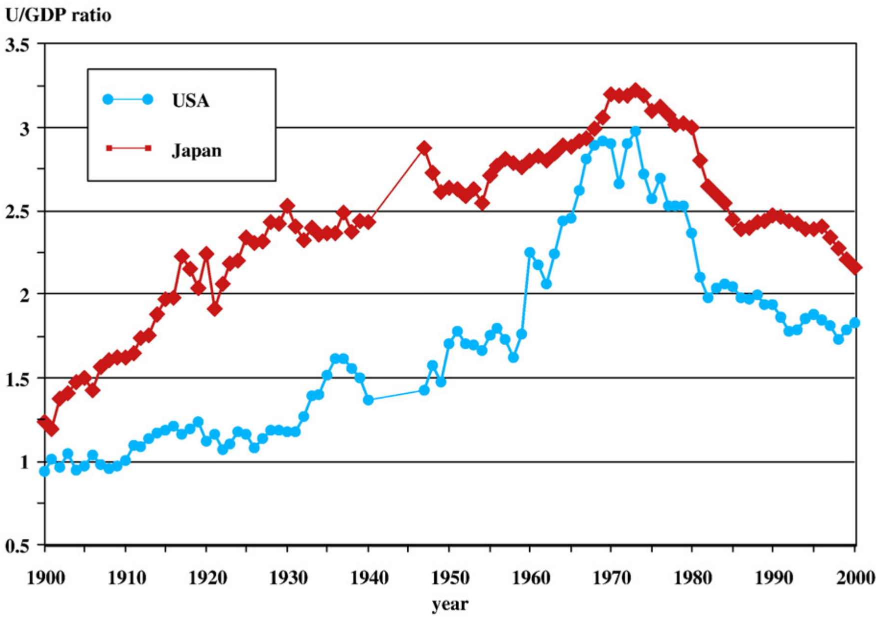


**Fig. A-7 – Useful work (U) to GDP ratio, US and Japan 1900–2000 excluding 1941–1947.**

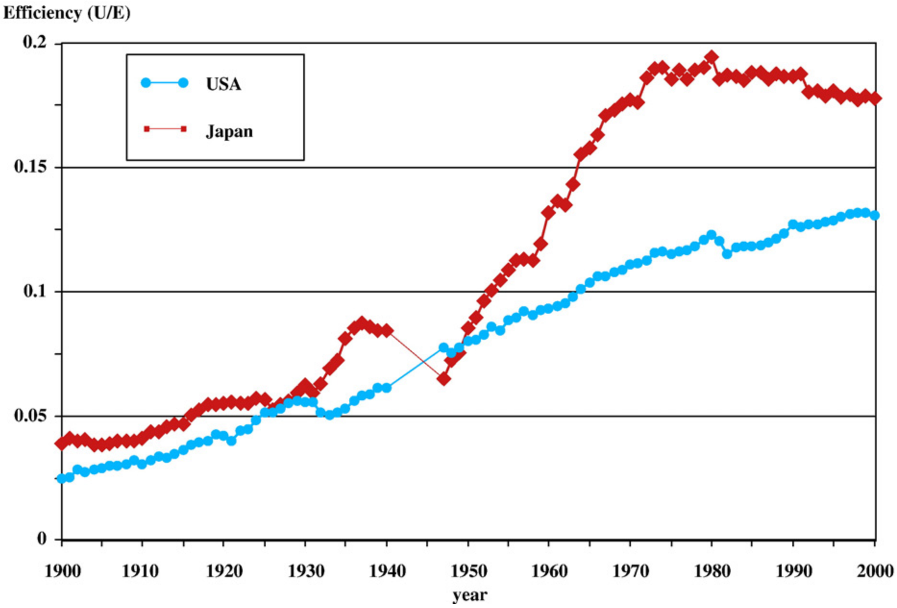


Fig. A-8 – Exergy to work efficiencies: US and Japan 1900–2000 excluding 1941–1947.

explained by either capital accumulation or increased labor supply. It is traditionally approximated as

$$A(t) = \exp[\lambda(t - 1900)] \tag{12}$$

where $t$ is the year and $\lambda=0.016$ for the US. In other words, throughout the twentieth century growth attributable to exogenous technical progress or TFP in the US has averaged 1.6% per annum, although growth was significantly slower in the 1930s and somewhat higher in the early postwar period. (Fig. A-10)

Forecasting models tend to treat this rate of TFP growth as a given, assuming that it can be expected to continue for the indefinite future. On the other hand, Japanese growth was considerably slower during the prewar period and significantly faster in the postwar era until 1992, since when it slowed down dramatically. It cannot be well approximated by a simple exponential. (An S-curve or logistic function would fit better).

The next logical step in the choice of production function is to choose the simplest *non-trivial* solutions of the growth equation and to select plausible mathematical expressions for the output

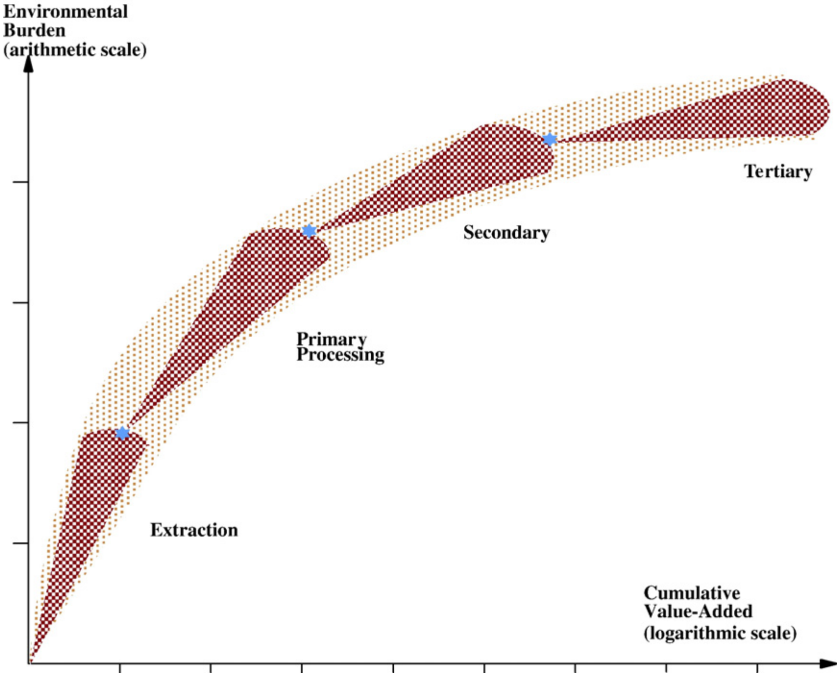


Fig. A-9 – Pollution and wastes vs. value-added.

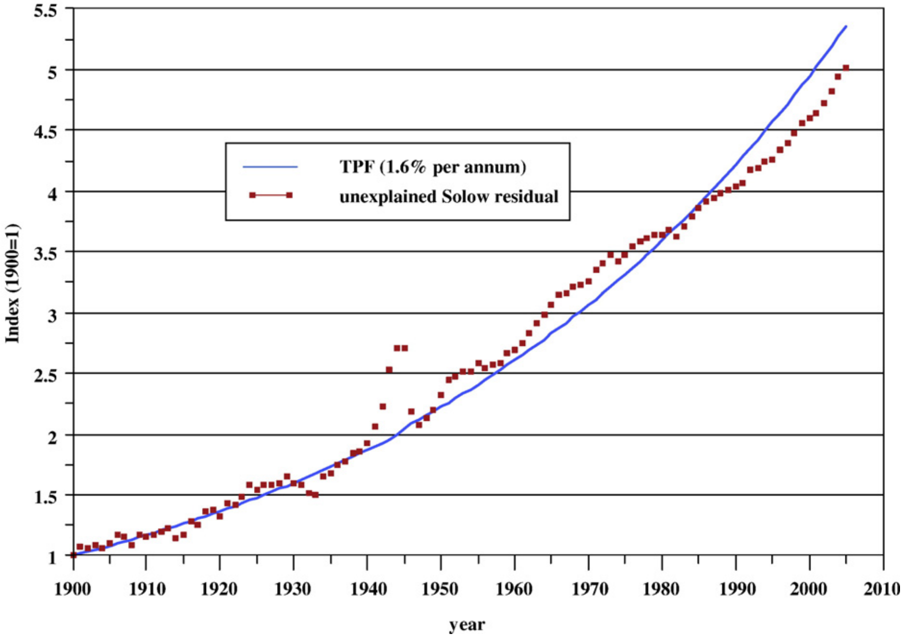


**Fig. A-10 – Technological Progress Function and Solow residual USA: 1900–2005.**

elasticities, $\alpha$, $\beta$, $\gamma$, based on asymptotic boundary conditions (Kuemmel, 1980; Kuemmel et al., 1985). To satisfy the constant returns (Euler) condition these elasticities must be homogeneous zeroth order functions of the independent variables. The assumption of constant returns to scale implies that, at every moment in time, equation (4) is satisfied. The first of Kuemmel's proposed choices can be thought of as a form of the law of diminishing returns (to capital). It is an asymptotic boundary condition conveying the notion that even in a hypothetical capital intensive future state in which all products are produced by machines, some irreducible need for labor $L$ and exergy $E$ will remain, viz

$$\alpha = a\frac{L+E}{L} \tag{13}$$

Kuemmel's second equation reflects the continuing substitution of labor by capital and exergy as capital intensity (automation) increases:

$$\beta = a\left(b\frac{L}{E} - \frac{L}{K}\right) \tag{14}$$

The corresponding production function is then obtained by partial integration of the output elasticities yields the linear-exponential (LINEX) form (Kuemmel, 1980; Kuemmel et al., 1985):

$$Y = AE\exp\left[a(t)\left(2 - \left(\frac{L+E}{K}\right)\right) + a(t)b(t)\left(\frac{L}{E} - 1\right)\right] \tag{15}$$

The functions (of time) $a(t)$ and $b(t)$ have been characterized by Kuemmel as 'capital efficiency' and 'energy demand' respectively. The resulting time-dependent elasticities of output are then determined by fitting the above functional form to real GDP from 1960 to 2004 for the UK, Germany, Japan and the US. Allowing the time dependent parameters $a(t)$ and $b(t)$ the GDP fits are extremely good (Kuemmel et al., 2000). On the other hand, neither $a(t)$ nor $b(t)$ *really* has a straightforward economic interpretation. Hence, such a model cannot be a reliable basis for forecasting. However, the resulting (calculated) time-dependent elasticities show a significant increase in exergy elasticity and a decline in labor elasticity, over time.

### B.3. *A new variable: useful work U*

We now introduce a two sector model with a third factor consisting of 'useful work' (denoted $U$), discussed in Appendix A, which is also the output of the first sector. By definition, $U$ is the product of resource (exergy) inputs $E$ times a conversion efficiency $f$. $U$ has the same dimensions as $E$, since $f$ is dimensionless. Capital, labor and useful work are not mutually substitutable; indeed there is some complementarity and interdependence between capital and work, and between labor and work. Thus the third factor $U$ is not truly independent of capital and labor. This means that not all combinations of the three factors $K$, $L$, $U$ are possible. (Some combinations, including extreme cases like $K=0$, $L=0$ or $U=0$ are impossible.) Capital and work have a strong synergy. In fact, capital – except for residential housing and money – can be defined for our purposes as the collection of all energy-conversion machines and information processing equipment, plus ancillary structures to contain and move them (Kuemmel, 1980). Thus capital goods are activated by energy (exergy), while exergy has no economic function in the absence of capital goods.

As a first approximation, it is now convenient to assume that the economy is a two stage system with a single intermediate product, to be defined in a moment. (This assumption is not unreasonable, bearing in mind that most of economic growth theory to date postulates a single-stage, single sector, composite product model.) The product of the primary sector (Sector 1) can be thought of as "energy services". For our purposes, energy

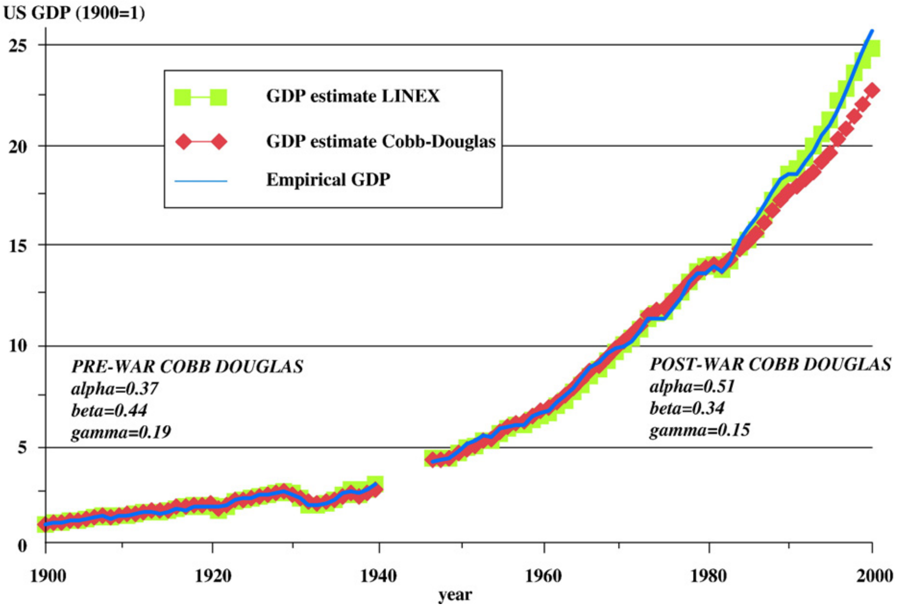


**Fig. A-11 – Empirical and estimated GDP, US 1900–2000 excluding 1941–1948.**

services can be defined more rigorously as "useful work" $U$ in the thermodynamic sense. Useful work includes muscle work by animals or humans, electricity, mobile engine power as delivered (e.g. to the rear wheels of a vehicle) and useful heat, as delivered in a space in a building or in a process. A full explanation of how these terms are defined and quantified can be found in another publication (Ayres and Warr, 2003).

Simplifying (13) we get:

$$Y = Efg = Ug \qquad (16)$$

where $f$ is the overall technical efficiency of conversion of 'raw' exergy inputs $E$ into useful work output $U$, as shown in Fig. A-8.

### B.4. *Statistical analysis of the time series*

Before we can have great confidence in the outcome of calculations with a production function, especially if after introducing a new and unfamiliar factor of production, it is desirable to conduct a number of statistical tests. In particular, we need to ascertain the presence of unit-roots, structural discontinuities, cointegrability and Granger-causality. The five economic variables in question are capital $K$, labor $L$, energy (actually exergy) $E$, useful work $U$ and output (GDP) $Y$.

To do statistical analysis on time series variables, they must be converted to logarithmic form, to eliminate any exponential time trend. But the logarithmic variables may or may not be stationary (trend-free with finite variance and co-variance) as required for the application of standard statistical procedures such as OLS. In general, we find that the time series (of logarithms) are not stationary i.e. they have 'unit roots'. The first question is whether the unit root is 'real' (i.e. due to a missing variable) or whether it is due to an external shock or structural break (discontinuity) in the time series. In general, we find that the latter interpretation suffices. Structural breaks can be attributed to wars, hyper-inflations, currency devaluations, depressions, or other major events such as the "oil crisis" of 1973–74.

Structural breaks can be identified most easily by examination of the residuals of several model. However, different models suggest possible breaks in different places. This is troublesome, because there is an element of circular logic involved, in that the models, in turn, depend on the locations and magnitudes of the structural breaks. However, when different models (such as Cobb–Douglas and LINEX ) are consistent in the sense that they show significant deviations in the same place, and when those deviations are easily explained in terms of exogenous events, it is reasonable to interpret them as structural breaks. To make a rather long story short (we have tested literally dozens of combinations), it turns out that the period of WW II (1942–45) is the only break that needs to be taken into account in both the US case and the Japanese case.[18]

We have carried out extensive cointegration analysis and Granger causality tests. A complete description of the lengthy statistical testing procedures involved, not to mention the underlying rationale, is far too complicated and specialized to reproduce here. The most robust result is that both exergy and useful work are causally related to output, and *vice versa*. In other words (as intuition also suggests) the causality is mutual.[19]

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[18] We note in passing here that for both countries there are several 'mini-breaks' that suggest the possibility of re-calibration of the model parameters. The leads, in practice, to a series of 'mini-models' covering as few as twenty or thirty years. However, an obvious constraint that is impossible to incorporate explicitly in the mathematical optimization process is the need for each variable to be continuous across breaks. Ignoring that condition leads to extremely implausible results.

[19] The full story can be found in an IIASA interim report which has been submitted for publication. It is available to specialists from the web.

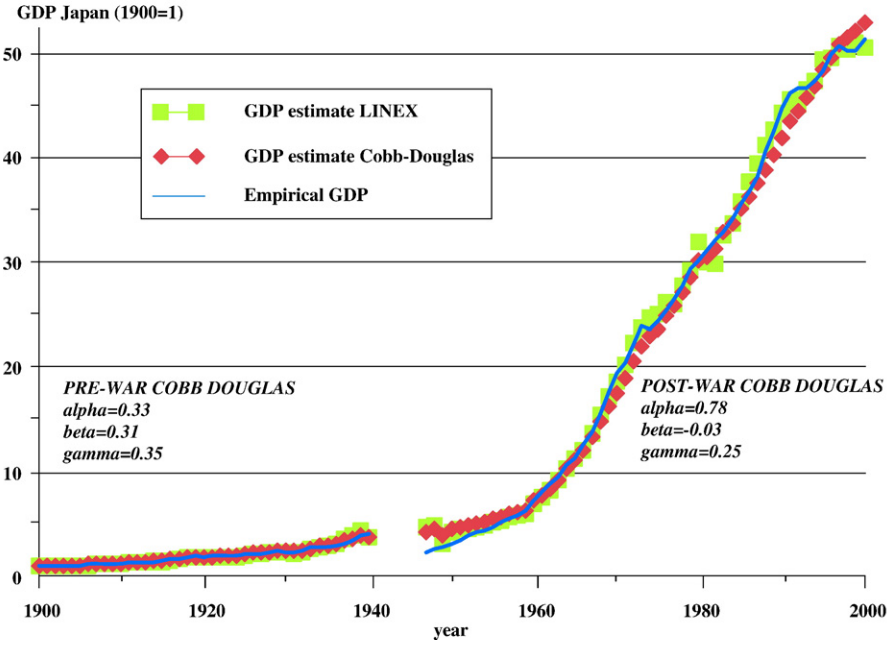

**Fig. A-12 – Empirical and estimated GDP, Japan 1900–2000 excluding 1941–1948.**

### B.5. *The choice of production function*

The Cobb–Douglas function is over-simplified in an important respect: it assumes constant elasticities of output. It is not realistic to assume constant elasticities over the entire century from 1900–2003. On the other hand, the model can be used for shorter periods separated by well-defined structural breaks. The essential result that we need to take into account is that exergy and, especially useful work, are important drivers of growth, and that their importance have increased throughout the century. We expect that the imputed marginal elasticity of resource (exergy) inputs will be much greater than the factor-payments (cost) share, as already suggested by others (e.g. (Kuemmel et al., 1985, 2000; McKibben and Wilcoxen, 1994, 1995; Bagnoli et al., 1996).

As already noted, we reject the traditional single sector, composite product model, on the grounds that the very act of isolating commercial energy as an output of the extractive industry (coal, oil, gas) constitutes a *de facto* sectorization. The Cobb–Douglas model using exergy $E$ as a third factor can be implemented by defining a sectoral boundary between extraction and downstream processing and service sectors. It is easy to show that that version of the model does not explain past economic growth. Our alternative version, however, incorporates 'useful work' $U$ as a third factor. The sectoral boundary shifts from extraction to include primary processing of fuels, electricity generation and usage (in motors, lighting, etc) and work done by mobile internal combustion engines (Ayres et al., 2003). It will be seen that this version of the model does have explanatory power.

**Table B-1 – Statistics of fit**

| | 1900–1940 | | 1947–2004 | |
|---|---|---|---|---|
| | Cobb–Douglas | LINEX | Cobb–Douglas | LINEX |
| *USA* | | | | |
| Dublin–Watson | 0.59 | 1.72 | 0.03 | 0.15 |
| Dickey–Fuller | −1.816* | −5.427*** | 3.540 | 2.306 |
| $R^2$ | 0.987 | 0.994 | 0.997 | 0.999 |
| *Japan* | | | | |
| Dublin–Watson | 0.55 | 0.96 | 0.11 | 1.10 |
| Dickey–Fuller | −1.317 | −3.162*** | −1.451 | −4.355*** |
| $R^2$ | 0.985 | 0.991 | 0.999 | 1.000 |

Critical test values for the Dickey–Fuller unit–root test *90%–1.606 **95%–1.950 ***99%–2.366.

Obviously useful work is required for its own production, as trucks carry coal to power plants and electric power is used in coal mines. It seems reasonable to postulate, as a first approximation, that capital, labor and useful work are used *in the same proportions in the production of useful work U as they are in the economy as a whole*. In fact, we assume that the mathematical form of the production functions $Y_1$, $Y_2$ and $Y$ are identical, except for a constant multiplier.

This being so, it follows that

$$\frac{K-K^*}{K}=\frac{L-L^*}{L}=\frac{U-U^*}{U}=\lambda \tag{17}$$

whence we can write

$$K-K^*=\lambda K \tag{18}$$

$$L-L^*=\lambda L \tag{19}$$

$$U=U^*=\lambda U \tag{20}$$

It follows that

$$Y_1(K^*,L^*,U^*)=(1-\lambda)Y(K,L,U) \tag{21}$$

$$Y_2(K-K^*,L-L^*,U-U^*)=\lambda Y(K,L,U) \tag{22}$$

and therefore

$$Y_1+Y_2=Y \tag{23}$$

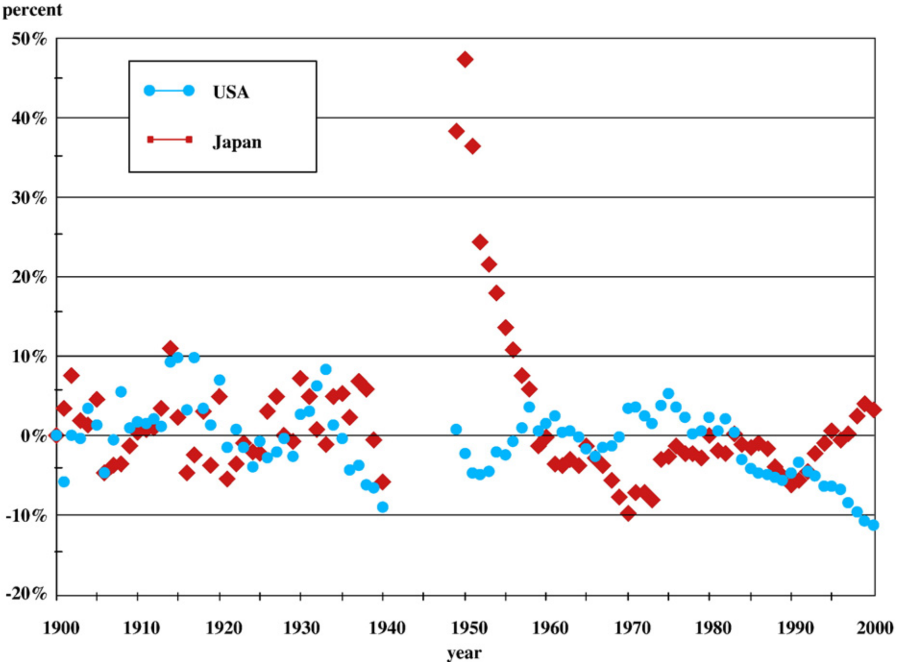

**Fig. A-13 – Cobb–Douglas residuals; US and Japan 1900–2000 excluding 1941–1948.**

We note that the above logic applies to *any production function that is homogeneous and of order unity*. The Cobb–Douglas function is a special case, in which the parameters $\gamma$, $\mu$, and $\xi$ are set equal to zero and $0<\alpha$, $\beta<1$. The more general LINEX function, adapted from (Eq. (16)) by substituting useful work $U$ for exergy $E$ is as follows:

$$Y = AE\exp\left[a(t)\left(2-\left(\frac{L+E}{K}\right)\right)+a(t)b(t)\left(\frac{L}{E}-1\right)\right] \tag{24}$$

As noted earlier, the functions (of time) $a(t)$ and $b(t)$ have been characterized by Kuemmel as 'capital efficiency' and 'energy demand' respectively. However, energy demand presumably would have to be reinterpreted as 'work demand'.

### B.6. Results

Figs. A-11 and A-12 show the hundred year GDP history of the two countries, US and Japan, respectively, together with the Cobb–Douglas and LINEX model fits, incorporating $U$ as a third factor in the production functions. Note that all the fits are nearly perfect during the prewar period, making the different

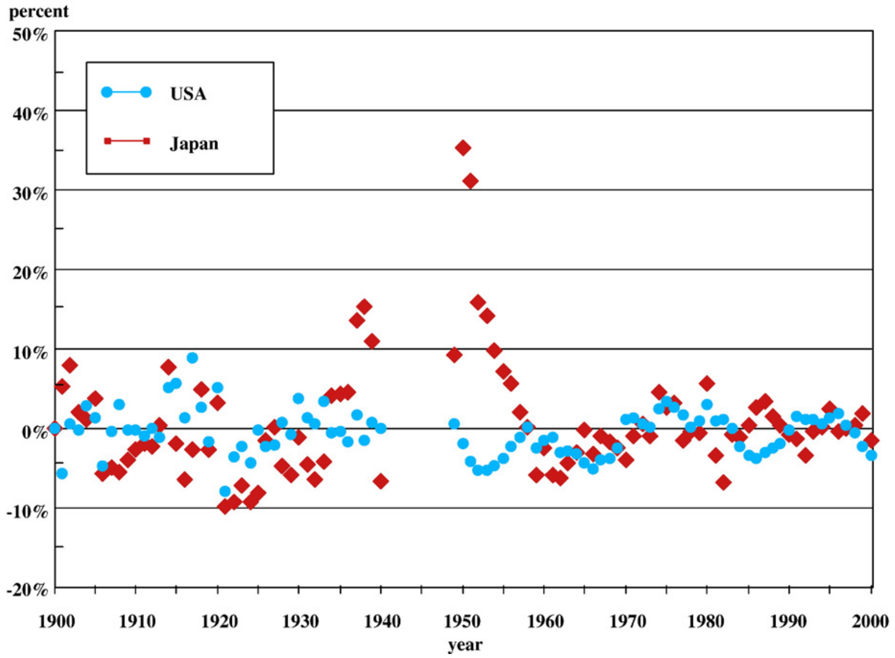

**Fig. A-14 – LINEX residuals, US and Japan 1900–2000 excluding 1941–1948.**

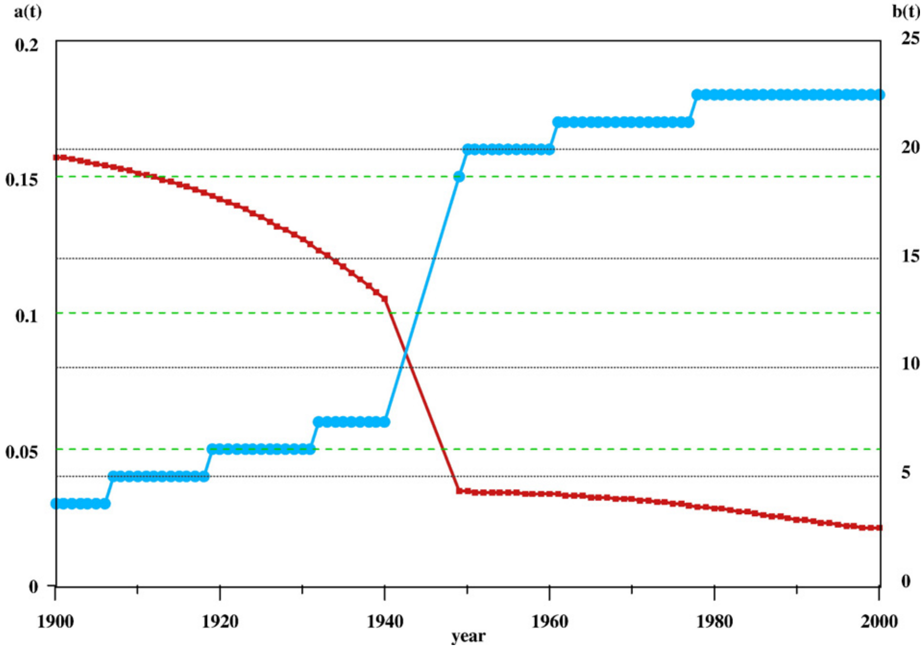

**Fig. A-15 – Parameters of the LINEX function US 1900–2000.**

models hard to distinguish. Table B-1 shows the statistics of the fits, for the cases where the two periods are fitted separately. (The statistics for the other case, where the fits are done for the whole period, are less good, as one would expect). Both the Cobb–Douglas and LINEX fits indicate a growing deviation between empirical and calculated GDP after 1990. We have reason to believe that this gap reflects the contribution of information and computer technology to economic growth, especially in the US.

Note that the $R^2$ measures are quite good, even for the Cobb–Douglas models, but the $R^2$ values are significantly better for the LINEX model, both prewar and postwar. The DW statistics are good for LINEX US prewar and for Japan postwar, but poor in the other two cases. We think this is because we have had to estimate the useful work output and the estimation procedure involves smoothing. This procedure can introduce some inadvertent serial correlation in the residuals. The Dickey–Fuller test for stationarity of the residuals is bad for all the C–D fits (not surprising) but quite good for the LINEX case for prewar US, and Japan, and also for postwar Japan. This is evidence of cointegration. The Dickey–Fuller test for stationarity (the unit-root test) is poor for the US

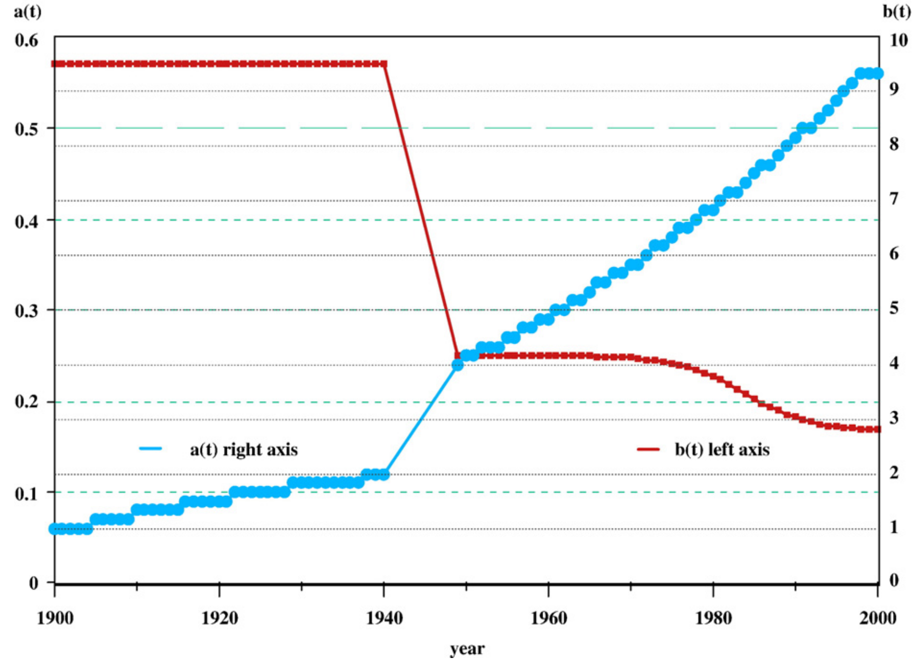

**Fig. A-16 – Parameters of the LINEX function Japan 1900–2000.**

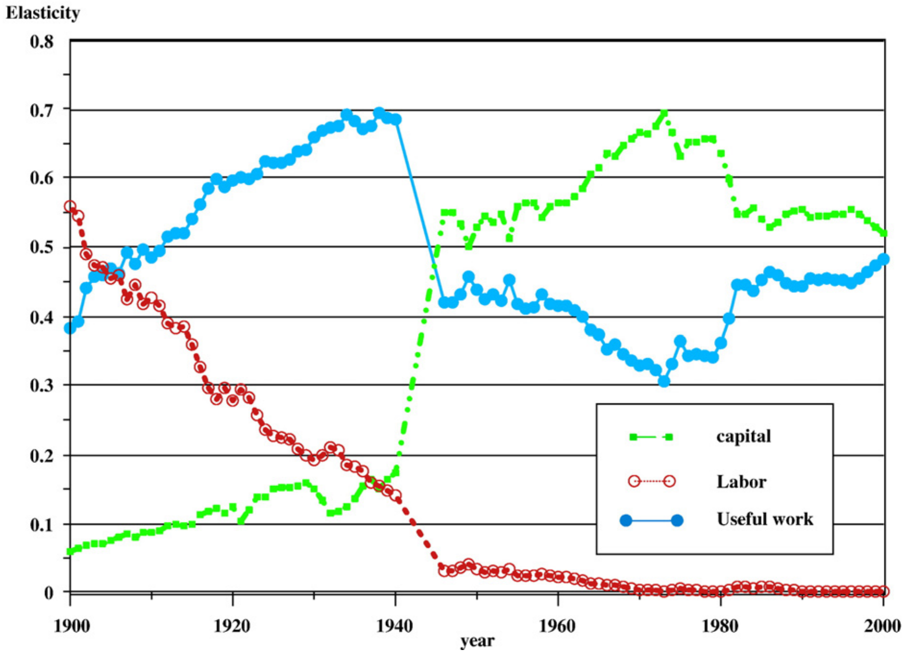

**Fig. A-17 – Elasticities of factors of production LINEX function: US 1900–2000 excluding 1941–1947.**

postwar, suggesting that as many as three 'mini-breaks' occurred during that period. As mentioned previously, such breaks may be associated with exogenous events such as wars, the "oil crisis" or major macro-economic policy changes.

The residual errors for the Cobb–Douglas and LINEX models, fitted over whole 100 year span, both with and without an adjustment for the break caused by WW II are given in Figs. A-13 and A-14 for the US and Japan respectively. The LINEX models incorporate S-curve "bridges" $a(t)$ and $b(t)$ to connect the prewar and postwar elasticities. These are plotted in Figs. A-15 and A-16. Evidently we can account quite well for economic growth in both countries without any requirement for an exogenous time-dependent multiplier, the traditional $A(t)$. In effect, the productivity gains (TFP) are essentially explained by the use of the $U(t)$ variable in the production function. The theory has effectively endogenized economic growth.

Finally the calculated output elasticities for the LINEX models of the US and Japan, respectively are shown in Figs. A-17 and A-18. The elasticities for the Cobb–Douglas case are, of course, constants, as shown in Table B-2.

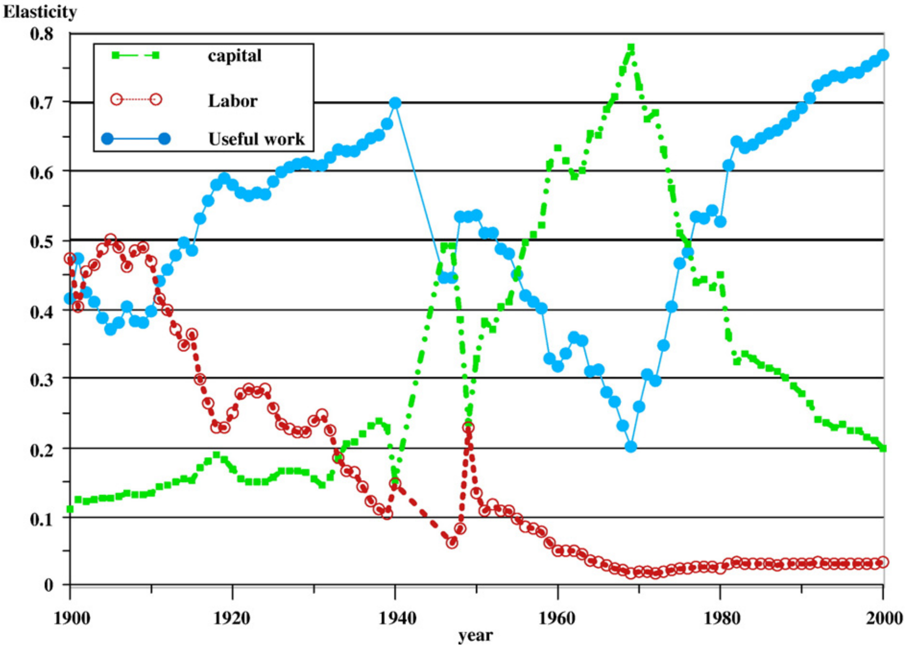

**Fig. A-18 – Elasticities of factors of production LINEX function: Japan 1900–2000 excluding 1941–1947.**

**Table B-2 – Fits of production functions**

| | Coefficients of Cobb–Douglas models | | |
|---|---|---|---|
| | Capital (*a*) | Labor (*b*) | Useful work (1 – *a* – *b*) |
| *USA* | | | |
| 1900–1940 | 0.33 ± 0.064 | 0.31 ± 0.038 | 0.35 |
| 1947–2004 | 0.78 ± 0.037 | −0.03 ± 0.018 | 0.25 |
| *Japan* | | | |
| 1900–1940 | 0.37 ± 0.094 | 0.44 ± 0.033 | 0.19 |
| 1947–2004 | 0.51 ± 0.038 | 0.34 ± 0.009 | 0.15 |

Coefficients of logistic-type models: LINEX parameters *a*(*t*), *b*(*t*)

| | *k* | *p* | *q* | *r* |
|---|---|---|---|---|
| *USA 1900–1940* | | | | |
| *a*(*t*) | 0.08 | 97.86 | 10.26 | |
| *b*(*t*) | −4.12 | 80.85 | 63.04 | 2.60 |
| *USA 1947–2004* | | | | |
| *a*(*t*) | 0.19 | 107.60 | 11.50 | |
| *b*(*t*) | −0.27 | 53.44 | 89.10 | 0.47 |
| *Japan 1900–1940* | | | | |
| *a*(*t*) | 0.13 | 74.24 | 6.38 | |
| *b*(*t*) | −0.06E-06 | 80.88 | 62.80 | 1.17 |
| *Japan 1947–2004* | | | | |
| *a*(*t*) | 4.53 | 233.62 | 202.74 | |
| *b*(*t*) | −0.23 | 18.02 | 84.88 | 0.69 |

Where

$$a(t) = \frac{k}{1 + e\left[\frac{\ln 81}{P}\left(\mathrm{time} - 1900 - q\right)\right]}$$

$$b(t) = \frac{k}{1 + e\left[\frac{\ln 81}{P}\left(\mathrm{time} - 1900 - q\right) + r\right]}$$

There are several other strong implications.

(1) One can now be quite certain that exergy (as delivered in useful work) is indeed a third factor of production, in agreement with economic intuition, if not with some earlier authors. In fact, the calculated elasticity of energy as useful work is up to ten times higher than those earlier estimates based on the factor share assumption.

(2) Future economic growth depends essentially on continued declines in the cost of primary exergy and/or on continued increase in the output of useful work from a decreasing exergy input. As a consequence, it is no longer realistic to project economic growth at historical rates indefinitely into the future. Energy prices are almost certain to increase, both because of increased demand and because of the need to cut greenhouse gas emissions. If the rate of technological progress in conversion efficiency slows down, economic growth will slow down as well. It can no longer be assumed without question or doubt that "our children and grandchildren will be much richer than we are" as quite a few economists have asserted. Though not discussed in the paper it is clear that policies that can deliver a "double dividend" in the sense of decreasing carbon-based fuel consumption and greenhouse gas emissions, while simultaneously cutting costs, must be sought more intensively than ever before.

(3) The results displayed in this paper graphically display the dramatic substitution, during the past century, of '*useful work*' (mostly by fossil-fuel-powered machines) for muscle work by humans and animals. Labor, in the absence of machines and sources of power, is now nearly unproductive at the margin, at least on the macro-scale. This result holds for both the US and Japan. In effect, labor is no longer scarce. One more unskilled worker, without tools and mechanical or electrical power, adds almost nothing to the economy. This has important implications for the future. It contradicts the assertions by many politicians and pundits that a declining birthrate needs to be reversed. On the contrary, the declining birthrate is more hopeful than worrisome.

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