Working Paper

Industrialization as a Historical Phenomenon

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WP-95-29
March 1995

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Abstract

Industrialization is shown as a time-specific and spatially heterogeneous process. The description of industrialization paths uses two concepts along a functional/temporal and a spatial dimension: *Technology clusters,* i.e., a set of interrelated technological, institutional and social innovations, drive particular (historical) periods of industrial output and productivity growth. A spatial taxonomy reflects the different degrees of development and intensiveness of industrialization among *core, rim,* and *periphery.*

In an inductive approach, industrial growth is described through the prism of changes in *technology clusters* and the spatially heterogeneous diffusion of industrialization on a global scale. "Industrialization paths" are discussed on the basis of the USA, Western Europe, Russia and Japan. The quantitative description focuses on macro-level indicators of industrial output, and the evolution of the productivity of factor inputs labor and energy. Energy intensiveness and carbon emissions are used as metric to assess changes in the environmental impacts of various industrialization paths, concluding that improvements in the efficiency of factor input use are part of the inherent incentive structure of industrial evolution. However, historical improvement rates will have to be considerably accelerated to lower absolute levels of industrial emissions.

Finally, the implications of industrial productivity growth and its distribution in the form of rising incomes (consumption) and free time (leisure) are discussed *inter alia* from an environmental perspective.

1. Introduction

Industrialization is a process of structural change. Sources of productivity and output growth as well as of employment move away from agriculture towards industrial activities, in particular manufacturing (Figures 1 and 2). Rising productivity and output in industry have been the main drivers for economic growth and increased national and per capita incomes, which in turn provide an ever enlarging market for industrial products for the building of social infrastructures and in form of consumer goods.

Like any pervasive process of economic or social change, industrialization is driven by the diffusion of many individual (but interrelated) *innovations*. These are not only of technical nature, but also organizational and institutional, transforming the entire social fabric of society. Also technology leading to vastly rising output, improved factor productivity, to new forms of production, products and markets, is at the core of the industrialization phenomenon, social and organizational innovations are of no lesser importance. In fact, the term "industrial society" has come to describe a particular way of economic and social organization, from science and industrial management to the fine arts. An industrial society is based pervasively on the economics of standardization and specialization of human activities to produce, not only ever more, but paradoxically, also an ever *larger variety* of final products.

Since the middle of the 18th century, the onset of what has been termed* the "Industrial Revolution", global industrial output and productivity have risen beyond the imaginable. Table 1 summarizes a few macro-indicators illustrating the present size of industrial activities on a global scale. We also include transportation activities (ton-km transported) because ultimately all goods tonnage shipped originates either as an industrial product or is processed at some stage by industry. From a quantitative perspective it is interesting to note that the 3 TWyr final energy consumed (corresponding to some 3 Gt coal equivalent) and its related 2 Gt of carbon emissions (including emissions stemming from the generation of electricity consumed by industry) rival the tonnage of the most important (in terms of weight) commodities produced and/or processed by industry.

*This term (Toynbee, 1884) with its implicit concept of discontinuity may in fact be a misnomer, ignoring the important developments in proto-industrial societies paving the way to accelerated rates of change since the mid-18th century. For a concise discussion see Cameron (1989).

Table 1. Basic Activity Data, Industry, AD 1990 (Source: Economist, 1990; ILO, 1991; IRF, 1991; UN, 1990).

	10^6 people employed	10^9 \$ value added	10^6 tons 7 major commodities[1] produced	10^{12} ton-km transported	GWyr final energy consumed (w/o feedstocks)	10^6 tons carbon emissions[2]
Market economies	130	4632	1095	6	1164	766
Reforming economies	80	975	515	8	851	584
Developing economies	300	1068	895	8	1116	733
World	510	6675	2505	22	3131	2083

1 In decreasing order of global tonnage: cement, steel, paper, fertilizer, glass, aluminum, copper.

2 Including manufacture of cement, carbon emissions from electricity production allocated to industry in proportion of industrial to total electricity consumption.

Industry thus is indeed a powerful agent of global change. It accounts for about 20 percent of employment, and 40 percent of value added, final energy consumption, and industrial carbon emissions, respectively. However, the relative weight of industry in anthropogenic activities varies widely in time and space primarily as a function of the degree of industrialization and the overall level of economic development. Especially the dominance of industry in the material, energy and "smoke stack" intensive economies of Central and Eastern Europe and the former USSR are clearly discernible in Table 2.

Table 2. Industry's Share in Anthropogenic Activities, A.D. 1990.

	% Share in			
	Employment	Value Added	Final energy (excl. feedstocks)	Carbon emissions[1]
Market economies	34.0	33.0	31.5	31.9
Reforming economies	40.1	59.3	52.6	46.7
Developing economies	16.9	36.8	36.3	47.9
World	21.6	37.4	37.3	38.7

1 Emissions from cement and for supply of electricity and heat included, biomass excluded.

In this paper we will try to sketch out the pathways of industrialization which have brought us to the present. We will in particular discuss the importance of technological and social change in the industrialization process and the course of various industrialization paths pursued in history. From a quantitative perspective, industrialization is indeed a success story in human history (though perhaps with mixed blessings). Based on updated estimates of Bairoch (1982), the global industrial output has risen by about a factor 100 since around 1750. Over the last hundred years, industry has grown by a factor of 40, or at an annual growth rate of about 3.5 percent per year. Per capita industrial production increased over the same time period by a factor of about 11, or at a rate of 2.3 percent per year. This means that rising per capita activity levels were a more powerful agent of change than human population growth. Despite the inherent inaccuracy of such long-term estimates, which additionally do not take into account the improvements in quality and variety of industrial products produced, they nevertheless provide an idea about the order of magnitude of the industrialization phenomenon.

The growth in industrial labor productivity was even more spectacular than output growth. Again the data are uncertain, but even the recent quantitative evidence does not change the impressive account of industrial productivity growth emerging from Colin Clark's (1940) classical *Conditions of Economic Progress.* Quantitative time series on industrial productivity growth (presented in more detail in the subsequent discussion) indicate a factor 200 (perhaps even more) improvement since the middle of the 18th century. Thus, an industrial worker in the US produces today in one hour what took an UK laborer two weeks of toiling 12 hour days of work some 200 years ago.

The growth in labor productivity perhaps best illustrates the crucial role of technological and organizational change in the industrialization process. In emphasizing technological, social and organizational innovations as drivers of industrial growth, we might ask what about natural resource endowments? Is the availability of energy and mineral resources not a *conditio sine qua non* for industrialization? Here we are inclined to consider resource availability as of secondary importance, especially for the industrial system based on spatial division of primary (raw materials) and secondary (manufacturing) activities that emerged with the availability of transportation systems, especially in the 19th century (sail ships and canals, followed by railways and steam-ships). First, without technology no natural resource can be harvested and processed for input to industrial activities. Secondly, the availability and quantity of resources itself is also a function of technology. Geological knowledge, exploration and production technologies, etc. are all important determinants for the quantity of resources available to humanity, and especially for the expansion of the resource base (cf. the case of off-shore oil). Thirdly, technology development can provide for *substitutes* such as the replacement of natural nitrate by man-made fertilizers, or natural by synthetic rubber.

Thus, in our interpretation, the different degrees of development and industrialization are *technology gaps* resulting from differences* in

* Note here the important enlargement of the traditional definition of comparative advantage. Whereas the classical definition revolves around the comparative prices of factor inputs (resources, labor, capital, etc.) modeled via a production function approach, "technology gaps" in addition account for differences in combinations and intensities of factor inputs which cannot be explained solely on basis of their price differences. For a more detailed discussion see in particular Dosi *et al*, 1990.

accumulation and innovativeness, and not from endowments or scarcity. Innovative capacity (and thus production, income and growth possibilities) is thus *created* (among others by an appropriate socio-institutional framework), and not given.

Historical analysis indicates a number of cases where successful industrialization was achieved even with only modest national natural resource endowments (e.g., France, Scandinavia, Austria, Japan). Considering the resource and environmental intensiveness of different industrialization paths (discussed below), the abundance of resources even appears as a mixed blessing as it can lead to persistently higher intensity trajectories of development. From such a perspective, one might wonder if coal-rich China will develop along the energy-intensive development path of the US, or alternatively along more energy-efficient pathways of industrialization along the French or Japanese experience.

Before we proceed further with an overview of various phases of industrialization and a discussion of selected examples, we start with a few definitional and conceptual remarks. Any artifact or operational practice supplanting existing ones can be considered an *innovation*. However, innovations encompass a whole continuum from small-scale, incremental changes affecting a particular industrial activity, to pervasive changes affecting the functioning and behavior of the entire economy and society at large.

1.1. A Taxonomy of Innovations

Incremental Innovations

Occurring more or less continuously across all industry or service activities, incremental improvements resulting from scientific research and development, engineering (e.g., the scale-up of plants and equipment) and "learning by doing" improve the efficiency in use of all factors of production. Although the combined effect of incremental innovations is extremely important, no single innovation by itself will have a dramatic effect, and in most cases it will pass unnoticed and unrecorded. For the present context, we note the importance of the *cumulativeness* of small incremental innovations in long-term overall productivity growth, but need not to be concerned to discuss them separately as sources of redirecting the course of industrialization.

Radical Innovations

These are discrete and discontinuous events; in recent times usually being the result of deliberate research and development activities in industry or in universities. Radical innovations offer the possibility of "quantum" leaps in productivity, overcoming resource limitations, or the development of entire new materials, products, etc. Despite their radical departure from existing engineering practice and technological vintages, they nevertheless "tie-in" in existing industrial structures, requiring no radical changes in industrial organization. The introduction of the Bessemer process, offering the possibility of low-cost, mass production of high quality steel in the 19th century, the introduction of nylon or the contraceptive pill in the 20th century are illustrative examples. Despite the importance for individual industrial sectors or sub-markets, their aggregate economic impact remains comparatively small and localized, unless a whole cluster of radical innovations is linked together to give rise to entirely new industries or services.

Changes in Technological Systems

These are far-reaching changes in technology, affecting several branches of industry or occurring across various sectors of the economy. They are combinations of both radical and incremental innovations, combined with *organizational and managerial* changes. Technological change introduced in one level of the economy will trigger corresponding changes both upstream and downstream in related branches. A good example is the introduction of electric motors in industry (cf. Devine, 1982). This new versatile decentralized source of motive power (as opposed to the previously used central steam-engine and power distribution via transmission belts) not only changed the entire way of organization of the shop floor, but also required associated changes upstream, i.e., in the production and distribution of electricity. Analyzing the effect of industrial drive electrification on the overall energy efficiency, Devine (1982) concludes that significant improvements (by a factor of three) were only achieved once these organizational changes indeed took place both at the level of the shop floor and in the centralized supply and distribution of electricity generation.*

Clusters and Families

Some changes in technology systems are so far-reaching in their effects that they impact the entire economy, even nearly every aspect of daily life. Such a change carries whole clusters of radical and incremental innovations and may also embody several new technology systems. For instance the development of the automotive industry was contingent *inter alia* on developments in materials (high quality steel sheets), the chemical industries (oil refining, in particular catalytic cracking), production and supply infrastructures (exploration and oil production, pipelines and gasoline stations), development of public infrastructures (roads), and a host of other technological innovations. The growth of the industry was based on a new production organization (Fordist type of mass production combined with Tayloristic scientific management principles), yielding significant real-term cost reductions, which made the car affordable to a wider social strata, thus changing settlement patterns, consumption habits of the population, leisure activities, etc. In turn, the automobile is just one artifact among many consumer durables which now belongs as a "standard package" (Keyfitz, 1991) to every household in industrialized countries.

Clusters of radical innovations and technology systems, interdependent and mutually cross-enhancing, give rise to whole "families" of technological innovations with associated new institutional and organizational settings. Thus, interlinkages and multiplier effects are responsible for the pervasive impacts of such techno-institutional "clusters" on the economy and society. Their effects cannot be assessed in simply "summing-up" the individual contributions of a range of individual radical innovations or technology systems even if detailed data were existing. Instead, they can only be described in qualitative terms. Such "clusters" have been referred to in the literature under various headings such as "general natural trajectories" (Nelson and Winter, 1977) or as "techno-economic paradigms" (Freeman and Perez, 1988). For

* Devine (1982) estimates the overall energy efficiency of a steam engine, coupled with mechanical power distribution to range between 3 to 8 percent. If only the steam engine is replaced by self-generated electricity, while keeping group drives and mechanical power distribution, the overall energy efficiency still remains at 3 to 6 percent. Conversely, combining utility generated electricity and decentralized unit drives (i.e., each equipment is driven by an independent motor) raises the energy efficiency by a factor up to three (systems' overall efficiency of 10 to 12 percent). All efficiencies apply to the 1920s. Current overall systems energy efficiency for industrial drives (incl. power generation, distribution, and motors) is in the order of 25 to 28 percent, i.e., twice as large as 70 years ago (Nakićenović *et al.*, 1990).

our purpose here it suffices to note that whole clusters or families of technologies, interwinded with associated organizational settings in the political, social and economic spheres, emerge to become a dominant development regime "regulated" (Boyer, 1988) by a supportive institutional framework. Such "clusters" drive particular periods of economic growth.

Above is essentially a Schumpeterian (1935; 1939) perspective on long-term economic growth and technological change. Industrial development is conceptualized to come in spurts, driven by the diffusion of clusters of interrelated innovations and interlaced by periods of crisis, and intensive structural change.* The existence of a succession of a number of such clusters over time should not give the impression that we deal here with various stages of a quasi linear development path (e.g., from textile to basic metal industries, on to mass-produced consumer durables) which can be repeated at any point in history. Instead, we contend that the emergence of such clusters is a time specific phenomenon, the success (in terms of contribution to economic growth) of which cannot be repeated quasi mechanistically on the same basis at later periods in history.

1.2. Innovation Diffusion

Any innovation, as radical and revolutionary it may be at the moment of its introduction, has however no immediate impact on the economy or society at large. It is only through its widespread *diffusion,* as it becomes increasingly adopted as standard production and consumption practice, that an innovation will have a noticeable impact. In fact the history of technological change entails a systematic bias in the direction of *successful* innovations. Many solutions introduced unsuccessfully in the past have sunk into oblivion, from the sail-powered railways to the Zeppelins. Hence, any historical discussion of technological change risks to give the impression of technological determinism. However, in discussing successful innovations it is important to keep in mind that

* Such a discontinuous paths of economic development has been corroborated by empirical studies ever since the seminal contributions of Nikolai Kondratiev (1926) and Joseph Schumpeter (1939), and received revived interest in the periods of economic crisis in the 1970s and 1980s (see e.g., van Duijn, 1983, Freeman, 1983, Vasko, 1987). Beyond the empirical corroboration of important historical discontinuities however, the interpretation and theoretical explanation of such "long waves" of economic and social development remains fragmented and open to further research. In particular, the issues whether we deal with a recurring, or even cyclical phenomenon endogenous to the economy, and what are the (combinations) of various causality mechanisms suggested, continue to be debated.

these have made their way in a highly uncertain environment, being shaped by a complex set of economic and social forces, which however can only be documented in rare instances to any sufficient detail to comprehend the most important causality links and events which have given rise to a particular diffusion trajectory.

Increasing adoption rates provide the basis to widen markets, gain additional experience with a given technology, develop it further and exploit learning curve effects and cost reductions from standardization and increasing economies of scale. Thus, diffusion is sustained by a self-reinforcing mechanism (a positive feedback) in which higher diffusion rates lead to increasing *returns to adoption* (Arthur, 1988), lower real-term costs and prices, ultimately also to increased product differentiation to occupy even most specialized market niches, etc. Diffusion stops either because markets become saturated, or increasing awareness of negative externalities associated with the further pervasive adoption of particular (technological) solutions block further diffusion. Symmetrical to the beginning of the diffusion phase in which a usually large number of competing design alternatives imply high risk and uncertainty (but also profit opportunities) for both suppliers and adopters of innovations, the saturation phase of a diffusion life cycle is equally disruptive. Used to past periods of high growth rates, industry has built up overcapacities, the future development path is uncertain, and economic and social transaction costs towards new solutions and alternatives are high.

Time

Above brief description of innovation diffusion already points to the perhaps most fundamental "law" distilled from thousands of diffusion studies: no innovation spreads instantaneously. The studies have also identified an almost invariant temporal diffusion pattern: slow growth at the beginning, accelerating growth (via the positive feedback mechanism outlined above), finally to level off into saturation. Hence the success of epidemiological models for the *description* (not: *explanation*) of diffusion phenomena. Diffusion requires significant time, in most cases of any economic or social significance several decades (for a comparative cross-national study of technology diffusion in industry see Nasbeth and Ray, 1974, and Ray, 1989). In some cases (like large-scale and long-lived infrastructures) it may well take between half to an entire century to achieve complete diffusion (Grübler, 1990).

Space

The diffusion of innovations is also a spatial phenomenon. Originating from focused innovation centers, diffusion spreads out through a hierarchy of sub-centers and from there further to their hinterlands (cf. Hägerstrand, 1967). Diffusion is therefore a *spatially heterogeneous* phenomenon. As a rule, peripheral regions tend to somewhat catch-up in the diffusion to early starters, albeit – as the development time is shorter – at significantly lower adoption levels. Thus, the intensity of adoption and development of particular systems is highest and most pervasive in those regions having first introduced an innovation and in which diffusion has been sustained the longest, sometimes reconfiguring the entire economic and social organization of society around particular group of artifacts (cf. the automobile in the US). Thus, inferring from realized diffusion levels of early starting regions/countries, likely market potentials for late adopters might be quite misleading.

Acknowledging this spatial heterogeneity in analogy to past examples of the diffusion of pervasive systems, yields a different scenario of the future growth of presently dominating artifacts such as automobiles (Figure 3). The analysis is consistent with observed patterns in the temporal and spatial spread of innovations: early starters (like the US) having the longest sustained period of diffusion and resulting highest ultimate adoption levels, whereas late starters (like Japan) tend to catch-up, albeit at significantly lower ultimate diffusion levels. The latter are roughly inversely proportional to the time lag in the introduction of particular systems.

From such a perspective, the future is not simply "more of the same" but instead characterized by the development and diffusion of new systems, better adapted to changing social and economic requirements. And we may add also environmental boundary conditions as a possible new decisive force shaping the further diffusion of existing and the introduction of new technologies.

To operationalize this spatial heterogeneity we use concepts developed within the framework of social geography. Regions leading the diffusion of particular systems and having highest adoption levels are referred to here as "core." The fact that they show in many respects similar development patterns with small temporal lags is an indication of their high degree of interconnectedness (information exchange, communication, trade flows, etc.). In decreasing order of the time lag and the diffusion intensity in the development of particular systems (and also in the degree of interconnectedness and extent of communication with the *core*), we differentiate between *rim* and *periphery*. In fact, Europe provides an appropriate microcosm to illustrate such a spatial taxonomy (Figure 4). Just consider the differences in degree of economic development, level and structure of industrialization, intensity of communication and exchange of goods, etc. between the inner countries of the European Community (core) and Europe's periphery, e.g., the Ukraine or Northern Africa.

It has to be emphasized that such spatial taxonomy not necessarily implies that regions have to be *physically* (geographically) close to each other. Instead, it is rather the degree of *functional* integration and similar structural and intensity characteristics in the development of the economic and technological base which determines whether a region is classified as belonging to the core, rim, or periphery. In fact, such spatial concepts have also been discussed within the framework of sustainability, arguing that its criteria may be more appropriately discussed over a spatially heterogeneous system, consisting of clusters of interacting systems, which may not necessarily be in geographic proximity to each other (Brooks, 1988).

When discussing industrialization, we interpret these functional regions as follows:

Industrialization starts in the *core*. The core countries subsequently display the highest degree of industrialization and also lead in the introduction of new technology systems, or of entire "clusters". Process and product innovations enlarge constantly the industrial base of the core and steer structural changes in its industry. Currently the core is the most advanced in the transition to a post-industrial, service dominated economy.

The *rim* has generally lower levels of industrialization, aiming at, and ultimately also catching-up to, the industrial core. Its technology base is quite heterogeneous consisting at the same time of areas with similar degree of sophistication and level of technology as in the core alongside more outdated technological vintages. Although exchange of information and goods (to the *core* as well as other regions) is less intensive than within/from the industrial *core*, it nevertheless already participates significantly in the international division of industrial production, manufacturing in particular. The importance of the industrial sector is already quite high and still growing, as shown in structural indicators of value added, employment and also in the materials (and smoke-stack) intensiveness of industry.

Finally, the *periphery* consists of regions with the weakest industrial and technological base, and remote from international flows of information and goods. Exports are dominated by primary commodities, industry mostly produces for local markets, although islands of "high-tech" and heavy smoke-stack industries exist. Structurally the economy is dominated by agricultural and service activities, however, largely operating outside the formal economy. Degrees of industrialization and urbanization are consequently still comparatively low.

Although such a taxonomy is necessarily a simplification and only crude instrument, it may be useful especially to illustrate the large disparities in levels and structure of industrialization observed in history and continuing up to the present.

2. The Spread of Industrialization: Technology Clusters, Sources of Growth, and Spatial Heterogeneity

Below we attempt to illustrate that industrialization, embedded within a broader framework of economic growth, proceeded through a succession of development periods based on the pervasive adoption of various "technology clusters". Such a succession is, however, not a rigid temporal sequence as various "clusters" coexist (with changing weights) at any given period in time. Older technological and infrastructural vintages coexist with the dominant technology cluster, and in same cases previous clusters (compared to the dominant technology base in the leading industrialized countries) are perpetuated, as was largely the case in the post-WW II industrial policy of the USSR. Elements of a forthcoming cluster are developed within specialized applications or in specific market niches, eventually to emerge as a new dominant technological mode after an extensive period of experimentation and cumulative improvements.

At any given period of time most of industrial and economic growth is, however, driven by the dominant technology cluster, frequently associated with the most visible technological artifact or infrastructural system of the time period, and studied under the leading sector hypothesis by economic historians [e.g., the "railways era" or the "age of steel and electricity" (Freeman, 1989)]. The reason why we emphasize the concept of technology clusters in particular is that any dominant new sector or infrastructural system studied under the leading sector hypothesis can explain only a fraction of the economic and industrial output growth.* Thus, we cannot in any way fully account for growth on the basis of single "leading" sectors, or a few individual industrial or infrastructural innovations, as important as they might be. Only the combination of a whole host of innovations in many sectors and technological fields will yield an appropriate entity to account for industrial and overall economic growth.

During the growth of the dominant technology cluster, many technological elements of the next one are being developed through scientific discoveries and subsequent small-scale industrial applications. However, it takes considerable time before hitherto isolated developments converge towards interrelation and cross-enhancing, yielding the forward and backward multiplier effects characteristic for whole technology clusters. A new cluster emerges eventually after a period of crisis of the dominant mode of expansion of industrial activities, involving (painful) structural adjustments not only in the economic sphere but also in the social and institutional domains.

2.1. A Qualitative Account of Technology Clusters Since the Onset of the Industrial Revolution

The tentative four historical clusters, and the possible emerging fifth illustrated below, have all important implications for industrial growth. New products and markets emerge, transportation infrastructures widen existing markets, new process technologies and forms of organization and management enable to raise industrial productivity. Macroeconomic and social policies provide for a distribution of the achieved productivity gains, and rising incomes in turn result in a powerful demand induced stimulus for industrial output growth. At the same time, energy, transportation and communication infrastructures, "meta-systems" by themselves, enable and facilitate the changes in industry and consumer markets.

* For case studies of coal, steel, and railways see e.g., Fishlow, 1965, Freeman, 1989, Fremdling, 1975, Holtfrerich, 1973; O'Brien, 1983; Tunzelmann, 1982)

Table 3 presents an attempt to categorize various phases of industrial and economic development through the concept of technology clusters. It lists the dominant cluster in the top row, and the emerging (dominating in the successive phase) below. Examples of key technologies in the areas of energy and transport systems, materials and industry, as well as in the final consumer sphere are listed. Finally, we attempt to categorize the dominant "organizational style" (Perez, 1983), i.e., the predominant mode regulating industrial, economic and social relations, and give a geographical taxonomy of centers of industrialization (core) and regions catching-up (newly industrializing or "rim" countries). All regions/countries not listed separately in Table 3 are classified as industrialization "periphery" for the purposes of this discussion.

Four historical and a prospective fifth future cluster are identified, nick-named after their most important carrier branches or functioning principles. These are: the *textile* industrialization cluster, extending to the 1820s, the *steam* cluster until about the 1870s, ***heavy engineering,*** lasting until the eve of WW II, and *mass production/consumption* until the 1970s and 1980s. Currently we appear in the transition to a new age of industrialization. Both its characterization as "total quality" [i.e., control of both the internal and external (environmental) quality of industrial production)] cluster as well as the technological examples listed are necessarily speculative.

It has to be emphasized that the classification presented in Table 3 is only a crude one and the given examples are illustrative and by far not exhaustive. Also the timing of the various clusters in Table 3 is only approximative. Below discussion of Table 3 will be brief and (over)simplifying, as each cluster and associated period of industrialization would certainly merit the space of a book for an adequate historical account.

1750–1820: "Textiles"

Historically, the beginning of industrialization as a process of structural change in which increasing proportions of the national income and employment are generated by industry sets in around the middle of the 18th century in England. Technological innovations transformed the textile manufacture in England and gave rise to what became later a new mode of production: the factory system. Important bottlenecks for industrialization and its concomitant spatial concentration of population and economic activities started to be overcome. Coal and Darby's coke combined with the stationary steam engine (particularly

Table 3. Important Technology Clusters for Economic Growth and Industrialization [(E=energy, T=transport and communication, M=materials, I=industry, C=consumer products)].

Cluster	1750–1820 "textile"	1800–1870 "steam"	1850–1940 "heavy engineering"	1920–2000 "mass production/consumption"	1980– "total quality"
Dominant					
E	water, wind, feed, wood	wood, feed, coal	coal	oil, electricity	gas, electricity
T	turnpikes	canals	railways, steamships, telegraph	roads, telephone, radio & TV	roads, air transport, multi-media comm.
M	iron	iron, puddling steel	steel	petrochemicals, plastics, steel, aluminum	alloys, specialty materials
I	castings	stationary steam, mechanization	heavy machinery, chemicals, structural materials	process plants, NC machinery, consumer goods, drugs	env. technologies, disassembly & recycling consumer services
C	textiles (wool, cotton), pottery	textiles, chinaware	product diversification (imports)	durables, food industry, tourism	leisure & vacation, custom-made products
Emerging					
E	coal, coke	city gas	oil, electricity	gas, nuclear	hydrogen?
T	canals	mobile steam, telegraph	roads & cars telephone, radio	air transport, telecommunication, computers	hypersonic? high-speed trains
M	puddling steel	mass prod. steel	synthetics, aluminum	"custom-made" materials, composites	recyclables & degradables
I	stationary steam, mechanical equipment	coal chemicals, dyes, structural materials	fine chemicals, drugs, durables	electronics, information technologies	services (software), biotechnologies
C	chinaware	illuminants	consumer durables, refrigeration	leisure & recreation products, arts	integrated "packages" (products + services)
Organizational "style"					
Plant/company level	individual entrepreneurs, local capital, small-scale manufacture	small firms, joint stock companies	"giants", cartels, trusts, pervasive standardization	Fordism/Taylorism multinationals, vertical integration	"just-in-time", TQC, horizontal integration
Economy & society	breakdown of feudal & medieval economic structures	"laissez-faire", Manchester liberalism	imperialim, colonies monopoly & oligopoly regulation, unionization	social welfare state, Keynsianism "open" society	economic deregulation, environmental regulation networks of actors
Industrial Geography					
"Core"	England	England, Belgium	Germany, USA, Benelux, France, England	USA, Canada, JANZ EC-6, England	OECD
"Rim"	Belgium, France	France, Germany, USA	Central Europe, Italy, Scandinavia, Canada, JANZ, Russia	USSR, Central & Eastern Europe, Southern Europe	4 Tigers, Russia, Eastern Europe, ??

JANZ = Japan, Australia, New Zealand

important for coal mine dewatering) put an end to fuelwood and charcoal shortages and provided for spatial power densities previously found only in exceptional locations of abundant hydropower. The improvements in parish roads and turnpikes and especially the "canal mania" around the turn of the 18th to 19th century enabled to supply the rapidly rising urban and industrial centers with food, energy and raw materials. Charcoal and the puddling furnace produced the first industrial commodity and structural material: wrought iron. Innovations in spinning and (after the 1820s also in weaving) enabled drastic falling costs and rising output particularly in the manufacture of cotton textiles. The introduction of fine porcelain from China gave rise to an expanding chinaware industry.

The nexus of innovations involving cotton textiles, the coal and iron industries, and the introduction of steam power constitute the heart of the Industrial Revolution in England. However, in order for these developments to take place, important preconditions have to be mentioned. The first was a drastic increase in agricultural productivity (cf. Grigg, 1987; Grübler, 1992). More complex crop rotation patterns, abandonment of fallow lands, field enclosures, new crops, and improved animal husbandry enabled to raise both agricultural output with at the same time fewer labor. Freed from agriculture, people sought urban residence and industrial employment. Another important precondition can be found in the institutional sphere. The separation of political and economic power, new institutions for scientific research and dissemination of its results, organization of market relations, etc., all mark the breakdown of feudal and medieval economic structures with their associated monopolies, guilds, tolls and restrictions on trade. Perhaps the intellectual and institutional/organizational changes were indeed the most fundamental (Rosenberg and Birdzell, 1986) as enabling and encouraging changes in the fields of industrial technology, products, markets, infrastructures, etc. Under a general "laissez-faire" attitude, no provision was made to socially smoothen the disruptive process of structural change in employment, rural-urban residence, value generation and distribution of income. Consequently, it should not come to a surprise to find violent manifestations of social and class conflict. Luddists and the Captain Swing (Hobsbawn and Rudé, 1968) movements provide historical evidence of the painful social adjustment process to the begin of industrialization.

1820–1870: "Steam"

In this period, lasting to the recession in the 1870s, industrialization emerges from a spatially and sectorally confined phenomenon to a pervasive principle of economic organization. Industrialization continues to be dominated by England, which reaches its apogee as the world's leading industrial power by the 1870s, accounting nearly for one quarter of the global industrial output. Industrialization spreads to the continent (Belgium, and the Lorraine and the Rhur in France and Germany, respectively) and to the Eastern United States much along the lines of the successful English model (textiles, coal and iron industry).

Coal (fuelwood in the Unites States) provides the principal energy form for industry, whereas transportation and household energy needs continue to be supplied mostly by renewable energy sources (wood and animal feed). The "steam" period is characterized by the emergence of mobile steam power (locomotives and boats), but transport infrastructures are still predominated by inland navigation and canals, reaching their maximum network size by the 1870s (England, France and the USA). Important innovations emerge in the fields of materials (Bessemer steel production), transport and communications (railways and telegraphs), and energy (city gas, and the systematic development of a coal based chemical industry), later on constituting the dominant technological cluster of the period of the second half of the 19th century until the Great Depression of the 1930s.

1870–1930: "Heavy Engineering"

Fueled by coal, this industrialization phase is dominated by railways, steam and steel. As such constitutes the most smoke-stack intensive period of industrialization. Dominated by the output of primary commodities and capital equipment the industrial infrastructure spreads on a global scale. Enlarging the industrial and infrastructural base becomes almost a self-fulfilling* purpose, driven by economies of scale at all levels of industrial production and organization. Standardization of mass produced components and structural materials, perhaps best symbolized by the Eiffel Tower, is another characteristic of the "heavy engineering" technology cluster.

* Note in particular the parallels to the industrialization path of the USSR in the post-WW II period as discussed below.

England loses its position as leading (in terms of production and industrial innovations) industrial core country to Germany and the US. The latter emerges as the world's largest industrial power by the 1920s, accounting for 40 percent of global manufacturing output (Bairoch, 1982), 60 percent of world steel production (Grübler, 1987), and 80 percent of cars registered worldwide (MVMA, 1991).

Railway networks and ocean steam ships draw even the most remote continent into the vortex of international trade, dominated by the industrialized core countries. Free world trade, greatly facilitated by the universal adoption of the Gold Standard, grows exponentially, but its political counterpart is imperialism and colonialism. The industrial "periphery" is destined to provide ever enlarging markets for the products of the industrialized core, while supplying raw materials and food (long-distance trade being made possible after the invention of canned food and refrigeration). Nevertheless, trade flows are dominated by trade *between* the industrialized core countries and with the industrializing "rim": Russia and Japan.

While the pace of technological change accelerates with the emergence of oil, petrochemicals, synthetics, radio, telephone and, above all, electricity, the institutional and regulative picture is less progressive. Emerging industrial giants, monopolies and oligopolies, perhaps best symbolized by Rockefeller's Standard Oil Company, are at the focus of government regulatory efforts, while the social question is only at the very beginning to become tackled. Legislation to limit child labor provide for elementary health care, reduce long working days (up to 16 hours per day) is introduced at a slow pace and implemented at an even slower one. The dissatisfaction with the prevailing capitalistic accumulation regime provides much stimulus for the further development of alternative theoretical expositions (Marxism) and the emergence of new social movements (labor movement, trade unionization) aiming at a more equitable distribution of productivity gains. The penetration of new production methods and technologies and associated increasing returns to scale are sustained by high investments, leading to significant productivity gains. As the income distribution is favorable to entrepreneurs, demand generation is also investment (profit) driven. Conversely, labor profits from productivity increases of industrialization primarily via increasing employment, and to a smaller extent from falling real-term prices of food and manufactured products and rising wages.

The widening "mismatch" between industrial growth and the social/institutional framework to provide for a more equitable distribution of productivity gains is the main cause of increased social conflict. A conflict which begins only to be resolved, by progressively "internalizing" labor costs into the economics of industrial growth, as symbolized by the social welfare state of the "mass production/consumption" period emerging in the 1920s, and more fully developing after WW II. It is our contention that much of the present discussion about internalizing environmental costs could find useful analogies in the way new institutional solutions were devised to resolve the issue of taking more fully account of the social externalities that went along with industrialization.

1930–1980: "Mass production/consumption"

The post-WW II economic growth phase and its unprecedented growth rates (particularly between the 1950s to the early 1970s) was based on a cluster of interrelated technical and managerial innovations, leading to productivity levels clearly superior to what was attainable under the "heavy engineering" paradigm. In particular, the extension of the continuous flow concept of the chemical industry to the mass production of identical units enabled unprecedented real-term cost and price decreases and thus mass consumption. Examples of typical products include the internal combustion engine and the automobile, petrochemicals and plastics, farm machinery and fertilizers, consumer durables, among many others. Petroleum played a vital role, both in terms of its availability at low (real-term) costs, as well as principal energy carrier and feedstock in the industry, residential, and especially transport sector. The prototype of the associated production organization being the Fordist type of assembly line, complemented on the organizational level by a separation of management and administration from production along the ideas of Taylor's scientific management. Additional economies of scale effects were realized by the increasing vertical integration of industrial activities and the emergence of enterprises operating on a global scale (multinationals).

From an infrastructural perspective, we have to highlight in particular the developments of transport and communication systems. Roads and internal combustion engine powered vehicles (cars in market economies and buses in formerly planned and in developing economies) have replaced railways as dominant transport infrastructures. Air transportation and global communication networks (telephone, radio and TV) have not only reduced physical distances but also enhanced cultural and informational interchanges. Science has grown "big" (de Solla-Price, 1963) and has been integrated systematically into industrial activities, from industrial R&D laboratories, to product quality control, even consumer research.

Although industrialization has become a global phenomenon an analysis of realized growth rates reveals only few examples of successful catching-up (notably Japan). Instead, catching-up appears to be more a phenomenon within given geographical regions or between regions with not too different degrees of industrial development. Thus, whereas Austria or Finland have indeed caught-up to the European core, disparities in income and level of industrialization between North and South America, or between Europe and India have not narrowed, in some cases (Africa) even widened. In terms of the spatial taxonomy adopted here, this implies that the industrial "core" has somewhat grown by members from the "rim" (Canada, Japan, Scandinavia, Austria, Switzerland, Italy), but the dominance of the core in industrial and economic power is as large as ever. The OECD countries still account for 70 percent of the world's industrial output (cf. Table 1 above) and for 75 percent of the world merchandise trade (World Bank, 1992). Over 80 percent of OECD's imports of manufactured goods is imported from other OECD members, another 9 percent from the industrial rim (Eastern Europe and 4-Tigers), and only about 10 percent from the rest of the world (World Bank, 1992).

Examples of the matching social-institutional framework associated with the growth of the oil-based energy and material intensive mass production regime of the OECD region include Keynsian policies leading to various forms of demand management, both direct via public infrastructure (roads, highways), defense and public service spending (in particular health care and higher education) and indirectly, e.g., in the form of income redistribution (enabling from the disposable income side mass consumption), generally subsumed under the term of the welfare state. Other examples include socio-institutional innovations such as large-scale consumer credits, publicity, development of mass communication, institutional embedding of labour unions or the development of various forms of "Sozialpartnerschaft" as institutional framework of a social consensus on the general growth trajectory. In our viewpoint, it is precisely this congruence between technologies and products and the (supportive) socio-institutional framework, which was characteristic for the development phase that enabled the economic expansion after WW II. However, it appears that this widespread social consensus is progressively vanishing and that we are witnessing a widening "mismatch" (Perez, 1983) between the socio-institutional framework* of a particular phase of economic growth and the attainment of (market, environmental, social acceptance, etc.) limits to its further expansion.

Changing social values, new technologies and growth sectors, new forms of production organization, shifts in the occupational profiles and the international relative cost advantage all imply the need for structural and institutional adjustment processes. The current focus on restructuring the formerly centrally planned economies should not blur the need for similar far reaching social and institutional "perestroikas" in the industrialized core countries. Faced with ultimately threatening environmental limits to the physical manifestations of our industrial metabolism, and obvious limits of traditional "end-of-pipe" regulatory approaches, human ingenuity is challenged to devise technological, organizational and institutional innovations for sustainable growth.

As many of the elements of such a new path of "total quality" are still embryonic, a further discussion beyond the propositions contained in Table 3 above would be too speculative for this paper. Nevertheless, we would like to make one observation. Despite industry is a powerful agent of global change, consumers matter increasingly more. Therefore, industry will have to abandon a narrow focus on the physical structures and artifacts it uses and produces if indeed closing the industrial metabolism is on the agenda. This is simply because even the most spectacular environmental improvement in industry or of an industrial product can be largely compensated by consumer decisions and unchanged behavior in *using* (and dispensing) industrial products. This problem is widely acknowledged in the energy field, where one can show that efficiency improvement potentials in end-uses are much larger than in industry. However, despite the availability of technologies like energy efficient cars or light bulbs, these are only slowly (if at all) taken up by consumers. Thus, for improving environmental compatibility we have to redefine the purpose of industry. Instead of providing merely products and using industrial technology for their final

*Boyer (1988) argues that the Fordist/Tayloristic "paradigm" after its universal adoption cannot contribute any further to productivity growth. The much discussed productivity slowdown is a result of the impossibility to further "deepen" the Fordist organizational scheme. New solutions (like the Japanese concept of "total quality control", TQC) have yet to become embedded within existing industrial relation structures.

disposal and recycling (e.g., in "dis-assembly plants"), industry will have to provide *integrated services,* i.e., instead of a car provide mobility, instead of electricity and oil provide for heating and lightning comfort, etc. This would also be a way out of the dilemma of (implicit) high consumer discount rates which has troubled analysts wondering why cost effective and environmentally benign investments (like efficiency improvements) are taken up by industry but not by consumers.

2.2. A Quantitative Account of the Rise of Technology Clusters

How can one empirically account for the rise of the various technology clusters discussed in the previous section? The usual approach is to take quantitative indicators of the growth of examples of products, technologies or systems, considered as representative for the much larger set of innovations comprising a particular cluster. Such analysis inevitably has to be partial, and unless appropriate "meta-systems" of importance to more than one sector of the economy (like energy or transport infrastructures) are used, could also be misleading as inferring from specific examples to the evolution of industry or the economy at large. In view of abundant literature (e.g., Hoffmann, 1931 and 1958; Woytinsky and Woytinsky, 1953; Landes, 1969; Rostow, 1978; Mokyr, 1990) containing valuable historical data and easily available output statistics of principal industrial commodities produced (e.g., Mitchell, 1980; 1982; 1983), there is no need to repeat this information here.

Instead, we will discuss two indicators representing aggregates of many processes of technological and economic change over time. The first is based on an analysis of the diffusion histories of many innovations over time in one country (the US), whereas the second one tries to describe the growth of the "mass production/consumption" cluster internationally based on principal component analysis of a large number of individual indicators.

Figure 5 reports the results of a diffusion analysis of 117 processes of technological change in the areas of energy, transport, manufacturing, agriculture, consumer durables, communication and military technologies in the USA since the 19th century.* The figure presents the

* For details see Grübler 1990.

weighted diffusion rate over time, i.e., the sum of the first derivatives of the diffusion functions estimated from empirical data, divided by the number of diffusion processes at any given period in time. This yields the *average rate of technological and economic change* in the USA since the 19th century or, in other words, it is the diffusion equivalent of the annual GNP growth rate. Rising average diffusion rates indicate the emergence of a whole technology cluster; the curve passes through a maximum and then tapers off as more and more diffusion processes tend towards saturation. A trend reversal indicates the progressive emergence of a new cluster, whose initial diffusion rates are however still low, exacerbating the period of structural change. It is not coincidental that the troughs of Figure 5 (lowest rate of technological and economic change) coincide with periods of pronounced recession, even depression in the US (1870s, 1930s, and since the beginning of the 1970s). As such the figure illustrates the rise and fall of three technology clusters in case of the US. [The first ("textiles") does not show on the graphic, because prior to the 1830s the US was basically an agrarian society.]

A second approach follows more a conventional methodology of international comparisons of economic development and structural change: *principal component analysis.* Glaziev (1991) analyzes 50 indicators in the areas of agriculture, construction, chemical industry, energy, electricity, transportation, and private consumption, over the period 1950 to 1986. Principle components as aggregation of the overall evolution of growth and intensity of the seven areas are calculated, and in a second step the principle component of the principle components of the first level is calculated. The result – though at first sight difficult to interpret as giving a dimensionless indicator – for the US, Japan, FRG, the UK and the (former) USSR is shown in Figure 6. The figure shows the evolution and intensity of development of the "mass production/consumption" cluster of the WW II period. It indicates that the US has most intensively developed this particular cluster and its associated industrial base and consumption patterns. Western Europe and Japan have followed suite, albeit at a lower intensity level, and in all the OECD countries the cluster starts to decline in the 1970s to 1980s, indicating a slowdown in growth and possible transition to a new phase of industrial growth. It is important to note the decisive differences in the intensity of the development path of the US, compared to Japan and Western Europe. Thus, while the OECD countries develop along similar lines, with Japan catching-up since the late 1950s, the intensity of development is quite different. This finding is consistent with spatial theories of innovation diffusion and the spread of industrialization discussed above. Early starters (the US) have the longest growth phase and develop a particular technology cluster more intensively, than late-starters, catching-up, but realizing lower intensity levels. The fact that the USSR is even below the Western European trajectory was to be expected, as it has developed most of the mass production technologies, but only a few of the mass consumption ones. Glaziev (1991) calls the USSR development path as one of "multimodeness", i.e., one of the simultaneous reproduction of an outdated technological mode ("heavy engineering") alongside with a more modern one. The failure of this industrial development policy has become apparent by now, and its environmental implications are increasingly becoming realized.

Our discussion aimed to provide some historical and quantitative evidence about the specifics of successive industrialization and development paths pursued. As a conclusion we caution against rapid convergence scenarios, especially with respect to the future of developing countries, as desirable from a human development perspective they may be. Whereas history indeed provides examples for successful industrialization strategies and pathways of catching-up, these take considerable time and have to make use of limited opportunity windows of development. Initial conditions matter, as does the level of educational attainment of the workforce and a supportive socio-institutional framework. A careful balance must be found between learning from historical industrialization experience and in finding new niches and investing in a forthcoming cluster of industrial and economic development rather than merely repeating outdated or progressively vanishing modes of industrial development.

3. Industrialization: Output and Productivity Growth

Figure 7 compares three data sets on the growth of global industrial output (Bairoch, 1982; Haustein and Neuwirth, 1982; Rostow, 1978) Despite inherent methodological and data uncertainties, and differences* in the estimates of industrial growth during the early industrialization phase, the estimates agree on the basic dynamic pattern of global industrialization since the middle of the 19th century: exponential growth. This however, only applies to estimates of the monetary value of industrial output. Its *physical* equivalent will show a different picture as the material intensiveness of industrial value added varies over time, and especially in the OECD countries is declining since decades (cf. Williams *et al.*, 1987). This "disintensification" of industrial activities will be illustrated in more detail in the following section on industrial energy and carbon intensity.

Table 4 summarizes the (broad) geographical distribution of industrial output growth, following the spatial taxonomy adopted here. Based on Bairoch's estimate, the industrial output of England in 1900 is used as normalizing index. Thus, Table 4 indicates that the industrial output of England in 1900 approximated that of the entire globe 150 years earlier. Conversely, global industrial output in 1980 was a factor over 100 larger than in England 80 years earlier, and an equal order of magnitude larger than global industrial output at the onset of the Industrial Revolution. The industrial core region is characterized by persistently higher growth rates in industrial output than the rim and periphery. Only in the period 1930–1980, the rim shows higher growth rates, as a result of it's catching up to the core discussed above.

The weight of the industrialized core countries in the early phases of industrialization was comparatively low. However, by the mid-19th century, the core countries have achieved already global dominance, accounting for over half of the globe's industrial output. Ever since, global industry is dominated by a comparatively small number of countries: the core persistently accounts for about two-thirds of global industrial output. The relative decline (over the period 1830 to 1870 even in absolute terms) of the periphery is a negative mirror image of the rise of the industrial core. Despite growth rates of about 3.5

* As the Bairoch (1982) data include a special attempt to estimate levels of industrialization outside Europe and North America, it represents in all likelihood a more realistic picture of the dynamics of early industrialization.

Table 4. The Global Geography of Industrialization (Level of Industrialization UK in 1900 = 100).

	1750		1830s		1870s		1920s		1980	1980/1750
Level in:										
Core	2		20		180		950		7400	3080
Rim	5		20		40		190		2300	430
Periphery	120		145		100		220		1300	11
World	127		185		320		1360		11000	87
Growth rates, %/yr										
Core		2.6		4.6		3.6		4.0		3.6
Rim		1.7		1.3		3.3		5.0		2.7
Periphery		0.2		–0.7		1.7		3.5		1.1
World		0.5		1.1		3.1		4.1		2.0
Regional shares, %										
Core	2		10		56		70		67	
Rim	4		11		12		14		21	
Periphery	94		79		31		16		12	

All figures rounded. Data source: Bairoch, 1982.
Regional shares and factor increase calculated from original data may differ from rounded figures.

percent annually over the last five decades, the industrial periphery has fallen further behind the most industrialized countries (4 percent per year growth rate). This means that both the absolute and relative gap between the industrial core and the periphery has widened.

It is beyond the scope of this paper to discuss reasons (or possible remedies) for widening disparities in levels of industrial development. One of the most frequently used lines of argument points to falling real-term primary resource prices and resulting deteriorating terms of trade. However, one has also to keep in mind the constant change in the industrial structure of the core, and especially the falling materials intensity of advanced industrialized countries. All told, prices of primary resource inputs in highly industrialized or even post-industrial economies matter increasingly less. Copper and bauxite even crude oil price changes hardly affect industries producing computers, software, or other high value density products like aircrafts, and it was especially these industrial branches which have shown the highest growth rates over the last decades. At the same time, raw materials prices affect developing economies not only in terms of import earnings but also as cost items to their comparatively material intensive economies. Oil price increases have affected the economy of many developing countries severely, and subsidized low domestic prices of raw materials are widespread phenomena. Thus, the deteriorating terms of trade can explain partly why industrial growth rates in the periphery were smaller than to be expected based on their factor endowments. However, in our view they are insufficient explanation for the persistently higher growth rates in the core. Instead, the "success" of the core appears more related to its dynamics of industrial innovation and the resulting rise in factor productivity in industry. A particular illustrative case are the improvements in the productivity of the factor input labor.

Figure 8 presents estimates of the improvement in labor productivity in manufacturing for a number of industrialized countries. It should be noted that the international comparison of industrial and manufacturing labor productivity is among one of the most complex tasks for comparative economic statistics. Differences in industrial output mix, relative price structure, labor qualification, industrial relations, hours worked, etc. still await definitive methodological and empirical resolutions. Therefore, the data presented in Figure 8 primarily serve to illustrate the evolution of labor productivity over time within a given country, than serving as a yardstick for international comparisons.*

* We have renormalized the individual country indexes to be roughly equivalent with the prevailing consensus on comparative international manufacturing productivity, e.g., the estimates of Dosi *et al.* (1990) for

Figure 8 indeed confirms significant productivity gains as a secular trend in industrialized countries, and as such is perhaps the best illustration of the impacts of technological and institutional/organizational change.

It may be perhaps surprising for some to see persistent differences in the levels of labor productivity in manufacturing among the industrialized countries (not to mention developing ones). Apparently, distinct national industrial systems (in terms of sectoral structure, technology base, etc.) with associated institutional settings (working time regulation, wage negotiation, etc.) have evolved. The cumulativeness of such national industrialization paths is responsible for persistent differences in productivity despite intense international trade and competition. Some of the historical differences can also be related to the relative availability of various factor inputs in industry. As in agriculture, labor was comparatively scarce for the US industry. Consequently, compared to England, the industrial labor productivity was higher in the US already at a moment when the US was still a "newly industrializing" country, as compared to the world's leading industrial power. We will return to this phenomenon of *historical path dependency* in the following section, when discussing the energy and environmental intensiveness of various industrialization paths.

4. Industrialization and Environment

The environmental implications of industrialization can perhaps best be described by Paul Gray's (1989) "paradox" of technological development. Industrialization has brought unprecedented levels of environmental impacts stemming from (impact-wise fairly well understood) effluents rising with the *scale* of industrial activities. At the same time, industrialization has introduced new materials and substances (e.g., CFCs), with hitherto unknown impacts on the environment. But at the same time, technological change that went along with industrialization as well as growing incomes generated by rising productivity have also enhanced our technological and economic capacities for remedies.

the year 1977–1978, and the overview of estimates by Broadberry and Crafts (1990) for the year 1985, from which we have adopted the median between industry of origin and expenditure based estimates. This yields for the early 1980s roughly the relation 2, 1.5, and 1 between the manufacturing productivity per hour worked in the US; Japan, Germany, France; and England, respectively. For a historical account of industrial labor productivity see Phelps Brown, 1973.

In fact, the central theme of this section is that industry has built-in an *inherent incentive structure* to minimize factor inputs (enabled by technological change). Thus, industry moves in principle in the right direction. The real issue is therefore how to *accelerate* such desirable trends. Moving in the right direction means for industry in principle two things: (1) minimize resource inputs per unit of economic activity, i.e., **dematerialization** and (2) improve the environmental compatibility of the materials used, processed, and delivered by industry. With respect to industrial energy use this means: **decarbonization**. In the introduction to this paper we have concluded that, simply from a quantitative perspective, energy and its related carbon emissions are the largest expression of industry's metabolism. This is the reason why we will use these areas as illustrative cases below.

4.1. Energy and Carbon Emissions

Figure 9 shows the evolution of industrial energy intensity per unit value added for selected industrial and industrializing countries. Although the data set spans only a limited period in time, judged by the time scale of industrialization as a historical phenomenon, it nevertheless shows the two most important trends: decreasing energy intensity in the industrialized countries, and increasing intensities in newly industrializing ones. The much higher energy input per unit value added in the latter is frequently interpreted as *potential* for short- to medium-term energy efficiency improvements. However, higher energy intensities are in most cases the result of differences in degrees of industrialization and resulting differences in structure and technology base of industry. Thus, we have to replace the temporal dimension by a more appropriate *functional* dimension, taking into account differences in levels and degree of industrialization.

This is reported in Figure 10, where the industrial energy intensity per unit value added is plotted against per capita levels of industrial value added, as a proxy of the "industrialization metric" between different countries. From such a perspective, the energy intensity of the Brazilian industry is in fact quite similar to the Japanese *at similar levels of industrial per capita output*. Conversely, the Nigerian example gives raise to concerns: increasing intensities of factor input use, but no significant growth in per capita levels of industrial output. The most spectacular improvements in industrial energy intensity were achieved in South Korea, illustrating that rapid industrial development and vigorous efficiency improvements are not mutually exclusive.

Again, as in the previous discussion of industrial labor productivity, we observe only conditional convergence between countries and persistent differences between various intensity "trajectories" of industrial development (e.g., US versus Japan). Industrial structures and intensity of factor input use thus arise from an accumulation process and from historical path dependency. This does not only apply to industry, but also to the entire economy. Figure 11 illustrates this for the overall energy intensity of different economies as a function of per capita income. It has also to be noted that improvements in energy intensity have been achieved over extended periods of time even under *low* energy prices. In the long-run, therefore, technological change appears to matter more than prices. The data on energy consumption in Figure 11 also include renewable energy (in particular fuelwood), because of its importance in the 19th century for the industrialized countries (in particular the US, cf. Schurr and Netschert, 1960) and its continued importance for many developing countries today. From such a perspective, initially rising intensity in fossil energy use has to be contrasted with the significant efficiency gains for the overall economy, when low-efficiency uses of traditional energy carriers are substituted by fossil-based technologies.

Initial conditions, development paths chosen, industrial structures and settlement patterns as well as different consumption patterns of the population that have evolved account thus for persistent differences between countries. This historical path dependency is perhaps best illustrated by the "high intensity" and "high efficiency" development trajectories revealed by Figure 11. From such a perspective, India moves in the direction of the French or Japanese development trajectory, whereas resource-rich China moves in direction of the US development path. However, at similar levels of per capita income, the US had about a factor 200 lower population than China today. From the perspective of the differences in population density (or rather of resource density per capita), it appears difficult to consider the practical (not to mention the environmental) feasibility of a US development path for China.

The above discussion is consistent with a typology of industrial development emerging from comparative macro-economic studies. For instance, Chenery *et al.* (1986) developed a typology of industrialization paths based on a differentiation of three classes of variables: size of the economy (small, large), sector orientation (primary versus manufacturing), and trade orientation (inward versus outward orientation). Over the post WW II period, the highest industrial growth rates in semi-industrialized countries were achieved in small, manufacturing, and outward oriented economies. What is equally important is to note that the relative factor productivity with its evolution over time shows persistent differences between the classes of countries analyzed. Again, conditional convergence is confined to countries belonging to a particular typological group rather than between groups. As such, it constitutes an important differentiation of Rostow's (1978) stage theory of economic development. Instead of a linear development model, various distinct development trajectories exist. The success of a particular industrialization strategy is also contingent on developing at least part of the industrial base on the technological productivity frontier. Perhaps the former USSR, or China's experience with rapid industrialization during the "Great Leap Forward" (e.g., steel production with backyard crucible furnaces fired with charcoal), can provide some lessons on the feasibility of industrialization based on outdated technological vintages and industrial structures.

Environmental compatibility of future industrialization, particularly in developing countries, should be compared with the historical experience of highly industrialized countries. This could provide some guidance about possible environmental impacts under a range of industrialization scenarios, and to assess their compatibility with the assimilative capacity of the biosphere. Therefore, Figure 12 illustrates industrial carbon emissions as an environmental indicator of industrialization. Analog to Figure 10, it shows the industrial carbon intensity versus per capita levels of industrialization. Carbon emissions from electricity generation are attributed to industry in proportion to the industry's share in total electricity consumption and based on the (changing) average fuel mix in electricity generation. Overall, the decreasing carbon intensity of industrial activities is dominated by the improvements in energy efficiency (i.e., by the decreasing energy intensity as shown in Figure 10 above). This, especially, because in the wake of the post 1973 period the fuel mix in industry, and particular in electricity generation, has become more "carbon heavy".

Another factor explaining the differences between industrial carbon intensity and its changes over time are changes in the structure of the industrial output. In fact, the energy and carbon intensiveness of industrial processes and products varies widely. For instance, about 50 percent (some 230 million tons C) of US industrial carbon emissions result from products contributing only to 15 percent (some 200 billion \$) of the industrial value added, whereas 50 percent (780 billion \$) of the industrial value added is produced with only 13 percent (60 million tons C) of the sector's carbon emissions. The specific carbon emissions per unit value added across different output categories of the US industrial sector in 1987 range from 2.27 kg C per US \$ to 0.03 kg C per \$, i.e., by a factor close to 70, with the industry average being less than 0.3 kg C per US \$ (Marland and Pippin, 1990). The highest carbon intensities per unit value added are shown for petroleum and coal products (SIC-code 29), followed by primary metals (SIC code 33), chemical and allied products (SIC-28), and stone, clay and glass products (SIC-32). Overall, the skewed distribution function of the industry sector's carbon emissions (Figure 13) indicates that changes in the output mix have also to be considered (although difficult to model, yet to predict).

The following section illustrates the importance of structural shifts in process technologies and energy supply mix in moving in the direction of "dematerialization" and "decarbonization" on the basis of a concrete example.

4.2. A Case Study of Carbon Emissions in US Steel Industry

Figure 14 reports estimates of specific and total sector carbon emissions for the US steel industry since the middle of the second half of the 19th century. Although minimizing carbon emissions was never on the agenda of industry to date, it is interesting to note the significant improvements (a factor 20!) in the carbon emissions per ton (pig iron) produced. Even more noteworthy is the secular trend of this decreasing carbon intensity, which follows a typical industrial learning curve when plotted versus the cumulative output as done in Figure 13. Thus, specific carbon emissions decrease by 17 percent for each doubling of cumulative output. As significant as these improvements were, their rate fell short of output growth. Consequently, total sector emissions (including emissions from generation of the electricity consumed by industry) increased over time to well over 50 million tons of carbon annually, but apparently have already passed through their historical maximum. However, the important point here is to realize the scale of emissions, if indeed historical output growth would have been achieved by simply intensifying existing process technologies and factor inputs.

The historical role of technology change has been, therefore, twofold: first, enabling significant output growth (and emissions) and, second, at the same time also *averting even worse* impacts, due to significant improvements in the efficiency of use of factor inputs.

Improvements in the carbon intensity of steel manufacture was achieved by a combination of gradual, incremental and also radical changes in process technology (Figure 15) yielding significant efficiency improvements, and in the energy supply mix (Figure 16). These two structural change processes operating *in tandem* are yet another illustration of the importance of interlinkages between different technological systems. Changes in the fuel mix are intimately tied to changes in industrial process technology, and both are instrumental for long-term energy efficiency improvements.

For instance, the introduction of modern steel process technologies in the 19th century was closely linked to the replacement of charcoal by bituminous coal as energy source and reductant. Modern process technologies for continuous casting or for flat glass production require continuous, clean and high temperature heat sources usually supplied by natural gas or electricity. The trend towards increased recycling and remelting of metal scrap requires electric arc furnaces and is a further explanation of the increasing electrification trend in industry. For instance, Nakićenović (1990) examines the trends towards a higher share of crude steel production from electric arc furnaces, concluding that by the year 2020 electric arc furnaces could produce over half of the global crude steel production. Thus, from a longer term perspective, industry also increasingly relies on higher quality (denser and cleaner) energy carriers such as natural gas and electricity, also in the wake of the post-1973 period this fuel substitution trend has slowed down or even was partly reversed.

As a conclusion from above example, it is important to emphasize the holistic nature of measures to accelerate desirable rates of industrial dematerialization and decarbonization. Structural changes in output mix, in process technologies, and energy supply systems all have to be deployed vigorously *together* if indeed reductions of industrial emissions are on the agenda.

For the future, however, not only measures in industry will be of importance, because ironically the success of industrialization is best illustrated by the growth of economic activities *outside* industry. Increased incomes and more free time enabled by productivity increases in industrial activities gave raise to the service and leisure economy of post-industrial societies. It is our contention that the latter activities will progressively surpass industry as a potential source of environmental impacts, and will constitute an important growing market for industrial services and products contributing towards a "greening" of our consumption habits.

5. Impacts of Industrialization on Consumption and Leisure

Industrialization had and continues to have far reaching social impacts. Changes in employment structure, urbanization, and above all increased life expectancy, rising incomes and reductions in working time are examples of social changes directly and indirectly resulting from industrial output and productivity growth. Contingent on a social consensus, productivity gains have been distributed among rising wages and incomes (Figure 17) and reductions of working time (Figure 18). As a consequence the population in industrialized countries enjoys today a level of health and longevity, material well being, and leisure time, beyond the imagination of even the most daring social utopias of the 19th century.

Perhaps the changes in time allocation patterns are among the social impacts of industrialization least known. That is why we briefly discuss them here. Some 100 years ago, a UK laborer had an average life expectancy at the age of 10 of about 48 years and at age 20 of about 40 years, i.e., a total life span of less than 60 years. Before education became mandatory, labor began young, and essentially men healthy enough to work until they died (average length of a work career: about 47 years). Over his lifetime a male worker worked about 150,000 hours,* or 60 percent of his available lifetime after subtracting necessary "physiological" time (i.e., the time required to eat, sleep and for personal hygiene).

Today a typical male worker in the UK works some 88,000 hours during his lifetime. Due to reduced working time and increased life expectancy he spends only about 25 percent of his available lifetime at the work place. Trends in working time reductions (at paid work) for

* All data from Armstrong, 1984 and Flora *et al.*, 1987. Long-term trends in working time are discussed in more detail in Ausubel and Grübler, 1990.

women have been less pronounced, but nevertheless noteworthy (reduction from 63 to 40 thousand hours over the lifetime; the shorter work career being the result of part-time employment as well as interruptions in child-bearing phase).

More free time, coupled with higher incomes has led to the development of lifestyles centered around private consumption and demand for services (cf. Gershuny, 1983). The structure of employment, industry, and production has followed suit. It is important to note to what extent resource consumption in post-industrial societies have become dominated by private consumption and leisure activities. Schipper *et al.* (1989) presents data on final energy consumption for the FRG, indicating a dramatic shift in the relative share of energy consumption between productive (i.e., industrial) and consumptive (i.e., services and private households) uses of energy. Industry accounted in 1950 for two-thirds of final energy consumption, whereas today it accounts for only one-third.

From an environmental perspective, it is therefore not only important how resource and impact intensive industrial activities are, but also to consider activities outside industry. Figure 19 presents a tabulation of the energy and carbon intensiveness per *unit of time* of different activities of the US population (Grübler, 1992). Working at the workplace, commuting, or staying at home or at leisure activities have all different implications for level and structure of energy and materials demand. International and intertemporal time-budget studies report on a broadly converging change in the structure of time allocation of the population (Figure 20). The cross-cultural data on the increase of leisure time relative to paid work (for men) and to unpaid work (for women) confirm the trend towards increasing leisure time, even as women continue to enter the workforce. Whether such changes lead to further increases in energy use can be inferred from the types of leisure activities selected (i.e., energy intensive activities involving travel, versus "sustainable" activities like gardening).

Perhaps the most important lesson provided by time budget research is to acknowledge the complexity of criteria underlying consumer choices and preferences. Efficient use of capital and energy are important, but if indeed time is the ultimate scarce resource for consumers, policies to reorient technological solutions and consumer preferences particularly in resource and environmental intensive activities such as transportation will have to go well beyond traditional intervention instruments, such as changes in relative price structures. In our viewpoint, it will become increasingly important in the future for industry to take up the challenge to assist consumers in more environmentally compatible life-style choices. Not only in providing new [such as (more or less) "green"] products, but also ways to ensure that environmentally friendly products are adopted and used appropriately. All this implies to redefine traditional markets for products and services in the direction of *intergrated packages*, focusing on the delivery of end-use *services* rather than on artifacts.

6. Conclusion

To conclude, let us reiterate the three central themes of this paper.

First, industrialization as a historical phenomenon is conceptualized as a succession of phases, characterized by the pervasive adoption of "technology clusters". The introduction of a whole host of technological, institutional and organizational innovations leads to productivity gains clearly superior to the mere intensification of traditional solutions. From this perspective, industrialization is a time specific phenomenon, characterized by (discontinuous) processes of structural change in the areas of economic structure, technological base and social relations. History matters because of the cumulativeness of socio-institutional and technological change. This results in distinct development trajectories, spanning extremes of "high-intensity" or "high-efficiency" industrialization paths, clearly discernible from historical data.

With respect to environmental impacts, we have argued that minimizing factor inputs is an inherent part of the incentive structure of industry. Improved factor productivity and lowering resource intensiveness of industrial production have accompanied historical structural changes in industry. This would indicate that industry is moving in the right direction, referred here as overall "dematerialization" and energy "decarbonization". This gives reasons to be cautiously optimistic, albeit historical trends will have to be accelerated significantly to reduce the absolute level of emissions and environmental impacts. As in the past, changes in technology, energy and transport infrastructures, and in social and institutional regulatory mechanisms will be instrumental.

If environmental compatibility indeed could become a new dominant paradigm of industrial development, future sources of industrial productivity growth will be primarily in this area. Such tendencies will of course be first discernible in the most advanced post-industrial economies (i.e., the industrial "core"). It is our contention that (as in the past) successful catching-up will only be possible if based on technological and institutional solutions not in conflict with the dominant "industrial paradigm" of the core. Industrial societies have been successful in the past to "internalize" social costs. Competitive cost advantage through child labor is not considered a "bad" solution today, but simply as *no solution at all.* This illustrates to what degree the internalization of externalities can indeed be achieved, but it would be illusionary to expect such a pervasive transformation to happen rapidly.

Industrialization has brought tremendous productivity gains, and resulting rising incomes and reduced working time, in short: *affluence and leisure.* From an environmental perspective activities outside the productive sphere (i.e., industry) are becoming increasingly important determinants of resource consumption and environmental impacts. Furthermore, private and leisure activities are more difficult to steer with traditional policy instruments, such as price signals to which industry adheres. Decision making criteria of consumers are complex and far from the "rationality" concepts assumed in economic models. A difference, painfully felt by advocates of energy efficiency programs, wondering why economic attractive options are not taken up by private consumers. Perhaps this will provide the largest future challenge to industry: not providing consumers with products, but with environmentally friendly *integrated solutions* to satisfy a particular *service demand.*

Acknowledgement

The assistance of Andreas Schäfer in the preparation of the tables and figures is gratefully acknowledged.

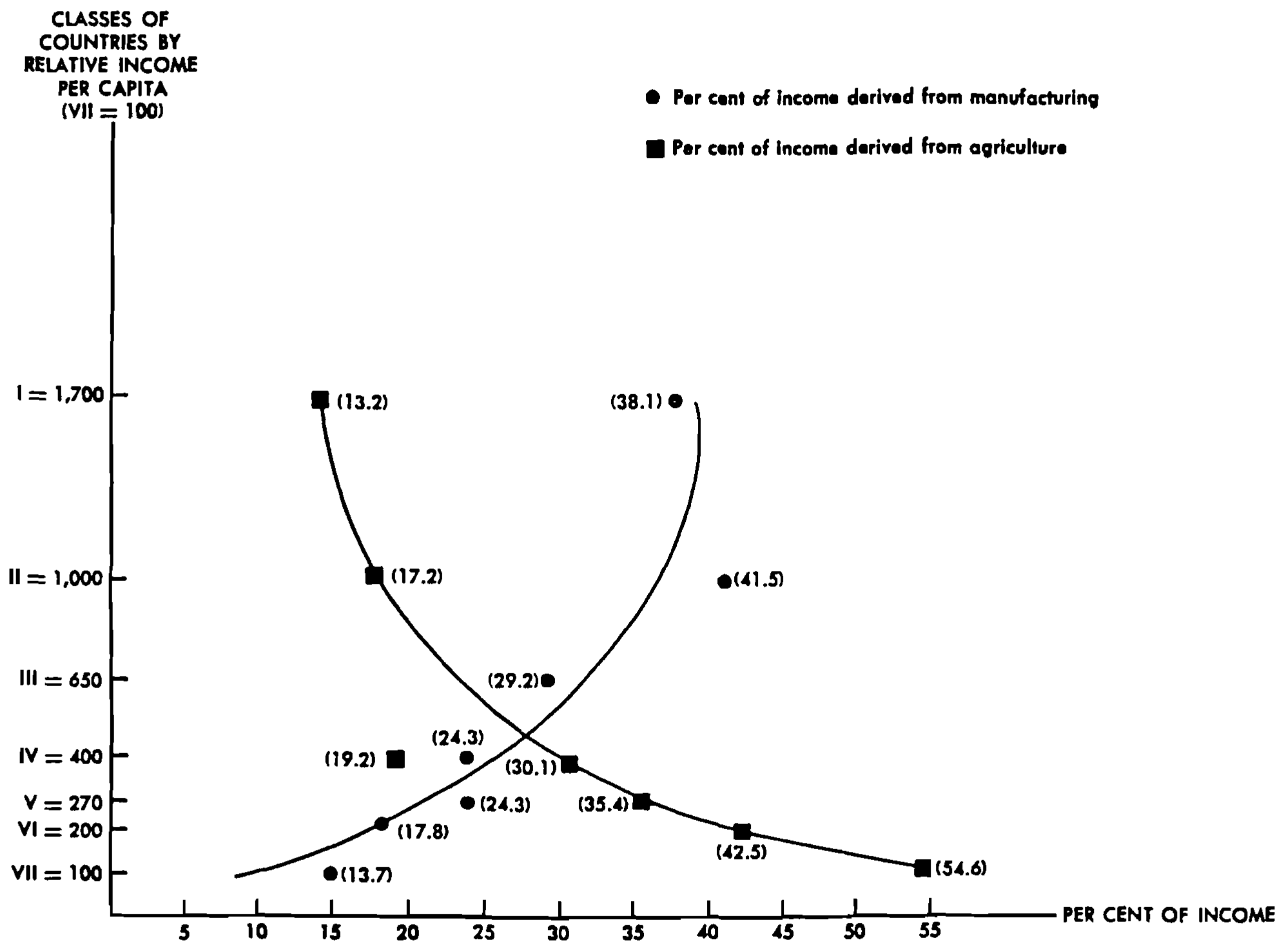

Figure 1. Industrialization: a process of structural change. Value generation and employment (cf. Figure 2 below) shift away from agriculture to industrial activities, manufacturing in particular. Source: Kuznets, 1958.

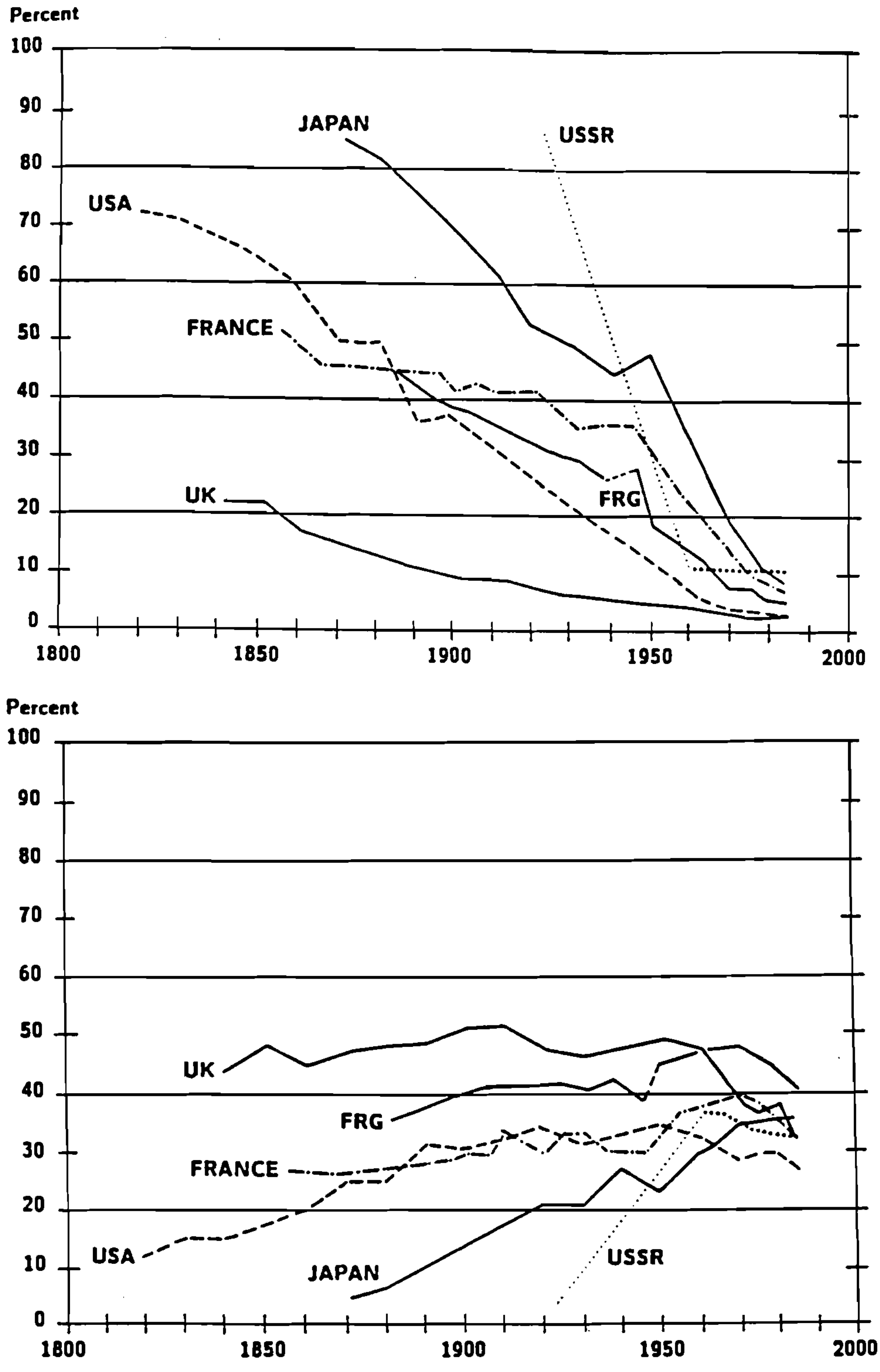

Figure 2. Industrialization as a process of change in occupational structure: share of work force employed in agriculture (top) versus share of workforce in industry (bottom). Note that industry now performs many activities previously residing in agriculture. Source: Nakićenović *et al.*, 1990.

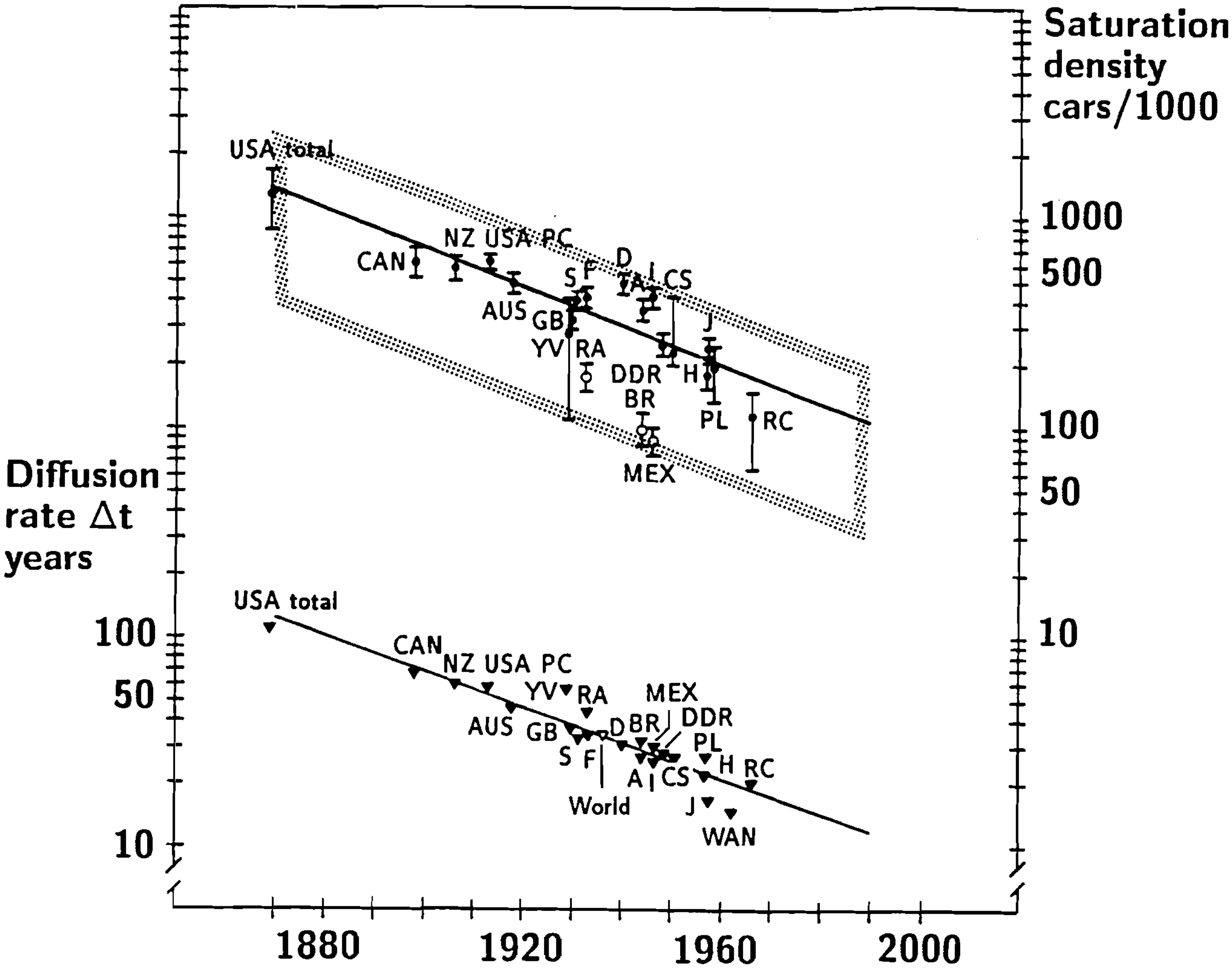

Figure 3. Spatial diffusion of artifacts: cars. Early starters have the longest sustained diffusion period and resulting highest adoption densities. The Figure reports the results of estimating the diffusion of passenger cars worldwide, and for a number of countries. Estimated diffusion time (Δt) and ultimate saturation levels (registered cars per capita) are plotted as a function of the introduction date of the automobile. The results are consistent with the spatial patterns of diffusion described above: late-comers tend to catch up (shorter Δt), albeit at significantly lower intensity levels. The resulting global scenario is with up to 600 million cars by the year 2010 significantly lower than forecasts based on linear extrapolation of past trends. Source: Grübler, 1990.

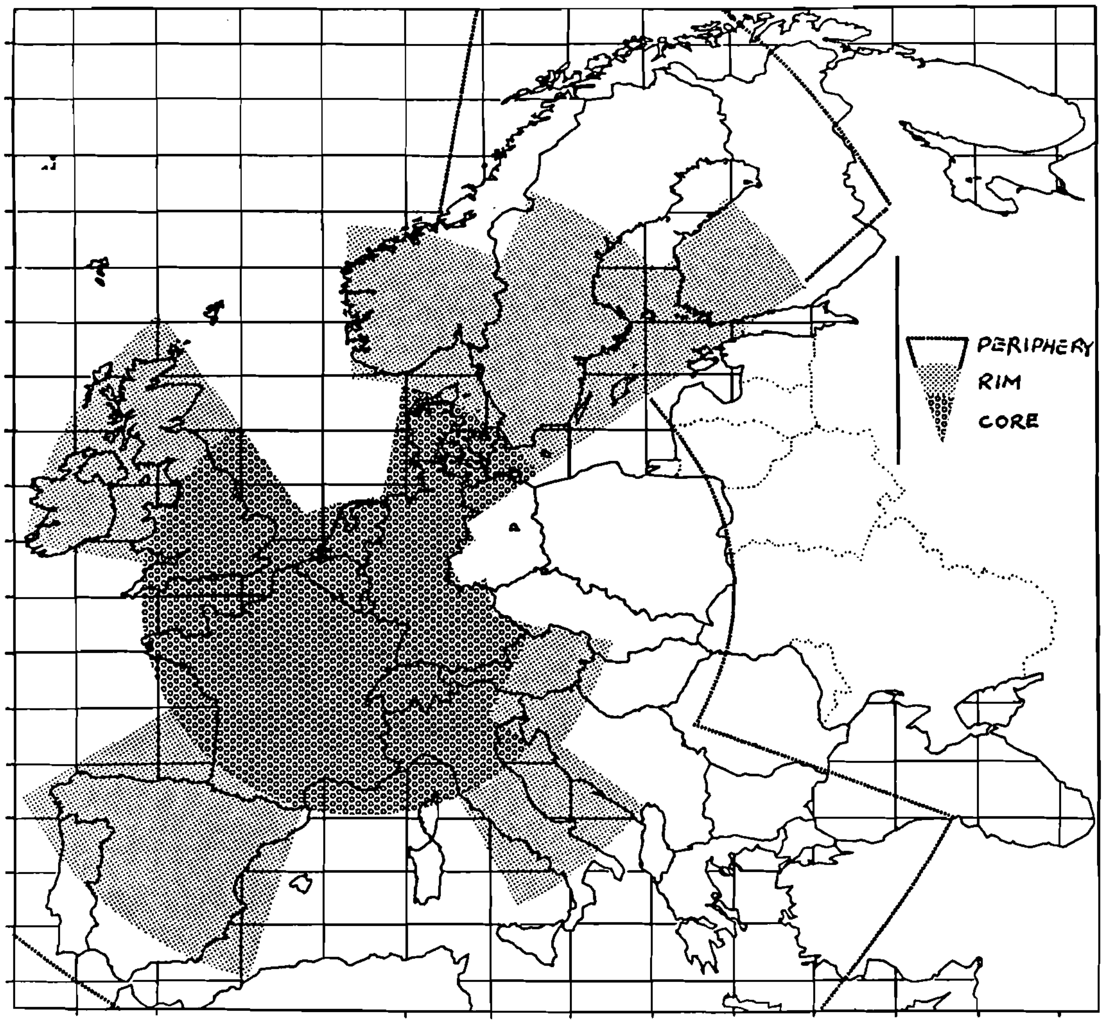

Figure 4. A spatial taxonomy of Europe: *core, rim,* and *periphery.* The core is characterized by highest levels of economic development and intense functional integration (trade and information flows, movement of people, etc.). Levels of development, degrees of modernization of industrial structure, and functional *integration* thin out from the core to the rim, and further to the periphery. Regions are defined on basis of their *functional* characteristics, and not necessarily by their geographical proximity. As such, differences in Europe between the inner EC countries, North Africa, and the Ukraine mirror disparities in industrial and overall economic development on a global scale. Source: Grübler and Nakićenović, 1990.

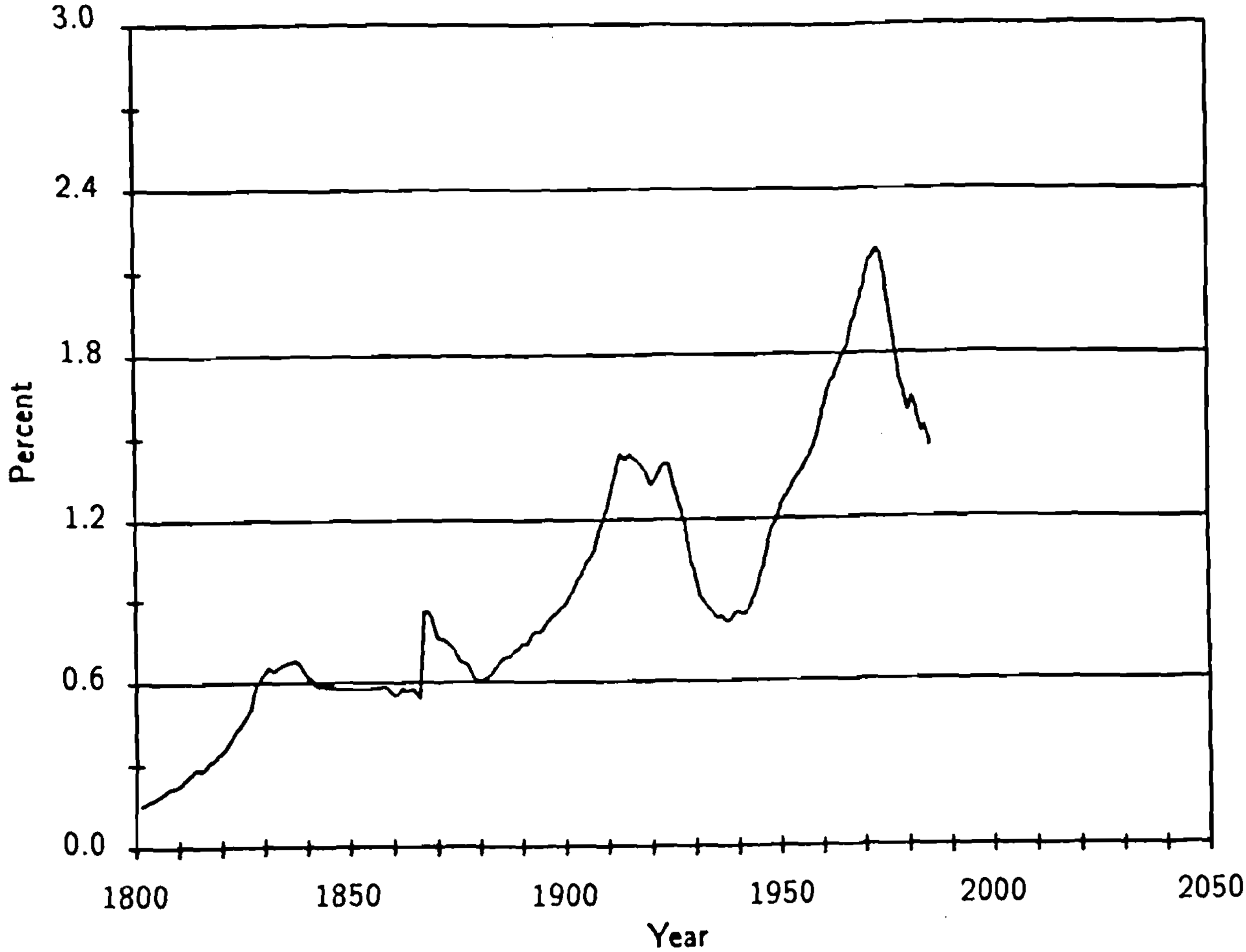

Figure 5. Average rate of technical, economic and social change based on a sample of 117 diffusion processes in the US (in percent per year). The diffusion equivalent of the annual GNP growth rate reveals pronounced discontinuities. Rising average rates of change indicate the diffusion of an entire "cluster" of innovations, providing the main sources for industrial output and productivity growth. Source: Grübler, 1991.

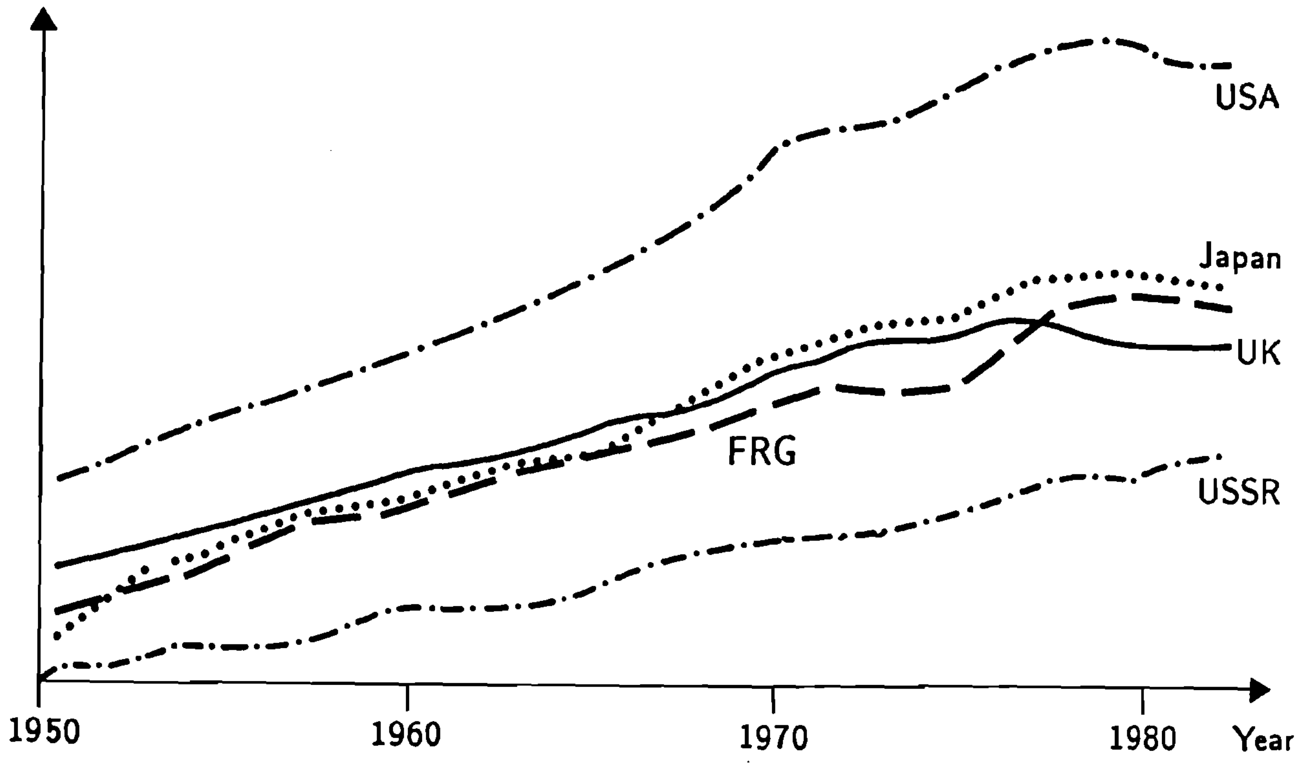

Figure 6. Dimensionless indicators of the evolution and intensity of the "mass production/consumption" cluster (referred by Glaziev, 1991, as "forth technological wave"). 50 indicators over the period 1950 to 1986 are analyzed by a two-step principal component analysis. The results indicate similar dynamics of the overall evolution in the OECD countries, with the US however showing persistently higher intensity levels. The former USSR lags behind and never reaches levels comparable to Western Europe, developing most of the materials and energy intensive mass production technologies and sectors, however only a few of the mass consumption ones. Source: Glaziev, 1991.

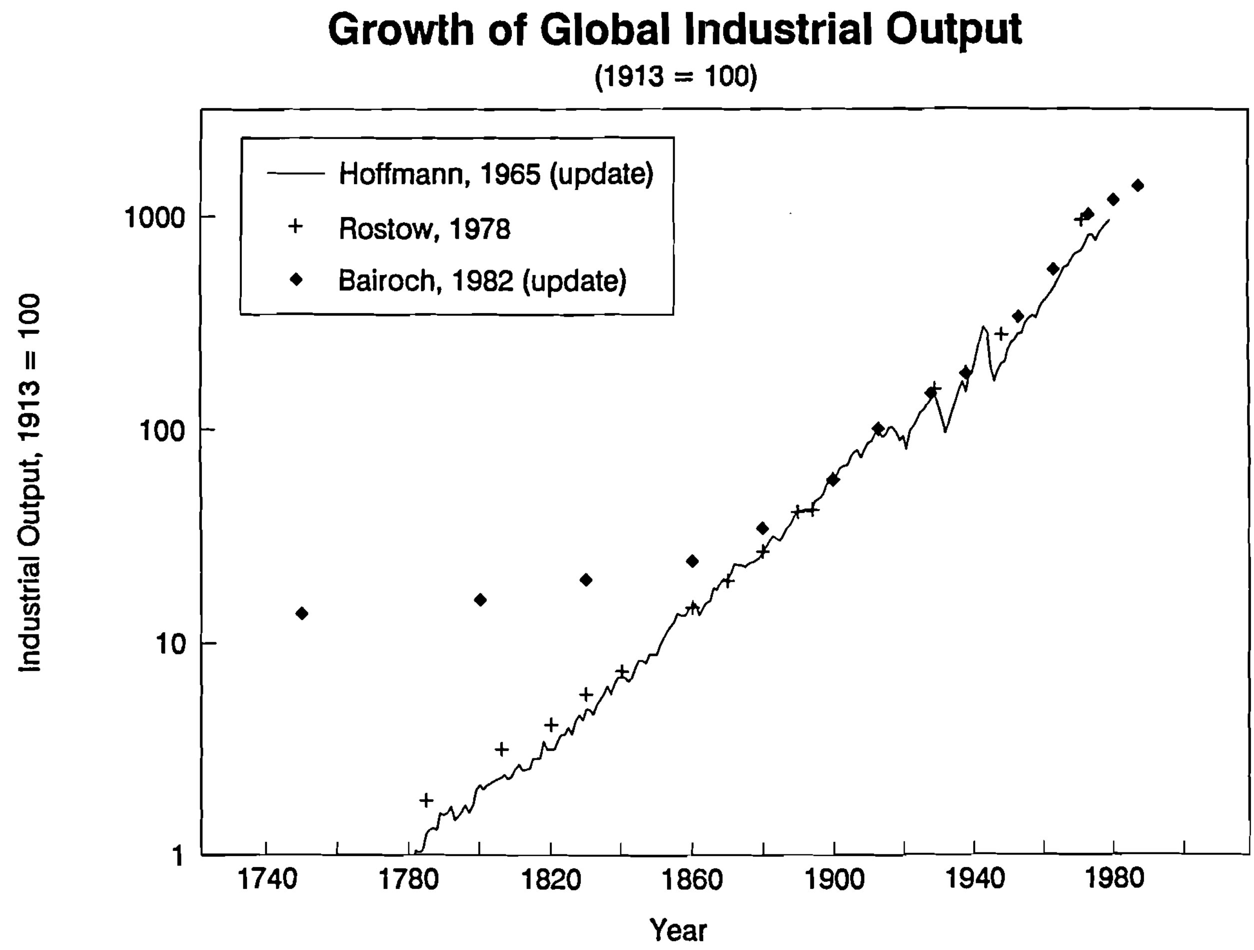

Figure 7. Growth of global industrial output, a comparison of three estimates (index 1913=100), revealing a basically exponential growth path since (the middle of) the 19th century. Data source: Bairoch, 1982, Haustein and Neuwirth, 1982, and Rostow, 1978.

Figure 8. Growth in manufacturing labor productivity (in $ per man-hour), ratio scale. Comparative productivity levels are only approximative, therefore weight should be given only to the *relative* evolution of productivity in a given country over time. Industrial labor productivity gains have been extraordinary, and enabled rising incomes (wages) and shortening of working hours. Industrial output and employment data are from Liesner, 1985, and Mitchell, 1980, and 1983; working hours from Maddison, 1991. Productivity figures between 1840 and 1930 have been harmonized with the estimates of Clark, 1940.

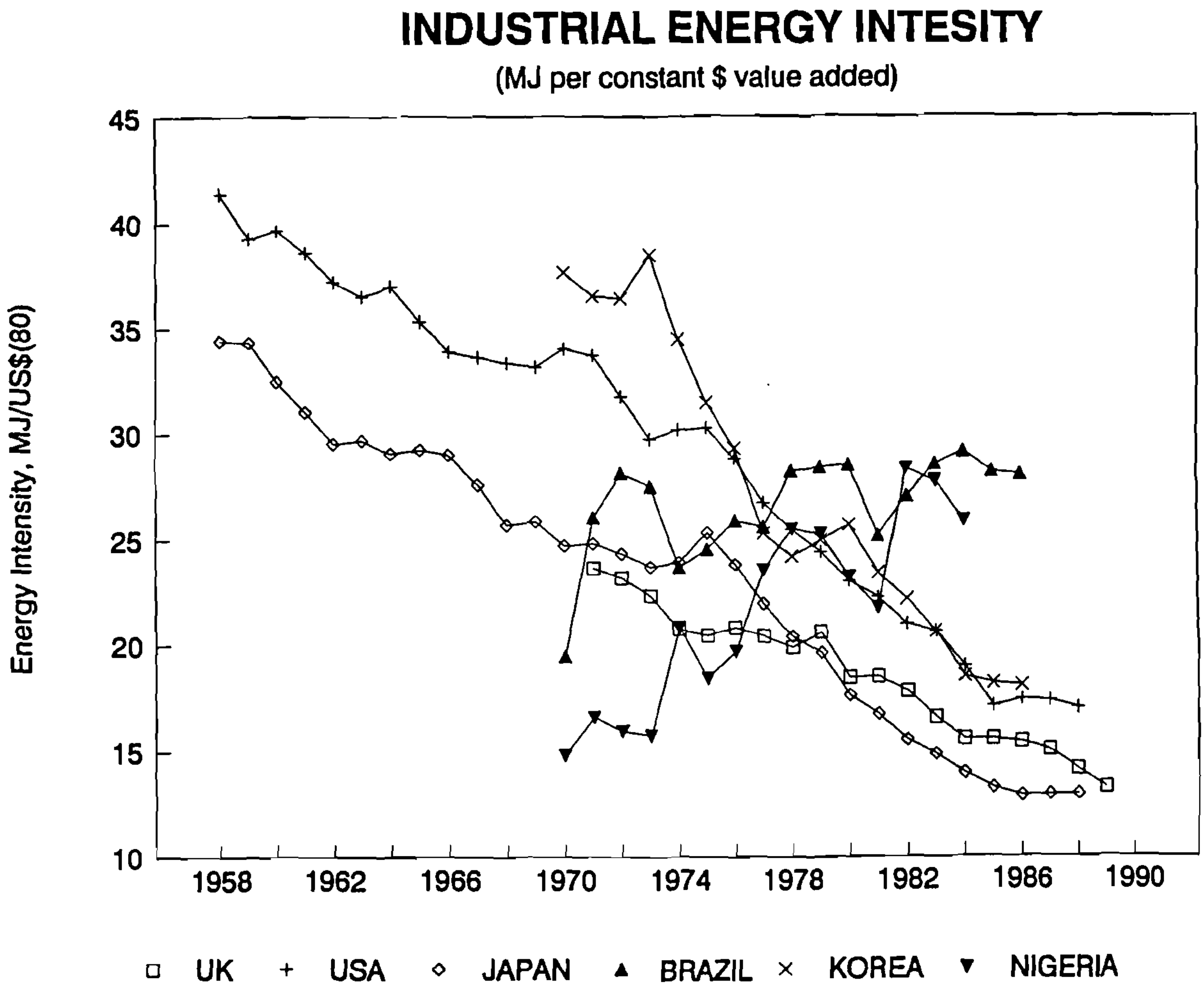

Figure 9. Industrial energy intensity (MJ per US $ 1980) for selected countries. Note the differences in rising intensities in Brazil and Nigeria and declining intensities elesewhere. Data source: LBL data base and IEA, 1991.

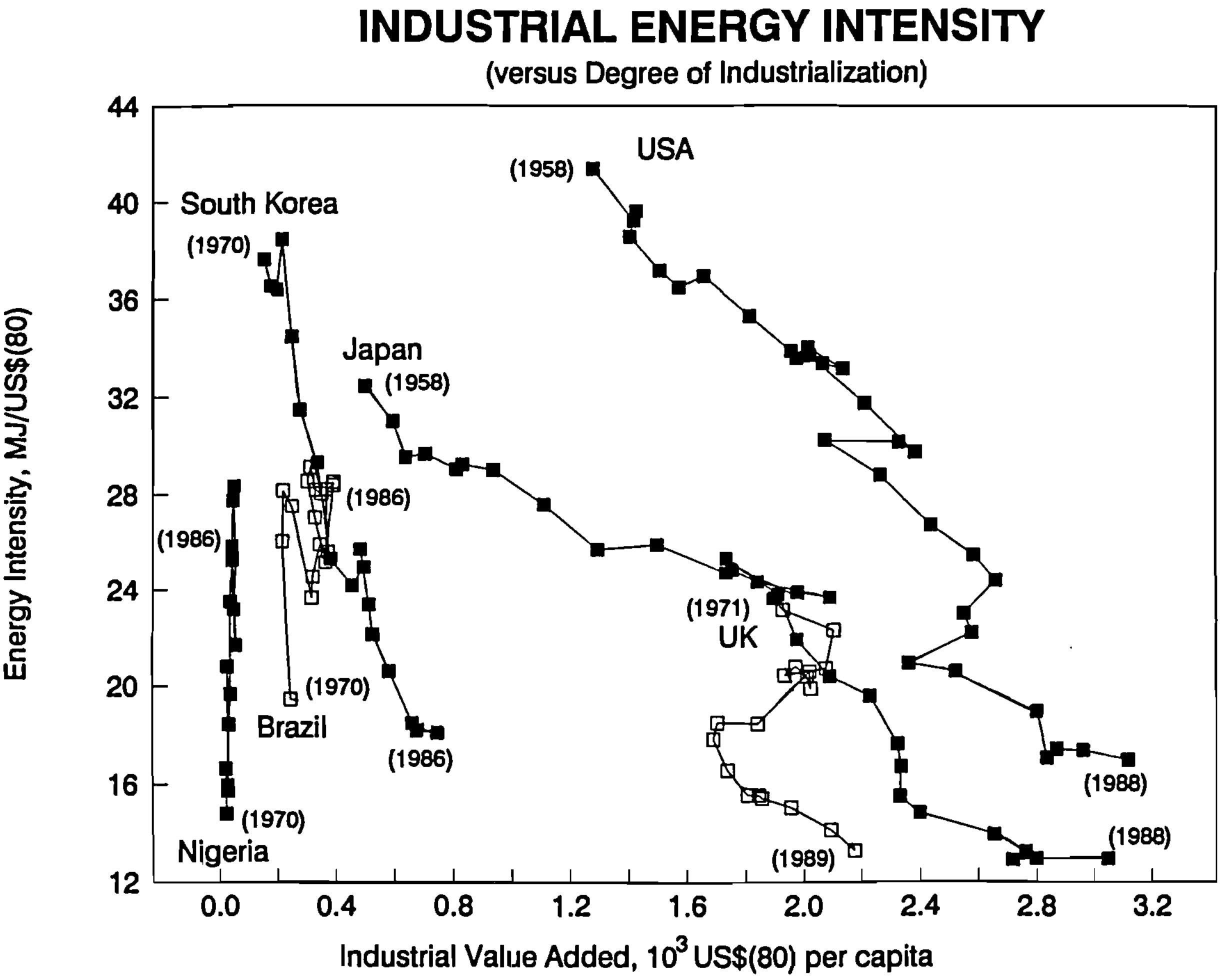

Figure 10. Industrial energy intensity (MJ per US \$ 1980) versus degree of industrialization [industrial value added (1000 US \$ 1980) per capita], as a more functional scale to assess the evolution of industrial energy intensity. Data source: cf. Figure 9.

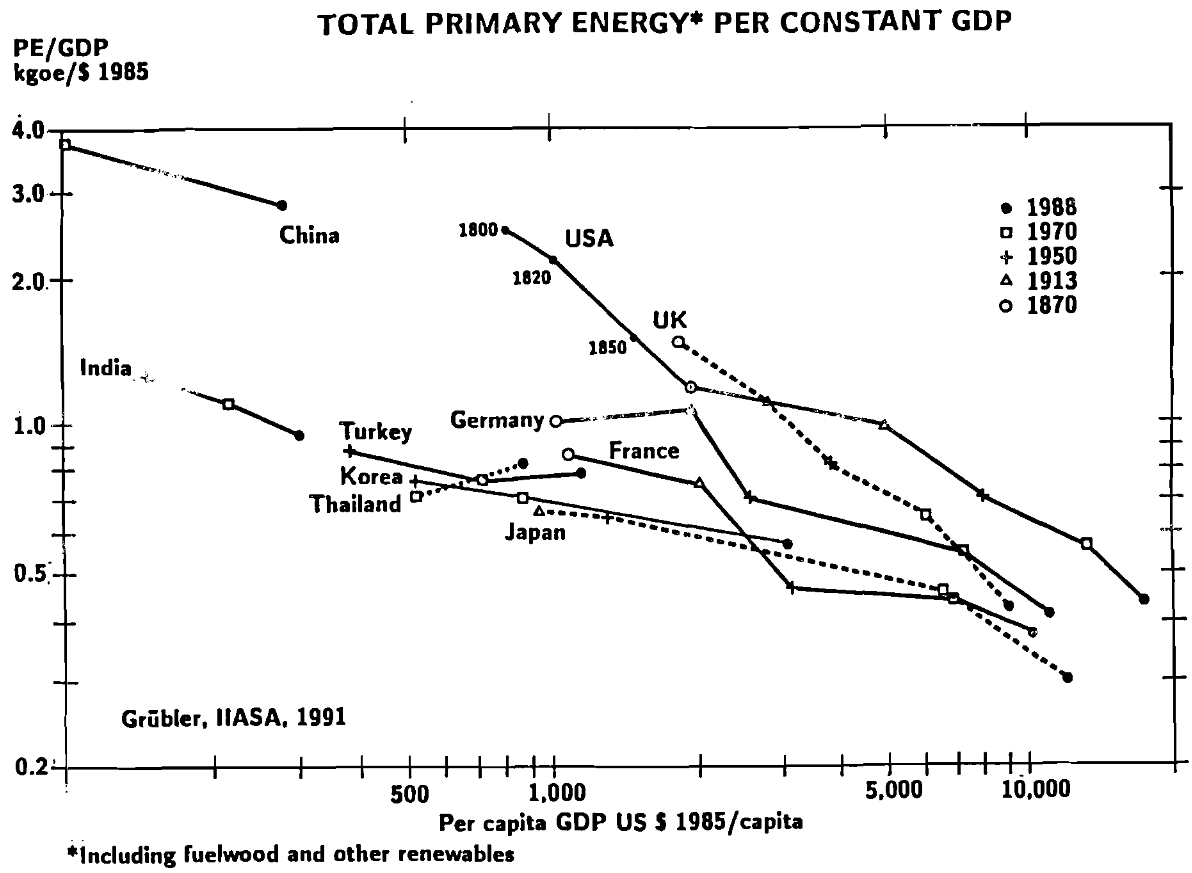

Figure 11. Total primary energy (including fuelwood) intensity per constant GDP (kgoe per US $ 1985) versus per capita GDP (US $ 1985 per capita). The Figure shows persistent differences in the energy intensity of various development paths pursued. The overall long-run improvement rate equals about 1 percent per year. Data source: Nakićenović *et al.*, 1990.

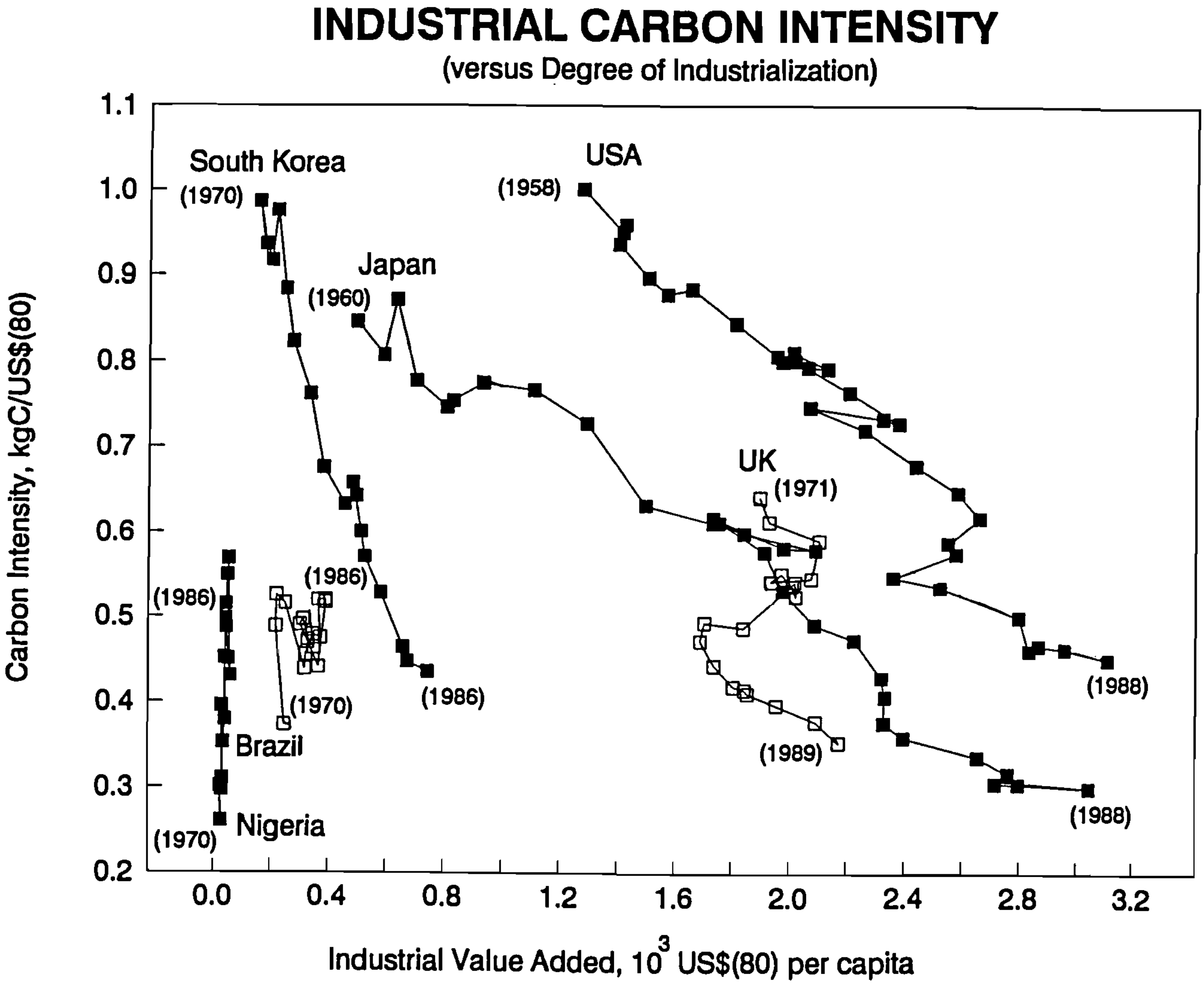

Figure 12. Industrial carbon intensity (kg C per US \$ 1985 value added) versus per capita level of industrialization (1000 US \$ 1980 per capita), cf. Figure 10 above. Data source: energy and value added: LBL data base, carbon emissions: emission factors based on Ausubel *et al.*, 1988; electricity production structure from IEA, 1991.

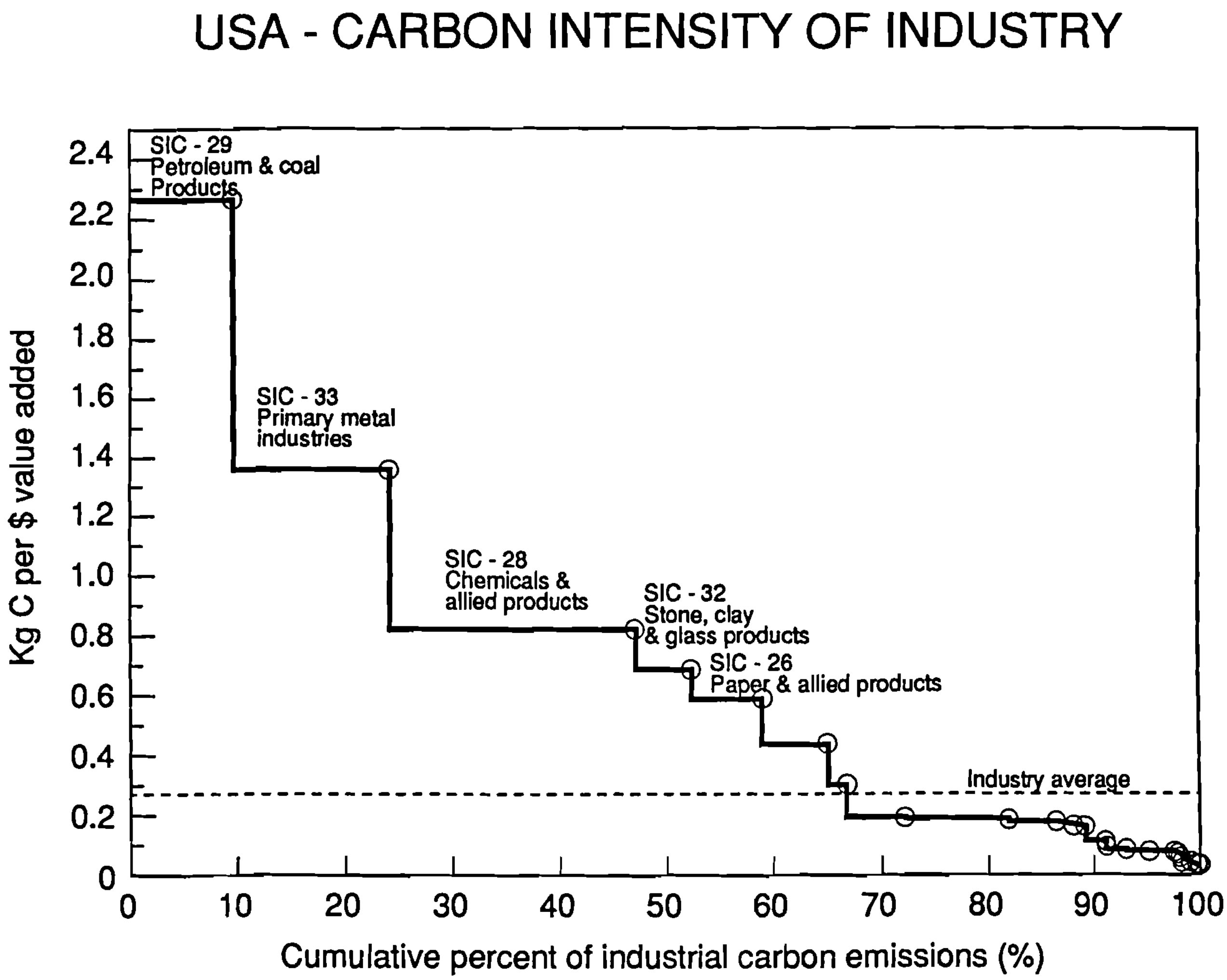

Figure 13. 1987 distribution of US industrial carbon emissions by carbon intensiveness (kg C per $ value added) for 2-digit SIC-code level product categories. The heterogeneity of the emission intensiveness between different industrial products indicates the importance of changes in industrial output mix for lowering overall specific industry emissions. Data source: Marland and Pippin, 1990.

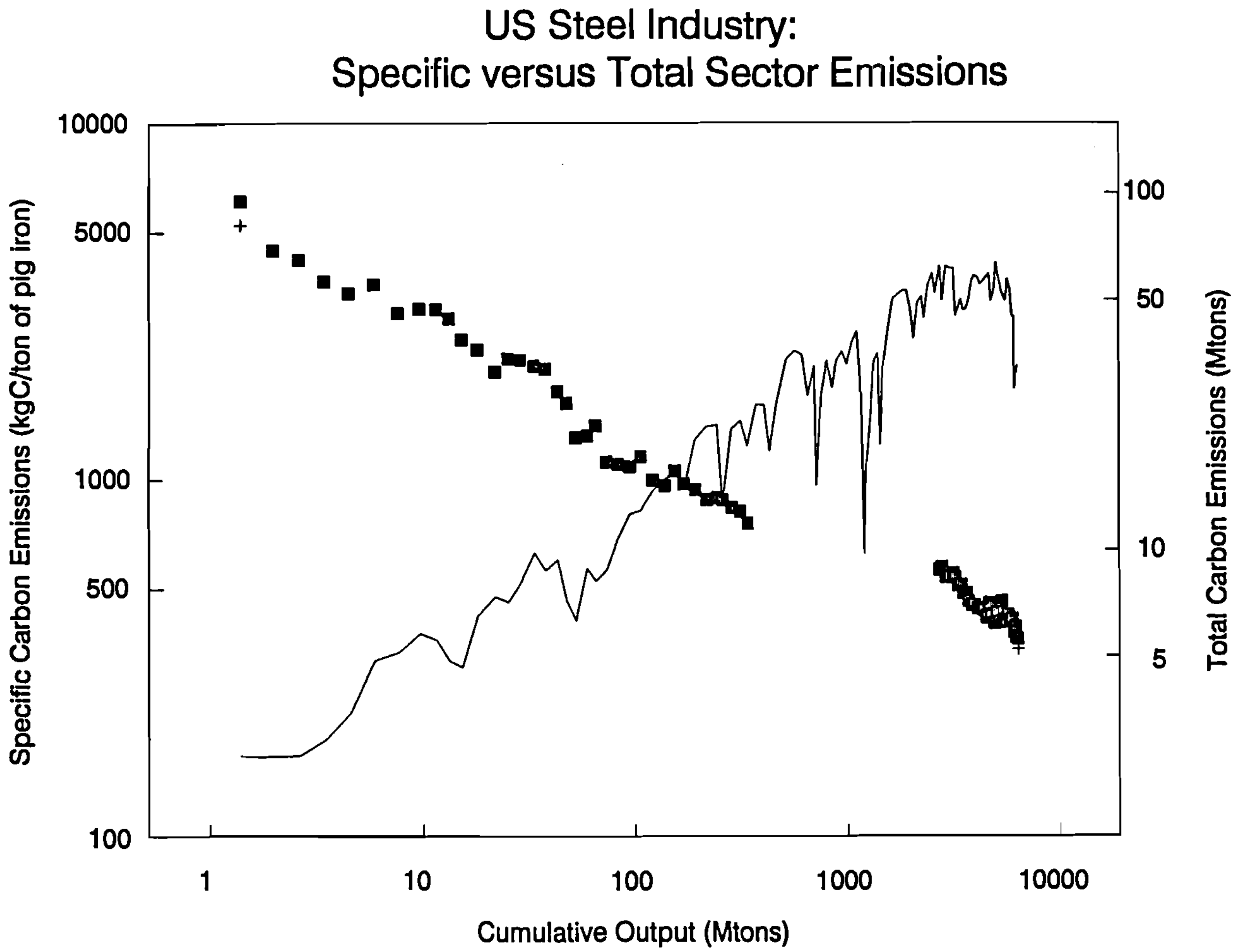

Figure 14. US steel industry: specific and total sector carbon emissions versus cumulative output. Carbon emissions from electricity production included in proportion of industrial to total final electricity consumption. It is particularly interesting to note that specific carbon emissions have decreased along a typical industrial learning curve, despite minimizing carbon emissions was up to now never on the industry's agenda. Specific carbon emissions decrease by 17 percent for each doubling of cumulative output. This is result of structural changes in process technologies and energy carriers used. Data source: Grübler, 1987; IEA, 1991.

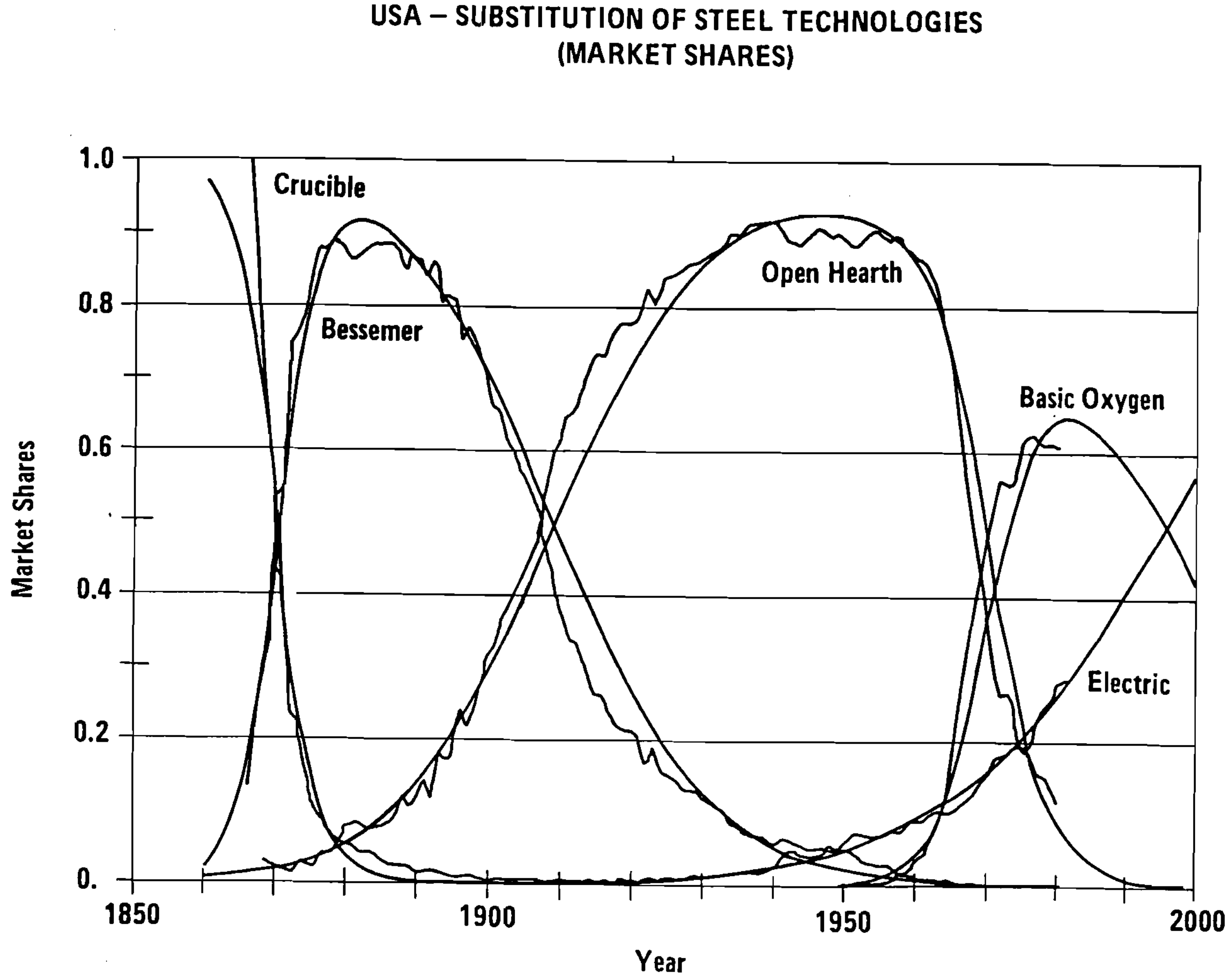

Figure 15. Process technology change in US steel manufacture (relative market shares of different processes in raw steel production). Jagged lines are historical data and smooth curves model estimates by a set of coupled logistic equations. The dynamic pattern of process technology change over time shown in the Figure is almost invariant across sectors and countries, also the timing and regularity of such technological substitution processes can vary considerably. Source: Nakićenović, 1990.

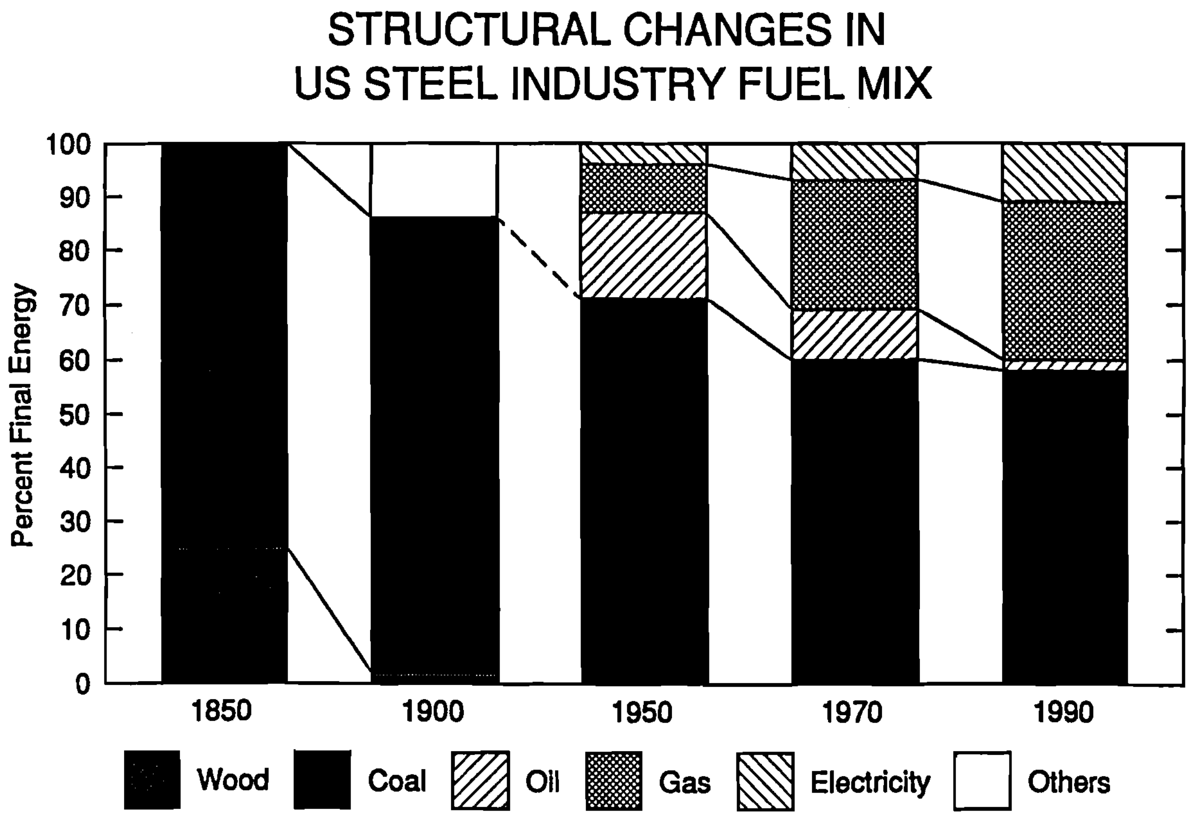

Figure 16. Structural changes in US steel industry fuel mix (percent of final energy). Changes in energy supply structures have accompanied changes in industrial process technologies (cf. Figure 15). Data source: 1850–1970: Grübler, 1987; 1990: IEA, 1991.

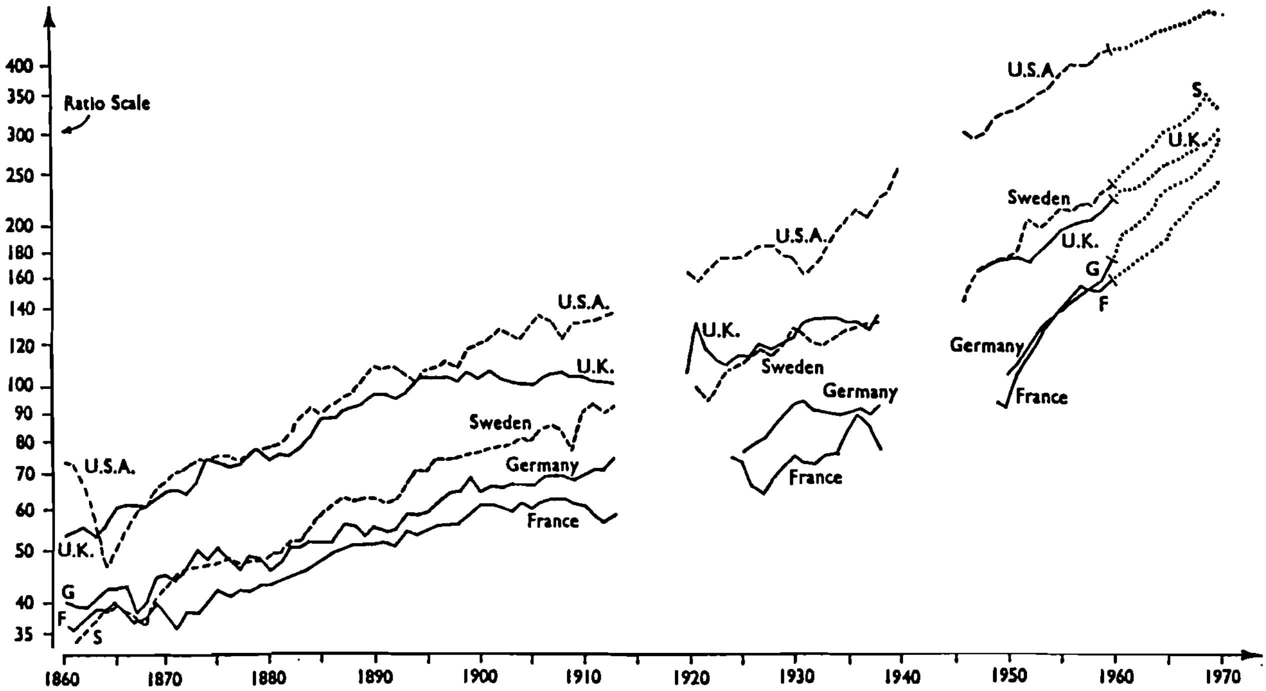

Figure 17. Long-term evolution of real wages in industry (index UK 1890–1899=100). Productivity gains in industrial activities have enabled rising incomes, consumption, and resulting further induced demand for industrial products. Source: Phelps Brown, 1973.

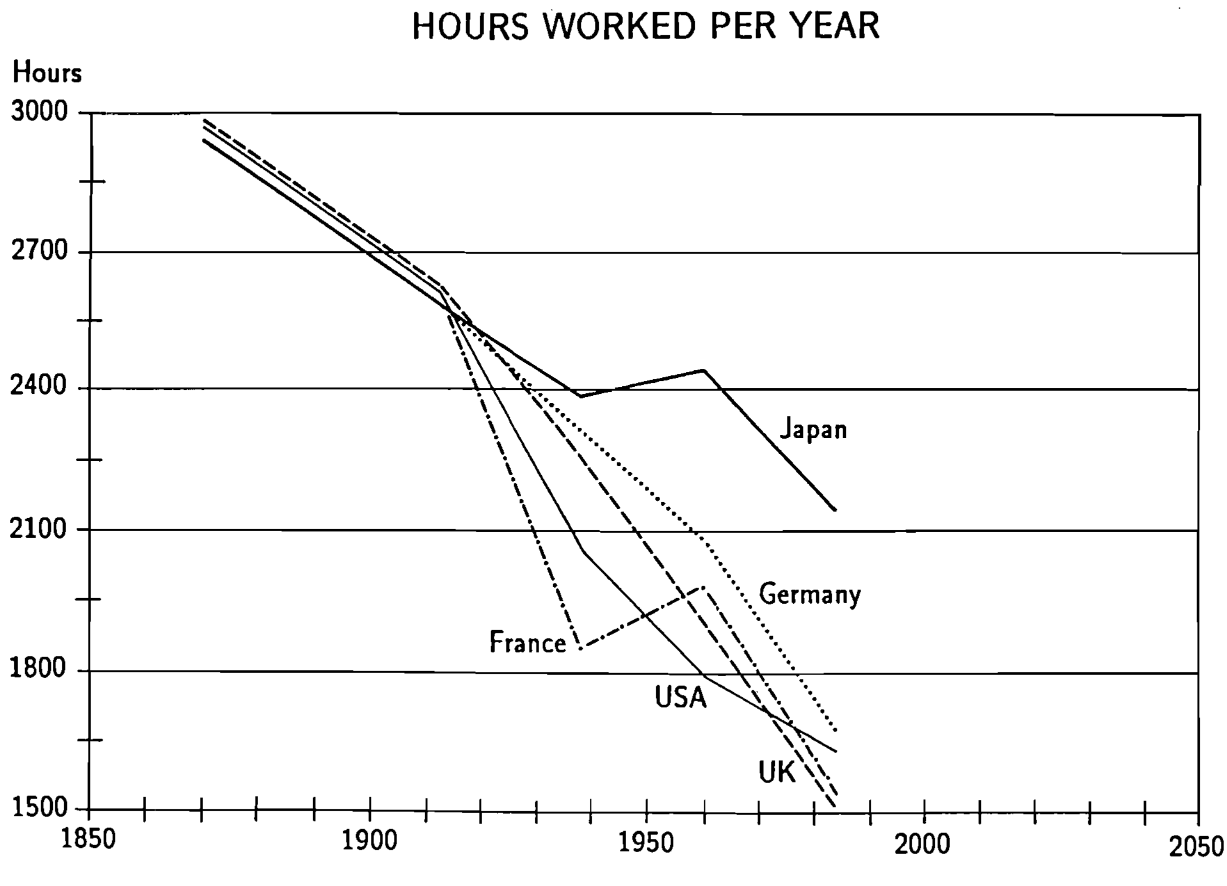

Figure 18. Hours worked per year in selected countries. A second result of rising industrial productivity was to enable significant reductions in working time. Increased incomes and reduced working time (and rising life expectancy) are important social achievements of industrialization. Data source: Maddison, 1991.

USA – TIME AND ENERGY CONSUMPTION

	Time* 10^9 hrs	Final Energy 10^9 kgoe	Density kgoe/hr
At Home*	835.5*	236.6	0.28
At Work	291.1	660.0†	2.27
Services	183.5	152.0	0.83
Travel‡	107.6	279.0‡	2.59
Total	1417.7	1328.4	0.94

	10^9 kg C	kg C/hr
Carbon Emissions	1201.6	0.85

* Excluding sleep

† Including industry transportation, industrial energy use, agriculture, feedstocks

‡ Only passenger travel

Figure 19. Energy and carbon intensiveness of different activities for the US population. Excluding physiological time (i.e., time required for eating and sleeping) each US citizen consumes on average about one kg of oil equivalent energy per hour and emits roughly the same amount of carbon. Note in particular the high carbon intensiveness per unit time of transportation. Source: Grübler, 1991b.

TIME BUDGET CHANGES IN 7 COUNTRIES, 1960s to 1980s

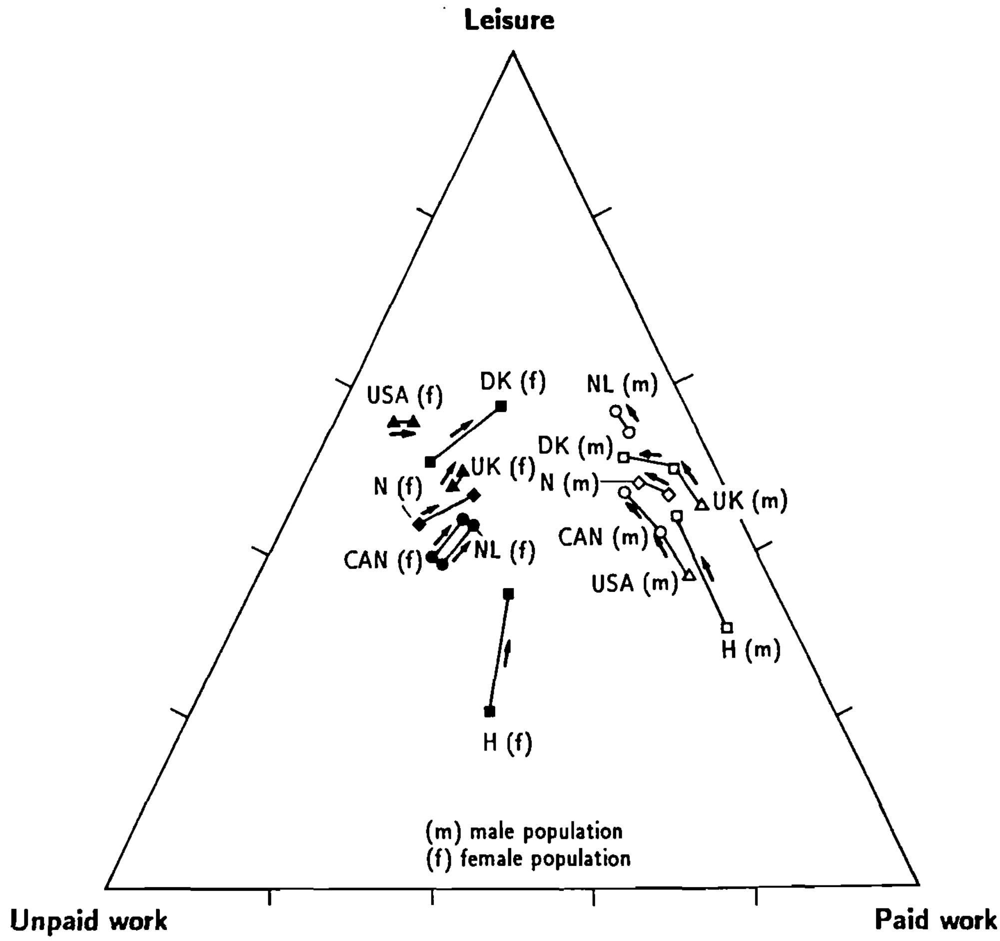

Figure 20. Relative allocation of time budgets to different activities, male and female population of seven countries, 1960s to 1980s. The Figure illustrates an international and gender convergence away from formal, contracted work to unpaid work (e.g., family care) and leisure activities. This transition from work to non-work in activity patterns can be clearly discerned also in energy demand statistics. In industrialized countries today about two-thirds of final energy is consumed outside the productive sphere (i.e., industry) for services and leisure uses of energy. Source: Gershuny, 1991.

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