THE GREENING OF TECHNOLOGICAL PROGRESS

An evolutionary perspective

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This article provides insight into technology–economy–ecology linkages which may help to define and accomplish environmentally sustainable development. An evolutionary perspective is adopted in which economic growth and technological change are viewed as a complex, non-linear, path-dependent process, driven by short-term benefits instead of longer-term optimality. The article discusses the externality issues of technological change and the need for institutional adaptation, and talks about the relationship between economic growth and particular trajectories of technological change. It is stated that some of the present technological trajectories have reached their environmental limits and need to be replaced by environment-friendlier trajectories. However, such transitions are hindered by technical, economic and institutional barriers since the new trajectories have not yet benefited from 'dynamic scale and learning effects' and because the 'selection environment' is adapted to the old regime. The determinants of the decision processes to generate and adopt cleaner technologies are identified and analysed, and some policy issues of stimulating environment-friendlier technologies are discussed.

Technological progress has changed and shaped the world. Whether it has always been beneficial is the subject of ongoing debate. Although technological progress in the industrialized countries has led to great prosperity, at least in a materialistic sense, the burdens on the lives of some individuals were often high. In a world that is more and more affected by technological

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change the range and scope of the problems broaden. Whereas the technological risks of the past, such as unsafe working conditions, are now usually averted, today's technological risks threaten larger areas and for a longer period of time. The *environmental* problems of past industrialization and application of technology, involving the use of new chemicals and synthetic materials, and the continuous flow of hazardous emissions, effluent and waste material, not only affect the lives of individuals but also the welfare of large communities, and indeed in some cases even affect the entire world. Unlike past technological 'externalities', current environmental problems stem from the accumulation of small effects, which at some point in time appear to exceed the critical boundaries of the ecosystem or at least the public perception of those boundaries. They represent a typical example of an evolutionary process in which apparently small events develop into a larger problem over a longer period.

In this article we try to provide some insight into technology–economy–ecology linkages, and especially into the economics of the technological system, which might help to define and accomplish environmentally sustainable economic development.[1] We do this from an *evolutionary* perspective in which economic growth and technological change are viewed as a complex, non-linear and path-dependent process, which is driven by short-term benefits instead of longer-term optimality.[2] Insight into the evolutionary character of economic growth and technological change is of great importance in designing appropriate policy to achieve substainable paths of economic and technological development. Policies designed to solve simple linear problems, such as the financing of environmental measures by the government out of the means of economic growth along the same growth paths, are inappropriate in our view.[3]

The structure of this article is as follows. In section 1 we discuss some positive and negative 'externalities' of technological change and the need for an early assessment of these effects. It is argued that the institutional framework should be oriented more towards the *prevention* of hazardous effects then being oriented towards the cure of them. In section 2 we deal with the interrelation between paths of economic growth and the accompanying networks of 'trajectories' of technological change. Some historical examples of technological transition are given. Subsequently, in section 3, we go into the economic aspects of the replacement of existing technological trajectories by ones that are more sustainable in terms of the environment. It is argued that the prevailing trajectories are dominant because, unlike their cleaner alternatives, they have benefited from 'dynamic scale and learning effects' and because the 'selection environment' is adapted to the old regime. In such a situation where the short-term costs of transition are high and the short-term benefits small, a technological transition will only come about slowly, dependent on the necessary institutional changes (government regulation, organizational changes, changes in people's lifestyle, habits, etc). In section 4 we focus on the (microeconomic) determinants of the decision to generate and adopt an environment-friendlier technology.

We end with some policy issues in section 5. The policy implications that follow from our evolutionary approach differ in some respects from traditional recommendations. Not only is a stricter environmental policy promoted, in which economic instruments are used more intensively, but we also promote a government policy that is much broader, which involves the removal of institutional barriers, a reorientation of education and science and technology policy, and the integration of ecological aspects in other areas of policy.

(1) Externalities of technological change

The understanding of the problem of positive and negative 'externalities' related to ways of production is relatively well established in the debate surrounding technology policy and in particular technology assessment. Technology assessment has emerged as an institutional procedure precisely because of the recognition of the 'externality' nature of much technical change. It appeared that a well informed assessment of new technologies could provide some reassurance about likely impacts or even shape it in a way that is desired. By definition, though, technology assessment can far better address what we call here the static distributional aspects of the impact of technology than the dynamic externality aspects of new technologies.

First, from a *static* point of view, and as emphasized in particular by Harvey Brooks,[4] there is an apparent paradox regarding the impact of technology. The costs or risks of a new technology frequently fall on a limited group of the population, whereas the benefits are widely diffused, often to the extent that the benefits to any restricted group are barely perceptible even though the aggregate benefit to a large population amounts to considerably more than the total cost to the limited adversely affected group. Examples abound. 'Automation', for instance, benefits consumers of a product by lowering its relative price, but the costs in worker displacement are borne by a small number of people, and may be traumatic. A large electrical generating station may adversely affect the local environment, while providing widely diffused benefits to the population served by the electricity produced. Workers in an unusually dangerous occupation such as mining carry a disproportionate share of the costs associated with the mined minerals which may have wide benefits throughout a national economy.

This disproportion between costs and benefits can, however, also work the other way as in many cases of environmental pollution and emissions. The effluent from a concentrated industrial area such as the Ruhr Valley or the American Great Lakes industrial zone may diffuse acid sulphates over a very large area which derives little benefit from the industrial activity, but may have its quality of life as well as agricultural productivity seriously degraded thereby.

The issue of sharing costs and benefits of technological change shows how extremely important it is, from both the national and international standpoints, first, to draw up 'rules of the game' to ensure that adverse effects are less harmful than they would be if everything was left to free competition, and, second, to establish such rules fairly early on, before vested interests, acquired privilege and the fierceness of competition jeopardize their compulsory application. One factor noted in recent times that might pose a potential threat is the complexity of systems.

Contemporary technologies are becoming extremely complex in two respects: they depend increasingly on scientific knowledge and equipment, and further, in order to operate, they assume an organizational fabric which itself is complex. One must indeed speak of systems here and not only of technologies: one is immediately involved in a network of sociotechnical relations involving factors of supply, maintenance, insurance etc, without which use of the technological product would be impossible. And the more complex the sociotechnical system, the more vulnerable the social organization is to accident or the obstruction of just one part of the system. At the same time, the knowledge needed to understand the technical operation of the system has become so specialized as to be esoteric to the majority of people. Specialists in increasingly narrow fields have been cut off from each other by their respective skills; with even greater reason, the multitude of non-technicians has been cut off from scientists and engineers.

The very scale and complexity of the scientific and technological enterprise mean that its potential consequences are unprecedented. As mentioned above, as the technological risks of the past (pit explosions, railway accidents, dam bursts) can usually be averted now, today's 'major technological risks' threaten larger areas and for a longer time. In the event of a disaster, these areas can no longer be easily isolated and hence evacuated. Moreover, toxic emissions and radioactive contamination may have effects that are not detectable for very many years or which last for several generations.[5]

This brings us quite naturally to the increasing importance of *dynamic* 'externality' issues. Here too, the debate surrounding the introduction of new technologies has addressed many issues which at present dominate the debate over environmental costs and long-term damage. Within a dynamic, evolutionary perspective, long-term externalities are, in Nelson and Winter's words, no longer

> susceptible to definitive once and for all categorization and are more intimately related to particular historical and institutional contexts. To a large extent, the problems involved are aspects of economic change. The processes of change are continually tossing up new 'externalities' that must be dealt with in some manner or other. In a regime in which technical advance is occurring and organizational structure is evolving in response to changing patterns of demand and supply, new non-market interactions that are not contained adequately by prevailing laws and policies are almost certain to appear, and old ones may disappear. Long-lasting chemical insecticides were not a problem eighty years ago. Horse manure polluted the cities but automotive emissions did not. The canonical 'externality' problem of evolutionary theory is the generation by new technologies of benefits and costs that old institutional structures ignore.[6]

The huge environmental problems and threats that the world is facing, such as the destruction of the ozone layer and the global warming, imply that present institutional regimes are inadequate.[7] Up until now the use or abuse of the environment has been regulated, if at all, by emission norms, product standards and bans, and—in some cases—charges and subsidies. It is found that these measures have been largely insufficient and have primarily led to the development and use of 'cleaning' technology such as 'end-of-pipe' technology and other treatment technology instead of 'clean' technology (cleaner production processes) through which environmental damage is prevented.[8]

The above implies that what is needed are 'rules of the game' through which the 'externalities' of technological change are prevented or reduced to acceptable levels. In the case of environmental policy, a more fundamental approach would be to define proper property rights, as a result of which polluters would be liable for the *environmental* damage they cause, just as producers of consumer products can be held liable for the negative health effects of their products.[9] As a consequence of the latter liability rules, especially those firms in the pharmaceutical industry spend a substantial amount of money on research trying to assess the potential dangers of their products to the public health and to prevent these hazards. The benefits of such a system are that there is not only an incentive for the prevention of environmental risks and damage, but also that those firms and organizations are made liable that are often in the best position to assess the negative environmental impacts, and, especially, to find solutions to prevent these problems at the design stage. Of course there are serious problems of implementation and enforcement attached to such a system: the damage has to be assessed, the polluters have to be identified and the shares of the individual firms that caused the damage have to be quantified. Also, such a system might be 'overdeterring', or, on the contrary, may not constitute a strong enough barrier. Also, it may lead to very high transaction costs (in terms of lawyer payments and tort costs).[10] So far, only in the USA under the 'joint, strict, and several liability rules' such a policy has been followed for contaminated waste sites. The possibilities of liability rules for environmental damage should, however, be more systematically explored.

Finally, the array of present environmental policy debates over some long-term 'externalities' of change, including technological change, in terms of impact on the physical global environment (air, land and water pollution), or even in terms of impact on society's future genetic capital (genetic manipulation, pre-embryo research), are all part of the same need for a continuous 'reassessment' of long-term costs and benefits of change and the accompanying need for institutional adaptation and 'experimentation'. Confronted with an increasing amount of negative environmental externalities of past growth and change, governments are today faced with a major challenge. How to assume the state's function as long-term—as opposed to short-term—social 'regulator' or change in a period not only characterized by an increasingly international environment, but also by continuous 'new' discoveries—some real, others perceived—of long-term negative environmental externalities of growth and change?

(2) Transition of technological growth paths: some historical examples

In this section we discuss, albeit briefly, the interrelation between the direction of economic and technological developments and their relation to the environment. We start from a relatively broad economic and technological perspective based on an evolutionary rather than linear line of reasoning, in which the future is the result of a somewhat unpredictable and complex interaction between economic actors endogenous to the process of change, ie affected by it, though at the same time affecting and directing it.[11]

In our view, economic growth, similarly to technological development, is primarily driven by short-term economic benefits and characterized as a non-linear, evolutionary process, typically path-dependent with many bifurcations and possibilities of 'locked-in' development, in which past history and historic events are important.[12] The direction and rate of technological progress and economic growth are in our view not considered as being autonomous and 'inevitable' but as an endogenous process related to the structure of economic incentives, the accumulated knowledge and expertise in scientific and business organizations and the socioinstitutional surrounding (regulation, values and social norms, lifestyles etc). Using the terminology now commonly used in the economics of technological change literature, economic growth is likely to be characterized by clusters of economically interrelated technological trajectories, which might give stimulus to growth in the whole economy.

Such clusters of technological trajectories have been identified with new technological systems[13] and new technoeconomic paradigms.[14] The network of technological trajectories related to cheap oil-based energy, combined with mass utilization of the automobile as cheap individualized transport system has often been identified with the post-war period of rapid growth. In a similar fashion, other networks (eg electricity) have been identified with respect to previous periods of rapid growth.[15]

As each system of 'network' technologies and infrastructure grows and develops further, more and more negative externalities occur. Congestion, nuisance of all kinds etc will gradually increase, so that the growth trajectory will eventually reach its limits. Canals in the 18th–19th centuries are a good example, as is horse transport in inner cities at the end of the 19th century. From such a perspective, we would argue that present environmental problems signal in a similar way to earlier congestion problems the limits of the particular growth trajectory. A brief historical analogy might clarify the point.

At the end of the 19th century the city of London was facing enormous congestion and environmental problems related to the use of horses as a means of transport. It is estimated that a horse produces no less than 15 kilos of manure per day. Most street corners in the city of London were stationed by so-called crossing sweepers, whose task was not to keep the roads clean, but to clear the way for pedestrians. At the end of the 19th century there were around 6000 crossing sweepers in London. Alternative means of transport had been available for years, but were not used because of restrictive regulations: the red flag amendment, for instance, set a speed limit for steam engines at 8 mph. The small-scale production restricted the realization of dynamic learning and scale effects, and the lack of infrastructure facilities (gasoline stations, garages etc) moreover prevented network externalities from arising. In relation to horses, cars had a level of about 200 times fewer emissions and waste (measured in grams per mile).[16] Whether this caused the eventual disappearance of the horse as means of transport and the rapid development and diffusion of cars[17] can be left to historians. What we do know is that the growth bifurcation that took place became feasible in environmental terms.

The parallel with today's environmental transport problem is striking. In our view, an alternative technological development trajectory is known and has been available for quite some time, ie the replacement of car commuter traffic by fully interactive telecommunication systems, allowing for activities like home-work, teleshopping, home-banking etc. These alternatives have been available in most Western countries for several years as often locally applied technological experiments, but without having much success. Even the ISDN telecommunications system, which has recently been highly praised, has been slow to diffuse and its commercial success not yet established. The reasons for this are similar to those given in the previous example: unforeseen and inappropriate regulations (for example, what is the status of home workers); the size of the infrastructural facilities required (eg initial required costs attached to an ISDN network); the wide range of institutional and infrastructural adjustments and facilities (for example the eventual need for a complete transformation of ideas related to the localization of work; the replanning of cities; the new role of leisure time etc).[18]

In other words, in some cases alternative technological 'network' possibilities do exist and are available. They do, however, as in the present case, face major barriers because the positive externalities involved can only develop over time and are prevented from doing so by the existing dominant technological growth trajectory. Their diffusion is in our view essential for an effective growth bifurcation to take place—growth less based on the highly inefficient individualized transport system of persons, but on the far more efficient transportation of information.

Another historical example of a technological transition that took place involves the use of wood in the railroad system. Nowadays it is often forgotten that even in the 19th century the railroad system depended for its expansion largely on wood, being the key material in terms of bulk.[19] At the beginning of the 20th century, because of shortages of wood, a crisis was forecast. We know that such a crisis never took place. What prevented the forecast crisis was, initially, the use of creosote and other technologies for preserving cross ties, and, later, especially in Europe, replacement of wood by concrete ties.[20] The saturation of the railroad network in the 1920s also contributed to this. Ausubel concludes the story of the railroad as the 'insatiable juggernaut of the vegetable world' with:

> So, in the railroad timber story, new technologies are both cause and cure of environmental problems. The new transportation system placed intense demand on natural resources, and innovations in turn alleviated the demand to the extent that today the issue is obscure or forgotten.[21]

Of course, present-day environmental problems and risks are different, and there is no guarantee that pollution and the danger of overexploitation of natural resources will be adequately taken care of—in fact we are not so optimistic about the appropriate changes in the institutional framework needed for such a transition—but the example above signals in our view a more fundamental point; it is not so much economic growth as such that is not sustainable in terms of the environment, but rather particular technological and economic growth paths that are not sustainable. As emphasized by Freeman in the Limits to Growth debate, 'the mistake of the MIT modellers (and some of the Marxists) was to confuse the "limits" of a particular development paradigm with the limits to growth of the system in general'.[22]

Thus, what is needed is a change in the 'technoeconomic paradigm', in the words of Freeman, or an 'ecological modernization', as others have called it, which is based on the principles of sustainable development, ie the closing of chains of materials, energy savings and cleaner processes and products, as put forward in the National Environmental Policy Plan of the Netherlands.[23] We elaborate on such a change below.

This change in technoeconomic paradigm involves a wide array of changes in industry, transportation and agriculture. It involves the substitution of certain hazardous substances and materials such as CFCs, asbestos and dangerous pesticides, the reduction of harmful emissions and the reduction and recycling of waste material, and a switch to other 'infrastructure technologies' (telecommunication, public transport). Insight into the market stimuli, the technological opportunities and the possibilities of redirecting technological advance is of great importance.

(3) Redirecting technological change: an evolutionary perspective

Within the economic literature of technological change a great deal of attention has been paid to the stimuli and direction of technological advance. A starting point for the evolutionary theory of technological change was the 1977 article of Nelson and Winter,[24] which characterized the generation of innovation as a purposive—but inherently stochastic—process and emphasized the importance of the institutional structure supporting or hindering the innovation. Their work has been followed by a series of contributions to the understanding of technological change as an evolutionary process.[25] In response to this work, Dosi distinguishes five 'stylized facts' that are typical of the modern innovation process: (1) the fundamental element of uncertainty in the innovation process; (2) the increasing reliance of major new technological opportunities on advances in scientific knowledge; (3) the increasing complexity of research and development activities mitigating in favour of formal organizations (especially of integrated manufacturing firms); (4) the importance of 'learning-by-doing' and 'learning-by-using' as sources for improvement of innovations; and (5) patterns of technological change which cannot be considered as simple and flexible reactions to changes in market conditions because; (i) the directions of technical change are often defined by the state-of-the-art of the technologies in use; (ii) quite often, it is the nature of technologies themselves that determines the range within which products and processes can adjust to changing economic conditions; and (iii) the probability of making technological advance is, among other things, a function of the achieved technological levels.[26]

These stylized facts point at the sources of technical change, in terms of knowledge and institutions in which it is generated, and at the direction of technological advance. Especially the notion that patterns of technological change cannot be considered as simple and flexible reactions to changes in market conditions (which goes back to Nelson and Winter's 1977 paper) is important here. It indicates that there are certain regularities in technological change. Many authors have developed several concepts for this phenomenon, such as 'natural trajectories' and 'technological regimes',[27] 'focusing devices'[28] and 'technological paradigms'.[29] These concepts are related to certain typical search heuristics within the scientific and technical community. Although the authors rightly emphasize the importance of engineers' belief and certain opportunities for technical improvement, we believe that the focus is too much on cognitive aspects, technical bottlenecks, and clear goals for improvement and too little on the *economic* supply and demand factors. In our view, technological advance proceeds very much along certain technological trajectories, which will not be left quickly, because the technologies in these trajectories have benefited from all kinds of evolutionary improvements, in terms of prices and technical characteristics, from a better understanding of the technologies on the user side, and from the adaptation of the socioeconomic environment (production modes, available skills, regulation, social norms etc). In this respect, we use the concepts of 'dynamic scale and learning effects' and 'selection environment' that is explained below.

First, the term *selection environment*, which stems from the evolutionary theory in biology, is borrowed by Nelson and Winter[30] who propose it as the basis of a model of the selection of innovations. It is chosen as a more general term than 'market' to emphasize the institutions involved and the mechanisms behind the selection of an innovation. The concept of selection environment consists of the following elements: (1) the nature of the benefits and costs that are weighed by the organizations that will decide to adopt or not to adopt a new innovation; (2) the manner in which consumer or regulatory preferences and rules influence what is 'profitable'; (3) the relationship between 'profit' and the expansion or contraction of particular organizations or units; and (4) the nature of the mechanisms by which one organization learns about the successful innovations of other organizations and the factors that facilitate or deter imitation.[31]

The nature and the size of costs and benefits depend on the characteristics of potential users: the capital structure (age and type of production techniques); available skills; market conditions such as competition, product cycles, prices of relevant inputs; financial resources of firms; flexibility and innovativeness etc. Since industries and firms differ widely between one another with respect to these characteristics, the selection environment is very heterogenous in this respect. The term 'selection environment' also directs attention to the changes in consumer preferences and changes in government rules, which are so important to the adoption process of cleaner technologies. And it focuses on information transfer and learning, which is necessary for the diffusion of technology and the appropriability conditions that affect the 'swarming of imitators'.

The important point here is that an innovation must be embedded in a technoeconomic system (which involves socioinstitutional elements). This technoeconomic system or network consists of economic supplier–user relations consisting of activities such as the extraction of resources, the production of particular materials, machinery, intermediate and final goods, and other activities such as transport, marketing, finance, insurance, repair, and waste disposal. Within this network, activities are coordinated and have been optimized in the past.[32] A new technology, being a new material, production technique or a new product, has to be integrated into this technoeconomic system, and may require changes in several components of the system.

In evolutionary terms, the success of an innovation depends on the characteristics of the selection environment. A new process or product must be embedded in the existing production processes of potential users and must comply with a diversity of qualitative demands (performance, user-friendliness etc). When a new technology is inadequate in certain qualitative (technical) respects or when existing production routines of users have to be changed, the diffusion of the technology in question will proceed slowly. In addition, unlike the new technologies, the distribution and reputation of the older products and techniques is established, and legislation and training are geared towards the existing production modes. All this helps in explaining why manufacturers strive to develop 'drop-in' innovations which can be easily embedded in existing production processes. For example, research efforts are directed towards the development of CFC (chlorofluorocarbons) substitutes (eg as the cooling medium in refrigerators) rather than towards the development of totally different production techniques and products (eg a refrigerator with a totally different cooling system). This also explains the dominance of 'end-of-pipe' techniques over 'process-integrated' changes because the former can simply be added to the existing production processes at relatively low costs.

In relation with the adaptation of the selection environment, existing technologies have generally benefited from *dynamic scale and learning effects*, which result in price reductions and all sorts of product improvements, and a better understanding of the product on the user side. These dynamic scale and learning effects are important for the diffusion process. Economies of scale, which result in lower costs of production, are particularly important in the processing industry (such as the chemical industry and the food, beverage and tobacco industries). Learning effects usually appear at both the supply and demand side. They constitute an important factor in the success of the innovation, in terms of its widespread use. These learning effects generally result in cost reductions in production and lead to constant product improvements (in terms of performance, new applications, durability and reliability).[33] Three types of learning effects can be distinguished: 'learning-by-doing' in manufacturing as a result of optimization of the production process,[34] 'learning-by-using' as a result of user information,[35] and finally 'learning-by-interacting' as a result of contacts between supplier and contractor.[36] The two latter types of learning effects usually result in product improvements, whereas the former typically results in lower prices.[37]

New technologies, both consumer products and production methods find themselves in an unfavourable position, especially in the introduction phase. They are relatively expensive, not well known, and in some cases insufficient in terms of quality.[38] This explains why the diffusion of a new technique or method proceeds slowly, especially in the beginning, or does not come about (many innovations fail to succeed), and explains the dominance of existing technological trajectories. For new technologies to survive the initial selection pressure and to become more developed and diffused, it is necessary to capture a market niche. Besides providing necessary financial means, the experiences of clients are an essential source of information in order for a product to be improved. Particularly customer complaints and insurance claims give important impulses to the further improvement of a product.

In reverse, the pace with which dynamic scale and learning effects take place is dependent on the diffusion process. The faster the diffusion, the faster firms may benefit from economies of scale and the faster learning effects occur.

Similarly, cleaner technologies (cleaner production processes, re-use systems, and cleaner consumer products) must compete with existing products and production methods. In our view, cleaner technologies are hindered more by the dominance of prevailing technologies than in the case of other innovations (this point is somewhat speculative and needs to be substantiated). The market demand for environment-saving innovations is mostly far smaller than the demand for other innovations, first because the objective of cleaner production is secondary to the objective of making profit, and second, because environment-friendlier alternatives, especially in the introduction phase, need to be improved both in terms of quality and price. Lack of information and knowledge about the technologies also seems to pose more problems in the case of clean technologies. There exists a diversity of environment-related aspects, particularly where products are concerned, and especially when consumers have little knowledge of these aspects. In addition, firms are often unaware of the damage of their production process and products to the environment. Finally, environment-saving innovations depend more on institutional and organizational changes. Not only do they depend on the regulatory policy of the government but they also require institutional changes within firms such as the setting up of an environment department, new tasks and the training of environmental experts.

(4) Determinants of the decision to generate and adopt a clean technology

Whereas we discussed the greening of technological change in rather broad terms above, here we focus on the microeconomic determinants of the decision to generate and adopt a clean technology.[39]

Before going into the determinants of environment-saving technological change, a few distinctions, common within the field of the economics of technological change, need to be made. First, technological change consists of three phases: at the beginning there is an invention (a new material, product, production technique); when the invention is used or introduced in the market we speak of an innovation; the spread of the innovation among users is referred to as the diffusion process. Second, innovations are divided into process and product innovations. For convenience, and somewhat different to what is usual, the term 'product innovation' is used for new or improved consumer products. Process innovations are considered here as innovations used by firms. And third, innovations can be divided into 'radical' and 'incremental' innovations. Radical innovations are new technologies and products that imply radical breaks with the past, whereas incremental innovations consist of small improvements of existing technologies. In the rest of this section we deal primarily with the factors relevant to the development and spread of radical innovations or innovations that contain important improvements over past technologies.

Determinants of the decision to generate a clean technology

Before discussing the determinants of the decision to adopt a clean technology, we deal with the determinants of the decision to generate the innovation, although the two are clearly linked. The willingness to adopt an innovation influences the willingness to generate the innovation, which requires money and effort. Innovations are in almost all cases the result of intended R&D activities by profit-motivated agents and involve some sort of perception of unexploited, technical and economic opportunities.[40] Within the literature of the economics of technological change there has been an intense debate about whether the development of innovations is primarily induced by available technological knowledge and opportunities, the so-called technology-push or supply-push argument, inspired by Schumpeter, or whether it is predominantly determined by market demand, the so-called demand-pull or market-pull argument as put forward especially by Schmookler. We do not go into this controversy here but simply take account of both stimuli, without elaborating on their relative importance. For a critical review of both standpoints, especially the latter, we refer to Mowery and Rosenberg.[41]

Besides the technological opportunities and necessary market demand, another factor is found to be relevant to the innovation process, ie the appropriability conditions that determine the effectiveness of the means of capturing and protecting the competitive advantages of the innovation.[42] These appropriability conditions include, among other things, the legal protection provided by patents, secrecy and technological lead. Together with market demand they determine the profits the innovating firm is able to capture from its innovation. Following Dosi, we distinguish between the following determinants of the innovation process: (1) the technological opportunities, (2) the structure of market demand, and (3) the appropriability conditions.[43]

The *technological opportunities* with respect to environmental issues differ widely between environmental problems and between and within different sectors. These opportunities range from particular technological opportunities to reduce effluent discharges and emissions, to possibilities to decrease the input of certain materials and energy. As in the case of 'normal' technology, these opportunities depend on accumulated scientific and technical knowledge, available equipment and capabilities in organizations. The distinction between product and process innovations is relevant in this respect. Process innovations are often developed by special firms within the environmental industry. Only the technologically advanced sectors such as the chemical industry and parts of the electro-technical industry have ample technical capabilities to develop cleaner process innovations themselves. Innovation in consumer products are usually developed in the regular firms themselves, with or without the help of other firms.

As indicated previously, the willingness to generate an innovation is related to the potential *market demand*, or the sales potential of the innovation. In the case of clean technology, the development of an innovation for the firm's own use only is usually not profitable. Here the distinction between product and process innovations is also relevant. The demand for cleaner production technologies depends mainly on government regulation because cleaner technologies generally result in higher costs. The demand for cleaner consumer products on the other hand does not depend so much on government regulation. The dramatic increase in the environment-mindedness of the public, and the willingness to pay more for cleaner products, constitute an important market stimulus for firms. Despite the larger environmental concerns of the public and the stricter environmental policy, research in the Netherlands shows that most firms that supply cleaner techniques and products so far have faced an uncertain market demand, partly due to slow changes in the regulatory framework and unclear regulations.[44] The factors that influence the demand for clean technologies are more explicitly dealt with when we analyse the determinants of the adoption process.

Finally, the decision to develop and supply an innovation depends on the *appropriability conditions*, ie the means through which a firm can reap returns from its innovations, and 'hold off other firms from eating too much and too rapidly into these returns'.[45] The development of an innovation is often expensive and involves much risk and will only be undertaken in case of sufficient sales potential. Imitation of the innovation by competitors undermines this. The danger of imitation is in general high because the knowledge that is incorporated in the innovation usually becomes available to others when the invention is brought to the market place—knowledge which can be used at a lower cost. Levin[46] distinguishes between the following five types of appropriability means—patents, secrecy, technical lead, learning-curve effects, and the extent to which a strong market position can be established. The appropriability conditions differ widely between innovations. Technical lead and learning-curve effects, together with complementary marketing effort, are the most important appropriability mechanisms for product innovations, whereas learning-curve effects, secrecy and technical lead are relatively important for process innovations. Patents are in most cases complementary appropriability conditions which are important in some industries, such as the chemicals industry, especially the drug industry, and the mechanical equipment industry.[47] Little is actually known about the appropriability conditions of clean technologies. Whenever, the appropriability conditions for certain technical opportunities are insufficient, there might be a task for the government to increase patent protection, to undertake or finance research projects or to stimulate cooperation between firms. In view of the public interest in rapid diffusion of clean technology, there is probably more government willingness to limit appropriation than in the case of 'normal' technology. Whether the government can influence the appropriability conditions enough, and whether such a policy is actually desirable, is unclear.[48]

Determinants of the decision to adopt a clean technology

Having dealt with the factors relevant to the decision to provide a cleaner innovation, we now consider the determinants of the decision to adopt it. Before doing so we note one important difference between 'normal' and cleaner techniques in this respect. The main reason why new, more efficient production methods are acquired and used is because of their supposed contribution to the trading results of a company. In this respect cleaner production innovations differ fundamentally from other types of innovation. Cleaner production generally costs money, although this is sometimes compensated for by savings in inputs or waste disposal costs. Thus, pollution control and prevention which is desirable from a social point of view will generally have a negative effect on firms' competitiveness and profits. Although companies might increasingly feel responsible for the damage caused to the environment, cleaner production does not represent an objective *per se* within companies. As a consequence, the decision to adopt these technologies depends heavily on government regulation.

Of the other, more traditional factors affecting the decision to adopt or not to adopt a cleaner technology we distinguish three key factors: (1) the price and quality of the innovation (quality in the sense of certain technical characteristics) that determine the costs and benefits for the potential user; (2) lack of information and knowledge; and (3) risk and uncertainty with respect to the economic consequences of the adoption of the innovation. These identified factors relate to the concepts of dynamic scale and learning effects and selection environment. Lower prices, quality improvements and new applications are related to the dynamic scale and learning effects. Information problems and uncertainty will be reduced when users learn about the technology.

The *price and quality* of the innovation clearly influence the decision to adopt a cleaner innovation. A relatively high price or unfavourable technical features have an undoubtedly negative influence on a firm's willingness to adopt the technology.[49] The willingness of polluting firms to adopt cleaner technologies depends on the cost consequences of adopting these technologies that differ widely between firms. They depend, among other things, on the size of the firm and, especially, on the type and age of the production techniques. If existing techniques need to be replaced earlier the cost burdens to the firms are usually very high, thereby obstructing the purchase of cleaner techniques. In general, small firms suffer from relatively high compliance costs due to their small scale. On the other hand the environmental image of the firm is gaining importance. Firms face pressure from consumers, local communities, the workforce and investors to produce cleaner. However, despite the increasing importance of these factors, environmental legislation is still the most powerful pressure.[50] Besides firms, consumers also confront a conflict in goals when considering the purchase of a cleaner consumer product. Products that are more environment-friendly are often more expensive and, especially when they are new, of lower quality. Further, because the improvement of environmental quality depends on the behaviour of others, they might decide not to buy these products. Such a situation where individual rationality conflicts with collective rationality is known as a social dilemma (or a prisoner's dilemma in game theory).

As in the case of 'normal' technological change, lack of *knowledge and information* may obstruct the purchase of a certain technique or product. Especially in the case of clean technologies, problems of knowledge and information are important due to the low priority of environmental management and the lack of organization of knowledge and information about environmental aspects in firms. Apart from being unfamiliar with environmental pollution of industrial activities and products, a great number of companies, especially small and medium-sized firms, lack the knowledge to take action against it.[51] This not only refers to knowledge in the sense of technical expertise required to adopt improvements; often, such companies might simply not know which techniques are available, where to turn in order to find out, and what forms of technical and financial support they might get. Also consumers are confronted with information problems. In general, consumers are not familiar with the environmental aspects of products and not able to compare products in that respect (there is even much disagreement among technical specialists on the environment-friendliness of products). The transfer of knowledge and information can be stimulated in several ways: through databases, fairs, demonstration projects and special consultancy agencies, and, with respect to consumers, education, product information and 'green' labels. Although the system of information transfer is important, the willingness of firms and consumers to acquire this information in our view is more important.

The *risk and uncertainty* that are related to the adoption of clean technologies constitute the last key factor. Many firms that are potential buyers will be reluctant to adopt cleaner techniques because of the economic risks involved. Production routines and procedures have to be changed and employees have to learn and become familiar with the new technology. These economic risks differ between firms due to differences in production modes. The risks of process-integrated changes that lead to changes in the radical changes in the production process are especially high; they require bigger organizational changes and can lead to production losses due to defects. The economic risks and especially the perceptions of these risks of clean technologies change over time and thus affect the diffusion process.

The success of environmental policy depends on the extent to which it offsets the above-mentioned obstacles. Whenever the higher costs or certain unfavourable technical characteristics are obstacles to the diffusion process—which is often the case in the early period of the technology life-cycle[52]—charges and standards can be used to compensate for these disadvantages. If problems of information and knowledge hinder the diffusion of clean technologies, 'green' product labels, information campaigns and special advisory agencies might be useful, although we would like to emphasize that a better transfer of information can also be stimulated in a more indirect way, ie through stricter regulation. Besides the type of instrument, also the flexibility, differentiation, timing and certainty of environmental policy are important.[53]

(5) Policy issues

We talked above about the negative 'externalities' of past economic growth and industrialization and their impact on 'free' amenities such as air, soil and water. In so far as the environmental problems we are facing illustrate the limits to growth along the current economic and technological trajectories, they also provide us with hints to possible 'new' directions in which further growth and technological development might be ecologically sustainable.

For such changes, insight into the interrelatedness of paths of economic growth and technological change, and into the possibilities of redirecting it, become important. For this we have adopted an evolutionary perspective in which economic growth and technological progress are viewed as a complex, non-linear and typically path-dependent process. In the absence of appropriate incentives for environmental protection, due to a lack of properly defined property rights and inadequate government regulation, technological progress and economic growth are driven in a direction that caused environmental degradation and the deterioration of 'environmental capital'.

What is needed is an ecological modernization or change in technoeconomic paradigm. The change of technological and economic patterns however is obstructed by the dominance of prevailing technological trajectories that have benefited from dynamic scale and learning effects, accommodated by the adapted supply and demand side. The adjustment and replacement of the past trajectories requires, therefore, not only strong incentives in the sense of relatively radical government measures, but also the removal of institutional barriers, new principles of environmental policy, a reorientation of education and science policy, and the integration of ecological aspects in other areas of policy. The short-term consequences in the sense of lower growth or even loss of welfare, in a materialistic sense, could be dramatic. Not only should large parts of the industrial activities either be closed or drastically changed, but also people's lifestyles, especially in the rich countries, would have to adapt to the acute environmental crisis. Whether the new growth trajectories provide us with more welfare and personal freedom is less relevant from the perspective that our welfare and freedom of choice are already decreasing as a result of the environmental degradation.

Coming back to the policy implications, we suggest the following. First, in line with what was stated above, a stricter environmental policy has to be implemented, in most cases being nothing more than simply to apply the polluter-pays principle.

Second, we propose a change in policy mix towards the use of economic instruments such as charges (for emissions, waste and products), tradeable pollution permits and deposit-fund systems (for instance for waste). The benefits of such instruments are many: (1) charges and tradeable pollution permits are more efficient because every polluter is given the choice between compliance and paying the polluter's bill, (2) there is a financial incentive to diminish all pollution—not merely to the level of emissions standards, (3) such a system depends less on the availability of pollution control technology—therefore it can be introduced more quickly, and once such a system is implemented it generally provides stronger incentives for the development and adoption of cleaner technologies than current policies of technology-based emission standards, and (4) it stimulates much more process-integrated technology (including recycling technology) instead of 'end-of-pipe' technology. Whether such a system can be implemented, at low enough administrative costs, and whether such a system is politically and socially acceptable, has to be studied on a case-by-case basis.[54]

Third, environmental policy should be more oriented towards the prevention of environmental problems instead of taking care of some of the worst effects of the environmental problems. Economic instruments such as charges and tradeable pollution permits serve this goal. Another way would be to price *all* products, pollution and industrial waste according to their environmental damage. Such a system would favour preventive technologies and discourage treatment technology that often leads to the transfer of environmental problems (mostly in the form of new or other hazardous waste problems). Pollution-prevention-pays programmes as in the USA might also be useful.[55] A lot of firms are not familiar with profitable environmental measures because of a low priority of environmental management and a lack of organization (thus being examples of what Leibenstein calls X-inefficiency).

Fourth, a reorientation of education and science programmes is needed, especially on the technical, economic, legal and health aspects of environmental problems and policy. Both firms and the government are in need of people with adequate knowledge of environmental aspects (either technical, economic or legal). As stated above, firms often lack knowledge about technical opportunities to reduce pollution and waste. At the government level, policy making is hindered by lack of knowledge about the health consequences of pollution and the costs and benefits of regulatory actions. Also, the enforcement of environmental policy is seriously hindered by lack of expertise and personnel.

Fifth, the integration of ecological aspects in other areas of policy is required. In many policy areas ecological aspects are insufficiently integrated, which hinders a transition to more sustainable economic and technological paths. Examples abound: agricultural policies are still primarily oriented at higher productivity and increasing production, despite the understanding that agriculture is responsible for serious environmental problems (water and soil pollution through the use of pesticides, herbicides and fertilizers, acid rain etc). There is also a clear lack of the environmental dimension in most technology policy, which seems much too focused on other technologies, especially high-prestige projects such as space and computer programmes, of which the costs are high and the benefits uncertain. Public policy with respect to transport is still more oriented at improving and extending the road infrastructure for cars and trucks instead of stimulating the use of public transport services such as trains and buses. And in the case of industrial policies there is not only a lack of integration of ecological aspects but the policies are in fact aimed at protecting the national polluting sectors against regulation, especially when regulation is less strict in other countries. Finally, the constitutional structure, in the form of tax policy and the regulatory framework of norms and standards, sometimes unnecessarily hinders technological change towards environmental protection. Recycling and treatment of waste material, for instance, in some cases is obstructed by emission standards and product norms that are developed for other, less urgent reasons. Public procurement policy can also be better used for environment purposes, especially with respect to building materials.[56]

Sixth, despite its evident importance as a principle to guide policy, the 'polluter-pays principle' is less useful in the international context. Because of the lack of international legislative and enforcement power, countries that are the victims of the pollution of other countries may have to pay for environmental measures in other countries in order to prevent being polluted by their neighbours. This may become an important issue because 'pollution knows no borders'. We do not want to be negative about this. Since less developed countries can demand to be compensated for not using CFCs in their refrigerators or for not emitting CO_2 or other trace gases that contribute to the greenhouse effect, they have some kind of an 'asset' for which they can let rich countries pay for. Also in the case of international environmental problems, industries in one country may decide to pay for environmental measures in other countries that are more cost-effective—just as electricity producers in the Netherlands are now planning to pay for forest plantation in Brazil to compensate for CO_2 emissions of a new power plant. All this of course makes perfect sense from an economic point of view.

Finally, the concerns and issues related to the environmental impact of growth and technological advance have suddenly re-emerged in a context very different from that of the mid-1970s when the issues were first brought to the forefront in the Club of Rome report. To begin with, the evidence on the environmental damage in terms of air, water and soil pollution is by now far more overwhelming. Second, the complexity and time-lags of the interactions between pollution and the ecological system and the surrounding economic and technological environments are still not well, but nevertheless better understood. Third, the public perception of the environmental problems is far more acute. The hymn to material progress with the environment to be adapted to the needs and requirements of such progress appears no longer to be sung with the same conviction. Fourth, at a time when national governments are waking up to the importance of the issues involved, it is the global dimension which is most acute. Particularly with respect to environmental issues, the national state, in Daniel Bell's words, appears indeed 'too big for the small problems of life and too small for the big problems of life'.[57]

Notes and references

1. In this article we deal with the environmental problems of past industrialization and application of technology and not with the present and future environmental problems which are related to population growth and poverty. Further, the focus is more on the problems of pollution than on the problem of overexploitation of natural resources.
2. A similar perspective is in R. U. Ayres, 'Industrial metabolism', in J. H. Ausubel and H. E. Sladowich (editors), *Technology and Environment* (Washington, DC, National Academy Press, 1989), pages 23–49.
3. A typical example of this is the announced extra spending on environmental care by the provincial authorities of Noord-Brabant in the Netherlands out of an unplanned amount of tax income derived from increased car ownership.
4. H. Brooks, 'Technology assessment as a process', UNESCO, *International Social Sciences Journal, 25*(3), 1973.
5. P. Lagadec, *La Civilisation du Risque* (Paris, Le Seuil, 1981); and P. Lagadec, *Le Risque Technologique Majeur*, collection Futuribles (Paris, Pergamon Press, 1981).
6. R. R. Nelson and S. G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, MA, Bellknap Press of Harvard University, 1982), page 368.
7. Thus, the environmental problems are not only examples of market failure but also clear examples of government failure.
8. The share of end-of-pipe technologies in pollution control investment in Western Germany in the period 1975–81 was between 67% and 78%, and in the USA in the 1973–82 period

between 76% and 81%. See V. J. Hartje and R. L. Lurie, *Adopting Rules for Pollution Control Innovations: End-of-Pipe versus Integrated Process Technology* (Berlin, Wissenschaftszentrum Berlin, International Institute for Environment and Society (IIUG), 1984), page 368.

9. We do not want to ban the use of traditional instruments of environmental policy such as standards and charges—although we would welcome a shift in the policy-mix in favour of economic instruments such as charges and tradeable emissions permits (see section 5).
10. For a discussion of this issue, see R. E. Litan, 'The safety and innovation effects of US liability law: the evidence', *American Economic Review, 81*(2), 1991, pages 59–64.
11. Although our approach is more economic in character, it corresponds to the idea of co-evolutionary development of R. B. Norgaard, 'Coevolutionary development potential', *Land Economics, 60*(2), 1984, pages 160–173.
12. The idea of technological change as an historic, path-dependent process, with possibilities of 'locked-in' development is worked out theoretically in Paul David's model of localized learning and Brian Arthur's model of increasing returns with adoption. In the words of P. A. David, *Technical Choice, Innovation and Economic Growth: Essays in the Nineteenth Century* (New York, Cambridge University Press, 1975), page 4: 'Because technological "learning" depends upon the accumulation of actual production experience, short-sighted choices about what to produce, and especially about how to produce it using presently known methods, also in effect govern what subsequently comes to be learned. Choices of technique become the link through which prevailing economic conditions may influence the future dimensions of technological knowledge. This is not the only link imaginable. But it may be far more important historically than the rational, forward-looking responses of optimizing inventors and innovators which economists have been inclined to depict as responsible for the appearance of market- or demand-induced changes in the state of technology.' More recently, it is Frank Hahn who writes: 'The path of history is the outcome of individual decisions and in turn helps to fix the latter. This is really the main message: the information available to agents at any time is determined by the particular path followed. The economy could have followed a different path and generated quite different information. There is something essentially historical in a proper definition of equilibrium and of course in the dynamics itself'. F. Hahn, 'Information dynamics and equilibrium', paper to Conference of Scottish Economists, as quoted by C. Freeman, in G. Dosi, C. Freeman, R. R. Nelson, G. Silverberg and L. L. G. Soete (editors), *Technical Change and Economic Theory* (London and New York, Pinter Publishers, 1988), pages 4–5.
13. C. Freeman, J. Clark and L. L. G. Soete, *Unemployment and Technical Innovation: a Study of Long Waves in Economic Development* (London, Pinter, 1982).
14. C. Freeman and C. Perez, 'Structural crises of adjustment, business cycles and investment behaviour, in Dosi *et al, op cit*, reference 12.
15. See Freeman *et al, op cit*, reference 13.
16. E. E. Montroll and W. W. Badger, *Introduction to Quantitative Aspects of Social Phenomena* (New York, Gordon and Breach, 1974), page 224.
17. A. Grübler, *Rise and Fall of Infrastructures, Dynamics of Evolution and Technological Change in Transport*, PhD Dissertation, Technische Universität, Vienna, 1988.
18. For a discussion of the factors affecting the diffusion of ISDN, see eg P. A. David and W. E. Steinmüller, 'The ISDN bandwagon is coming, but who will be there to climb aboard? Quandaries in the economics of data communication networks', *Economics of Innovations and New Technology, 1*, 1990, pages 43–62.
19. J. H. Ausubel, 'Regularities in technological development: an environmental view', in J. H. Ausubel and H. E. Sladowich (editors), *Technology and Environment* (Washington, DC, National Academy Press, 1989), pages 70–91.
20. *Ibid.*
21. *Ibid*, page 72.
22. C. Freeman, 'Prometheus unbound', *Futures, 16*(5), October 1984, pages 494–507.
23. Nationaal Milieubeleidsplan (NMP) (National Environmental Policy Plan), Tweede Kamer, vergaderjaar 1988–1989, 21137, no 1–2, The Netherlands, 1989.
24. R. R. Nelson and S. G. Winter, 'In search of useful theory of innovation', *Research Policy, 6*, 1977, pages 36–76.
25. For an overview of the literature, see G. Dosi, C. Freeman, R. R. Nelson, G. Silverberg and L. L. G. Soete (editors), *Technical Change and Economic Theory* (London and New York, Pinter Publishers, 1988), and for a wide collection of important contributions, see G. Dosi, 'The nature of the innovation process', in *ibid.*
26. *Ibid*, page 223.
27. Nelson and Winter, *op cit*, references 6 and 24.

28. N. Rosenberg, 'On technological expectations', *Economic Journal, 86,* 1976, pages 523–535, also published in N. Rosenberg, *Inside the Black Box* (Cambridge, Cambridge University Press, 1982), pages 104–119.
29. G. Dosi, 'Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change, *Research Policy, 11,* 1982, pages 146–162. For a discusssion of all these concepts, see G. Dosi, 'Sources, procedures and microeconomic effects of innovation', *Journal of Economic Literature, 26*(3), 1988, pages 1120–1171; and R. P. M. Kemp, 'An economic analysis of cleaner technology: theory and evidence', paper presented at the 'Greening of Industry' Conference in Noordwijk, the Netherlands, 17–19 November 1991.
30. Nelson and Winter, *op cit,* references 24 and 27.
31. Nelson and Winter, *op cit,* reference 27, pages 262–263. The distinction between the generation of an innovation and its selection does not imply that these two phenomena are not linked. On the contrary, the decision to develop an innovation, which involves R&D costs, depends on the characteristics of the selection environment, and the selection environment is shaped by technological change.
32. Four kinds of networks can be distinguished: (i) the firm as a network of activities (R&D, manufacturing, management, marketing); (ii) the economy as a network of interacting suppliers and users, and involving a certain infrastructure; (iii) the technological system (the whole of machines, techniques, components, technical standards); (iv) the socioinstitutional network (education and training, regulation, values, power balance, attitudes to technology and change etc). It is within and through these networks that learning and adaptation takes place that may be referred to as network externalities (see section 2).
33. Learning curves, or experience curves, are a well known phenomenon in industry. Despite their widespread practical acceptance, theoretical research on the learning curve has been limited, and there have been relatively few published empirical studies (M. B. Lieberman, 'The learning curve and pricing in the chemical processing industries', *Rand Journal of Economics, 15*(2), 1984, page 213). A notable exception is the Project PIPPA (Post-Innovation Performance and Policy Analysis) that studied the incidence and origin of post-innovation in a large number of products and their manufacturing processes (in L. Georghiou, J. S. Metcalfe, M. Gibbons, T. Ray and J. Evans, *Post-Innovation Performance: Technological Development and Competition* (London, Macmillan, 1986)).
34. K. J. Arrow, 'The economic implications of learning by doing', *Review of Economic Studies, 29,* 1962, pages 155–173.
35. Rosenberg (1982), *op cit,* reference 28.
36. B. A. Lundvall, 'Innovation as an interactive process: from user–producer iteration to the national system of innovation', in Dosi *et al, op cit,* reference 25.
37. W. J. Abernathy and J. M. Utterback, 'A dynamic model of process and product innovation', *Omega, 3*(6), 1975, pages 639–656, have developed a dynamic model of process and product innovation. In their model, in the early stage of development, when the product market is ill defined, the rate of product innovations is relatively high in the early stage of development whereas in the later stages of the product lifecycle, when the product is more adapted to user-needs, and when price competition becomes more important, process innovations, aimed at reducing costs, are more frequent.
38. The importance of improvements of an innovation in favour of a wide diffusion is something well known to historians of technology. N. Rosenberg, *Perspectives on Technology* (Cambridge, Cambridge University Press, 1976), page 195, write '... most inventions are relatively crude and inefficient at the date when they are first recognized as constituting a new innovation. They are, of necessity, badly adapted to many of the ultimate uses to which they will eventually be put; therefore, they may offer only very small advantages, or perhaps none at all, over previously existing techniques. Diffusion under these circumstances will necessarily be slow.' Rosenberg also points to the importance of secondary innovations (for example in machine and tool development), infrastructural facilities and the availability of technical skills required (which corresponds to our concept of selection environment).
39. Although 'cleaner' or 'environment-saving' technology would be a better term, we use the more common term 'clean technology' in the following (for a discussion of different concepts and terms, see R. P. M. Kemp, A. A. Olsthoorn, F. H. Oosterhuis and H. Verbruggen, *Instrumenten voor de stimulering van milieutechnologie* (Policy instruments to stimulate cleaner technology), (Leidschendam, the Netherlands, VROM, 1991—a shorter version of the report is published by EZ, Den Haag); R. P. M. Kemp, A. A. Olsthoorn, F. H. Oosterhuis, H. Verbruggen, 'Policy instruments to stimulate cleaner technology', paper presented at the EAERE-Conference in Stockholm, 11–14 June 1991. Clean technology is used here as a general term for all techniques, processes and products that avoid or

diminish environmental damage and/or help save raw materials, natural resources and energy. As such it is a bit of a misnomer: first, no technology of course is clean in a strict sense, and second, as stated before, a distinction should be made between 'clean ' and 'cleaning' technology.
40. Dosi, *op cit*, reference 25, page 222.
41. D. C. Mowery and N. Rosenberg, 'The influence of market demand upon innovation', *Research Policy, 6*, 1979, pages 102–153.
42. R. C. Levin, 'A new look at the patent system', *American Economic Review*, American Economic Association Proceedings, 1986, pages 199–202.
43. Dosi, *op cit*, reference 25.
44. P. IJlst, C. T. M. Stokman and E. T. Visser, *Informatieoverdracht en informatiebehoefte in de milieuproduktiesector in Nederland* (Information transfers and information needs in the environmental industry in the Netherlands), (Zoetermeer, EIM, 1988).
45. R. R. Nelson, *Understanding Technical Change as an Evolutionary Process* (Amsterdam, North Holland, 1987).
46. Levin, *op cit*, reference 42.
47. *Ibid.*
48. For a discussion of this, see *ibid.*
49. Although lower prices increase demand, potential buyers may also decide to postpone their purchase when further price falls are expected (see Rosenberg, *op cit*, reference 28).
50. A. Frank and H. J. J. Swarte, *Milieutechnologieën: toepassing in kleine en middelgrote ondernemingen* (The use of clean technologies in small and medium size firms), (Rotterdam, The Netherlands, Erasmus Studiecentrum voor Milieukunde, 1986); and H. E. Williams, J. Medhurst and K. Drew, 'Corporate strategies for a sustainable future', paper presented at the 'Greening of Industry' Conference in Noordwijk, the Netherlands, 17–19 November 1991.
51. Frank and Swarte, *op cit*, reference 50.
52. Abernathy and Utterback, *op cit*, reference 37.
53. We do not plan to go deeper into the topic of policy instruments to stimulate clean technology. For a discussion on this topic see J. Cramer, J. W. Schot, F. van den Akker and G. Maas Geesteranus, 'Stimulating cleaner technologies through economic instruments: possibilities and constraints', *Industry and Environment Review, 13*, April–May–June 1990, pages 46–53; and Kemp *et al, op cit*, reference 39.
54. High administrative costs for charges can make such a system less efficient than a system of standards, which contradicts the traditional theoretical argument by economists that a system of charges is more efficient. In addition, whereas the costs of pollution control for a certain sector will be lower in the case of charges compared to the costs of pollution control under a regime of standards, the sum of the total costs of pollution control and the payments for the remainder of the emissions will generally be higher than the total costs of pollution control under direct regulation, unless the polluting sector is financially compensated.
55. D. Huisingh, L. Martin, H. Hilger and N. Seldman, *Proven Profits from Pollution Prevention: Case studies in resource conservation and waste reduction* (Washington, DC, Institute for Local Selfreliance, 1986).
56. Of course, a cleaner environment is not the only government objective. The point here is that technological transitions generally proceed slowly since they require all kinds of institutional changes that do not occur rapidly.
57. J.-J. Salomon and A. Lebeau, *L'écrivain Public et l'Ordinateur: Mirages du développement* (Paris, Hachette, 1988).