Evolutionary Theorising on Technological Change and Sustainable Development

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We acknowledge financial support from, funded by the Netherlands Organisation for Scientific Research (NWO). We gratefully acknowledge useful comments by Jeroen van den Bergh, Patrick Criqui and Henri de Groot on an earlier version of this paper. Of course, the usual disclaimer applies.

OCFEB Research Memorandum 9912, 'Environmental Policy, Economic Reform and Endogenous Technology', Working Paper Series 2

Table of Contents

Abstract

This paper examines the significance of evolutionary theorising on technological change for (technology) policies aiming to move society into a more ecologically sustainable direction. It is argued that fundamental changes in production processes and consumption patterns underpinned by alternative technological trajectories are required for achieving environmental sustainability. Such changes, which go beyond the control of particular pollutants and eco-efficiency improvements, are referred to as technological regime shifts. Technological regime shift changes do not refer so much to the diffusion of environmental technologies but rather to system changes producing environmental benefits because the new regimes or trajectories are inherently more environmentally benign. An example of such a shift is found in the use of gas turbine for (co)generating electricity and heat. An important question is: how do technological regime shifts occur, and how can environmentally beneficial regime shifts be stimulated? Evolutionary theory, which emphasises the non-linear, branched nature of sociotechnical change, offers a useful framework for understanding and managing regime shifts. It draws attention to the lock-in phenomenon and also suggests a way in which it can be escaped: through the development of niches for new technologies. It appears that evolutionary perspectives have something to offer here, but they need to be further developed to be of practical use.

1. Introduction

Technological change plays an important role in the context of environmental issues. The way in which energy and materials are transformed in the economic process ('throughput') depends mainly on the state of technological knowledge. Hence, technological innovation can change the composition of the material basis of economic processes – a prerequisite for sustainable development. Since the early 1970s economists have paid attention to understanding the mechanisms underlying 'technological change for the environment' and the factors that govern diffusion of environmentally relevant technologies (for an overview see Grübler, 1999).

Most technological change consists of incremental improvements of existing technologies and the diffusion of technologies that are integrated in existing production modes. Mainstream economics is well suited to deal with these issues, both in theoretical and empirical research. One can, for example, think of endogenous growth models addressing the controversies on the relationship between economic growth and the environment (e.g. Aghion and Howitt, 1998, Bovenberg and Smulders, 1995, Smulders, 1998), the attempts to endogenize technological change in (empirical) models assessing environmental policy or energy use (e.g. Den Butter *et al*., 1995, Carraro and Galeotti, 1997, Goulder and Schneider, 1999, Messner, 1997, Xepapadeas and De Zeeuw, 1999), models of innovation in pollution control (e.g. Downing and White, 1989, Mendelsohn, 1984, Milliman and Prince, 1989) and technology diffusion models (e.g. Jaffe and Stavins, 1994; Kemp, 1997, 1998).

Complementary to developments within mainstream theorising, economics has faced a revival of evolutionary approaches over the last decade initiated by the seminal work of Nelson and Winter (1982). Within evolutionary economics most attention is paid to the field of economic theorising on technological change. In general, the main differences between the neo-classical and the evolutionary contributions to the economic analysis of technological change arise essentially from the objections evolutionary economists have to the (aggregate) production function approach, widely used by neo-classical economists. Among others, Nelson and Winter (1977, 1982), Dosi (1982) and Sahal (1981) have argued that 'the production function-view' on production and technical progress suffers from providing limited insight in the occurrence of technological innovation processes, because the development of new techniques ('blueprints') is exogenous to the economic process. Obviously, this criticism has been superseded with the development of the neo-classical literature in which technological change is endogenised (starting with Lucas, 1988, Romer, 1986, 1990). Still, from an evolutionary point of view critique has been put forward to the neo-classical approach (see e.g. Nelson 1994). The core of this critique is that still a large gap exists between the formal treatment of technology within neo-classical models and what is known from empirical research on sources, procedures, directions and effects of technical change and the characteristics of innovative firms (see Dosi 1988). It is beyond the scope of this paper to explore the differences and similarities of both approaches in detail. Elsewhere (Mulder *et al*. 1999) it has been argued that it is fair to conclude that in the last couple of years the views on technology as expressed by neo-classical and evolutionary economists are converging in a Schumpeterian (modelling) framework.

In this paper we have confined ourselves to the evolutionary approach to technological change. Our objective is to examine its significance for (technology) policies aiming to move society into a more ecologically sustainable direction. More specifically, in the paper concepts from the evolutionary literature on technological change are applied to environment-saving technological change. To this end, particular attention will be paid to the issue of ecological restructuring, that is the replacement of existing trajectories of consumption and production by more sustainable ones. Ecological restructuring goes beyond the control of particular pollutants and eco-efficiency. It involves a change in technology systems or technological regime (for example in transport, chemical industry, and agriculture) offering magnitude environmental improvements. It is argued that an evolutionary perspective is particularly appropriate for understanding technological regime shifts towards environmental sustainability, as an emergent process in which niches play an important role.

The organisation of this paper is as follows. Section 2 starts with introducing some distinguishing features of evolutionary theorising on technological change. It continues then with arguing that the distinction between incremental and radical innovations made within the literature is of importance, because moving society towards ecological sustainability requires not only stepwise improvement of existing technologies and systems, but also fundamental changes in production processes and consumption patterns that are underpinned by alternative technological regimes and trajectories. In section 3 we discuss technological paradigms, trajectories, regimes and niches as useful concepts for understanding fundamental (technological) changes or shifts towards sustainability. The development of the gas turbine is described as an example of a technology that has developed into an environmental technology through a process of niche development. Section 4 offers some implications for environmental policy in general as well as a discussion of strategic niche management as a particular policy that follows from our discussion of the role of niches in technological regime shifts towards sustainability. Section 5 concludes.

2. An evolutionary view on technological change and sustainable development

Recently, initial attempts have been made to apply concepts from the evolutionary literature on technological change to the issue of environmental technological change (see, for example, Freeman, 1996 and Kemp, 1997). In this section we provide a brief sketch of the way technology is dealt with in evolutionary economics and, consequently, its relevance for studying technological change in the context of sustainable development.

A distinguishing feature of evolutionary theories on technological change stems from the used concept of technology. Technologies are not defined in terms of a stylised input-output relationship, but are seen as being linked with other technologies, economic activities and production and user practices and a whole range of institutions that form a technological system (Hughes, 1989) or regime (Kemp *et al*., 1994, Rip and Kemp, 1998). From this point of view *technology* is then defined as a combination of artefact (tool) and method (concept) to solve problems posed to human individuals and societies by their natural and social environment. In line with this definition *technological change* can be defined as interaction among human actors (i.e. societies), their set of technologies and the natural and social problem posing environment leading to the solving of some of the 'old' problems and occurrence of new ones requiring a change in the type and composition of technologies (and human actors/societies). In evolutionary approaches technical change is thus contextualised: it is seen as something that occurs within actor networks and is shaped by technological capabilities being available (in companies and knowledge institutes), demand and cost conditions (which depend on the technologies in use and established consumption patterns) and is informed by managerial and engineering notions of what is technologically possible and economically worthwhile to do[1].

The evolutionary economic literature on technological change makes the important distinction between incremental and radical change in technology and technology systems. Incremental innovations are relatively minor changes of processes and products that occur more or less continuously. They may often occur, not so much as the result of deliberate R&D, but stemming from experiences of engineers in the production process or as a result of initiatives and suggestions by users. They are frequently associated with scaling up of plant and equipment and quality improvements of products and services. Although their combined effect is extremely important in the growth of productivity, no single incremental innovation has dramatic effects (Freeman and Perez, 1988).

Radical innovations on the other hand are discontinuous events. They are usually the result of deliberate R&D in enterprises and research activities in university and government laboratories. They are stochastically distributed over sectors and over time. Over a period of decades they may bring about structural change, although they are relatively small and localised in terms of their aggregate economic impact, unless a whole cluster of radical innovations are linked together. When innovations are technically and economically linked, Freeman and Perez speak of new technology systems.

Most of environmental technical change consists of incremental improvements of existing technologies and the diffusion of technologies that are integrated in existing production modes. But, elsewhere (Ayres and Simonis, 1994, Freeman, 1996, Kemp

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[1] It is to be noted that the distinction between the (neo-classical) stylised input-output representation of technology on the one hand and the (evolutionary) contextualised view on the other hand corresponds to a certain extent with the distinction between top-down versus bottom-up approaches. The top-down approach refers to elasticity based macro-economic models with a highly abstract representation of technology, whereas the bottom-up approach refers to 'true' technology-based activity analysis models (cf. Böhringer, 1998).

and Soete, 1992, and Kemp, 1994) it has been argued that with respect to the environment, the control of particular pollutants and the adoption of eco-efficiency options within existing production modes will not be enough for achieving environmental sustainability. Moving society towards ecological sustainability requires not only step-by-step improvement of existing technologies and systems but fundamental changes or different (technological) regimes[2]. It has been argued that a sustainable future asks for 10- to 50-fold improvements in resource productivity to be achieved in the richer societies within the next 50 years (Weaver *et al*., 1999).

What is needed in addition to these options are more or less fundamental changes in production processes and consumption patterns that are underpinned by alternative technological trajectories. For example, with respect to the production process fundamental changes in technology systems seems to be required in the long run. One can think of a change towards decentralised electricity systems based on the use of renewables, the shift to precision agriculture or to biological agriculture which does not rely on the use of fertilisers, antibiotics, pesticides and herbicides, or, in the case of chemistry, the shift to low pressure and temperature chemistry relying on catalysis. Such changes are referred to as technological regime shifts.

A contextual view of technology as a system in context, as it is developed within the evolutionary economic literature, helps to understand why particular options are chosen by profit-motivated companies, the reasons of which have to do with the process technologies in place, adoption capabilities and mental models of industrialists and nature of the regulations and market conditions. It helps to understand why companies in the 1970s and 1980s opted for the use of pollution control technologies and why since the late 1980s prevention and re-use of waste material was aimed for. The use of ('end-of-pipe') pollution control technologies resulted from government pollution control policies and the absence of company environmental management systems. In the 1980s pollution prevention rather than control became the focus of governmental policies and managerial tools for pollution prevention became available, stimulating technology responses that shifted away from pollution control technologies to production process changes and recycling. Regulatory attention towards prevention and the use of integrated approaches for dealing with environmental problems thus coincided with the development of environmental design capabilities and management systems and the preference of business for preventative solutions that help to achieve environmental benefits at lower costs. Technological change was interlinked with institutional and social change: a shift in regulatory philosophy, pressures from environmentalists, growing environmental awareness at the supply and demand side, changing managerial perceptions, and the introduction of environmental management systems to address environmental problems.

[2] This is also recognised in a recent policypaper by the Dutch government on the implementation of climate policies after the Kyoto-protocol (VROM 1999, p 94-99).

3. Technological regime shifts and niches

In our view, evolutionary theories on technological change are particular useful for understanding technological regime shifts towards sustainability. Unfortunately our understanding of technological regime shifts is limited, despite the parlance of ecological modernisation (Huber), industrial transformation (Vellinga et al., 1998) and technological trend breaks in policy circles and science. Most of our knowledge about technological regime shifts comes from historical studies of technological transitions and structural change. Before we turn to the findings from such studies we first examine the concepts of technological paradigms, regimes and trajectories that have been developed in the evolutionary economic literature which deals with technical change.

3.1 Technological paradigms, trajectories and regimes

The concept of technological paradigms has been developed by Dosi (1982) in analogy to the Kuhnian notion of scientific paradigms. It has an abstract flavour and focuses on the processes in an economy or society at large. It is defined as "...a "pattern" of solution of selected techno-economic problems based on highly selected principles derived from the natural sciences, jointly with specific rules aimed to acquire new knowledge and safeguard it, whenever possible, against rapid diffusion to the competitors." [3]It combines thus the artefact as well as the outlook on problem solution related to this artefact in terms of search directions, scientific methods, and scientific area of research. In Dosi's view the concept of technological guideposts (Sahal, 1985) is strongly related to this conception since a guidepost is 'the basic artefact whose techno-economic characteristics are progressively improved.'[4]

Technological trajectories can be perceived as expressions of a paradigm. They are a phenomenological expression of the realisation of choices about components, methods and theories made to solve technical problems. The trajectories are the outcomes of the 'logic of design' (Clark, 1985) and functional requirements which influence the further development of a solution concept (Sahal, 1985). They are also shaped by economic, social, cultural and political factors as numerous studies (for example, Bijker *et al*., 1987) have shown. Technological paradigms itself emerge from a set of hierarchical interactions in socio-economic systems (Clark, 1985), which is made up of the interaction of user and producer groups (Andersen, 1991).

Regimes are defined by Kemp et al. (1994, p. 15) as '...the overall complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, institutions and infrastructures which make up the totality of technology.' This definition is naturally conducive to a co-evolutionary view on the interaction between social economic and technological factors driving technological evolution.

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[3] Dosi 1988, p 1127.

[4] ibid. p 1127

3.2 Technological regime shifts

Changes in technological paradigm or regime may be associated with environmental improvements of the order of several magnitudes, not in the short term but in the longer term when the new system is optimised in ecological terms. For example, the change to a hydrogen economy will lead to dramatic reductions in greenhouse gas emissions, but only if the hydrogen is generated through the use of photovoltaics and other types of renewables (or the use of nuclear energy). The same is true for electric drive systems. This is depicted in the following figure which relates the magnitude of environmental improvement to a distinction of incremental change, optimisation and renewal (or transformation) of technology systems. The exact figures will differ from case to case.

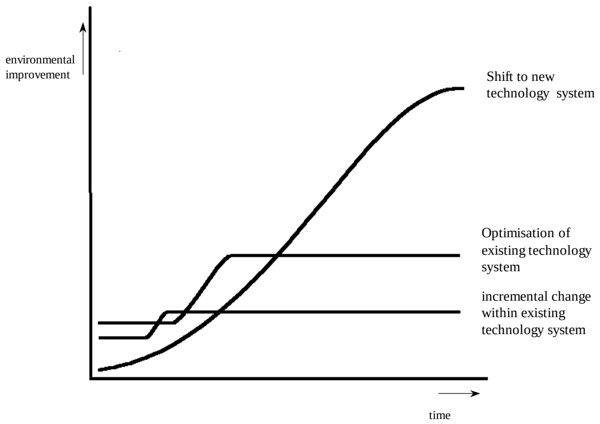

Figure 1
After Weterings et al. (1997, p18).

Technological regime shifts require radical innovations to take place. Incremental innovations alone are, by definition, not able to bring about the necessary systemic changes. Of course, it is not necessarily a priori clear whether an invention will lead to incremental or radical changes. This will only become clear over the period of development of a technology. It is also not certain that radical change will be best. But again this is something that can only be learned through time. Of course, actors have expectations about the incremental or radical character of innovations and these should be taken into account. In any case, we believe that there is a need to at least explore radical change, and not to rely solely on the incremental options, 'drop-in' innovations. This helps to hedge the risk that incremental options are not sufficient. Moreover the costs of radical technologies in terms of discomfort and adjustment may be kept low if the technologies are used in situations (domains) in which their gains count high and their disadvantages are relatively low because of local circumstances. An example is the use of electric vehicles in transport fleets in urban areas in which there is a lot of pollution, or the use of renewables in remote areas. By doing so, society may learn about those options and stimulate their further development. We return to this issue in section 4.1 when we talk about strategic niche management.

An important question is: how do technological regime shifts occur? Obviously, each technological transition or regime shift is unique in its own way, but there are also general features. In a study of technological transitions for the European Commission (Kemp *et al.*, 1994) the following elements were identified as key aspects of technological regime shifts. These are:

1. Long time periods. It often takes 50 years for a new technology system or regime to replace an old system.
2. Deep interrelations between technological progress and the social and managerial environment in which they are put to use. Radically new technologies give rise to specific managerial problems and new user-supplier-relationships; they require and lead to changes in the social fabric and often meet resistance from vested interests; moreover, they may give rise to public debates as to the efficacy and desirability of the new technology.
3. New technologies tend to involve "systems" of related techniques; the economics of the processes thus depend on the costs of particular inputs and availability of complementary technologies. Technical change in such related areas may be of central importance to the viability of the new regime.
4. Perceptions and expectations of a new technology are of considerable importance. They include engineering ideas, management beliefs and expectations about the market potential, and, on the user side, perceptions of the technology. These beliefs and views of the new technology are highly subjective and will differ across communities. They also are in constant flux, and the progression of these ideas may either be a barrier or a catalyst to the development of a particular technology.
5. The importance of specialised applications in the early phase of technology development. In the early phase of a radically new technology there is usually little or no economic advantage of the technology; moreover, the existing technologies tend to improve during the development phase (the 'sailing ship' effect).

Technological regime shifts thus entail a number of structural changes at different levels: the technical, social and organisational realm. Furthermore, they are the result of decision-making and action of many (heterogeneous) actors. Although there is no established view on what drives such structural changes, we believe that niches (for new technologies) play an important role in this transformation process.

3.2 Niches

For technologies a niche is a field of application of one or more interrelated new technologies. A niche consists of a resource base and a set of distinct selection criteria (Levinthal, 1998). The resource base sustains the innovation. The resources consist of knowledge, capability, time and energy, organisation, and finance. The niche may be a technological niche or a market niche. We talk about a technological niche when some kind of protection of an unremunerative technology is provided (for example through subsidies or other type of preferential treatment, special services offered at a low price), otherwise we talk about a market niche.[5] Technological niches usually precede market niches as most innovations are not immediately cost-effective at the early phase of development. Nevertheless they are worth to be explored in specialised fields of application in which costs are less important than performance.[6] In order to find a wider use, they need to be further perfected, which requires learning and adaptation.

Niches are important in technological transitions because they facilitate processes of learning (about the technology and the market) and processes of societal embedding (capital formation, the set up of distribution, dissemination of knowledge, gaining of user acceptance, etc.). Niches determine what steps can be taken productively, they act as a stepping stone for further change, such as the capturing of new domains of application[7]. This may serve to overcome barriers of entry such as economies of scale, institutional arrangements or regulatory frameworks in favour of the established technological regime. Overcoming these barriers helps the technology to find wider use in the original niche and to invade new ones in a later stage.[8] Niches

[5] Market niches may be divided in market niches created by military and market niches for non-military goods. For radical innovations the first application is often in the military sector.

[6] A good example of such a development can be found in the field of radial tyres, in which a radical innovation was initially developed in the distinct niche of high-performance sports cars (Foster, 1986, quoted in Levinthal, 1998).

[7] This can be reffered to as a 'speciation event' (Levinthal, 1998).

[8] An example is the current organisation Mobility Carsharing Switzerland. Starting with 2 co-operatives including a dozen people in 1987 committed to the idea of car sharing it grew out to an organisation with 22,000 members in 1998. The early members supported the development of this service innovation in various ways: by providing cheap money (at an interest rate which was very low or even zero), by taking care of the billing, cleaning, repairing, of the cars and by spreading the virtues of the system by words of mouth. They also accepted small problems and inconveniences and were instrumental in obtaining preferential conditions for the system in local communities (e.g. cheaper parking lots), all of which helped to lower the economic threshold for such an arrangement (Harms and Truffer, 1998; Kemp, Truffer and Harms, 1999). The further professionalisation and introduction of electronic access, reservation and accounting systems helped the system to attract new users and expand geographically. MCS is now developing into a mobility organisation which is promoting intermodal travel, through linkages with public transport companies and special price arrangements for public transport. The early protection was important. It seems highly unlikely that organised car sharing could have been built up by a professional provider. Up-front investments for achieving an attractive density of the location network would have been extremely high, and the users' requirements for well-performing system would have been much higher. By relying on bottom-up initiatives, a product profile could gradually shape, and the organisations could slowly professionalise.

it seems are an important part of the evolutionary process of technological transitions, what we call technological regime shifts.

Niches help to create an evolutionary path to a new regime by providing an impetus to learning and investment. For example, experiences with a new technology in the niche help to gain user acceptance, change established views (both at the supply and demand side), to benefit from feedback from users, to achieve cost economies in the production and use of the technologies, to promote the development of complementary assets, and finally to foster the building of a constituency behind a product—all of which is important for achieving greater use within a niche and expand into new areas. Niches facilitate a cascade of further innovations and by doing so create a new development path.

The process of niche development and technological regime (TR) change is depicted in Figure 2 (where the small areas denote niches).

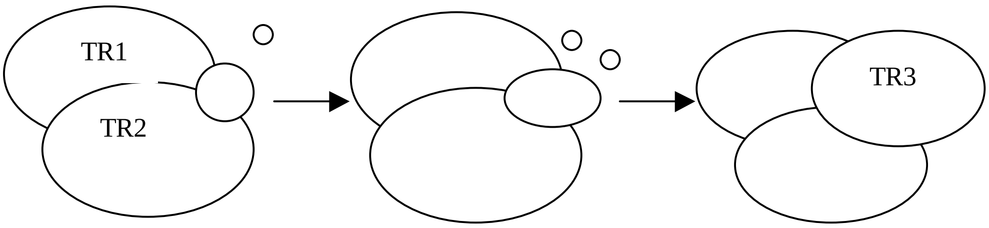

Figure 2

Figure 2 provides a simplistic representation of the process of niche development, that leads to the establishment of a new technological regime TR3 (say a hydrogen economy with large-scale distribution of fuel cells, a decentralised energy system with different mixes of renewables, or a regime of intermodal transport alongside the regimes of collective transport and individual, car-based transport). It does not show the ways in which existing regimes contribute or constrain the process of niche development,[9] and the effects of the new emerging regime 3 on the existing regimes (in the form of induced innovation under the pressure of competition)[10]. Absent in the figure are also changes in the socio-technical landscape (infrastructures, settlement

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Today they have reached a standard that also allows users with high quality demands to join the system.

[9] The relationship between new and old technologies may be competitive, neutral or symbiotic (Pistorius and Utterback 1997).

[10] Two examples of induced innovation in environmental technology are clean coal technology and the catalytic converter that were developed under the pressure of alternative technologies: gas turbines in the case of coal and lean burn engines in the case of the converter. The story is more complex because there were also government regulations that pressured companies to develop clean technologies.

structures, political institutions, lifestyles and culture) and changes within the regimes that are occurring independently from the development of the new regime, that are shaping the depicted process.

The existence of a niche for a new technology is not a guarantee that the technology will diffuse more widely. An example is battery electric vehicles, which were only able to capture the niche of milk cart. They were unable to capture a niche in the automobile market. One of the reasons for this was that the selection criteria of the milk cart users were very different from those of automobile users. The gap in technological performance could not be bridged, despite significant environmentally motivated research programmes to develop batteries for automobiles. Currently automobile producers are investing their money in hybrid electric vehicles (Toyoto is already mass-producing one, the Prius) and fuel cells for automobile propulsion. But this does not mean that the options of a battery electric vehicles is completely dead. Hybrid electric vehicles may pave the way for BEV by creating a market for batteries for automobiles which may help to achieve scale and learning economies in production and having people go through the experience of electric driving (which is less noisy with less vibrations). This raises the question on what criteria one should decide for experimentation with new technologies in protected fields of application.

Some people would say that one should experiment with technologies that offer the prospect of economic success, so-called winners. Clearly the technology should be attractive, but this need not be limited to attractiveness to users. Social and environmental benefits should also be considered and may provide an important reason for experimentation, especially since these benefits are often undervalued in the market. In view of fostering regime shifts towards sustainability, there is also a special need to support technologies that are outside the existing regime or paradigm. Of course, it is exactly these kinds of solutions that are often unattractive from a user point of view. On the other hand there may be niches in which the costs do not count high. If such niches exist, we may use strategic niche management. Furthermore, the choice of technology should also be informed by the possibilities for improvement and branching. Attractive technologies eligible for support are technologies that have great development potential and a synergy with ongoing developments (like the evolution of user preferences and societal values, policy developments, areas of rapid technical advances).

The selection of the technology can be done in a consultative and co-operative mode together with stakeholders or in a more competitive mode through the use of tenders in which people (consortia) are asked to come up with proposals. Design choices should not be fixed from the beginning, to prevent lock-in to suboptimal designs. There is thus a need for experimentation with a multitude of options. Since the experiments with new technologies should show whether these improvements can be attained, or whether unintended (beneficial?) effects occur, diversity in technological approaches and social settings is to be striven for. A key insight from evolutionary economics is that you can not determine ex ante the best technology but only discover this ex post. It is thus important to have a variety of options, to stimulate a broad learning process.

3.2.1 The gas turbine as an example of niche development

The operation of a process of niche development is illustrated here at the example of the gas turbine. It shows strong links with other developments of primary movers, such as steam engines/turbines and even the internal combustion engine.[11] Today's gas turbines for electricity generation running on natural gas are just one application of the basic turbine design principle. Compared with conventional electricity generation by steam turbines (using coal or fuel oil), they allow to reduce emission of pollutants by a factor of 2 for NO_x and CO_2 and a factor of 250-1000 with respect to SO_2 (see Islas, 1999).

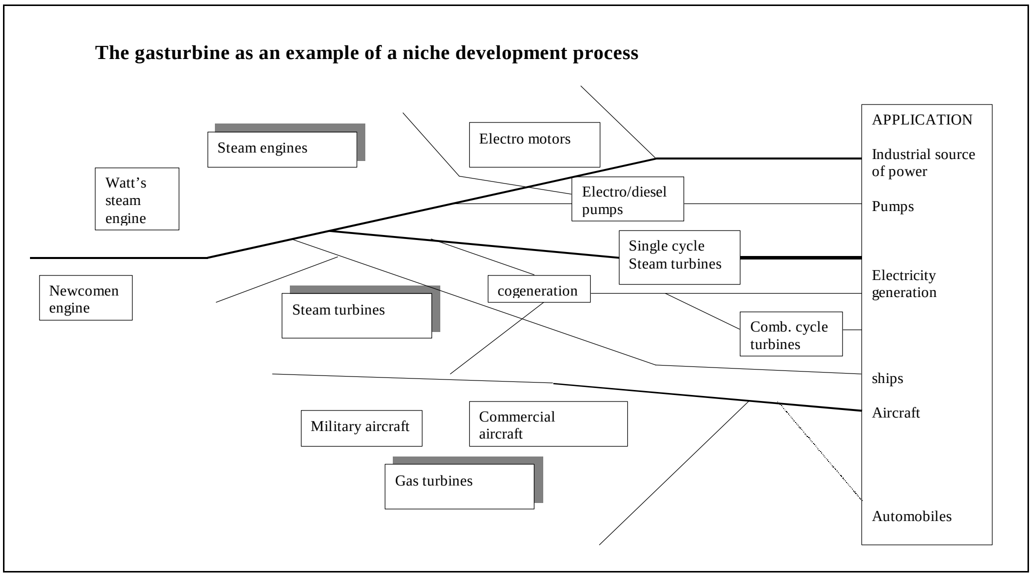

Figure 3

The first gas turbine was patented in 1791. Initially the concept did not compete successfully against steam machines and internal combustion engines. In 1882 steam turbines were invented and they diffused relatively quickly into electricity generation. The first real gas turbines were build at the beginning of this century in Europe and the US. Due to technical problems and insufficient understanding of the necessary scientific principles, thermal efficiency remained low (at around 3%), compared to steam turbines and internal combustion engines. This lead to the abandonment of gas

[11] See Gille (1986), McNeil (1990), and especially Islas (1997) for a more complete presentation of the history of gas turbines. The following exposition is based on these sources.

turbines as standalone solutions in electricity generation until the end of the first decade of the 20th century.

But research in the application of gas turbines continued in aviation (supercharging devices, later jet engines) and industrial applications (blast furnaces, mines, yeast production). Interest increased also in electricity generation after WWII again, when the gas turbine was recognised as a universal power source.

Islas (1997) identifies two main design trajectories of gas turbines in electricity generation. The first 'aero-derived' one, depends on direct application of knowledge developed in the research of jet propulsion technologies, and the second, 'industrial' one, depends on the combination of steam turbine and supercharging/jet engine gas turbine technologies. The advantage of both types of gas turbines relative to conventional power generation, are a rapid start-up time, which allows quick reaction to electricity demand peaks, and lower operating cost. Gas turbines thus found niches as auxiliary devices to meet peak electricity demand, to guarantee greater reliability of electricity services (which was especially important after black-outs in the 1960s in the UK and North America - see footnote 4, Islas 1997) or to serve decentralised areas of small demand.

Interest in gas turbines in electricity generation increased even further after the first and second oil crises. In the 1970s, development of moved on to a genuine cogeneration (combined cycle) gas turbine. Latest designs developed in 1980-95, reach outputs of 130-220 MWs and an efficiency of 45%-55%. Although gas turbine performance surpassed that of steam turbines at the beginning of the 1970s, diffusion of the technology took place only later through economic pressure by increasing oil prices and social pressure towards environmentally (more) benign technologies and away from nuclear power (Islas, 1999).

The history of (gas) turbines is thus also a good example of how niche processes can fuel the process of regime shifts by the interaction of technology hybridisation[12], changes in the perceptions of engineers, decision-makers and society.

One possible new application can be found in electric hybrid propulsion in which an electric engine and an other source, for example, a gas turbine are combined. Within the recently completed Dutch National Programme on Sustainable Technology Development (STD) (see Weaver *et al*., 1999) the environmental impact of a serial hybridisation of an electric engine and gas turbines in public transport has been investigated. A simulation programme (developed by TNO-WT) is used to compare the 'environmental performance' of several ways of propulsion in modes of high quality public transport as to be expected in 2010 compared with the present situation. Figure 4 shows the result of the simulations.

[12] Here the application of aviation propulsion technology to electricity generation, respectively the combination of steam and gas turbine technology.

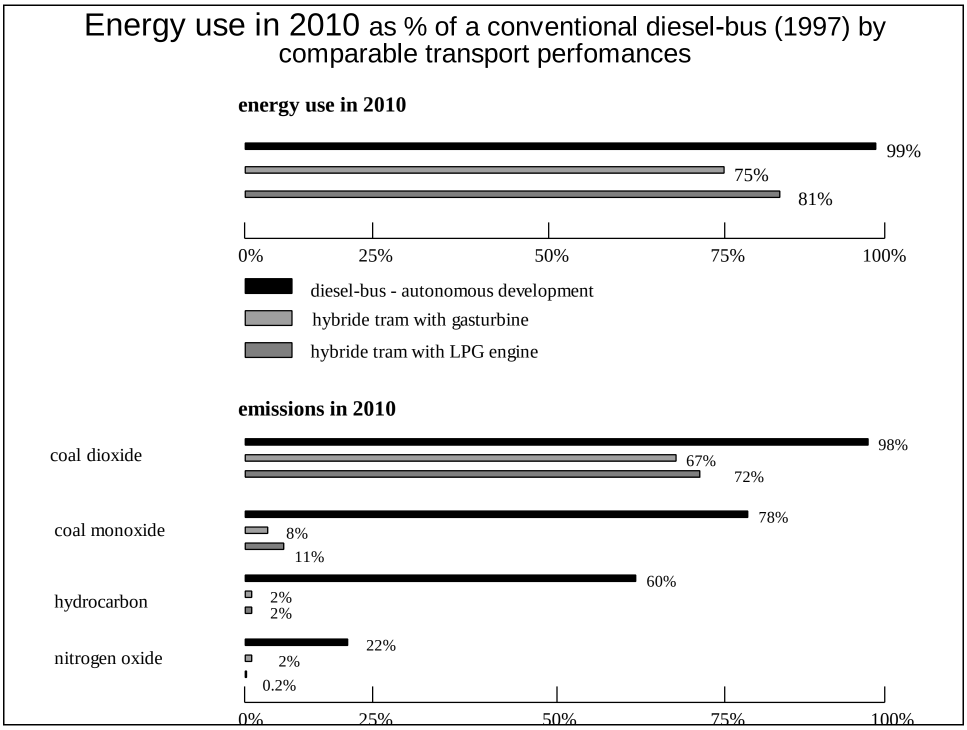

Figure 4

Source: Klosterman et al. (eds.) (1997, p43)

The niche development process of gas turbines may thus continue. There may yet be another application, which is automobile transport. The dashed line in Figure 4 depicts this.

Finally, it is to be noted that wind turbines also went through a distinctive process of niche development. They were first used as stand alone technologies at farms in windy areas, later on they were used in wind farms, first in the US (California) and Denmark, later on in other countries.[13]

[13] A discussion of the development of wind turbines in Denmark and California is given in Kemp *et al*. (1997) focusing on the evolution of protection and selection pressures over time. It is described how the different institutional settings and early design choices gave rise to distinctively different technological trajectories: one trajectory based on small robust designs which were gradually scaled up (in Denmark) and one trajectory based on large scale designs based on insights from aerodynamics (in California), with the first trajectory winning out against the second one.

4. Policy implications

The value added of evolutionary economics in the context of environmental policy lies mainly in the recognition of the way in which society is locked-in into particular technologies (see e.g. Cowan and Hulten, 1996). When talking about 'environmental technological change', policy-makers face the challenge of escaping technological lock-in into environmentally unsustainable practices and triggering a 'shift' away from unsustainable systems. In other words, the relevant competition processes refer not so much to (two) similar introduced technologies (as in the 1989 Arthur model) but more to the relation between an existing (dominant) polluting technology(systems) and an introduced clean technology(systems).

In this paper it has been argued that environmental sustainability requires eco-restructuring, that is the development of new technology systems (for example in transport, chemical industry, agriculture) offering magnitude environmental improvements. This raises the question: how to achieve this? A practical approach derives from the branched, niche-based character of technological development, which is to create semi-protected spaces for new technologies, especially technologies that may lead to more sustainable trajectories. New (sustainable) technologies are possibly not initially fully competitive because they face barriers of entry such as economies of scale, institutional arrangements, lack of information or regulatory frameworks in favour of the established technological regime. This implies a rationale for government intervention aiming to facilitate a transition process away from unsustainable technological regimes.

A more general policy recommendation derives from the importance to have a variety of technology options, in order to escape a lock-in into unsustainable technological systems. This asks for policies that stimulate a broad learning process and the existence of a variety of potential technological development paths, even if they may not be optimal in the long term. Policies striving only for widespread diffusion and implementation of so-called best-available-technologies may turn out to be counter-effective in the long run since they may reinforce a lock-in into existing technological regimes.

At the end of this paper we will discuss in more detail a method to foster technological regime shifts towards sustainability through the management of niches. This method is called strategic niche management.

4.1 Strategic niche management for environmental technologies

Strategic niche management (SNM) is a new approach, first suggested by Rip and further developed by Schot *et al*. (1994), Kemp *et al*. (1998) and Weber *et al*. (1999). SNM refers to the process of managing the process of individual niche experimentation in such a way as to enable future regime change, by linking experiments and building on the basis of their results larger niches for new technologies (Weber and Dorda, 1999). In other words, it is aimed at modulating the dynamics of socio-technical change through the creation and management of spaces (niches) for the use of a new technology. In the spaces the technology is partly and temporarily protected from the normal selection pressures of business.[14] Selection of the spaces should based on at least two considerations. Firstly, it should be based on the degree of attractiveness of the technology in the local context and, secondly, on the extent to which the setting allows for learning processes (about the market for the technology and the best design configuration and support policies).

SNM involves the real use of technologies, in selected (protected) settings. The actual use of a new technology is important for articulation processes to take place, to learn about the viability of the new technology and build a network around the product whose semi-coördinated actions are necessary to bring about a substantial shift in interconnected technologies and practices. As we have argued, this is important in fostering regime shifts.

SNM is especially appropriate for so-called pathway technologies. Pathway technologies are technologies that (may) pave the way for new developments. They help to bridge the gap between the current regime (in which they may be used for certain purposes) and a new and more sustainable one. They are usually compatible with both the old and new regime and allow for a cascade of innovations. Energy storage is an example of a pathway technology: energy storage is a key technology for the use of renewables but also useful within the centralised energy system as it may be used to deal with peak demand, helping to reduce peak loads. Electric propulsion and transport telematics (electronic information and reservation systems about transit) are examples of pathway technologies for transport. Both technologies have a great development and a great potential for achieving environmental sustainability benefits. Both have been supported by public policies through special research programmes and there has been investment from industry in these technologies but there still is a gap between research and diffusion. A special type of support action is needed to bridge this gap. The Zero Emission Mandate of California which required that a certain percentage of new vehicles sold (2 per cent in 1998 and 10 per cent in 2003) are zero emission vehicles (at the point of use) is an attempt to cross this gap. It consisted of a forced introduction of zero emission vehicles in the market. It gave a big boost to the development of batteries, electric propulsion systems, quick recharging systems, and even the use of lightweight materials. Some examples of SNM-like experiments with more sustainable transport technologies - such as electric vehicles, individualised forms of collective transport (such as dial-a-ride services), organised car sharing, bicycle pools - are described in Hoogma *et al*. (1999).

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[14] The protection of innovations is not something unusual. Much innovations depend on research that is done within public laboratories or universities. In addition, companies themselves create a protected space for research by allowing researchers to do particular kinds of research, to use office time, space and equipment. Sometimes an entirely new company unit is created in which a new product is developed free from the usual decision calculus. An example is the Smart car for which a technological niche is created through company subsidies, but with the prospect or hope that the car will become remunerative or that the knowledge obtained will pay off in some manner. Some research is done secretly because it may threaten positions within a company or for fear of failure.

SNM is an example of process management for the introduction and diffusion of new technology and a deliberate attempt to make the co-production of technological options, use, policy measures and sustainable development visible and productive (Weber *et al*., 1998). It differs from strategic planning or control policies based on the achievement of set goals. SNM is more reflexive and open-ended, aimed at the exploration and creation of new paths by building on developments at the local and supra-local level.

The advantage of SNM is that is targeted to specific problems and needs connected with the use of new technologies and practices. User experiences are used to inform private investment and government support policies. By carefully choosing an appropriate domain the costs may be kept low. Windows of opportunity are exploited at the local level while at the same time a transition path is created to a new and more sustainable system in a non-disruptive way. It will help actors to negotiate and explore various interpretations of the usefulness of specific technological options and the conditions of their application. Thus, SNM highlights choices and options and makes the introduction process more transparent and do-able for all parties involved including producers, users and policy-makers (Weber *et al*., 1998).

SNM has been attempted by companies for radical innovations such as optical fibres, cellular telephones, aspartame, and computer axial tomography (CT) scanners (Lynn *et al*., 1996). It is a new approach for policy makers although some government policies such as the ZEM in California could be labelled as de facto SNM policies. In our view there is a need for policy makers to go beyond demonstration projects and to promote user experiments with new technologies. It is worth stressing that SNM is not limited to doing user experiments. SNM may also be used by private and public decision-makers for technologies that already exist in the market. For example, state authorities could use SNM as part of an ecological restructuring policy.

Finally, it is to be noted that SNM is not a substitute for existing policies, but a useful addition, which may help to increase the variety of technology options and, thus, work towards more sustainable technology systems. In doing so, SNM contributes to the goal of ecological restructuring, which, as stated, goes beyond the control of particular pollutants and the adoption of eco-efficiency solutions. It is an example of an 'evolutionary' policy, aimed at deliberately shaping paths, creating circles of virtuous feedback through carefully targeted policy interventions, rather than at correcting perceived market failures. It thus helps to overcome the weakness of current environmental policies that often have been found to have a weak influence on innovation.[15]

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[15] A discussion of the pros and cons of different environmental policy instruments, especially the choice between the use of economic incentive and regulatory standards, is offered in Kemp (1997).

5. Conclusion

Until now, economists have almost solely applied standard or neo-classical theory to the issue of environmental technological change in the form of pollution control techniques or energy (saving) technologies. This situation has started to change. Recently, initial attempts have been made to apply concepts from the evolutionary literature on technological change to the issue of environmental technological change. Within evolutionary economics technologies are not defined in terms of a stylised input-output relationship but as sociotechnical configurations, linked with other technologies, economic activities and production and user practices and whole range of institutions that form a technological system or regime. In other words technological change is contextualised. This approach may help to understand the process of adoption and diffusion of environment-saving technologies, because they take into account institutional and social factors that are commonly ignored in neo-classical analysis of technological change.

Most of environmental technological change consists of incremental improvements of existing technologies and the diffusion of existing technologies that are integrated in existing production modes. However, it can be argued that the control of particular pollutants and the adoption of eco-efficiency options within existing production modes will not be enough for achieving environmental sustainability. What is needed in addition to these options are more or less fundamental changes in production processes and consumption patterns that are underpinned by alternative technological trajectories. Such changes are referred to as technological regime shifts. Evolutionary economic concepts such as technological paradigms, trajectories, regimes and niches are considered being useful concepts which may contribute to understanding regime shifts towards sustainability because they provide insight in the nature and development of 'sustainable innovations'.

The value added of evolutionary economics in the context of environmental policy lies mainly in the recognition of the way in which society is locked-in into particular unsustainable technologies. When talking about environmental technological change, policy-makers face the challenge of escaping technological lock-in into environmentally unsustainable practices and induce a shift away from currently unsustainable systems. Escaping lock-in into unsustainable technologies and technological systems is a difficult task. It requires policies that include the use of economic incentives but will not be limited to it. Incentive-based policies need to be accompanied by a mix of technology-specific policies fine-tuned to technical change. There is a danger that incentive-based policies are a too weak and indirect influence. These technology-specific policies would consist of an integral approach in which technological, economic, structural and cultural factors are taken into account. Examples are: the creation of innovation networks, experiments with new technologies, the articulation of visions of technology futures, and R&D programmes for radical technologies that offer environmental benefits. Such policies seem to fit better within an evolutionary than a neo-classical framework that black-boxes technology.

A particular policy for achieving environmental gains, which follows from the importance of niches in technological regime shifts, is Strategic Niche Management (SNM). It is a valuable policy tool that may help to increase the variety of technology options, learn about them, and inform private and public support policies, especially for radical technologies offering environmental benefits. In doing so, SNM contributes to the goal of ecological restructuring – which, as stated, goes beyond the control of particular pollutants and the adoption of eco-efficiency solutions.

We are led to the conclusion that, given the important role of technological change in the context of sustainable development, evolutionary economic theorising on technological change may contribute to our understanding of moving society towards sustainability. However, whereas mainstream neo-classical theorising is characterised by a uniform approach and strong analytical capabilities, evolutionary theorising and research is still mainly confined to detailed case-studies while lacking a generalised formal treatment of technological change. Consequently, evolutionary economics has not yet provided the analytical tools that may predict and illuminate the process technological regime shifts. We suggest evolutionary modelling of industrial and technological dynamics and socio-technical scenario analysis as being promising lines for further research. By socio-technical scenarios we mean a method that aims to fill the gap between technology foresight studies at a sectoral level on the one hand and macro-economic scenarios like the ones commonly used by policymakers on the other hand. Socio-technical scenarios can be used to examine how technologies and society interact and change through a process of co-evolution.[16]

In sum, major shifts in economic structure and technological processes seems to be needed in order to realise sustainable development. Obviously, such shifts involve uncertain and irreversible changes, the possible selection of suboptimal solutions, learning by doing and using, lucky errors in decision-making and a persistent (economic) disequilibrium. It appears that evolutionary economic theorising on technological change has something to offer here but need to be further developed to be of practical use.

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[16] In the research project 'Environmental Policy, Economic Reform and Endogenous Technology' (PRET) for the Dutch Environment and Economy programme, an attempt is made to develop the sociotechnical scenario method further and to apply it to the problem of future transport and energy. Contours of the method can be found in Geels and Schot (1998) who propose the following building blocks for making sociotechnical scenarios:

- A variety-producing mechanism such as niche creation.
- A stability-producing mechanism such as a technological regime
- Factors operating at a macro-level (sociotechnical landscape)
- Mechanism for coupling of changes at all three levels, thus allow for multi-level development over time.

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