Towards the Fifth Kondratiev Upswing: Elements of an Emerging New Growth Phase and Possible Development Trajectories

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Preface

One of the most important questions relating to global sustainability pertains to the nature of the future development paths followed by LDCs. Their future contribution to global environmental stresses may become so dominant as to make unilateral courses of action by individual (group of) countries unviable. Certainly, population growth is one of the key variables in this context. However, another important factor to consider is whether a worldwide homogenization of life styles and resource consumption levels along the past energy and resource intensive historical development path of industrialized countries will take place.

This paper argues that the next phase of development may be different from the past. Future economic growth and development may depend more on the introduction and widespread diffusion of new activities which add value with less energy and material inputs and thus have smaller environmental impacts than traditional *smoke-stack* development strategies. The authors consider that developing countries may even have a strategic advantage in the transition to such a new mode of development because they are less committed in terms of their capital vintage structure, their management practices, and lifestyles, to the previous development model. The arguments and empirical evidence assembled here indicate the broad direction and characteristics of such a new development phase. There are reasons to be cautiously optimistic; given that appropriate policies are implemented a transition to a sustainable development path may not only be feasible, but also be consistent with historical experience.

However, the authors refer also to a "hidden agenda" that goes beyond the dimensions of pure economic and technological restructuring. They caution against the frequently postulated short-term global convergence tendencies. They also indicate the importance of the social and institutional embedding of environmentally compatible technologies and economic activities and emphasize the role of science and technology policy in making the best use of the opportunity windows that occur in the transition to a new phase of development. As such, the paper provides background for further discussion and analysis of the general problématique addressed by the Environmentally Compatible Energy Strategies (ECS) Project at IIASA.

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Towards the fifth Kondratiev upswing: elements of an emerging new growth phase and possible development trajectories

Vers la cinquième phase d'essor Kondratievien: prémisses de l'emergence d'une nouvelle phase de croissance et trajectoires de développement possibles

Der fünfte Kondratieffsche Aufschwung: Elemente einer neuen Wachstumsphase und mögliche Entwicklungspfade

コンドラチエフ第5波の上昇期へ向って — 顕在化する新成長段階と予想される発展軌道

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Abstract: This paper takes a long-term view on economic growth from an essentially Schumpeterian perspective. The authors consider that since the early 1970s we have been witnessing a volatile and turbulent transition towards a new phase of socio-economic development, in which the diffusion of a host of inter-related new technologies, institutions and forms of organization could lead to a renewed period of economic growth and prosperity. They argue that the beginning of such a diffusion phase, in which the ultimate characteristics of the future development trajectory are being shaped, could constitute an opportunity window for reducing the disparities between countries as a result of their different degrees of economic development. They consider in addition that the successful catching-up will depend more on an effective introduction and diffusion of the elements of the emerging new development regime than on a growth model along the trajectories and intensity level of the previous model of development.

Keywords: economic growth; global development; Kondratiev upswing; Schumpeterian growth model; structural adjustments; diffusion of technology; energy; transport; communications; developing countries; technology transfer.

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Biographical notes: Dr Arnulf Grübler received his masters degree in engineering from the Technical University of Vienna, where he was also awarded his PhD. Dr Grübler first joined IIASA in 1976 to work with the Energy Systems Program and between 1979 and 1984 was affiliated with the Resources and Environment Area. His main areas of research were on quantitative assessment models of energy resources and on the natural resource requirements and environmental impacts of energy options. He returned to the Institute in 1985 and since January 1986 has been a Research Scholar within the Technology, Economy, Society (TES) Program. His scientific interests include long-term technology development as well as comparative analysis of the dynamics of processes of change within and between different economic and social environments. In addition to his work at IIASA, Dr Grübler has conducted research assignments with the East–West Center, Honololu and the World Bank, Washington, D.C., and has served as consultant to a number of organizations including the Centro per il Sistemo Informativo, Torino; the Eduard Pestel Institut für Systemanalyse und Prognose, Chemie Linz AG., Austria, and Shell International Petroleum Co. Ltd, London.

Helga Nowotny is Dr. iur. of the University of Vienna and has a PhD in sociology from Columbia University, New York. From 1974–87 she was Founding Director of the European Center in Vienna. She has held various teaching and research positions at King's College, Cambridge, Institute for Advanced Studies, Vienna, University of Bielefeld, University of Graz, Wissenschaftskolleg zu Berlin, Maison des Sciences de l'Homme, Paris, and Wissenschaftszentrum für Sozialwissenschaften, Berlin. Since 1987 she has been a Professor at the University of Vienna and Director of the newly founded Institute for Theory and Social Studies of Science. Dr. Nowotny has contributed to publications in the area of sociology, social policy and social studies of science and technology.

Résumé: Cet article est un analyse à long terme de la croissance économique vue dans une perspective essentiellement Schumpeterienne. Les auteurs considèrent que depuis le début des années 70, nous avons vécu une période de transition turbulente vers une nouvelle phase de développement socio-économique, où la diffusion d'une multitude de technologies, d'institutions et de formes d'organisation nouvelles pourrait amener une nouvelle période de croissance économique et de prospérité. Ils soutiennent que le commencement de cette phase de diffusion, où la trajectoire du développement futur prends sa forme, pourrait constituer une opportunité permettant de réduire les disparités entre les pays ayant atteint des niveaux différents de développement économique. Ils pensent en outre, que la réussite du rattrapage dépendra davantage de l'introduction et de la diffusion effective des éléments du nouveau régime de développement que d'un modèle de croissance suivant les trajectoires et les niveaux d'intensité realisé avec le modèle de développement antérieur.

Mots-clés: croissance économique; développement mondial; essor Kondratievien; modèle de croissance Schumpeterien; adjustements structuraux; diffusion de la technologie; énergie; transports; communications; pays en voie de développement; transfert de la technologie.

Zusammenfassung: Dieser Beitrag liefert eine Langzeitstudie des Wirtschaftwachstums aus einer im wesentlichen Schumpeterschen Perspektive. Die Autoren sind der Auffassung, daß wir seit den frühen 70iger Jahren Zeugen eines erratischen und turbulenten Uberganges zu einer neuen Phase der sozioökonomischen Entwicklung sind, in welcher die Diffusion eines Bündels independter neuer Technologien, Institutionen und Organisationsformen zu einer erneuerten Periode des ökonomischen Wachstums und der Prosperität führen könnte. Der Beginn einer solchen Diffusionsphase, während der sich die elementaren Charakteristiken der Wege der zukünftigen Entwicklungspflade herausbilden, könnte ein mögliches Fenster zur Reduktion der zufolge der unterschiedlichen Grade der wirtschaftlichen Entwicklung zwischen Staaten darstellen. Überdies sind sie der Auffassung, daß das erfolgreiche Aufholen mehr von der effektiven Einführung und Verbreitung der Elemente des neuen Entwicklungsbereiches abhängen, als von einem Wachstumsmodell, welches auf den Trajektorien und Intensivitätsnivaus des vergangenen Entwicklungsmodelles beruht.

Sachwörter: Wirtschaftswachstum; globale Entwicklung; Kondratieff; Aufschwung; Schumpetersches Wachstumsmodell; strukturelle Anpassung; Technologiediffusion; Energie; Transport; Kommunikation; Entwicklungsländer; Technologietransfer.

要約　本論文は，本質的にはシュンペーター的観点から経済の長期的展望を行ったものである。１９７０年代の初期以降われわれは，社会経済の発展が波瀾に富んだ軌跡を描きながら，新らしい段階へ移っていったのを目撃した。その中で，相互に関連し合った新技術や，制度，組織の形態といったものが，数多く且つ広く普及したことで，新らたな経済の成長と繁栄への道がひらけた。このような普及の初期段階で，将来の発展の基本的方向が形成されたのであるが，この段階でまた，経済発展の度合が異なるところからくる国家間の不均衡を減らす好機をとらえることができた。成長に首尾よく追いつくには，昔のシュンペーター的発展のモデル軌道や，強度の水準に沿った成長の規範に頼るよりも，顕在化する新しい発展様式の要素を効果的に導入し，普及させることにより多く依存するだろう，と考えられる。

キーワード　経済成長，世界的発展，コンドラチエフ上昇，シュンペーター的成長モデル，構造調整，技術の普及，エネルギー，交通，通信

> "Add as many mail-coaches as you please, you will never get a railroad by so doing."
> Joseph A. Schumpeter, 1935 [1]

In this paper we take a long-term view of economic growth from an essentially Schumpeterian perspective. We consider that since the early 1970s we are witnessing a volatile and turbulent transitional period towards a new phase of socio-economic development, in which the diffusion of a host of inter-related new technologies, institutions and forms of organization could lead to a renewed period of economic growth and prosperity. We argue that the beginning of such a diffusion phase, in which the ultimate characteristics of the future development trajectory are being shaped, could constitute an opportunity window for reducing disparities between countries as a result of their different degrees of economic development. We consider, in addition, that successful catching-up will depend more on an effective introduction and difussion of the elements of the emerging new development regime than on a growth model along the trajectories and intensity levels of the previous model of economic development, i.e. an argument following the powerful lines of Schumpeter, quoted above.

Examples of emerging technological elements in the area of energy and transport and communication technologies will be outlined. The importance of integration into international flows of technical knowledge, skills and capital in order to most effectively make use of the growth (and catching-up) opportunities opened up by the diffusion of a new socio-technical 'bandwagon' will be sketched out. On the basis of historical examples, we will try to support the argument that heterogeneity both in the socio-technological options as well as in the ultimate intensity (diffusion, or resource consumption) levels was and will continue to be an essential factor to be kept in mind when elaborating scenarios and policies, particularly for developing countries. As such, we refute the prescriptive character of some scenarios which are based on the implicit assumption that diffusion and resulting resource consumption levels realised in a previous expansion phase are realistic (even desirable) targets for followers at later times. Heterogeneity in the ultimate realisation levels of a new socio-technic development phase also has important repercussions on our perception of future sustainability, which is often perceived as being threatened in scenarios assuming strong homogenization in development patterns, lifestyles and resource consumption levels.

1 Structural adjustments and the emergence of a new socio-technical development phase

The evolutionary path of successive replacements of traditional by new forms of development and economic growth, driven by the diffusion of technologies and institutions, and interlaced by economic restructuring and transformations in social relations is captured in Schumpeter's 1939 [2] notion of long waves in economic development — i.e. a seesaw-like pattern of Kondratiev [3] pulses of expansionary and recessionary (restructuring) periods experienced in market economies during the last two centuries. Rather than a process of continuous growth, long-wave theory supports the idea that growth itself comes in pulses stimulated by the appearance and widespread diffusion of social, institutional and technological innovations, leading to new forms of organization of production, new products, new infrastructures and even whole new industries.

In the work of Freeman [4], Freeman and Perez [5], Mensch [6], Marchetti [7], Nakicenovic [8] among many other authors, the conceptual and empirical description of long waves, diffusion, invention and innovation processes have been laid, albeit from different methodological and theoretical perspectives [9]. Within a Schumpeterian notion of the importance of innovations we emphasize in particular the discontinuous nature in which innovations are introduced and especially how they *diffuse* (become embedded) into the economic and social system.

One should note in this context that innovations have to be defined in a broader sense than technology (i.e. product and process innovations) alone, as the growth potential of an inter-related set of technological innovations and associated 'best' engineering and management practices (i.e. a technological 'trajectory' in the sense of Dosi [10]) can only be realised in conjunction with new organizational forms in production and social relations as well as new skill levels. The inter-relatedness of both the technological and the social/institutional innovations enabling major economic upturns and explaining their pervasive effects throughout the economy and society is captured in the concept of a 'techno-economic paradigm' as discussed by Perez [11] and Freeman and Perez [5].

Along a similar line we consider in the present context that a set of inter-related social and technical innovations drives particular historic economic expansion periods. In each of such particular development phases a synergetic aggregate of major technological and organizational innovations and the direction along which economic growth takes place enables an expansion of the levels of productivity and allows greater economic development than was possible (sustainable) under a previous development regime.

Such a new development regime emerges, however, only through a process of restructuring in response to the saturation of the growth potential of the previously dominant form and direction of economic growth, i.e. in response to the fact that a particular phase of economic expansion approaches a number of limits (market, environmental, social acceptance, etc.) and becomes increasingly characterized by diminishing returns and an accelerating pattern of incremental innovations [12].

A new development (growth) regime thus enables the limits of market saturation to be overcome and allows further productivity increases of the previous dominant mode of economic growth and development. The full-scale realisation of the growth potentials opened in a new development phase is however conditional on a process of restructuring, involving in-depth and far-reaching social and institutional changes. It also entails the development of new technologies and products, the rise and decline of entire industries and infrastructures, changes in the international location of industries, and technological leadership. The transition to a new development (growth) regime calls for transformations in the skills and composition of the workforce, the education and training system, the system of industrial relations, structure (e.g. level of integration) of enterprises, production and management 'styles' and practices, and the international trading and financial system, among others. It is via the widespread diffusion of new technologies, products and institutions shaping a new development regime that an economic upturn and a prolonged period of economic growth is made possible. The final form of the elements and structure of a new development regime, as well as the time-span within which the required restructuring is effected to permit a new expansionary phase, will in turn depend upon the interests, actions, relative strength and the interplay between the social forces involved in its formation.

From a long-term perspective it appears that Kondratiev cycles as a model of the discontinuous nature of economic development — i.e. a succession of periods of regular expansion and growth interlaced with periods of intensive restructuring (recession, even depressions, accompanied by turbulence and volatility in prices, financial markets and social relations) — are in principle caused by the discontinuous manner in which technical, social and organizational innovations are introduced and become absorbed by the economic and social fabric. The coupled dynamics of both the discontinuous introduction and diffusion rates of innovations result in strong discontinuities in the long-term economic development, where 'boom' periods are followed by 'seasons of saturations' [13], in which a large number of innovations, responsible for much of the previous economic growth, reach their market and diffusion saturation. Such discontinuities in the long-term economic development emerge even without a rigid clustering in either the introduction dates (as originally maintained by Mensch [6]) or the saturation periods of the diffusion of innovations.

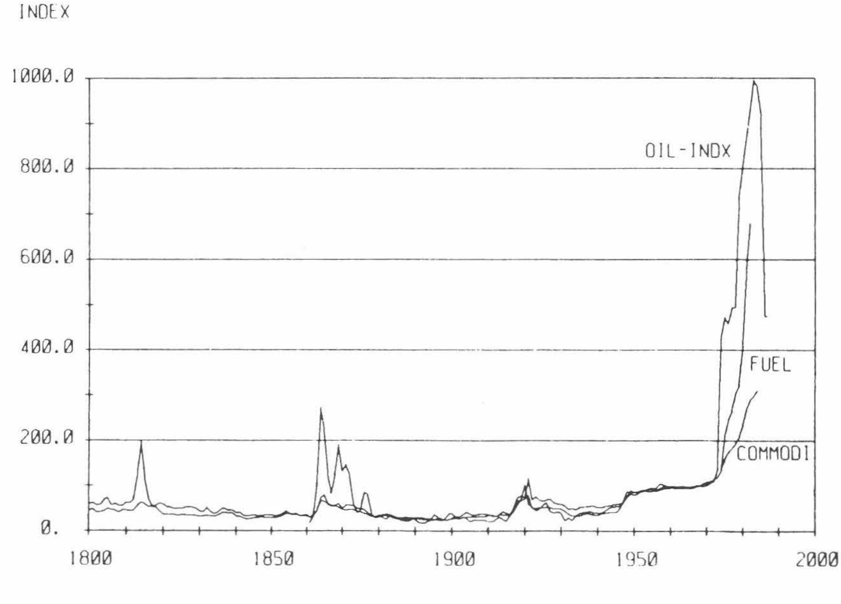
Long waves are an international phenomenon, as manifest in a wave-like, broadly synchronous, movement of aggregate indicators like the diffusion of technologies, industrial output, prices, etc. As such, we suppose that any macroscopic event affecting simultaneously the economic and social evolution of a number of core countries of a particular development phase, will most likely have a common causality and will in particular be capable of reverberating at a worldwide level, also affecting fringe countries. This does not hold only for the growth periods of a Kondratiev cycle, but even more so for the downswing and recessionary periods marking the transition between two consecutive growth or development regimes.

It is also argued that, in addition to the saturation phenomena outlined above, the depression of a Kondratiev cycle (as distinct from an economic recession) may be triggered by a progressive 'mismatch' [11] between the dynamics of the emerging technological elements of a new 'socio-technical paradigm' already existing latently or on a small scale during the end of an upswing phase of a Kondratiev cycle, but being effectively barred from large-scale diffusion and final realisation of the ultimate technological trajectories [14] due to the dominance of the previous 'paradigm', and the dynamics (or rather the inertia) of the existing socio-institutional framework supporting it.

At the same time, the period of restructuring provides an opportunity window for followers to catch up, as in the initial formation of a new development regime local skill levels can be translated into new value-generating activities and products with relatively modest capital outlays, as opposed to the import of capital-intensive mature technologies and goods production facilities, say in the form of large-scale integrated steel plants, textile industry and so on, considered as traditional areas of comparative advantage of developing and newly industrializing countries. Finally, one may even consider that followers have a certain strategic advantage in such transition periods as they have no comparable heavy commitment in terms of vintage capital structure, infrastructures, levels and composition of skills and organizational/institutional settings to the previously dominant (and progressively vanishing) mode of economic growth.

Periods of intense restructuring are especially characterized by increasing volatility

Figure 1 Energy prices and wholesale price indexes showing periods of stable prices and periods of high volatility (restructuring periods). *Source*: Nakicenovic [63]



in energy and raw material prices (as illustrated in Figure 1 in the case of the USA; the speculative character of crude oil spot markets or the price instabilities in the silver market may serve here as further illustrative examples) and instabilities in financial markets (e.g. the October 1987 crash). These instabilities stem from the emergence and widespread application of speculative instruments as a result of a lack of productive investment possibilities *vis-à-vis* saturating traditional markets and the uncertainty about the growth potential and ultimate realisation of the elements of a new development phase. This period is finally accompanied by structural unemployment as a consequence of market saturation in the dominant growth sectors of the previous upswing as well as by increasing tendencies for mergers and acquisitions due to the above-mentioned shift in the search for profit opportunities away from productive investments. Considering the still significantly higher yields attainable in financial markets (see for instance the swift recovery from the October 1987 crash) and the massive investments into mergers and acquisitions (over $300 billion in 1988 in the USA alone) it appears likely that a redirection towards productive investments could occur only after large-scale destruction of speculative capital and/or reduction in the disparities in yields between financial and productive investments.

In Table 1 we give an illustrative summary representation of some of the characteristics of past development phases underlying each Kondratiev cycle, in terms of principal growth sectors (top row in Table 1), emerging technologies that will dominate the next cycle (second row) and management and industrial organization principles (bottom two rows).

2 Elements of a possible new growth phase

Before we address some of the elements which we consider as characteristic of the emerging new development and growth phase of the fifth Kondratiev, let us briefly note some

Table 1 Characteristics of major economic development phases (Kondratiev cycles). *Source*: Pry [25]

1770–1830	*1820–1890*	*1880–1945*	*1935–1995*	*1985–2050*
Water power Ships Canals	Coal Railroads Steam power Mechanical equipment	Cars Trucks Trolleys Chemical industry Metallurgical processes	Electric power Oil Airplanes Radio & TV Instruments & controls	Gas Nuclear Information Telecommunication Sattelite comm. Laser comm.
Mechanical equipment Coal Stationary steam power	Electricity Internal combustion Telegraphy Steam shipping	Electronics Jet engine Air transport	Nuclear Computers Gas Telecommunication	Biotechnology Artifical intelligence Space comm. & transport
	Economy of scale (Interchangeable parts)	Administrative Management (Taylor)	Professional management	Participative and interconnected systems management
Concept of the industrial firm Division of labour	Concept of mass production Interchangeable parts	Concept of management structure and delegation	Concept of decentralization	Concept of systems structure

important characteristics underlying the growth phase of the fourth Kondratiev, i.e. of the post Second World War era. The post-war economic growth phase was associated with a cluster of inter-related technical and managerial innovations, leading to productivity levels clearly superior to those attainable with previous technologies (primarily based on coal and the steam engine) and systems of production organization. In particular, the extension of the continuous-flow concept of the chemical industry to the mass production of identical units made with energy-intensive materials enabled unprecedented real cost and price decreases and thus led to the mass consumption of these products. Examples of typical products include the internal combustion engine and the automobile, petrochemicals and plastics, and consumer durables, among many others. Petroleum played a vital role [15], both in terms of its availability at low real costs, as well as its role as the principal energy carrier and feedstock in industry, residential and especially transport sectors. The prototype of the associated production organization was 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.

This technological 'style' was 'matched' [11] by the social and institutional framework, a match which was achieved however only after a period of deep depression and social turmoil in the 1930s. Examples of the social-institutional framework associated with the growth of the oil-based energy- and material-intensive mass production regime of the post-war boom include Keynsian policies leading to various forms of demand management, both direct via public infrastructure (roads, highways), defence and public service spending (in particular health care and higher education) and indirectly, e.g. in the form of income redistribution (enabling mass consumption from the disposable income side), generally subsumed under the term 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 socio-institutional framework of a consensus on the general growth trajectory. It is precisely this congruence between technologies and products and the (supportive) socio-institutional framework, which was characteristic of the development phase that enabled the economic expansion after the Second World War.

We argue that the above-mentioned 'consensus' is progressively vanishing, and that we are in fact witnessing a widening mismatch 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 and the emergence of a new development phase as represented in changing social values, new technologies and growth sectors, new forms of production organization, shifts in the occupational profiles and the international relative cost advantage. The structural and institutional adjustment processes entailed in the transition to a new development phase cannot be treated comprehensively within the present paper (a good discussion is for instance provided in the report of the 'interfutures' project of OECD [16], and some tentative discussion relative to science policy in developing countries is presented in the last chapter of this paper) but their very existence is widely recognized and summarized under the heading of various institutional reforms, be it deregulation (and re-regulation), *perestroika*, crisis of the welfare state and of labour unionism, etc.

In the previous development phase, productivity increases were primarily obtained by increasing economies of scale in the mass production of energy- and material-intensive products. We argue that in the next phase of economic expansion, criteria of system integration, flexibility and quality, environmental compatibility, value- and information-intensive (and relatively material- and energy-extensive) products and a production system in which the whole philosophy of just-in-time, high turn-round times and inventory minimization, unprecedented quality and precision levels, environmental compatibility, etc. will become dominant. Unlike in the previous upswing, productivity increases will no longer be based on increasing economies of scale, but instead on increasing *economies of scope*.

In the following three sections of this paper, we discuss tentatively some elements of a possible new development (growth) phase, without however going into detail regarding the socio-institutional framework that will emerge, once these elements become indeed pre-eminent. The areas in which we discuss the emerging new tendencies include the fields of energy, manufacturing and finally transport and communication.

3 Energy

The area of energy has, due to the extreme price volatility since the beginning of the 1970s, been the focus of attention of analysts, policy-makers and the general public. In particular the structural transition in the primary energy supply mix with the market dominance of petroleum (and the oil producers cartel OPEC) having reached its zenith of importance and starting to decline, if only in relative market share terms, and the apparent decoupling of energy from general economic growth, have been the most important characteristics of the 1970s and 1980s. These shorter-term developments have however somehow masked the perspective on the longer-term tendencies in the evolution of the energy system. In particular, it was historically never resource scarcity proper which led to the transition to new energy carriers, but better compatibility of new energy vectors with the social, economic and environmental requirements and boundary conditions of evolving societies. It was not the scarcity of wood fuel [17] which led to the transition to coal starting in the 18th century, and it was not the lack of resources and supply sources which led to the transition away from coal to oil, after the middle of the 19th century. The driving forces were instead the higher quality, energy density and thus improved possibilities for transportation and storage, versatility and ease of use, as well as the emergence of new applications, which led to the transition to new forms of energy carriers.

From a historical perspective, the respective transitions from wood to coal, from coal to oil and the present transition away from oil enabled at the same time the achievement of ever-higher energy efficiencies and the resolution of urgent environmental issues [18]. The transition from wood fuel and charcoal to coal resolved the problems of deforestation in areas close to the main centres of consumption. It was not until the transition away from coal that the famous London smog finally disappeared. The substitution of horses as transport by the automobile at the beginning of this century resolved in a similar way an urgent problem of urban pollution — horse manure — only in turn to result in a new qualitative and quantitative dimension of environmental impacts, which are only just starting to be tackled adequately (e.g. by the introduction of catalytic converters on cars).

From a long-term perspective the observed 'decoupling' of energy demand from economic growth since the beginning of the 1970s, i.e. the improving energy efficiency of economies is far from being a historically unique event. (For the whole of the OECD this efficiency improvement since 1973, i.e. energy input per unit of GNP, averaged about 2% per year. Taking 1960 as base year the efficiency improvement corresponds to a rate of 1% per year.) If we account in particular for non-commercial energy carriers (wood and feed) in the total energy balance in the USA since 1800 and examine the energy input per value of (constant) GNP generated, we observe a (discontinuous) decrease in the energy requirements per unit of GNP with an average rate of 1% per year over the last 200 years (as documented by Nakicenovic [19]).

From this long-term view, we argue that further increases in the energy efficiency, improved environmental compatibility, enhanced system integration and robustness, and finally increasing flexibility, safety and quality of energy carriers (for instance by growing importance of grid-dependent energy vectors, including electricity), will evolve as principal determining factors as opposed to considerations of security and geopolitics and 'Malthusian myths' of resource and supply constraints, which were considered as the main future driving forces under the impression of the oil shocks of the 1970s.

These driving forces become especially important under two main tendencies emerging from the energy debate. The first lies in the increasing globalization of environmental issues, in particular the increase in atmospheric carbon dioxide concentrations and the possibility of significant climatic changes, as opposed to the more local concerns (urban smog) and regional concerns (in particular acid rain) which have been predominant thus far in the scientific and policy arena. The second trend (or rather, likely hypothesis) deals with the future evolution of energy prices in general and that of oil in particular. We argue that the hypothesis that energy price levels will remain relatively low in real-terms over the medium-term (e.g. over the next 20 years) no longer appears simply a possibility but instead rather likely. This is because of further efficiency improvements in energy use, the emergence of value- and information-intensive (as opposed to material- and energy-intensive) products as principal elements of a possible new economic upswing, as well as the considerable potential for further technology improvements (and cost reductions) at all steps of the energy chain from exploration, production to end-use.

As various studies at IIASA have demonstrated (e.g. Grübler and Nakicenovic [20], Rogner [21]) there exists considerable growth potential for natural gas and gas-related technologies (in particular gas-turbine technology) which appear particularly well suited to meet the above-listed requirements. As an illustration, we have assembled in Table 2 the evolution of the economically and technically recoverable gas reserves for different geographical areas since 1970. The most obvious conclusion is that the concept of energy reserves and resources has to be considered as a dynamic and not a static one. Whereas natural gas reserves accounted in 1970 for only half of the petroleum reserves, they have now reached near parity. Reserve-to-production ratios exceed 58 years globally and even 80 years for non-OPEC developing countries. Since 1970, net reserve additions have grown globally nearly three times faster than the increase in gas demand and, as Table 2 illustrates, the dynamics of natural gas finds have been particularly noteworthy in developing countries (increasing by more than a factor 6 since 1970), despite the relatively modest (in comparison with North America and Europe) exploration effort going on in these countries. All told, a large potential for further gas finds apparently exists, particularly in those countries not endowed with petroleum. Over 100 countries have identified commercially-viable gas reserves. However, there are also a number of countries (16 alone in Africa with total gas reserves in excess of 900 billion cubic metres of natural gas, i.e. over 90 years the present gas production of the African continent, excluding the OPEC members Algeria and Nigeria), in which exploitation of identified gas deposits has not yet been started due to the lack of an appropriate transport and end-use infrastructure. The lack of appropriate infrastructure leads even in some oil-producing developing countries to considerable wastage. Nigeria, for instance, flared in 1986 three-quarters of its associated natural gas

Table 2 Natural gas reserves and production 1970–1988, in 10^9 cubic metres. *Source*: CEDIGAZ [58]

Area	*Gas reserves*[1]		*Gas production*		*Ratio 1988/1970*	
	1970	*1988*	*1970*	*1987*	*Reserves*	*Production*
North America	9236	8040	685	546	0.87	0.80
West Europe	4118	5416	77	196	1.32	2.55
USSR and East Europe	9516	42481	232	793	4.46	3.42
Japan, N.Z., Australia	560	2469	4	20	4.41	5.00
OPEC	12619	39870	38	185	3.16	4.87
Subtotals	36076	98276	1036	1740	2.72	1.68
Non-OPEC developing	2022	12407	41	151	6.14	3.68
World totals	38098	110683	1077	1891	2.91	1.76

World: reserve to production ratio 1970: 35.4 years 1988: 58.5 years

Non-OPEC developing countries: R/P 1970: 49.3 years 1988: 82.2 years

Note 1: Reserves as of 1 January

production in the absence of facilities for re-injection and a transport infrastructure.

The large potential contribution of the known gas reserves to the energy balance particularly of oil importing developing countries is clearly illustrated in Table 3, comparing natural gas revserves and production with the energy requirements in terms of commercial and total (i.e. including non-commercial) energy requirements. With the exception of Brazil, the known reserves are sufficiently large to support increased utilization of natural gas and a significant share of gas in the energy balance of these countries. The same can also be said for other developing countries, which are presently self-sufficient in oil, or even net exporters. Most of them (one notable exception being China) have large natural gas reserves, which are only in rare cases starting to be tapped (see Table 4). The fact that many developing countries (particularly in Africa) have not been able to obtain sufficient technological and financial assistance for the development of their national energy endowments raises a number of questions about the adequacy of present policies of financial assistance in the energy sector of these countries. We are led to question policies providing funds for much-needed oil imports but not sufficient means to substitute these by abundant national gas reserves. Therefore, in order that the apparent geological resource potential be realised, appropriate mechanisms will have to be rigorously developed for technical assistance, and especially for financing hydrocarbon (in particular natural gas) exploration and for the development of the associated infrastructure for its efficient use in developing countries even under low energy prices.

Important market potentials for increased use of natural gas reserves also exist in developing countries: in the industrial sector (e.g. for fertilizer production), in the household sector (bottled natural gas liquids), and even in the transport sector (e.g. compressed natural gas cylinders, a technology already developed and used on a large scale, for instance in Italy since the 1950s). However, the largest potential for natural gas may be in the decentralized production of electricity based on gas turbines. From the end-use side, gas-turbine technology offers particularly promising prospects in view of the criteria of flexibility, environmental compatibility and energy efficiency. Manufacturers' guaranteed

Table 3 Net oil importing developing countries with significant gas reserves[1] in 1987. *Source*: CEDIGAZ [58] and UN Energy Statistics [59]

	Proved reserves[2] *EJ*	*Production*[2] *1987 EJ*	*Energy consumption*[3] *Commercial EJ*	*Total*	*Ratio gas reserves to energy consumption Commercial*	*Total*
Africa						
Ivory Coast	3.8	0	0.072	0.153	52.8	24.8
Mozambique	2.5	0	0.051	0.192	48.4	12.9
Rwanda	1.9	0	0.009	0.060	211.1	31.7
Sudan	3.2	0	0.051	0.235	62.7	13.6
Tanzania	4.5	0	0.032	0.465	140.1	9.6
South America						
Brazil	4.0	0.111	4.246	6.789	0.9	0.6
Chile	4.6	0.028	0.404	0.463	11.3	9.8
Columbia	4.4	0.156	0.869	1.046	5.0	4.2
Asia						
Afghanistan	2.3	0.106	0.057	0.105	40.7	22.1
Bangladesh	13.7	0.141	0.175	0.435	78.2	31.4
India	38.2	0.319	6.182	8.532	6.2	4.5
Pakistan	23.8	0.452	0.868	1.095	27.4	21.7
Papua New Guinea	3.3	0	0.036	0.091	90.8	35.9
Thailand	7.0	0.167	0.658	1.138	10.6	6.1
Yemen, North	4.0	0	0.038	n.a.	105.0	n.a.

Note 1: Countries with gas reserves greater than 50×10^9 m^3
Note 2: Average conversion rate used: 10^9 m^3 natural gas equals 38×10^{15} J or 0.038 EJ
Note 3: n.a. = not available

Table 4 Non-OPEC, non-oil-importing developing countries with significant gas reserves[1] in 1987. *Source*: CEDIGAZ [58] and UN Energy Statistics [59]

	Proved reserves[2] *EJ*	*Production*[2] *1987 EJ*	*Energy consumption Commercial EJ*	*Total*	*Ratio gas reserves to energy consumption Commercial*	*Total*
Africa						
Angola	2.1	0	0.044	0.120	46.6	17.1
Cameroon	4.2	0	0.149	0.229	28.1	18.3
Congo	2.6	0	0.007	0.023	374.0	113.9
Egypt	12.4	0.239	0.998	1.037	12.4	11.9
South America						
Argentina	28.8	0.585	1.750	1.860	16.0	15.5
Bolivia	5.4	0.106	0.066	0.082	81.8	65.9
Ecuador	4.3	0.002	0.204	0.269	21.2	16.1
Peru	12.9	0.049	0.421	0.502	30.7	25.7
Asia						
Burma	10.2	0.046	0.103	0.274	98.9	37.2
China	34.2	0.787	21.893	23.667	1.6	1.4
Malaysia	56.5	0.589	0.748	0.825	75.5	68.5

Note 1: Countries with gas reserves greater than 50×10^9 m^3
Note 2: Average conversion rate used: 10^9 m^3 natural gas equals 38×10^{15} J or 0.038 EJ

efficiencies above 50% are presently being realised (compared to about 32 to 34% for coal, oil or nuclear power plants) and 60% appears technically feasible. Flat economies of scale and low initial investments give this technology a particular advantage for flexible, modular and decentralized applications for electricity generation, e.g. in island operation mode (thus reducing the high capital requirements of electricity transmission and distribution networks associated with large-scale, investment-intensive hydropower projects). Bottled natural gas liquids or similar commercial high-density energy carriers offer considerable energy efficiency advantages (up to a factor 8 [22]) over traditional renewable fuels for cooking purposes and could help to reduce local wood fuel shortages.

Increased reliance on domestic natural gas resources could reduce the dependence on oil imports and reserve oil products for premium market segments (in particular the transport sector). The use of high-efficiency gas turbines is in addition not confined to the availability of natural gas, as equally biomass (e.g. sugar cane residues, corn stover or rice husks) can be used as fuel. Williams and Larson [23] estimate for instance that the gas-turbine capacity which could be supported by biomass globally exceeds 100,000 MW(e), most of it in developing countries.

To summarize, the considerable economic and environmental advantages of natural gas (practically sulphur free, lowest nitrogen oxides and carbon dioxide emissions of all fossil fuels [24]) can only be realised in developing countries when appropriate instruments for technology transfer and financing of exploration activities and development of the necessary transport and distribution infrastructure are developed. In many developing countries this will also have to be supported by appropriate adjustments to the institutional and legal framework. Without such instruments the incentives for large multinational *oil* companies for natural gas exploration outside petroliferous provinces will — especially under continuing low energy prices — most likely not be sufficient to open the natural gas option for developing countries outside the already large number of countries in which significant gas reserves have been identified to date (see Tables 3 and 4) or to ensure that appropriate technical assistance and sufficient capital are made available for developing a natural gas supply and usage infrastructure in these countries.

4 Manufacturing

Mass production and mass consumption of energy- and material-intensive products have been at the core of the fourth Kondratiev upswing, particularly since the Second World War. Following this particular mode of economic growth, conventional wisdom holds that economies of scale and cost reductions via labour-saving technologies will consitute the major future driving forces in the manufacturing sector. We argue, however, that the emerging future development trajectory will be characterized by a shift in the value-generating activities away from energy- and material-intensive products towards value- and information-intensive ones.

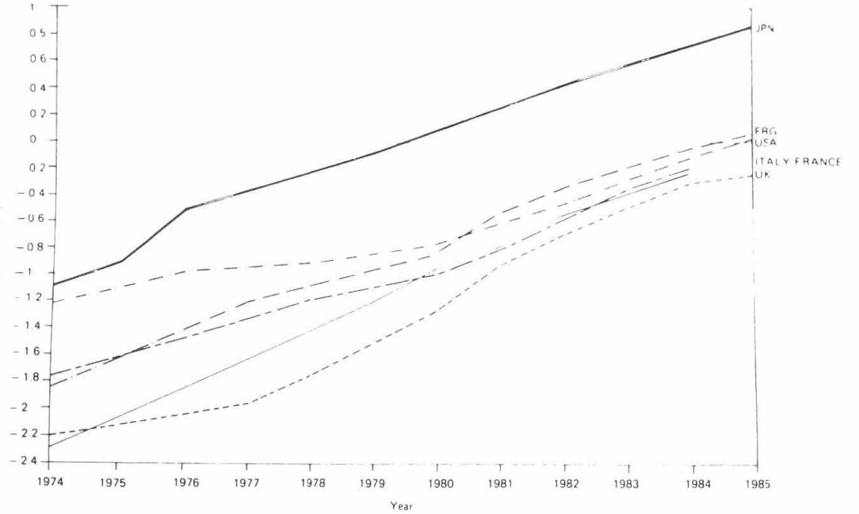
At the same time, the social and institutional dimension could possibly start to outweigh the proper technological one in the innovations paving the way to a new economic upswing. Reducing barriers to innovation, increasing flexibility, complexity and quality of the outputs of the economic system as well as the reduction of the time required between design and marketing, are possible more dependent on socio-institutional factors than on the availability of technological innovations alone. At the same time a host of technological innovations are at the brink of widespread diffusion into the manufacturing sector, all of which will contribute to shape the structure and the determinants of future evolution of the manufacturing sector in the direction of material-extensive, value- and information-intensive products, the production of which will be progressively shaped by the whole philosophy of just-in-time production, rapid turn-around times and inventory minimization.

One of the key technological factors in the future evolution of the manufacturing system has already emerged: low-cost micro-electronics. These developments enable flexible batch production networks, where all activities (managerial, administrative, productive, etc.) are integrated in an information-intensive system. Such production systems could progressively gain importance over the traditional continuous or production-line based mass-production system with its traditional segregation of managerial and production functions. The concept of integration will also shift from vertical (i.e. a company is engaged in all stages, from primary raw material production up to final product manufacturing and marketing) to horizontal integration, i.e. an increasing specialization, cooperation and eventually emergence of large specialized international companies performing specific tasks, such as design, marketing or financing, as discussed for instance by Pry [25].

The elements of this possible new development phase, which is often referred to as the 'information and communication' Kondratiev, are in the areas of micro-electronics and photonics technologies, enabling a quantum leap in performance and potential productivity increases [26], the emergence of material and energy efficiency improving technologies (examples include gas turbines, electronic applications in automobiles leading to reduction of specific fuel consumption, recent advances in aircraft propulsion, like ultra-high-bypass engine designs, offering a 40% improvement in fuel efficiency, electric arc steel, etc.) as well as technologies enabling fast, flexible and extremely high-quality production of even small batch sizes: industrial robots, flexible manufacturing (FMS) and computer-integrated manufacturing (CIM) systems. These technological developments are supported by developments in the application of micro-electronics and information technologies in the area of transportation of goods and the overall logistics chain which enable the realisation of 'just-in-time' production principles and the general minimization of inventory requirements. Last but not least, new organizational and institutional mechanisms are important prerequisites in order that the potential of these technologies may become translated into increased productivity and quality of production. These include new types of horizontal integration and specialization of service activities, which were previously performed within the manufacturing sector, such as CAD/CAM design, marketing, advertising, financing etc., new forms of quality assurance and management methods and finally increasing flexibility in work time organizational patterns (which are however presently only just starting to emerge). Another possibility appearing in the manufacturing sector as a result of the introduction of flexible manufacturing systems and of a pervasive diffusion of 'just-in-time' philosophy may be that in future not only manufactured goods but also manufacturing capacity trading (e.g. through futures contracts) may become important [27].

Of course, our discussion of the elements of a new development phase in the industry/manufacturing sector can only be indicative and illustrative. An excellent overview on technological issues, in particular on their globalization and effects on international competitiveness, is contained in a series of reports issued by the US National Academy of Engineering, in particular those by the US NAE [28], Guile and Brooks [29], and Muroyama and Stever [30]. In the following we would like just to provide a few illustrative examples of the technological and institutional/organizational characteristics of the fifth Kondratiev. Figure 2 illustrates the time pattern in the penetration of industrial robots

Figure 2 Industrial robot population trends in selected countries, in installed robots per 1000 employed in industry (logarithmic scale). *Source*: Tani [31]

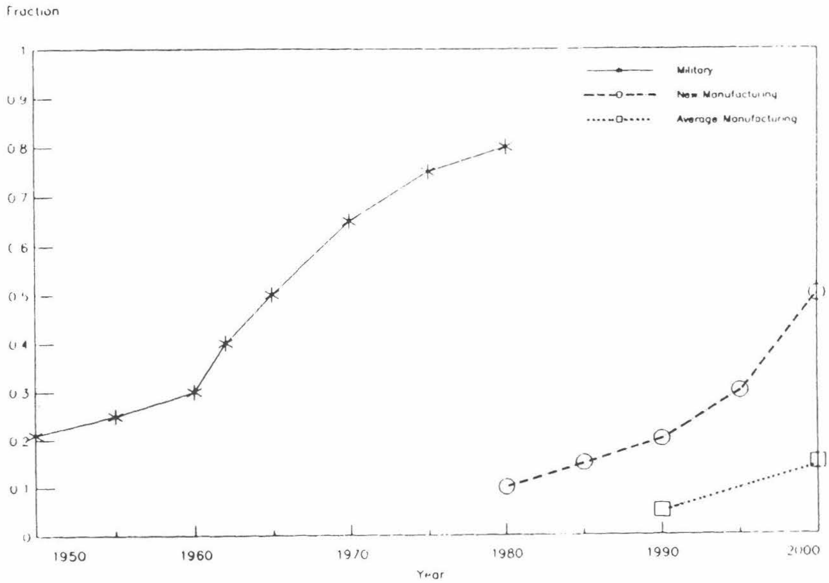


(measured by the logarithm of the industrial robot density, i.e. robots per 1000 employed in industry) based on the work of Tani at IIASA [31]. Noteworthy is the similarity in slope of the diffusion curves, with only Japan having a lead of around 7 years over other industrialized countries. The dynamics of the introduction of these systems appear thus rather harmonized in different industrialized countries. As other studies at IIASA have shown (e.g. Tchijov and Sheinin [32] on the driving forces of the introduction of FMS and CIM systems) the main driving force for the introduction of such advanced manufacturing systems is not so much labour reduction but increasing the quality and speed of production, and in particular reducing inventories.

The whole philosophy of just-in-time production and inventory minimization is probably best illustrated by the case of the Cadillac Allanté, a car body manufactured by Pininfarina in Turin, Italy and transported by air over 5000 km to Detroit for final assembly of engine, powertrain and electronics by General Motors. This 'production line' stretching over 5000 km is apparently economic considering all the direct and indirect costs of potential damage risks, insurance and the production inventories that would be locked in ocean freighters for weeks. From such a perspective, further dematerialization (i.e. increasing the value generated per kilogram of material input) of manufactured goods and increase in their value through higher software [33] and information content (Figure 3), would tend to increase further the importance of air freight transport. The close relationship between new flexible, inventory-minimizing manufacturing systems and access to high-quality transportation systems will be taken up again in the next section on possible future characteristics of transport and communication systems. Before we turn to this point let us address likely future tendencies in the manufacturing sector with some reference to newly industrialized (NICs) and developing countries.

A first possible consequence of the tendencies emerging in the manufacturing sector of relevance to NICs and developing countries may consist in the relocation of certain manufacturing activities (say in the textile sector) back to highly developed countries. Labour cost advantages would under such tendencies no longer be a decisive locational

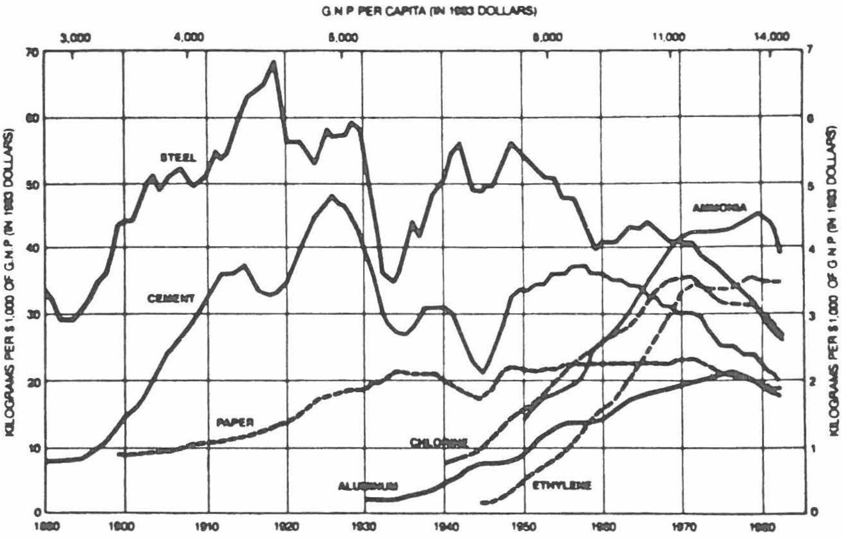
Figure 3 Software as fraction of total capital investments in the USA. *Source*: Ayres [64]



advantage if indeed quality, flexibility, small batch sizes, inventory and time reduction between design and marketing become the main driving forces in the manufacturing sector. In order to maintain a locational advantage it appears necessary to provide access to advanced communication and transport infrastructures (e.g. location of production facilities for export of manufactured goods close to airports) as well as to develop a new institutional and organizational framework, if the above-discussed characteristics of the manufacturing sector become indeed pre-eminent. On the other hand, NICs and developing countries may here have also a definitive strategic advantage, as they have no similar heavy commitment and full adoption of the traditional style of the manufacturing system and the socio-institutional framework supporting it. Taking advantage of the opportunities opened by an emerging new development phase, and introducing an institutional framework supporting it, may thus turn out to be easier than in the USA, with its heavy commitment to large-scale Fordist mass production based on Tayloristic management principles, or in Europe with its rigidities of the labour market.

As a final note with respect to the manufacturing sector let us consider also the basic industries like steel production. We have argued above on the increasing tendencies towards 'dematerialization' in terms of material consumption per unit of economic activity of developed economies. These tendencies have been impressively documented in the studies of the Princeton group, e.g. by Williams, Larson and Ross [34] and are illustrated in Figure 4 for the case of the USA. This 'dematerialization' observed for advanced economies is the result of both changes in the output mix of these economies (shift to higher-value and information-intensive products, in particular the growth of the service sector) and in the availability of new materials (plastics, special alloys, composites, ceramics, etc.) enabling the same (even an improved) level of service (e.g. tensile strength) to be provided using less material input (measured by weight).

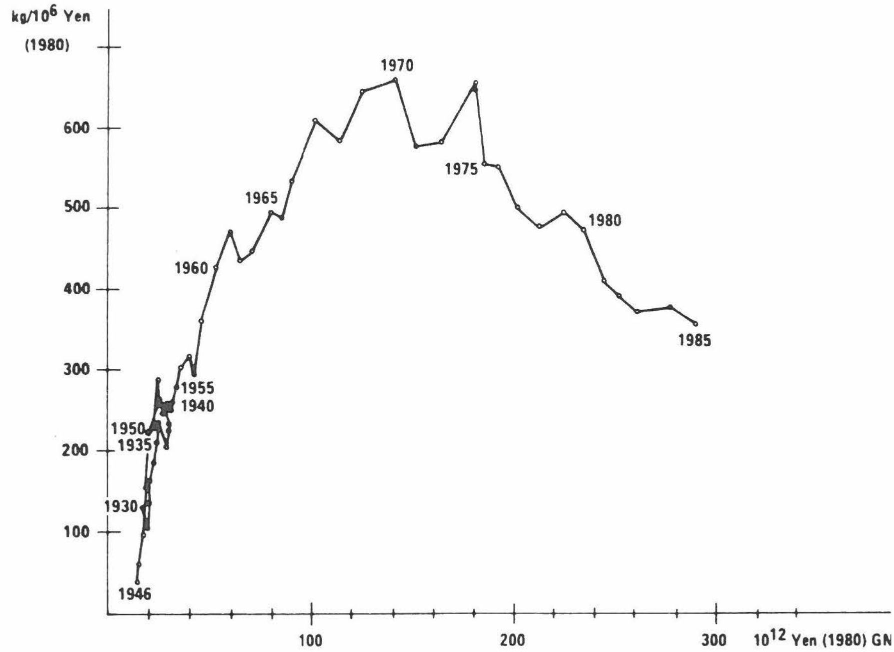
Figure 4 Materials consumption (in kg) over GNP (in 1983 US$) in the USA. *Source*: Williams *et al.* [34]



The increasing material input to the economy thus appears to be the result of a particular historical development phase, which presently appears already beyond maturity and being progressively replaced by a new regime. The correlation of material intensity with the level of economic activity, as illustrated in Figure 5 for Japan, the country which has caught up most spectacularly in this kind of development trajectory, has often led to a (prescriptive) extrapolation of this development strategy for other countries. It has been argued that, in order to achieve similar economic growth, follower countries would equally move up the material-GNP intensity curve, which was established on the basis of the historical experience of industrialized countries. This type of approach is for instance well visible in older forecasts on the level of world steel production. Reality has constantly fallen significantly short of such forecasts, as the global steel production has since the 1970s been characterized by a saturating market and output figures have fallen in the 700–800 million tons per year range, compared to forecasts of well above the level of one billion tons.

We argue that the saturation in the global steel output is a good indicator that: (a) developed countries move progressively in the direction of increasing dematerialization, and (b) that follower countries, whilst increasing their steel output, are not likely to do it in a (quantitatively) comparable way to that of the industrialized countries in the post Second World War period, because the particular development trajectory (high growth in steel-intensive sectors/products like automobiles, shipbuilding, etc.) characteristic of the economic growth of the fourth Kondratiev is not likely to be repeated. Here we do not imply that the basic material sector will not continue to be important for economic development, rather we argue that a comparable growth (i.e. an increase globally by a factor of 7 since the Second World War) to that of the previous phase of economic growth will not take place, as the particular historic development pattern based on massive diffusion of car ownership, consumer durables, etc. is progressively giving way to a new, emerging material- and energy-extensive growth trajectory.

Figure 5 Steel production intensity (kg per million 1980 Yen) versus GNP (in 10^{12} 1980 Yen) in Japan 1930–1985. *Source:* Grübler [35]

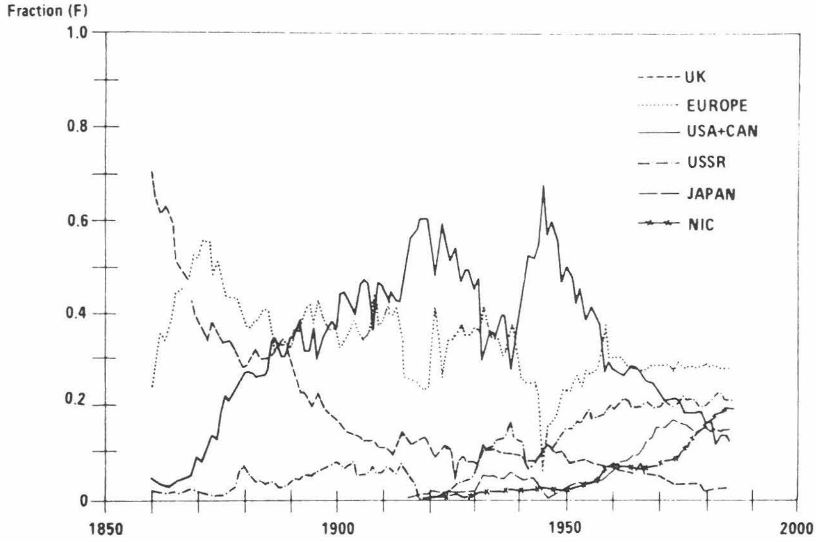


Even under a saturation (or only modest growth rates) of the basic material production, the much stronger dematerialization tendencies of developed countries will result in a further shift in the relative market shares (and most likely also of absolute production capacities) of the location of basic materials production. However, this is historically not a unique event. As Figure 6 illustrates, the world market dominance in the location of steel production has experienced in the past similar in-depth relocation phenomena. The UK had lost its market dominance to other European countries by 1870; UK and Europe lost dominance to the emerging USA, which became the largest world steel producer by the 1930s (end of the third Kondratiev), in turn losing out after the Second World War to newly emerging centres of steel production: the USSR, Japan and later NICs. If these historical tendencies continue to unfold as in the past, the share of NICs and developing countries in the world steel production will increase significantly at the expense of all other producers, including Japan. Scenarios developed at IIASA indicate that this share will increase to over 30% by the year 2000 and could approach 50% after 2010 [35]. At the same time this production will progressively shift from large-scale integrated steel mills to more flexible and higher-quality (including environmental) production, e.g. based on 'mini-mills' with recycled scrap and electric arc furnaces, continuous casting and a shift in production to high-quality speciality products.

5 Transport and communication

We consider two main trends emerging in the area of transport and communication. The first consists of a host of new technologies, allowing unprecedented levels of speed, variety

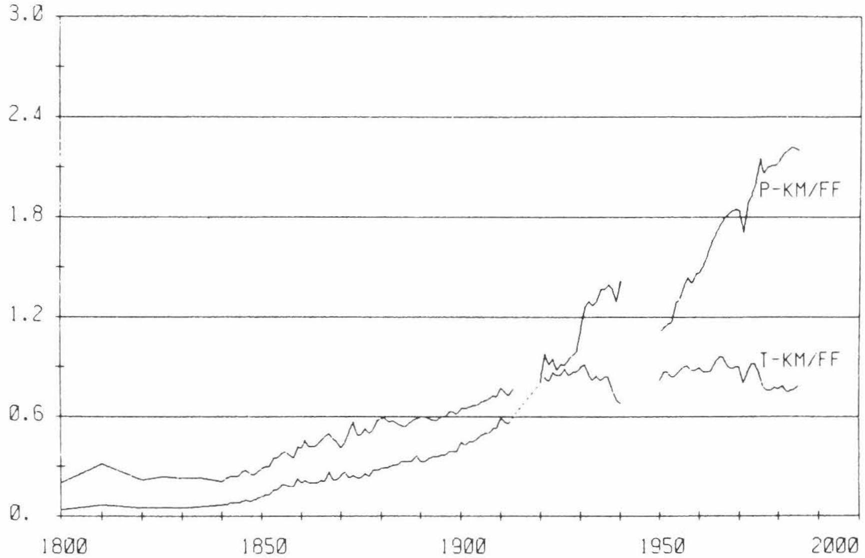
Figure 6 Share of different countries (regions) in world crude steel production. *Source:* Grübler [35]



and information density in communication. The second relates to the above-discussed future characteristics in the manufacturing sector (integration, small-batch production, increased flexibility and reduction of design to marketing lead times) and their resulting repercussions on the transport sector. Here in particular high-speed, high-quality transport systems (such as air transport) and nodes in the international transport network, which provide for the best integration of the various hierarchical levels (global/international, regional, national and local) and equally between different modes of the transport system, will be favoured.

From a traditional viewpoint, the future of transport systems will be shaped by increasing economies of scale (e.g. larger, centralized warehouses) as well as by rapid structural change (e.g. a drastic short-term 'renaissance' of the European railways via upgrading of the existing infrastructure). We anticipate, however, that the future of transport and distribution systems will be shaped more by the quest to enhance speed and flexibility and thus in the reduction of inventory requirements following a just-in-time philosophy as well as by the emergence of new forms of organization and management. For example, transport and warehousing functions will be transferred from manufacturing companies to specialized service enterprises. Organizational and management issues will without doubt be central elements shaping the comparative competitive advantage of different transport modes in the future. The latter may well turn out to be of greater importance than investments in upgrading existing infrastructures. At the same time the possibility should also be considered of the emergence of new infrastructures (e.g. Maglev trains in large urban corridors along the lines of the Japanese Shinkansen, or in connecting large air transport hubs). The development of new infrastructure systems, and especially their complementarity and *integration* into existing transport infrastructures, may be considered as an important area of strategic public infrastructure policy in the longer term, as opposed to the more short-term tactical concerns of present policy, trying to deal with bottlenecks (congestion) or negative externalities (i.e. environmental pollution) associated with intense road traffic in urban areas and international transit corridors.

Figure 7 Ton- and passenger-km per constant GDP (in 1913 Franc) in France 1800–1987. *Source*: Grübler [13]

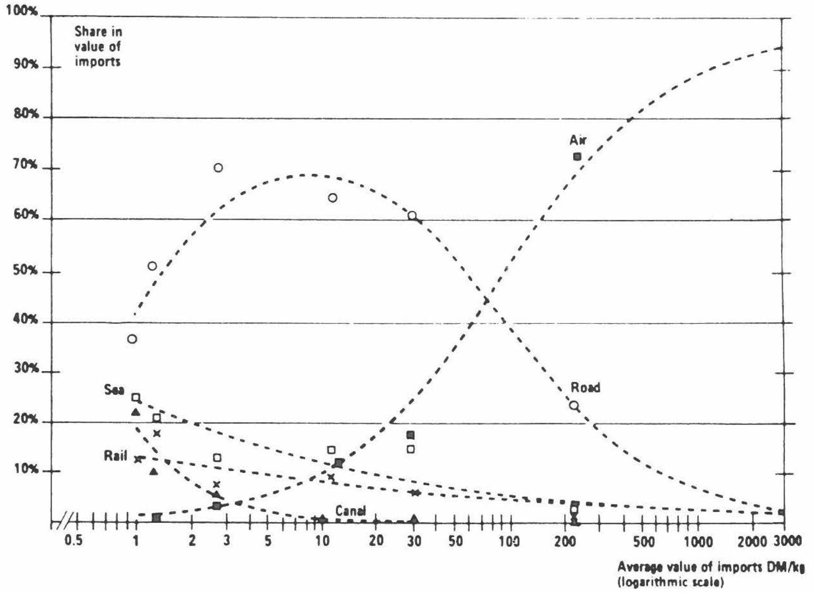


These driving forces shaping the future of the transport system, i.e. quality, including speed and environmental compatibility, flexibility and the application of 'just-in-time' principles to the area of transportation, and even to the whole logistics chain (i.e. including warehousing operations), enabled by the introduction of new information and communication technologies, will become ever more pervasive in the transition to higher shares of high-value goods ('dematerialization', i.e. decrease in energy- and material-intensity and increase in information and software content per unit value) in the manufacturing sector discussed above.

The apparent 'dematerialization' tendencies of advanced economies as reflected in indicators of material consumption per unit of economic activity (Figure 4 above) are also mirrored in indicators of transport intensity, as illustrated in Figure 7 in the case of France. The long-term perspective adopted in Figure 7 allows one to draw some conclusions with respect to likely future evolutions of transport intensities of advanced economies. As regards goods transport, industrialized countries appear to be at the brink of a major turning-point with respect to the material- and transport-intensiveness of their economies. Particularly since the early 1970s, the goods transport intensities started to decline [36], however, it is also noteworthy that similar tendencies are *not* observed with respect to passenger transport. This points to the complementary character of the growth in passenger transport and communications systems, discussed below.

The reason for the apparent 'decoupling' of goods tonnage transported per unit of economic activity in industrialized countries is obvious. It stems from the gradual transition in the output mix of these economies in the direction of information- and value-intensive, but material-extensive, products and the availability of higher-quality and lighter substitutes in the form of advanced materials. This transition also has important repercussions on the type and quality of transport services required for the delivery of high-value goods, favouring transport modes with higher quality with respect to flexibility (i.e. smaller

Figure 8 Share of different transport modes in the value of imported manufactured goods versus value density of products (in DM per kg, logarithmic scale) in the FRG in 1986. *Source*: Grübler [13]



shipment sizes) and speed and reliability in delivery (such as truck and especially air transportation). This is illustrated in Figure 8, where the share of different transport modes in the imported value of manufactured goods as a function of the value density is reported for the FRG in 1986. Figure 8 illustrates that the most valuable goods are transported by more efficient and faster means of transport. Basic materials such as coal, gravel, scrap and raw materials in the value range of a few DM per kilogram are mostly transported by sea, canal and rail. As the value of the products increases, trucks become more competitive and constitute the dominant transport mode in the value range up to 100 DM/kg. Most manufactured goods such as automobiles or machine tools fall below this threshold. Going to even higher value densities, i.e. goods with values exceeding 100 DM/kg, such as electronics, computers or precision instruments, one can see that they are usually shipped by air. Incidentally, the highest-value manufactured goods (excluding precious metals, drugs or caviar) are aerospace products and aircraft themselves, all exclusively transported by air. We have discussed above that, with the growing importance of just-in-time production regimes, the importance of air transport may increase even in the lower value density product categories and have illustrated this emerging tendency with the example of the air lift between Turin, Italy and Chicago in the fabrication of the Cadillac Allanté car body. The increasing importance of air transport for freight will most likely result in further co-location of production facilities and services close to airports, in much the same way as industrial activities condensed along previous transport infrastructures: canals first, followed by railways, and later roads and highways. Access to infrastructure and interconnection to international trading flows of high value density products are, under the above-discussed tendencies, equally important for newly industrialized and developing countries in order to maintain locational advantages in the manufacturing sector.

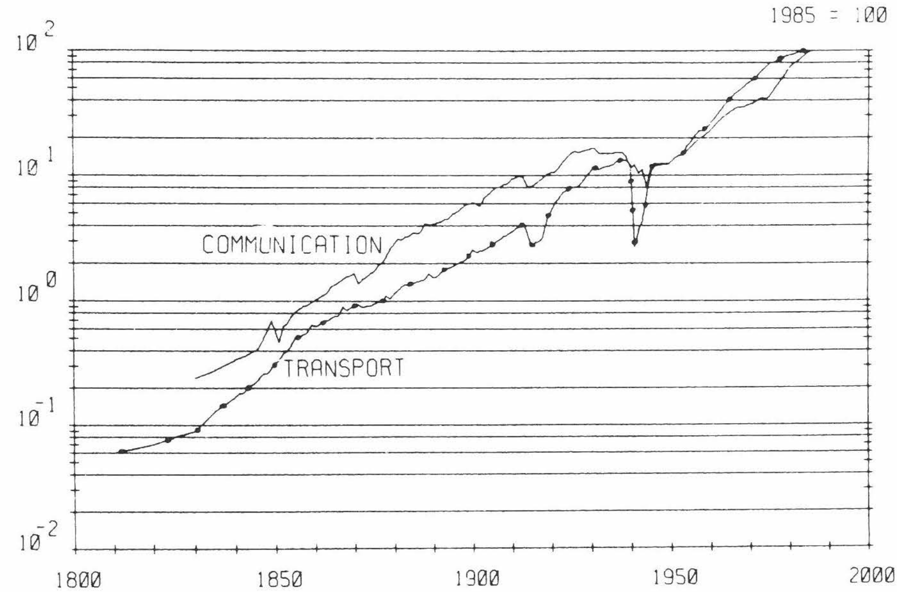
As we have discussed above, new communication systems are likely to be among the most pervasive systems emerging in the fifth Kondratiev. In this context, it has frequently been argued that future developments in communication technologies will result in significant displacement effects of passenger travel. Whereas certain effects of new information and communication technologies, e.g. on business travel requirements, are likely to occur, there appears to be compelling historical evidence that transport and communication systems have evolved in unison (although over historical time periods not always at exactly the same rate) pointing to the complementary, even synergistic, relationship between passenger transport and communication. Figure 9 illustrates this historical relationship in the case of France, where the volume of passenger travel operations (i.e. sum of all passenger-km) is compared to the total output of the communication sector (i.e. sum of all messages transmitted in the form of letters, telephone calls, telexes, etc.), with 1985 being normalized as index 100. From such a long-term perspective, the relationship between transport and communication results in the case of France on average in 6 passenger-km travelled per message transmitted. Only in periods of particularly fast growth of new transport systems, like the railway growth in the second half of the 19th century or the growth of the automobile after the Second World War, does this ratio of transport intensities per message transmitted increase. From such a perspective, the future growth of new communication systems may just be enough to catch up with the intensive growth of passenger transport since the war and to re-establish a balanced growth path between passenger transportation and communication demand.

To sum up the above discussion on emerging trends in the area of transport and communication, we have concluded that a considerable growth potential exists for further expansion of passenger travel and also for high-quality and high-speed (i.e. air transport) services in transporting (high-value) goods, whereas the transport intensity of bulk, low-value goods appears to be declining in advanced economies. Finally, considering the strong growth dynamics in the Asian-Pacific region, the possibility of an emergence of a new 'gravity centre' in transport (goods and people exchange) in this area also appears likely.

Especially in view of likely developments in the manufacturing sector and the potential pervasive diffusion of new communication and information technologies, the questions of *integration* and *access* to the appropriate infrastructures will be of crucial importance for newly industrializing and developing countries. Equally important appears the integration and the *complementarity* of the various hierarchical levels of transport and communication infrastructures (e.g. connection of regional to international airports, emergence of new hubs, etc.). From a development perspective, the emergence of new infrastructures would in principle also allow the possibility to jump one step in the development chain of transport and communication systems — for instance, communication networks based on Integrated Services Digital Networks (ISDN) or the development of high-capacity regional air transport systems rather than a development along the lines of post-war mass motorization and highway construction, as experienced in developed economies. The technological base for such developments can also be established in developing countries, as illustrated for instance in the recent project of cooperation between MBB, Germany and China on the development of a medium-sized (100 passengers) regional aircraft, to be produced in China. The successful Brazillian aircraft industry, producing small commuter aircraft may serve here as another illustrative example that the technological base is already partially developed and does not necessarily rely on a complete importation of the required technology.

In the longer term, we anticipate the possible emergence of new ground-based, high-speed, energy-efficient mass transit systems (e.g. based on superconductivity) both at the regional level (e.g. Maglevs) and for local traffic. The further development of urban high-

Figure 9 Index (1985 = 100) of transport (total passenger-km) and communication (total number of messages transmitted) output of France 1810–1987. *Source*: Grübler [13]



capacity transit systems (e.g. Metros) in developing countries appears as the only feasible alternative in response to high growth rates of urban areas and the environmental pollution stemming from intense automobile traffic in metropolitan areas (as for instance the case of Mexico City and many other rapidly growing urban areas in the Third World).

6 Diffusion bandwagons and development trajectories

After addressing some tentative propositions regarding the possible form of the future trajectory of development as a result of the diffusion of a whole new set of technological and institutional innovations, which we have termed the 'information and communication Kondratiev', we would like to discuss three characteristics of the diffusion of pervasive socio-technical systems, derived from a historical analysis: (1) the *inter-relatedness* of a cluster or set of technological and institutional innovations, explaining their pervasive effects throughout the economy; (2) the *international nature* of the diffusion of such innovation clusters, in terms that a set of core countries display an inter-related dynamic in the development (growth) of such innovation clusters, with late-comers catching up. This development frequently results in a relatively synchronous pattern in the completion dates of the expansion of particular innovation clusters. The coupled diffusion dynamics between core countries stem from their integration in terms of exchanges in technologies, capital and human resources. Finally, (3) we observe *heterogeneity* (i.e. explicit differences) in the ultimate diffusion (i.e. density or consumption) levels achieved in different countries taking part in the realisation of a particular development phase.

6.1 Inter-relatedness

The inter-relatedness of a whole host of technological and institutional innovations becomes readily apparent when the growth of very large pervasive infrastructures is analysed in detail. For instance, the development of the railways as the dominant transport mode of the second and third Kondratievs was contingent on a whole host of technological innovations, spanning the development of the steam engine (e.g. improving traction power), developments in material science to avoid (initially frequent) explosions of the steam boiler, developments in steel technologies for fabrication of steel rails, in communication technologies for signalling purposes (the telegraph), fuel technologies and improvements in energy efficiency [37], chemical industry (e.g. pesticides for treatment of wooden railway ties [38]), engineering and construction disciplines (e.g. construction of bridges, first trans-Alpine crossings and tunnels like the Semmering crossing or the Simplon tunnel), etc. The above list could be supplemented by hundreds of further cases, but already the few illustrative examples provided serve as an indicator of the importance (and the interdependence) of a whole set or 'cluster' of technological innovations, which are required in order to develop such pervasive systems as new infrastructures. In addition, organizational and financial innovations were also of vital importance for the construction and operational management of railways, not only in the industrializing core countries but equally in the periphery [39].

Because of the inter-relatedness of innovations, new infrastructure systems are in fact a good macro-indicator for particular historical expansion periods, like the eras of canals, railways or the automobile (road). The pervasive effects on economic development of the development of such large systems do not stem only from a variety of multiplier effects (in terms of forward and backward linkages to other sectors of the economy), but especially from the fact that new infrastructure systems allow ever higher quality of service to be achieved, thus raising the productivity of economies to levels which would not have been possible by a simple intensification of use of old infrastructures. (Recall here the lines of Schumpeter in the introduction to this paper.) Thus, the development of railways for instance has to be considered as a fundamental quality leap in the productivity level of economies, which would have been impossible to achieve by a further development of stagecoaches and inland navigation systems. The pervasive effects of new infrastructures are not simply a contention, which we raise in this paper in order to use the diffusion of railways as an illustrative example, but the importance and pervasiveness of infrastructures are equally recognized by economic historians. In fact infrastructures are considered so important that their growth has been studied under the leading sector hypothesis [40] and their impact has been assessed in calculating the 'social savings', i.e. the costs incurred by an economy of *not* having a particular infrastructure [41]. We conclude thus that the *inter-relatedness* of a set of innovations, which make the diffusion of large complex infrastructures at all possible, and their resulting forward and backward linkages to the rest of the economy, explain their pervasive character and justify their use as indicator systems for particular historical economic expansion periods. In the following examples we will consider the case of the development of the railways as the most pervasive infrastructure system of the 19th century to illustrate the characteristics of the diffusion of such large-scale systems.

6.2 *Diffusion bandwagons*

In order to illustrate with an historical example the particular trajectory and development pattern of the expansion of economies in a particular development phase, as represented by its principal transport infrastructure, we consider below the growth of the railway network in a number of countries, measured in terms of the network size. The growth of the railway network of industrialized countries was a long process. In most cases it took around 100 years between the start of construction of the first line and the final completion of the network, which was achieved in basically all industrialized countries by the 1930s. Since then the length of the world's railway network has remained constant at around 1.3 million km, with however the network in industrialized countries contracting (due to the growth of successful competitors such as road and air transport), whereas in developing and industrializing countries the growth of the railways continued into the 1960s and in some countries (e.g. China, India or the USSR) even continues at present.

The absolute network size developed was significantly different between countries, both in absolute as well as in relative (i.e. in density) terms. The USA once had the largest railway network of any individual country and the maximum network size was attained in 1929 with over 482,000 km. In the UK the maximum network size was attained in 1928 with close to 33,000 km, and in France in 1933 with around 43,000 km. These figures already point to one interesting fact: the near simultaneous saturation in the expansion of the railway network in all industrialized countries by the early 1930s. In order to compare the dynamics of this expansion process, irrespective of the differences in the absolute network size (which is a result of the size of the country considered, its geography, the location of main industrial and urban centres, etc.), we re-organize the data using a logit model, by which we approximate the empirical data on network expansion by calculating the parameters of the relevant growth processes described. The most important feature of the logit model [42] is that it allows us to consider each individual case within its own relevant boundary condition, i.e. the growth of the railways of a particular country is always compared in relation to the maximum network size (the saturation level of the growth process) attained in this country. Table 5 presents the results of an analysis of the expansion of the railway network of a number of industrial core countries, as well as the world total. It can be seen that the logit model performs reasonably well not only in estimating the ultimate saturation level of the expansion process of the railway network in these countries (maximum network size is systematically within less than 10% deviation from the estimated value), but equally in the fit of the empirical data by the logit model (R^2 values well above 0.99) [43]. The growth parameters a and b are denoted by t_0 (the time at which 50% of the estimated final network length is achieved) and by Δt (the time in years required to grow from 10% to 90% of the ultimate saturation level). As shown in Table 5, the dynamics of the expansion of the railway network in all industrial core countries are within a very similar range (Δt of 47 to 57 years). Only the late-comer Tsarist Russia is growing with a Δt of 37 years faster (catching up) than the other industrial core countries.

Figure 10 represents the expansion of the railway network of the countries of Table 5 in the logit transform and exhibits clearly the coupled dynamics of the diffusion process in these countries, which proceeds in the form of an *international diffusion bandwagon*. As such it indicates the interconnection of the development trajectories in the expansion of the railway networks in these countries, an interconnection stemming from the integration of core industrial countries in terms of technology and capital exchanges. This statement does not only hold for the expansion of the railway network, but in a similar way applies

Table 5 Growth of railway networks (km). *Source*: Grübler [13]

Country	Estimated saturation length (K)	Maximum length achieved	t_0	Δt	1% of maximum length	Maximum length	Density[2] Length in 1925	
	1000 km	1000 km	year	years	year	year[1]	per 100 km²	per 10,000 inhabitants
Austria–Hungary[3]	24.5	23.0[8]	1883	51.8	1841	1913[8]	8.0	10.2
France	42.5	42.6	1876	47.1	1841	1933	9.7	13.7
Germany[4]	66.8	63.4[8]	1882	57.0	1841	1913[8]	12.2	9.6
Russia	73.9	70.2[8]	1890	37.4	1851	1913[8]	0.3–1.5	4.8–8.4
USSR	147.8[5]	145.6	1949	43.6	1921	1986	0.7[5]	5.5[5]
UK[6]	33.9	32.8	1858	56.6	1834	1928	16.0	8.8
USA	526.1	482.7	1891	54.5	1840	1929	4.3	38.1
World	1322.9	1255.0[7]	1893	56.9	1844	1930	1.0	6.7

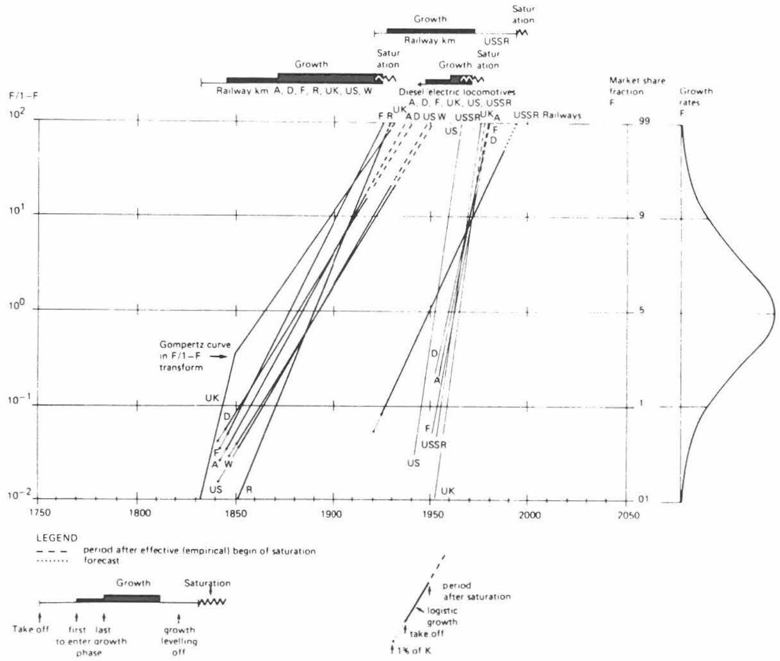
Note 1: Mitchell [60]
Note 2: Density as calculated by Woytinsky [61] for 1925 except Russia and USSR (own calculation). Range of figures for Russia corresponds to density for whole and European part territory respectively. Density figures for USSR are for 1986 network size.
Note 3: Austria alone after 1919
Note 4: Including Elsaß-Lothringen; excluding E-L maximum network size was approximately 60×10^3 km by 1938
Note 5: Including intercept (73.9×10^3 km); 95% probability that K lies within $145.5–150.2 \times 10^3$ km. Density figures for 1986 network
Note 6: Parameters refer to a Gompetz function ($t_0 = K/e$ instead of $K/2$).
Note 7: Mothes [62]
Note 8: Important territorial changes thereafter

also to later basic transformations in the technology base of railways. To illustrate this, Figure 10 contains also the diffusion envelope of the substitution of (coal powered) steam traction by diesel and electric traction in the railway sector of a number of countries. It becomes apparent that the substitution of steam by diesel/electric locomotives proceeds with a similar dynamic (logistic) trajectory in all countries analysed, independent of their economic system — i.e. a diffusion bandwagon which can be observed for an important transformation of the technological base of a mature technological system, like the railways after the Second World War.

A corollary of the diffusion bandwagon observation is that the particular viewpoint advanced here to describe historical development trajectories may serve in addition as an empirical measure to identify the countries, which by the nature of their different growth trajectory (i.e. expansion of their railway networks even after the 1930s), are apparently *decoupled* from the growth dynamics of the core countries participating in a particular economic expansion phase such as the railway era. The second expansion pulse of the USSR after 1930, as well as the continuing growth of railway networks in many developing countries (i.e. their different diffusion trajectories), may be interpreted as an indicator that these countries have not been integrated into the dynamics of economic growth and development of the industrial core countries driving the post-war expansion of the world economy.

To summarize our findings stemming from an analysis of the international character of the growth of railway networks (as an infrastructure indicator of the second and third Kondratiev economic expansion periods), we state that the growth in a particular development phase proceeds in all core countries participating in such an expansion period by a similar dynamic, i.e. in the form of an international diffusion bandwagon. By 'similar

Figure 10 Growth pulses in the expansion of the railway network and in the replacement of steam locomotives, in fractional growth achieved of maximum network size and of total traction power. Note logit (log [$F/1-F$)]) scale. *Source:* Grübler [13]



dynamic' we do not want to imply that the growth rates are distributed uniformly between different countries, but rather that early starters exhibit a similar dynamic while late-comers showing a catch-up effect. The result is that the final realisation in the diffusion of a particular socio-technical system (in our case the steam/coal/railway development phase) becomes completed within a short time span in all countries participating in this particular phase of development [44]. The example of the expansion of the railway networks points also to the critical importance of integration into technical knowledge, skills and capital flows for the successful participation in a particular expansion 'bandwagon'. This becomes in particular important for late-comers in the successful catching-up to the core countries.

6.3 Heterogeneity in diffusion levels

We have concluded above that the expansion of the railway network was completed in all industrial core countries at latest by the end of the 1930s. Already in Table 5 we have illustrated the resulting *densities*, i.e. the length of railway lines per country area and *per capita* at the time when the expansion process was completed. Based on this historical example we may conclude that the diffusion of infrastructure networks and systems, whilst being comparable in terms of the dynamics (Δt), resulted in different absolute as well as relative density levels. Different diffusion levels (densities) are the result of the diverse geographical, economic and social environments (boundary conditions) prevailing in different countries. Consider just the density levels presented in Table 5. The spatial railway densities range between 0.7 (USSR, 1986) and 16.0 (UK, 1923) km railway lines per km^2

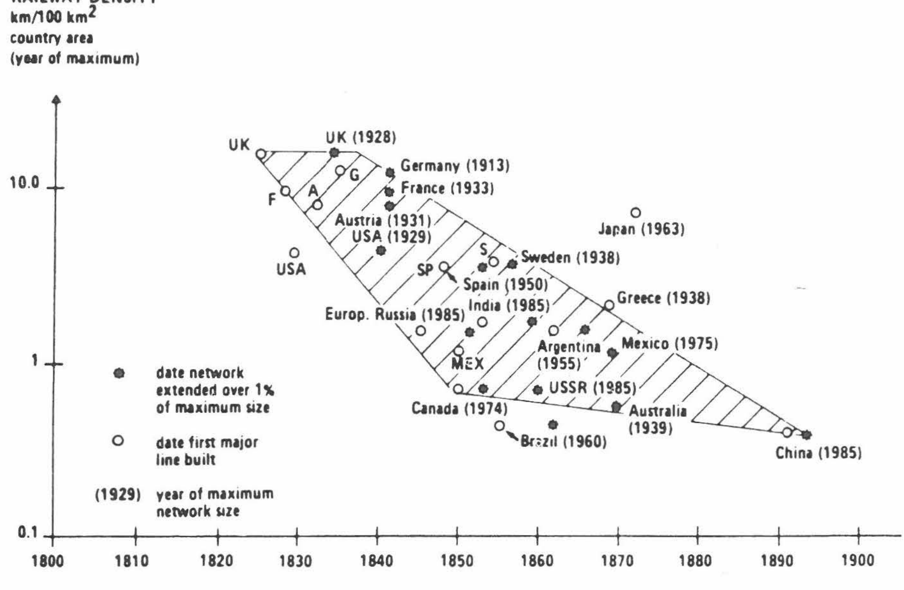
territory, i.e. by a factor of more than 20. *Per capita* railway densities range from 5.5 (1986, USSR) to 38.1 (USA, 1923) km per 100,000 inhabitants, i.e. a factor of approximately 7.

With respect to ultimate density levels achieved in a particular infrastructure development phase it is also interesting to extend our analysis to those countries that were not part of the 'railways bandwagon' of Table 5 and Figure 10. We have noted above that a number of developing countries continued railway construction after the saturation and contraction of railways in the industrialized core countries. Interestingly enough, construction in these countries occurred to the same extent as the railway network in industrialized countries contracted [45]. This implies that the growth of the railway network in any late follower country did *not* occur to the same extent as in the core countries participating in the 'railways bandwagon'. In analysing the diffusion level, i.e. the railway density per km^2 country area [46] resulting from the growth of these to varying degrees 'railway late-comers', we observe an interesting fact: the diffusion levels appear to decrease the later a country started construction, as illustrated in Figure 11.

Two empirical measures are developed to assess the starting date for the construction of a national railway network. First, the year the network extended for the first time to over 1% of its final maximum size, using either the historical dates indicated in Figure 11 or in cases such as China where the network is still growing the latest year for which data were available. The second measure records the date the first railway line of national importance was constructed.

Figure 11 suggests that the railway densities can be regrouped by a declining 'density envelope' as a function of the date railway construction began. The later a country started, the apparently proportionate fewer railway lines it constructed. The only exception is Japan, where construction started rather late (in the 1870s) but a network of a similar scale (density) as in the industrial core countries forming the 'railways bandwagon' was constructed. This

Figure 11 Spatial railway density (km railways per 100 km^2) envelope versus network construction date. *Source*: Grübler [13]



is possibly an indication that Japan was preparing as early as the second half of the 19th century for its spectacular catching up in the 20th century by developing its infrastructural endowment (in addition to the educational system, science and technology policy, etc.).

As similar analysis [13] suggests, Figure 11 does not hold only for railways but also for the diffusion of more recent transport systems, in particular for the diffusion of car ownership. There also the diffusion levels of countries following later do not reach the levels of the first countries to start motorization. If a similar development pattern were to unfold as in the case of the railways, this would imply that a comparable (private car) motorization in countries of the second and third world as in industrialized countries should *not* be expected.

Instead of developing along the technological and infrastructural lines of past economic expansion periods of industrialized countries, we consider that successful catching up will depend more on developing the technologies and infrastructures of the forthcoming development trajectory discussed in some detail above. Exaggeration sometimes serves to illustrate a particular argument: imagine the validity of a long-term economic growth or development scenario constructed around indicators of the length of canals and railways, the installed horsepower of steam engines or the specific energy consumption of Bessemer steel production (more than 10 times as high as at present) of industrialized countries around 1870 and suggesting this as a target for the industrialization and catching-up of Japan in 1930.

Thus we draw two main conclusions with respect to the density levels resulting from the diffusion of large, pervasive infrastructure systems. Firstly, diffusion levels are different (heterogeneous) even within the core countries developing along a similar trajectory at various historical economic expansion periods, as a result of different boundary conditions prevailing in individual countries. Therefore it is absolutely pointless to infer from the diffusion level achieved in early starter countries (e.g. the UK for railways or the USA for automobiles) to other countries. The railway network of the USA was highly developed (in fact the largest in the world) by 1930, yet its spatial density was only one-quarter that of the UK. No one could seriously suggest that the railway network in any of the countries presented in Table 5 was not sufficiently developed by 1930. Still, the diffusion levels (network density) were very heterogeneous even among the countries forming the 'railways bandwagon', and the fact that in the USA the ultimate automobile density may approach one vehicle per inhabitant after the year 2000 does not imply that such a level is a realistic (or desirable) forecast for Austria or France, where density levels below 0.5 cars per inhabitant appear to be typical for the ultimate saturation level [13].

Finally, we may also consider possible heterogeneity (diversity) in the technological design and institutional embedding of infrastructures. Even if a similar functional structure, say in the transport sector, exists between different countries, this functional similarity may be achieved by different technological and/or organizational settings. For instance, there exists a striking functional similarity in the long-distance passenger transport systems between the USA and the USSR. In both countries the dominant long-distance passenger transport mode is based on the internal combustion engine and road infrastructure; however in the case of the USA, transport is mainly by (private) individual road vehicles, whereas in the USSR it is via (collective) bus transport operations. On the other hand, the trend towards public air transport (measured in terms of the increasing market share of air transport in total long-distance passenger-km) is similar in both countries.

The heterogeneity in diffusion levels and technological and institutional design and embedding options becomes even larger when considering countries which are not among the core countries of a particular (infrastructure) development phase. Returning to our example of the railway network densities, we observe that China would have to increase its present railway network by a factor over 20 (!) in order to achieve a similar spatial railway density to that of the industrialized core countries in the 1930s. This does not only appear highly infeasible, it also would be simply absurd to suggest a repetition of a growth trajectory of a past development phase, which has already started to vanish and is of little importance for further economic growth in industrialized countries [47]. We contend that a similar statement also holds true for the massive diffusion of car ownership to levels anywhere near those presently achieved in industrial countries.

If we observe heterogeneity in diffusion levels and design and institutional options within developed countries, we may conclude that such heterogeneity is even greater between developing countries themselves. In fact, it is argued by Nowotny [48] that heterogeneity and social divergences have become inherent *structural* characteristics of developing countries, which are often (inappropriately) subsumed under a common heading ('the South', etc.). Thus, we suggest that traditional conceptualizations in terms of bipolar models (North–South) may indeed be over-simplifications, especially when considering the initial conditions and catching-up possibilities in a new development phase, which are and will be extremely heterogeneous between developing countries. This heterogeneity will especially have to be considered when developing criteria of sustainability of various development trajectories. Brooks [49] argues that such criteria will have to be defined over a spatially heterogeneous system, consisting of clusters of interacting spatially-related systems, which may not necessarily be in geographic proximity to each other.

Thus, any scenario of future development and catching-up has to account for the different boundary conditions prevailing in different countries when assessing diffusion levels, and even technological choice options. As a result (desirable) diffusion levels (e.g. infrastructure endowments) cannot be defined through a *normative* framework, in inferring from the diffusion levels achieved in one country, to another one. Early starters may serve as a 'development model' only at very specific periods in time, i.e. when catching-up within a particular diffusion bandwagon characteristic of a given development phase, but not at later time periods.

With particular reference to developing countries we argue that precisely the very nature of the transition to an emerging new development phase holds important implications for investment strategies and in particular for anticipated resource consumption levels. Under the hypothesis of such a transition all traditionally employed indicators to describe (appropriate) levels and trajectories of development (like the example of railway densities or car ownership rates discussed above) become progressively inadequate. This is also the reason why Malthusian resource limits resulting from the extrapolation of indicators, which were appropriate only under a previous growth regime (say *per capita* car ownership or oil consumption, steel intensity per unit of GNP, etc.), are in fact hypothetical, as they ignore fundamental historical experiences of economic development — the process of change and structural transition to new phases of development. Thus, the very concept of sustainability, especially when entailing economic development and technological change, has to be redefined as an evolutionary one. Brooks [49] argues that within the context of sustainable development the rate of change of the structure of demand (i.e. the transition to a new development phase) may be a more serious limiting factor than absolute levels of demand and resulting strains on the (exhaustible) resource base, because of the constant evolution of the latter through improvement in exploration (e.g. the significant increase of the resource potential of natural gas discussed above), extraction, recycling and substitution technologies.

In summarizing the above discussion let us repeat briefly the main arguments of relevance for the formulation of possible trajectories for catching-up under a newly emerging development phase. Based on historical examples we have tried to illustrate the importance of integration into international flows of capital and technological knowledge in order to most effectively make use of the opportunities opened up by the diffusion of a new socio-technological 'bandwagon' embodying a quantum leap in potential productivity of economies and opening up a wide range of growth opportunities. This holds important implications for the development of appropriate financial and technological resource transfers to developing countries, especially in the areas which we have identified as emerging as key technological elements of the information and communication Kondratiev.

At the same time we have refuted the prescriptive character of some development scenarios in that we argue that heterogeneity both in the socio-technological options as well as in the ultimate intensity (diffusion) levels realised was, and will continue to be, one of the essential factors to be kept in mind when formulating scenarios and policies for the introduction and assessment of the growth potential of new technologies, particularly in developing countries. This heterogeneity in the technological (design) options and ultimate penetration levels stems from different geographic, social, etc. boundary conditions prevailing in different countries and from the fact that successful catching-up is more contingent on development of the technological elements and infrastructures of the new development regime than on repeating a trajectory of a past expansionary period. As such, heterogeneity in the ultimate realisation levels of a new socio-technic development phase and non-repetition of intensity levels of previous ones have important repercussions on our perception of future sustainability, which is often perceived as being threatened by scenarios assuming strong homogenization in development patterns, lifestyles and resource consumption levels.

7 Two hidden agendas in the development process

One of the major goals in analysing processes of technological innovation and diffusion is to gain a deeper understanding of the conditions for economic development and for effectively catching-up, especially urgent in view of the gap that remains and even becomes wider between highly industrialized, industrializing and developing countries. Most studies preoccupied with such analysis are based upon the central assumption of the crucial role that technological innovation and technology issues play in the process of development, an assumption which seems warranted when looking at international trade and economic growth models.

Yet, there is also a 'hidden agenda' beneath the purely technological issues. It touches, on the one hand, upon the much less tangible institutional preconditions and arrangements which accompany or precede effective economic and technological development. The second 'hidden agenda' deals in particular with the role of science and science policy in developing countries within the process of absorption and development of technology, as a further 'intangible' precondition for catching-up.

Institutional preconditions for catching-up range from the obvious ones, like levels and spread of education or the diffusion of technical skills in a society, to very complex ones, which are intricately bound up with the historical development, its continuities and especially its discontinuities within a society. Rosenberg and Birdzell [50] have argued, for instance, that the West began its rise from an economic and technological position somewhat behind that of Chinese and Islamic civilizations of the same period. The authors cite among the many factors contributing to the Western success story such institutional arrangements as the early separation of the political and economic spheres, or economic decentralization. Rosenberg and Birdzell distinguish between two patterns of economic growth: one associated with an expansion of trade and economic resources, and the second, primarily attributable to scientific and technological innovation, essentially starting with the 18th century. Innovation is interpreted in a wider sense; as such it includes experimentation (inventions and their further systematical development) within science, but also 'experimentation' within the economic sphere, with respect to new products, methods of manufacturing, modes of enterprises, organization of market relations, in the transport and communication systems, etc.

As the history of science and technology in the West shows, scientific activity was for the most part not undertaken in response to economic needs, and for most of history in the West and elsewhere, science and industry might have existed in completely different worlds. However, it was the gradual linkage of innovative activities in such different spheres as the world of economic enterprises and that of science, a linkage achieved through institutional arrangements and mechanisms such as decentralization of authority, scientific autonomy as well as the emergence of professionalization as a set of rules, attitudes and behaviour, by which science and technology became the key factors shaping and fuelling economic growth. Even if many of these and similar arguments can be disputed in details and warrant further evidence, it is nevertheless also clear that institutional configurations played a decisive role in "how the West grew rich" [50].

These institutional configurations are often taken for granted when looking at technological evolution alone, but we consider the institutional framework of the embedding of science and technology to be of decisive importance not only when considering the inception of innovations (i.e. inventions) and the capacity to absorb them into the economic and social spheres (in translating them into products, processes, forms of organization and so on), but especially also for the subsequent diffusion phase, as the latter entails a whole host of consecutive incremental innovations and adaptation (improvement) processes, without which no particular innovation (not to mention large, pervasive socio-technological systems) could diffuse (become absorbed) into the economic and social strata.

The second agenda somewhat 'hidden' from traditional inquiries of technological processes and their diffusion patterns, is science itself. It remains eclipsed in much, if not practically all, the literature on the effective conditions for economic and technological catching-up. Science seems also to be absent from policy documents: the Brandt report, to cite but one example, does not mention science even once. One of the reasons for such oversights might stem from the fact that analysts of technology transfer or diffusion processes are often oblivious of the work performed within 'science studies', just as those who work within the latter area are often not trained in the economic disciplines nor do they consult the relevant literature.

Occasionally however, controversial statements about the relevance of research on science and technology in developing countries surface, which illustrate the wide range of different orientations, assumptions, conceptual frameworks and policy priorities which exist in this particular area. On the one hand, there exists a more 'technology oriented' point of view, where the principal emphasis is on the (short-term) economic effects that the development of science and technology may have in developing countries. The argument presented goes along the lines, that one should mainly consider the short-term economic dimension of science and technology, which can bring relief to some of the present urgent needs which developing countries are confronted with. In addition, and this is the most controversial argument, but one which follows logically from the primary emphasis in the short-term economic benefits resulting from science and technology, the role of science itself is up for discussion when compared to that of technology. When compared to the basic research performed in highly industrialized countries, the achievements coming from developing countries appear, with a few exceptions, irrelevant. Given the enormous gap that exists in resources, personnel, equipment and organization of research, indigenous scientific research in developing countries must become either a kind of 'bare-foot science' or remains the dream of an unrealistic luxury, which developing countries cannot afford as long as other more pressing needs remain unmet. A second line of argument goes in the opposite direction, namely that without appropriate scientific skills and a more universal orientation, developing countries may never be in a position to effectively absorb technology and to develop the local modifications and add-ons, without which any technology transfer must remain limited in its capacity to contribute to the solution of the most urgent local problems.

Thus divergent points of view exist, with one side arguing for a pragmatic short-term economic benefit oriented approach with emphasis on international technological (import) linkages, while the other side argues for a more universal orientation and emphasis also on indigenous scientific development, which might be an important strategy to enable developing countries to participate in what is, after all, a shared cultural heritage of humankind. These divergent viewpoints also reflect a dilemma that scientists in developing countries know only too well — a dilemma between a 'local' orientation, geared to practical, useful and relevant work, which however carries little prestige and rewards from the international scientific community, or of maintaining an international orientation and identity but becoming at the same time alienated from the national context (see, for instance Shenhav [51] on this point).

Such a dilemma, acutely felt on an individual as well as on a collective level, can be traced to the fact that science in developing countries (again with a few exceptions) "is but a marginal add-on to the knowledge flows that transform their social and economic life" (Hill [52]). Science is thus not connected with the user environment in the same way as is the case in industrialized countries. Therefore, independent of what are the pressing, immediate needs in different national contexts, the question remains, how in the long run can a social and economic context be generated which allows science to take root in developing countries, and appropriate preconditions be generated for the effective absorption, adaptation or indigenous developments of technologies, production methods, etc. all of which are mediated by science and upon which catching-up will be contingent.

Someone who has used all his scientific authority and international standing to criticize both governments of developing and industrialized countries for failing to recognize the crucial importance of science for technological and economic development has been Abdus Salam (e.g. [53, 54]). The widening gap in living standards is, he maintains, principally a science and technology gap, which is due to the fact that expenditures on science and technology are orders of magnitude higher (both in absolute amounts, and also as percentage of GNP) in industrialized than in developing countries. Typically science and technology expenditures range between 2 to 2.5% of GNP in the industrialized North compared to some 0.2% in the developing South [55]. The corresponding figures for defence, education and health care however, do not show a similar order of magnitude of structural difference. They are 5.6% (of GNP) for defence in both hemispheres, 5.2%–3.8% for education and 4.8%–1.5% for health care in the North and the South respectively. Salam interprets these figures as a lack of commitment towards science in developing countries and as a lack of self-reliance in the technology area, which results in an ever-widening science and technology gap with potentially staggering consequences.

By neglecting the science base of technology, the science transfer which must always accompany technology transfer (if it is to mean more than simply the importing of designs, machinery, technical personnel or even commodities) is also neglected. "Very few within the developing world appear to stress that the science of today is the technology of tomorrow and that when we speak of science it must be broad based in order to be effective for applications". It is thus important to be concerned about science transfer at least as much as about technology transfer. When speaking about science transfer one can consider four stages. First and foremost, scientific literacy and science teaching must be reached at all levels, including at least one complete science library as a minimum infrastructure in *all* developing countries. In a second stage, the indigenous scientific community of developing countries should be consulted on which technologies would be relevant and worth acquiring, since there is no substitute for motivated and competent local scientific advisers. Third, at least a limited number of developing countries should be able to address and to solve problems of agriculture, of local pests and diseases and how to most effectively make use of local resources and materials. Science should in this particular stage be primarily geared to address application-oriented problems within a local context, but in connection to the full body of scientific knowledge available internationally. Only then the fourth stage is set for basic research, being able to bear fruits in form of high technology, and for carrying out science-based research in view of specific applications.

At present, there are several pilot projects under way, which attempt to realise precisely what the later stages of the science transfer model outlined above imply: putting to use science for local needs in agriculture, disease and pest control as well as helping to find new uses for local materials and resources. Such strategies are also needed for resources, but they could open up a road forward, one in which a conscious social choice could become available for the first time. In highly industrialized countries there constantly operates a process of selection, in which scientific discoveries (inventions) that show potential economic and social benefits become translated into innovations. A similar social choice mechanism could also possibly by implanted deliberately in those developing countries which have reached a higher stage of science transfer, but which are lacking a comparable set of economic forces and social (regulatory) frameworks operating as selection mechanisms in developed countries.

Creating technological applications tailored to locally (abundantly) available materials and resources is but one example for a science-based technology policy, which does not follow blindly a path modelled after the experience (and specific requirements) of developed countries. Similar attempts with great potential are undertaken also in the area of biotechnology, which has a vast potential in radically transforming agriculture, energy and medicine in the longer-term and which could also open new avenues for social choices. At the same time a reconceptualization of the production process appears possible, allowing a radically different 'customer-tailored' type of production in line with meeting user demand specifications of unprecedented levels, in a similar way as we have discussed above for possible emerging new production principles in the manufacturing sector of highly developed countries.

In order to take advantage of such new developments, it is apparent that science-based applied technological research in developing countries cannot proceed without new networks of cooperation. New networks are needed, both between research institutions within developing countries and also through new and stronger links to developed countries.

The question of the role of science in the development process and whether its role (what we have termed a 'hidden agenda') can be defined in unanimous agreement remains open. By its very nature there is no one-way, causal link between scientific capability or level of commitment and investments into science and economic growth and development. However, as the sketchy propositions outlined above tried to make clear, the role of science has to be seen as crucial in a larger cultural, social and institutional context which leads to a possibility for implanting indigenous social choices rather than responding to (i.e. importing) the technological choices stemming from market and social clearing processes in the developed world. Promotion of science, both in terms of committing funds as well as in fostering the growth of indigenous scientific communities, may indeed by an important, if not *the* important condition for full participation in a universally shared heritage which holds the keys for further relief of poverty and betterment of human conditions, as well as to the sustainable global development of natural resources.

Investing more into science, even if the sums involved remain modest compared to spending levels of industrialized countries, may permit the further growth of an indigenous local community of scientists who are potentially important bearers and transmitters of knowledge which is part of international and national public knowledge. It also offers an opportunity for the growth of a relatively autonomous sphere within society, which is not under direct influence and control of governments and decision makers, and which is distinct in outlook, values and orientation from a trading or merchant class. The few developing countries which have succeeded in building up a respectable and sizeable scientific community — above all Argentina, Brazil, China and India — and whose performance in many fields compares with that of highly industrialized countries, are, perhaps not by chance, countries with a large population and a highly differentiated social structure. Moreover, they are countries with an old tradition of scientific creativity and accomplishments, or heirs to such a tradition. However, there is no reason to believe that commitment to science and scientific values is limited by the size of a country.

Yet, as much as science may be esteemed in its own right or as a cultural reinforcement for self-reliance and participation of developing countries in the shared heritage at the global level, it will in addition be of crucial importance to link scientific discoveries to technological innovation so that they will yield material benefits as well as a higher problem-solving capacity. Not only because of the crucial (and still far from being adequately understood) step from scientific inventions to technological innovations, but also because of the continuous further development and incremental improvements necessary in order for technological diffusion, opening the real economic dimension and impact of technological change becomes possible.

This brings us back to the question raised initially about the conditions for catching-up effectively by those who otherwise would remain trapped in the vicious circle of 'locked-in' development, where the gap between the rich and the poor remains or even widens. Until more recently, quite a number of growth models assumed a somewhat automatic or semi-automatic mechanism at work (of 'take-off' or 'competitive exclusion'). Recently, attention has shifted to identify more closely and in detail those periods in which 'windows of opportunity' are open at least for a limited time period. Also here a distinction is made between the mere 'use' of technology already available at the world level and acquiring the capacity for participating in the generation and improvements of technologies opening the possibility to catch up. The latter, however, pre-supposes a command of sufficient scientific and technological knowledge for a real participation in a particular period and field of technological development.

What Pasteur said about the individual scientist, namely that the 'chance' of scientific discovery meets only those whose minds are prepared for it, holds true also for nations and their chances of utilizing windows of opportunity as long as they are open. Catching-up would mean, under such a perspective, to be in a position to take advantage of the opportunities which are created by technological transitions or 'paradigm' changes, bearing in mind that such opportunity windows exist only temporarily.

Perez and Soete [56] in particular have discussed in more detail the costs and the timing of entry in a process of technological evolution, once it has been set in motion. At the outset, there is every reason to believe that the vast majority of new technologies will originate primarily from the technologically most advanced countries. Perez and Soete consider in addition, that at least in some of the advanced economies the diffusion of major new technologies and systems will be hampered by heavy investment outlays already made in the past into more established technologies as well as by (slow) institutional and social adjustment processes to a new 'paradigm' of economic growth and development. Theoretically this could imply that a new technological trajectory might have better, unhampered starting and diffusion conditions in those countries which are less committed to an old technological regime in terms of actual production, investments, skill levels and organizational and institutional embeddings. This is, in a nutshell, one lesson to be learned from the historical experience of industrialization and technology diffusion in 19th century Europe and the USA [57]. Historical experience suggests that windows of opportunity exist for late-comers. It remains however less clear if the historical conditions that prevailed in the 19th century in a small part of the world are comparable to those prevailing today in a world that has become linked globally through the reverberating effects of techno-economic innovation waves.

Perez and Soete [56] consider that the requirements for entry in the first phase (i.e. the beginning) of the lifecycle of a new technological system are relatively low as regards experience or managerial ability and capital requirements (contrary to the import of capital-intensive mature technologies), which would make them amenable for some developing countries. However, there are two additional requirements which also would have to be met: first, to overcome or to compensate for the lack of locational and infrastructural advantages, and second, to dispose of the scientific and technical knowledge necessary to make use of the opportunities opened. It is certainly true that much of the knowledge required to enter a new technology system in its early phase is public knowledge (available at universities for example). At the same time it is also apparent that many of the skills and incremental improvements necessary for the successful introduction and subsequent diffusion of a new technological system can only be acquired by a process of 'learning by doing'. Science policy in developing countries should under such a conjecture not only be concerned with the appropriation of (in principle free) public knowledge at the international level, but also of how this knowledge can effectively be translated to respond particularly to national and local requirements for new processes, products and services.

Perez and Soete suggest that it is this 'time for learning' for everybody, which creates one of the favourable conditions for catching-up. The second one is created by offering low threshold costs for newcomers in terms of the appropriation of knowledge and its translation into technical skills, etc. In addition, newcomers do not face the high costs of getting rid of the capital vintages, experience and externalities of the 'wrong sort' of superseded technologies. In other words, opportunities accrue to those who are sufficiently prepared and who do not have to face the costs of obsolescence and decommissioning of older technological systems and infrastructures.

Thus, technological innovation processes could allow for breaking a vicious cycle, especially (possibly only) in the very early phase of the lifecycle of a newly emerging technological system, i.e. in the transition period to a new development phase in which the ultimate characteristics and trajectories of economic growth and catch-up opportunities are being formed. However, this puts an even greater premium on being prepared to perceive and seize the opportunities which thus arise: any developing country that can take advantage of this sort of opportunity must have developed a position (probably through decades of efforts in entering mature technologies) to deploy sufficient scientific capabilities, technical skills and supportive institutional frameworks in order to be ready for catching up.

8 Conclusions

By adopting a long-term Schumpeterian perspective on economic development we have tried to emphasize in particular the discontinuous manner in which technological, organizational and institutional innovations become absorbed into our economies and societies. From such a perspective we appear to be in the midst of a transition to a new phase of development, which will be quantitatively and qualitatively different in its final realisation in the form of new technologies, infrastructures, skill levels, institutional and organizational settings and in the dominant driving forces shaping the future structure of economies and the trajectories of their evolution.

We have tentatively sketched some of the technological characteristics of the emerging new development phase of the fifth Kondratiev in the areas of energy (natural gas), transportation (air transportation) and manufacturing (micro-electronics). Generally we anticipate that the principal future driving forces will be more in the direction of enhancing qualitative characteristics in terms of efficiency, environmental quality and system integration shaped by the philosophy of 'just-in-time' production, than in a repetition of the quantitative growth trajectory of energy- and material-intensive products and processes characteristic of the post Second World War development phase.

With reference to developing countries, we consider that successful catching-up will be more contingent on the development along the directions of the emerging fifth Kondratiev than on imitation of a growth trajectory of a past (and progressively vanishing) development phase. Under such a conjecture, concerns about future sustainability (as a result of a prescriptive extrapolation of development trajectories and resource consumption levels from the experience of industrialized countries) may have to be reconsidered.

Windows of oppportunity for catching-up are opened in such a transition phase to a new mode of economic growth as the appropriation of scientific and technical knowledge is an easier task at the beginning of the lifecycle of a new technological system than in later phases. In addition, developing countries may even have a strategic advantage in such a transition phase to a new development mode as they have no comparable commitment in terms of infrastructures, capital vintages, skill levels and organizational and institutional settings to the previously dominant mode and trajectories of the evolution of the techno-economic system.

Successful catching up appears from such a perspective to depend primarily on the preparedness to anticipate and to develop along newly emerging directions rather than to follow a prescriptive development path of the progressively vanishing 'socio-technical paradigm' of the past. It will also be contingent on other factors, including the development of appropriate locational and infrastructural endowments and the level of education and skills.

Finally, we would like to emphasize that whilst the technological dimension, as nexus and growth stimulating factor towards a fifth Kondratiev upswing, is certainly central, one has to consider equally the importance of the social and institutional embedding of technologies, as a key factor in the diffusion of large pervasive systems. The role of science and of scientific capabilities in the appropriation of technical knowledge and in the development of local skills and areas of applications of new technologies, as well as the role of an appropriate organizational and institutional environment in the development and diffusion of technological systems, will without doubt be decisive factors for success or failure in making best use of the opportunity windows opened in the transition towards a new phase of growth and prosperity.

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15 Of similar importance is coal, fueling the steam engine and railway Kondratievs ending with the Great Depression in the 1930s.

16 OECD (1979) *Interfutures: Facing the Future, Mastering the Probable and Managing the Unpredictable* OECD, Paris

17 This is best illustrated by the fact that even present day global energy consumption could theoretically be met by the global wood reproduction rate

18 For an illustrative discussion on how perceived major environmental concerns become resolved

due to the dynamics of technological change and efficiency improvements see Ausubel [38]

19 Nakicenovic, N. (1986) *Patterns of Change: Technological Substitution and Long Waves in the United States* WP-86-13, IIASA, Laxenburg, Austria

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23 Williams, R.H. and Larson, E.D. (1988) 'Aeroderivative turbines for stationary power' *Ann. Rev. Energy* Vol. 13, pp. 429–489

24 A scenario based on a transition to a carbon-free (e.g. hydrogen-based) future energy system relying heavily on the natural gas option would result in carbon dioxide emissions and concentrations orders of magnitude lower than projected in conventional scenarios, as illustrated by Ausubel, Grübler and Nakicenovic [71].

25 Pry, R.H. (1988) 'The changing nature of industrial management' Draft, IIASA, laxenburg, Austria

26 It has been noted, that the introduction of micro-electronics and computers in service activities like banking have up to now not resulted in significant labour productivity increases. This situation has been referred to as the so-called 'Solow paradox'. Certainly, this paradox may be the result of a more general measurement problem, in particular that conventional productivity measures fail to account for information inputs, in addition to labour, capital and energy (as argued for instance by Ayres [64]). There appear however two additional reasons for this development: first the introduction of new technologies enabled a quantum leap in the quality of service offered, ranging from automatic teller machines to access to new forms of financial instruments by a large public. Second, the productivity potential of new technologies could not be fully realised precisely because of the mismatch between the opportunities opened by new technologies and the (static) nature of the socio-institutional framework into which they are embedded. As an illustration of this point consider for instance the bank opening hours in most European countries.

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33 It is indicative that software constitutes already presently a major fraction (above 80%) in military investments. Similar tendencies are also to be expected for the manufacturing sector, as illustrated in Figure 3, taken from Ayres [64].

34 Williams, R.H., Larson, E.D. and Ross, M.H. (1987) 'Materials, affluence, and industrial energy use' *Ann. Rev. Energy* Vol. 12, pp. 99–144

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36 Note that this observation does not imply a decrease in the total goods transport volume (i.e. in ton-km performed), rather it implies an increasing decoupling (or decreasing elasticity) of growth in transported volumes from GNP growth.

37 For example, railroads were fired with wood in the USA well into the 1870s and by coal only thereafter; locomotives in Tsarist Russia were fuelled with *mazout*, i.e. (petroleum derived)

fuel oil. The transition from steam to either diesel or electricity resulted in significant improvements of the energy efficiency (energy requirements per unit of traction power) of locomotives.

38 Ausubel, J.H. (1989, forthcoming) 'Regularities in technological development: an environmental view' in J.H. Ausubel and H.E. Sladovich (eds.) *Technology and Environment* US National Academy of Engineering, Washington D.C.

39 French capital was for instance essential in the construction of the railway network of Austro-Hungary and Tsarist Russia; the dominance of British engineering and capital in the construction of railways in Latin America or in India provides another illustrative example.

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41 This line of research was especially followed by the 'new economic history school'. Excellent quantitative assessments of the impact of railway development are for instance Fishlow [72] and Fogel [73] for the USA, Fremdling [74] for Germany or Hawke [75] for the UK. For assessments of social savings (ranging from 5 to 10% of GNP in industrialized countries to 25–40% in case of Mexico) see for instance O'Brien [76].

42 The model considers the fractional growth achieved in relation to the maximum network size (the saturation level of the growth process K) at any particular time t, i.e. $F_t = K/y_t$ (where K describes the maximum network size and y_t the network size at time t) to follow the relation $F_t/(1-F_t) = \exp(at+b)$. The growth achieved at time t thus depends on t and the two growth parameters a and b, describing the slope of the growth curve and its location in time. The fractional growth achieved over the fractional growth remaining to be achieved (i.e. $F_t/(1-F_t)$) if represented on logarithmic scale follows the linear growth model ($at+b$) and can thus be compared in terms of its dynamics between different countries, irrespective of the different ultimate saturation levels reached.

43 Only the growth of the public railway network of the UK proceeds along an asymmetrical growth pattern, described more appropriately by an alternative diffusion model (a Gompertz curve) or the two-phase logit model as presented in Figure 10.

44 A brief examination of the available statistics (Mitchell [60]) suggests that the countries in which the expansion of the railways (i.e. the completion of the diffusion of the railway bandwagon) is much larger than the examples analysed in Table 5 and Figure 10. Basically all European countries had reached their maximum length of the railway network in the 1930s, including the Netherlands (1929), Denmark (1932), Belgium (1933), Switzerland (1937), Sweden and Greece (1938) and finally Italy (1940). This provides thus further evidence for the clustering ('season') of saturations hypothesis, formulated above.

45 Consequently the global railway network has remained roughly constant at around 1.3 million km over the last 50 years.

46 Because of the strong population dynamics of these countries, *per capita* densities show even larger disparities to industrialized countries and are also decreasing for most developing countries.

47 This does not of course imply that developing countries should not construct any new railway lines. For the transport of low-value goods, say soy beans or iron ore, railways would be an efficient and cost-effective transport mode for these countries. Our conclusion just refers to the fact that we do not consider successful catching-up of these countries to rely in any similar way on the development of an infrastructure, which was essential for the growth of industrial countries in the 19th century.

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