Evolutionary Theorising on Technological Change and Sustainable Development

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Abstract

In this paper we investigate the added value of an evolutionary economic approach of technology and technology policy in the context of sustainable development and environmental policy. 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. In the paper this is illustrated with a few examples from empirical socio-technical scenario studies. It is argued that an evolutionary perspective is particularly appropriate for understanding technological regime shifts to environmental sustainability, as an emergent process in which niches play an important role. This is illustrated with the case of the evolution of the gasturbine .The added value of evolutionary approaches lies in the contextualised view on technologies in which they are not defined in terms of a stylised input-output relationship but are ‘lumpy’ and linked with other technologies, economic activities and production and user practices and whole range of institutions that form a technological system or regime. In addition it is will be argued that the added-value of evolutionary economics with respect to environmental policy lies mainly in the recognition of the way in which society is locked-in to particular unsustainable technologies. Escaping lock-in into unsustainable technologies and technological systems requires policies that include the use of economic incentives but will not be limited to it. These policies should consist of an integral approach in which technological, economic, structural and cultural factors are taken into account. Within this context we discuss finally strategic niche management as a new perspective on how technological regime shifts to environmental sustainability may be managed. Evolutionary perspectives have something to offer here, but 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 very reason for this lies in the fact that the way in which energy and materials are transformed in the economic process ('throughput') depends mainly on the state of technological knowledge. This implies that technological innovation can change the composition of the material basis of economic processes. Although technology knows an ambivalent relationship with respect to environmental degradation (Gray 1989) - it is both a source and a remedy of environmental degradation -, in general most attention is paid to technological change as a way to enhance sustainable development, or even more explicit as a way to 'solve' environmental problems.

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. While, in general, traditional mainstream approaches have been criticised over the years, practical considerations made it reasonable to apply largely neo-classical methodology in both theoretical and empirical research. This situation has started to change. In particular, the seminal work of Nelson and Winter (1974, 1977, 1982) became a starting point for a revival of evolutionary approaches in economics, a tradition that goes back to such (diverse) authors as Veblen (1898) and Schumpeter (1934). Still, evolutionary theorising and research based on it is missing out on developing an integrated perspective on socio-economic issues. We feel this is largely due to difficulties with formalising an evolutionary view on technological change within economic models.

In this paper we evaluate the evolutionary economic viewpoint of technological change in the context of sustainable development. It has been argued that a transformation of the present economic system towards a sustainable economic system requires new policies, institutions and mechanisms (Opschoor 1992). Major shifts in economic structure involve uncertain and irreversible changes, selection of existing alternatives, learning by doing, lucky errors in decision-making and a persistent economic disequilibrium. In this respect an evolutionary approach may be useful to provide a framework for studying irreversible processes, path-dependent change and long-run mutual selection of environmental and economic processes and systems (Mulder and Van den Bergh 1999).

The aim of this paper is to apply concepts from the evolutionary literature on technological change to environment-saving technological change. We will investigate the relevance and the added value of an evolutionary economic approach of technology and technology policy in the context of environmental policy. To this end we will apply concepts such as bounded rationality, path-dependency, routines, learning and selection processes, transition dynamics, uncertainty and (complex) systems dynamics – to the problem of technological regime shifts to environmental sustainability. This implies that attention will be paid to the issue of ecological modernisation: the replacement of existing trajectories of consumption and production by more sustainable ones. Ecological modernisation 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, agriculture) offering magnitude environmental improvements. It is argued that an evolutionary perspective is particularly appropriate for understanding technological regime shifts to environmental sustainability, as an emergent process in which niches play an important role, offering a new perspective on how such shifts may be managed: by strategically managing niches for environmentally sustainable technologies.

The organisation of this paper is as follows. Section 2 starts with a brief sketch of the way technology is dealt with in neo-classical and evolutionary economics and continues with an elaboration of the evolutionary approach to technological change. A number of concepts are discussed with an emphasis on the role of niches. In section 3 we investigate to what extent these evolutionary concepts can be applied to fruitful research on environmental change. Particular attention will be paid to strategic niche management as a new perspective on how technological regime shifts to environmental sustainability may be managed. Section 4 concludes.

2. Economic theory and technological change

Both neo-classical and evolutionary economic theories are characterised by a specific perception of the phenomena under investigation. Obviously, different assumptions lead to different hypotheses and subsequently different outcomes of investigations. In this section we provide a brief characterisation of both approaches before we elaborate in more detail the evolutionary economic approach.

2.1 Evolutionary and neo-classical economics: what makes the difference?

In neo-classical economics technology is defined in terms of a production function. A stylised production function is defined as $Q = F(K, L, t)$ where Q is output, K and L are capital and labour inputs, and t is time. In other words, the neo-classical production function can be defined as a specification of all conceivable modes of production in the light of the existing technical knowledge about input-output relationships (Sahal 1981). Technology is in general considered as in an abstract way and represented by a parameter A in the production function. For example, in case technological change is labour-augmenting the production function is defined as Q = F(K, AL, t). Technological change can be defined as a change in the economy's information set detailing the relationships between inputs and outputs in the economy (Stoneman 1983, Gomulka 1990). In short: technological change is defined as increasing technological knowledge. It is common practice among neo-classical economists to distinguish between a movement along the production function, referring to factor input substitution, and a shift of the production function, referring to technical progress.

Whereas technology traditionally has been incorporated in neo-classical economic models as an exogenous factor *A*, over the last decades, a number of attempts have been made to endogenise technology in economic models (e.g. Arrow, 1962, Phelps, 1966, Nordhaus, 1967, Shell, 1966 and 1967). Recently a new class of neo-classical models has appeared that are labelled endogenous after their key feature to make technological change endogenous (e.g. Lucas 1988, Rebelo 1991, Romer 1986, 1990). An essential characteristic of this wave of models of technological change and economic growth is a broadening of the capital definition. This is mainly done by defining capital not only in terms of physical capital but in terms of human capital as well. Where the early attempts to endogenise technology modelled technological progress as a side-effect of economic activities, recent endogenous growth models explicitly take intentional technological progress into account, for example, as a result from intentional activities in R&D[1]. These developments in economic growth theory have inspired efforts to endogenise technological change in a range of economic models of technology innovation and diffusion, including models that deal with environmental policy (e.g. Bovenberg and Smulders 1995, Den Butter et al. 1994, Carraro and Galeotti 1995, Messner 1997, Smulders 1998).

The most recent development in the neo-classical literature on endogenous technological change is the Schumpeterian approach (Aghion and Howitt 1992 and 1998). In this approach a more vertical way of modelling technological progress is employed, taking into account the obsolescence of old intermediate outputs as an integral component of technological progress. Evolutionary economists often refer to Schumpeter (1934) as well as the intellectual starting

[1] For surveys of this literature we refer, among others to, Aghion and Howitt (1998), Barro and Sala-i-Martin (1995), Van de Klundert and Smulders (1992), Lucas (1988), Helpman (1992) and Verspagen (1992).

these features in favour of a more diverse and complex picture including heterogeneity, uncertainty and path-dependency.

The 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 in the way it is used by neo-classical economists. Among others, Nelson and Winter (1974, 1977, 1982), Dosi (1982) and Sahal (1981) have argued that this view on production and technical progress suffers from providing no insight in the occurrence of technical 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. 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 the formal 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 *et al*. 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, in particular in the context of Schumpeterian models, convergence has been taking place in the view on technology as expressed by neo-classical and evolutionary economists. In this paper we will elaborate the evolutionary approach to technological change in order to investigate its significance for (technology) policies aiming to move society into a more ecologically sustainable direction.

The added value of evolutionary approaches is that technologies are not defined in terms of a stylised input-output relationship but that technologies are ‘lumpy’ and linked with other technologies, economic activities and production and user practices and whole range of institutions that form a technological system (Hughes) or regime (Kemp et al., 1994, Rip and Kemp, 1998). From this point of view we can define *technology* than 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 solution 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.

2.2 An evolutionary approach to technological change

The evolutionary economic literature on technological change makes the important distinction between incremental and radical change. 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. In the modern period they are usually the result of deliberate R&D in enterprises and research activities in university and government laboratories. They are unevenly distributed over sectors and over time. Examples are nylon or `the pill'. Over a period of decades they may have dramatic effects, that is, they do bring about structural change, but in terms of their aggregate economic impact they are relatively small and localised, 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. Changes in technology systems affect several branches of the economy and give rise to entirely new sectors. Their use often requires organisational and managerial innovations. An example is the cluster of synthetic materials innovations, petro-chemical innovations, machinery innovations in injection moulding and extrusion, and innumerable application innovations introduced in the 1920s until the 1950s. Technology systems involve different poles: a science pole, a technology pole and a market pole. The last pole consist of production activities and the range of applications for which the technology is used. Such system can be quite complex, as the following figure for gas turbine shows.

<figure gasturb. here >

Most of technical change consists of incremental improvements of existing technologies and the diffusion of existing technologies that are integrated in existing production modes. But, elsewhere (Freeman, 1996, Kemp and Soete, 1992, and Kemp, 1994) it has been 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. For example, with respect to the production process fundamental changes in technology systems seems to be required in the long run, like 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 and 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. Here the discussion of technological paradigms and technological regimes by evolutionary economists is particularly useful.

Paradigms, Regimes and Trajectories

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 of 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."[2] 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.'[3]

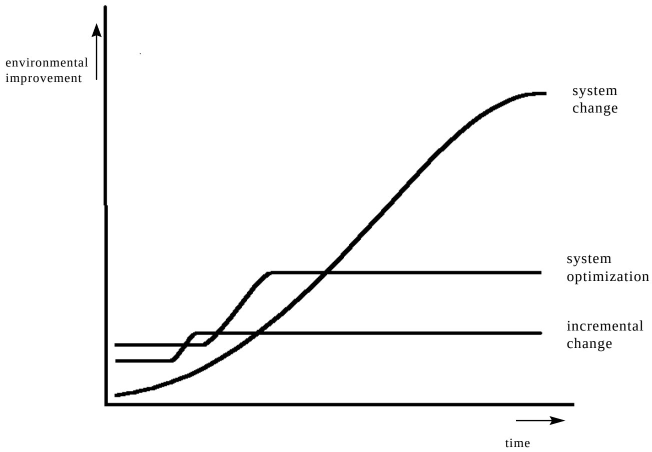
[2] Dosi (1988, p. 1127).

[3] Cp. ibid. (figure 2, p. 38).

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). Technological paradigms itself emerge from the a set of hierarchical interactions in socio-economic systems (Clark 1987), which is made up of the interaction of user and producer groups (Andersen 1991).

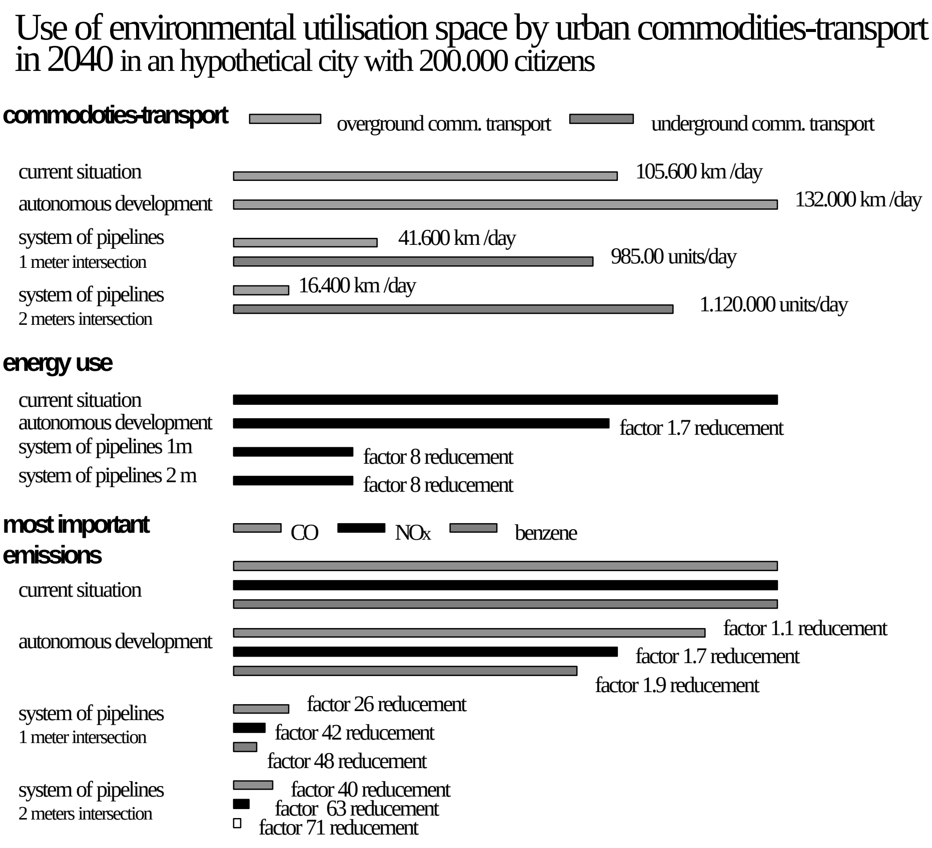
Regimes are defined by Kemp et al. (1994, p. 15) as '...the overall complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, institutions and infrastructures which make up the totality of technology.' This definition is naturally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

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, 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 makes a distinction of system optimisation and system renewal (or transformation). The exact figures will differ from case to case.



Source: Weterings et al. (1997). '81 Mogelijkheden: Technologie voor duurzame ontwikkeling', eindrapport van de milieugerichte technologieverkenning, in opdracht van Ministerie van VROM' (1997),p.18 and after F.W. Geels, presentation MATRIC project, 23.2.1999, Universiteit Twente.

Moving society towards ecological sustainability requires not only step-by-step improvement of existing technologies and systems but fundamental changes or (technological) regime. 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). This postulation is supported by the results of the recently completed Dutch National Programme on Sustainable Technology Development (STD). Within this programme a range of projects was carried out on the basis of the method of 'backcasting', i.e. a sustainable future vision serves as a starting point for reasoning backwards about ways to meet the expected future human needs and wants in a sustainable way. Scenarios and demonstration projects have been developed to sketch long term technological developments that may support sustainability. The programme has developed studies in the field of transport, water, food, chemical industry and housing. Figure ... provides an illustration of a study about several ways to meet future demand of urban commodities transport in the context of environmental impacts.



Source: DHV, Pipe-line transport for urban commodities transport; illustration proces, Amersfoort 1997 in: STD 'key' Mobility, Den Haag 1997, p 40

From this example it is clear that regime shifts are required to realise sustainability in the field of urban transport.

Unfortunately our understanding of technological regime shifts is limited. The same is true for technological trend breaks to environmental stability, despite the parlance of ecological modernisation and industrial transformation in policy circles and science. Most of our knowledge about technological regime shifts comes from historical studies of technological transitions and structural change.

Technological regime shifts

Of course, 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. Technological change is connected with social change and rooted in social systems and organisational networks. It is guided by engineering ideas of technological opportunities and very much driven by the economics of the production and use of new technologies that depend on the development of complementary technologies and government research and procurement policies. New technological systems are not created on the basis of blueprints by system builders, although they may be guided by certain visions, but evolve through the actions and strategies of many different actors. They are the collective outcome of decision making and actions by myopic actors acting and reacting to changing circumstances, created by earlier actions and events. New regimes grow out of existing regimes through a process of transformation in which old elements are combined with new elements, although we should perhaps add that this is a contention rather than an established fact since history can be read in different ways (one in which there is a lot of continuity and one in which there are discontinuities). Although there is no established view on what drives such changes (according to economists it is changes in cost and demand conditions, whereas in historic accounts it is cascades of „events«, complex conjunctures in which complex actors encounter complex structures Hirsch and Gillespie, 1997) we believe that niches (for new technologies) play an important role in this transformation process.

Niches

Niches are important 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.) that are necessary for the further development of a new technology or technology system. Niches help to create virtuous cycles that allow a new technology to escape lock in, by helping the technology to overcome initial barriers of high costs, the non-availability of complementary technologies and the non-alignment of a new technology to the external environment during the infancy period of a new technology when it has not yet benefited from dynamic scale and learning economies.

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 (about their needs and the functioning of a technology) which helps to inform companies' research, production and marketing policies, achieve cost economies in the production and use of the technologies, promote the development of complementary assets, and foster the building of a constituency behind a product, which is necessary for exercising political influence, the programming and pooling of research or the introduction of quality assurance schemes. Niches thus provide an impetus to learning and investment. The real use of a new technology is crucial, as some things one can only learn from experience. Real experiences are also necessary for institutional adaptations.

Building on Lancaster and Kotler, niches are characterised by the functionality requirements of users and the resources available for sustained innovative efforts. Niches are a version of a domain of application for a technology. The difference between established technologies and niches is a different set of selection criteria, which is working in the niches, and the size of the domain of application. Levinthal (1998) has applied the concept of niches to the developments of new technological variants at the example of wireless telecommunication. He uses the analogy of punctuated speciation taking place in niches.

There basically are 2 types of niches: technological niches and market niches. When there is protection the niche is a technological niche, when there is not, we talk about a market niche. Market niches can usually be found in big markets in which one technology is not capable of satisfying all user needs in terms of price and performance characteristics. Protection may be offered by industry (when they do not subject certain innovation projects to harsh economic evaluation criteria, or when they create special organisational units for new projects), or by governments through research programmes or public procurement. Also users or NGO may provide protection. This happened in the case of organised car sharing in Switzerland where people were willing to accept low quality services and took care of the cleaning and maintenance of vehicles (Kemp *et al*. 1998). The original niche may be expanded once the technology is further developed, complementary technologies are available and the structure of cost and demand changes. There may be a process of niche branching, fusion and system development.

Niches it seems are an important part of the evolutionary process of technological transitions, what we call technological regime shifts. They act as an incubator for new technology and a stepping stone for further change--like the opening up of new domains of application and the development of a new regime in space and time.

The process of niche development and regime change is depicted in Figure 3 (where the small areas denote niches).

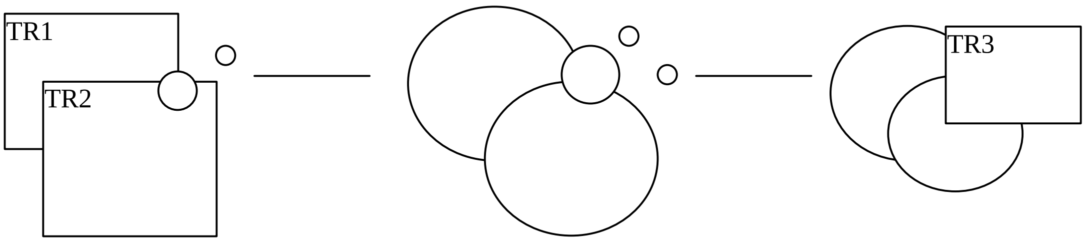


Figure 3 provides a simplistic representation of the process of niche development, that leads to the establishment of a new regime (say a hydrogen economy with large-scale distribution of fuel cells, a decentralised energy system with different mixes of renewables specified at the local levels, or a regime of intermodal transport alongside the regimes of collective transport and individual, car-based transport). It doesn't show the ways in which existing regimes contribute or constrain the process of niche development,[4] and the effects of the new emerging regime 3 on the existing regimes (in the form of induced innovation under the pressure of competition)[5]. Absent in the figure are also changes in the socio-technical landscape (infrastructures, settlement 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.

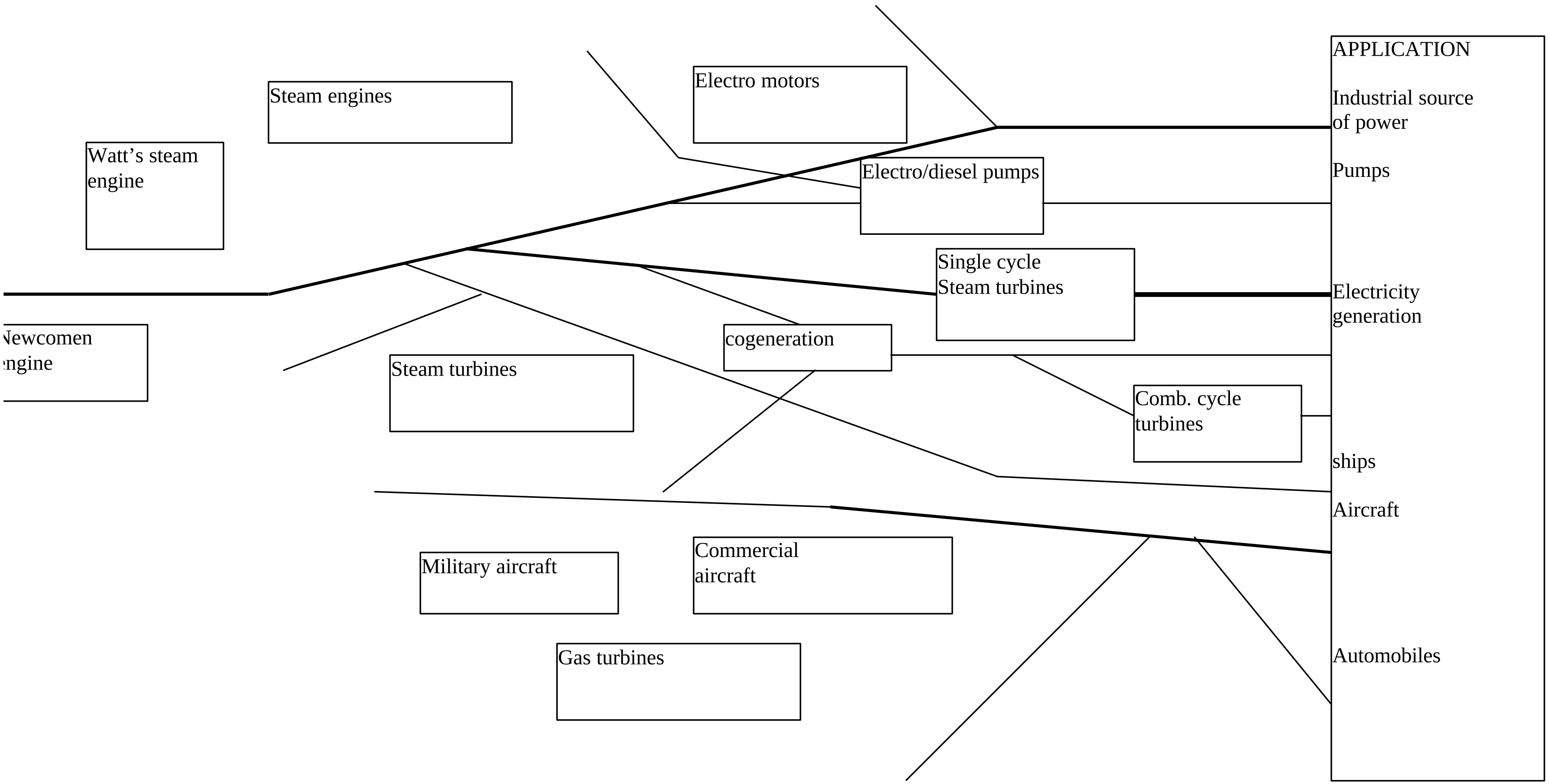
A good example of a process of niche development is the gas turbine, which developed from a supercharging device to a aircraft propulsion technology and from a propulsion technology to a technology to generate heat and electricity, offering environmental benefits compared to steam turbines that constitute the dominant technology to generate electricity. The gas turbine

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

[5] 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.

thus developed to an environmental technology through a process of niche development which is depicted in Figure 4. (shaded boxes represent the technological regimes).

The gas turbine as an example of a niche development process



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.[6]

The existence of a niche for a new technology is not a guarantee that the technology will diffuse more widely. An example are battery electric vehicles which were only able to capture the niche of milk cart. They were unable to move 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. 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).

Finally, a concept which shows the applicability of the niche concept, is industrial ecology. Industrial ecology is based on the idea of symbiosis between industries where waste outputs of one become the inputs for other companies. This set-up creates niches, e.g. in the case of the Danish city Kalundborg (Cohen-Rosenthal and McGalliard 1998). At the beginning the idea was to save on costs for resources, but it was realised that environmental gains could be made too. This leads to new developments in technology. In general, "…niche industries such as used-oil recycling, fly-ash for concrete production, and organic solid waste composting for soil enhancements have developed in many countries." (ibid. p. 26).

Methodology of research on technological transitions.

We now turn to the question how technological transitions may be studied. In our view technological transitions, conceptualised as technological regime shifts, may be studied in 3 ways. The first is the use of 'appreciative theory': the development of theories (in the form of

[6] A discussion of the development of wind turbines in Denmark and California is given in Kemp et al (19987) focussing on the evolution of protection and selection pressures over time. It is described how the different instititutional 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.

generalisations) on the basis of empirical characteristics of the investigated technology domain and general insights from technology studies[7]. This method can be used to develop a theory of technological transitions for the respective domain that is investigated. The second method is evolutionary modelling. Such models should take include the features of path dependence and emergence described earlier on: that is they should incorporate circles of positive and negative feedback and take into account hierarchical structures. The third method is that of scenarios for socio-technical development paths. In these scenarios technology should be endogenised and be based on real existing technological opportunities and investment plans of companies. It should also adopt a systems view, by viewing the technologies as part of wider systems that incorporate social and regulatory elements. The scenarios would contain 2 elements: end states at a particular point in time (2015 or 2050) and the process by which such end states are reached, by what 'events', evolution of supply and demand, and, especially, interactions between interconnected actors (companies, users, regulators, and societal groups). There should be at least one scenario based on system optimisation and one on system renewal or transformation. These scenarios might be called socio-technical scenarios, because of the explicit focus on (the coupling of) technical and social elements. The contours of socio-technical scenarios are described in Geels and Schot (1998). A first, imperfect, empirical attempt, for electric vehicles, can be found in Kemp and Simon (1998). In the final part of this section we will explore a few implication of the second method: evolutionary modelling.

The approximation of the behaviour of social systems made by neo-classical methodology corresponds to relatively simple, almost closed systems (in a strict sense closed except for exogenous shocks). Every analytical representation requires the 'closure' by defining system boundaries and concepts as well as filtering noise out. This is good scientific practice for analytical purposes. It is difficult, though, to deal with situations of an 'open future' created by emergence under such conditions. Modelling practice suggests to deal with it by building a simple, less complex representation that mimics reality sufficiently to allow for extrapolation. The question then is what to do if one wants to model the occurrence of structural breaks and emergence? By increasingly adding details to prevent missing out on little but decisive changes, one runs into the danger of building a representation that is equally complex as reality. For this reason we suggest to use a modelling approach that uses the concept of 'requisite complexity' (it is introduced in Reschke 1999b following Ashby's (1956) 'requisite variety') to guide modelling. It describes the trade-off between parsimony and structural

[7] see Nelson and Winter (1982:45-48) for a discussion on appreciative theorizing.

complexity. It goes away from the idea of using the most simple possible characterisation on the basis of phenomenological evidence and replaces it with that of using deeper structural information.

We have argued that a single invariant concept of a »technology» in itself does not exist in the strict sense of the term. We have to consider this in our research and modelling. Technology as such describes the aggregation of the individual views of the persons promoting specific variants. It is thus important to model this in a feedback loop running from the aggregation to the individuals' perception. If we want to model the diffusion processes correctly we have to take account of the variety (e.g. in population type models). This should enable us to reproduce emergent phenomena occurring in a co-evolutionary process which is characterised by opening and closure of niches, recombination processes, swarms of innovations (Schumpeter 1993 [1934]) and stagnation, punctuated equilibrium phenomena (Anderson and Tushman 1986), system shifts. In short: we have to set up a hierarchic system of interacting agents and population(s) of variants. Depending on focus and aim of our analysis this might mean for modelling that we have to go down to the level of individual engineers, R&D departments or business units/firms or industries.

A comparison of neo-classical and evolutionary economic frameworks (Reschke 1999a) suggests, that the characterisation of micro-level processes is one of the main sources of differences between the perspectives. Niche processes are one way to integrate evolutionary micro level processes. Heterogeneous behaviour of interacting agents in niches as well as interaction with society at large plays a crucial role. Behavioural differences are based on different views on the world hold by different agents. These differences in details are driving the evolutionary process. That is one reason why we need historical case studies to investigate development processes in order to be able to build good simulations.

The historical case study in itself is not the main goal of this exercise, but rather the uncovering of the causal relationships between the phenomena described in the case stories. The description of the case history is just a signal to the scientific public on the quality of the historical study. It allows to check the systemic relationships and interaction patterns necessary to generate a structural simulation model. These are the crucial output of the historical analysis.

Conceiving the development of technologies as niche process allows economists to go deeper than the aggregate view of technologies. It is a framework for investigating the link between outcomes on the phenomenological level, often the only thing captured in standard economic exercises, and the structural mechanism that are driving these outcomes on the micro level. Knowledge of these structural mechanisms is required to build meaningful simulations of evolutionary technological developments.

As argued above, regime shifts associated with technological system change involve a large degree of emergence and uncertainty. To model this type of processes is in general not easy, but in contrast to purely reductionist analytical approaches can ‘emergence friendly’ (simulation) models at least in principle capture the conditions, systemic relationships, necessary to bring about emergent events. This allows us to study whether the parameters characterising technological systems are conducive to desired structural changes in an economy, respectively whether and which policy measures might be needed. This modelling approach requires complementary individual case study research to gather detailed data. The intention is to emulate a similar degree of complexity and the same evolutionary characteristics as the system under study in a tractable and well documented simulation.

Economists sometimes assume that uncertainty can be modelled in terms of stochastic or even probabilistic terms. Insofar as uncertainty refers to the type of events involving emergence of novelty or exogenous shocks their numerical characterisation poses a difficult to insurmountable problem for traditional modelling approaches. The requisite complexity approach to simulation may be more successful insofar as emergence and uncertainty may also stem from the complexity of essentially deterministic interactions. These can be captured in structural models and combined with stochastic processes. The methodological problem is not even that the random generators used are not really random (but are based on some underlying deterministic process). Rather the problem is that what is called uncertainty and emergence is the outcome of a process of complex interactions. Various authors have tried to cope with this under the heading of chance (see e.g. Eble (1998), Kwasnicki (1994), Monod (1971), Riedl (1989 [1976]).

3. Technological change and sustainable development

In this section we investigate to what extent the above discussed evolutionary concepts can be applied to fruitful research on environmental technological change. Afters some general remarks on the environment-technology interaction we turn to the added value of the evolutionary approach to technological change in the context on sustainable development. Illustrations are given from the development of eco-friendly products and the use of gasturbines as a technology that involves an escape of technology lock-in with respect to electricity generation. Finally we discuss strategic niche management as a promising policy for moving society into an environmentally sustainable direction.

3.1 Environment-Technology interaction

Since it was launched by the Brundtland-commission (WCED 1987) »sustainable development» has over a quite short period of time become the dominant concept in the study of interactions between the economy and the biophysical environment, as well as a generally accepted goal of environmental policy. Although there has been, and still is, debate on the precise definition of the concept of sustainable development (see Van den Bergh and Hofkes 1998) a broad consensus exists that it means that economic activities should be consistent with: sustainable use of renewable natural resources, protection of ecosystem features and functions, preservation of biological diversity, a level of harmful emissions remaining below critical (assimilative) thresholds, and avoidance of irreversible damage to the environment and nature (see Daly 1990). Non-renewable resources pose some difficulties in the context of sustainable development. One can choose to reduce their use as much as possible, oriented towards a long-run goal of being completely independent of them. This can be based on investments in renewable alternatives (depending on the potential uses, e.g., supplying energy or materials) and technological progress in general (materials and energy efficiency increases in production and consumption).

The role of technological progress in environmental issues is given with the fact that the way in which energy and materials are transformed in the economic process ('throughput') mainly depends on the state of technological knowledge. This implies that technological innovation can change the composition of the material basis of economic processes. Although technology knows an dual nature with respect to environmental degradation (Gray 1989), in general most attention is paid to technological change as a way to enhance sustainable development, or even more explicit as a way to 'solve' environmental problems (see e.g. Ausubel and Sladovich 1989 Ausubel and Langford 1997).

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 of technical change consists of incremental improvements of existing technologies and the diffusion of existing technologies that are integrated in existing production modes. Mainstream economics is well suited to deal with these issues, both in theoretical and empirical research. We refer to endogenous growth models addressing the controversies on the relationship between economic growth and the environment (e.g. 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. 1994, Carraro and Galeotti 1995, Messner 1997), models of innovation in pollution control (e.g. Downing and White 1989, Mendelsohn 1984, Milliman and Prince 1989) and diffusion models (e.g. Bass 1980).

So far, only a few contributions to modelling the environment-technology interaction have been made from an evolutionary point of view. On the basis of neo-austrian capital theory Faber and Proops (1990) have developed an economy-environment model which allows for endogenous innovation and technical progress. Driven by resource scarcity, technical change occurs by way of a so-called rolling myopic plan approach, that is a series of overlapping finite time-horizon plans. This approach is supposed to reflect limited knowledge about the future and bounded rationality. A non-linear model of technological change, based on some elements from the theory of self-organisation, has been formulated in Edenhofer and Jaeger (1998). Their model is a modified version of the Goodwin-Silverberg model (Silverberg 1984) and employs the mathematical method on predator-prey relations to derive a selection process in which techniques expand or contract due to their superior profitability. As a result long-run fluctuations in prices, wages and patterns of output are produced within the model, basically driven by innovations. The latter consist of rising energy prices, due to environmental policies (taxes, energy cap). The model shows that environmental policies (taxes, energy cap) are able to establish the conditions under which the new (energy efficient) technology is evolutionary superior.

As noted earlier in this paper, realising sustainable development requires to go beyond incremental technological changes. This implies not only the need for radical technological change but also the need for an integral approach in which technological, structural and cultural factors are taken into account. It is in particular here that an evolutionary approach may proof its added value since it claims to asses the issue of ecological modernisation, defined as the replacement of existing trajectories of consumption and production by more sustainable ones, and in doing so to go beyond the control of particular pollutants and eco-efficiency. It requires the development of new technology systems (for example in transport, chemical industry, agriculture) offering magnitude environmental improvements. Fruitful theorising should include, among others, the notion of niche development and management, sustainable regimes and regime-shifts, the evolution of large technological systems and innovative networks (see Foray and Grübler 1996, Kemp, Schot and Hoogma 1997, Kemp 1996, 1997; Rip and Kemp 1998).

3.2 Evolutionary theorising on technological change and sustainable development

A contextual view of technology, 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 the market on which they operate. For example, it helps to understand why companies in the 1970s and 1980s opted for the use of pollution control technologies (because of government pollution control policies and the absence of company environmental management systems) and why since the late 1980s, when pollution prevention rather than control became the focus of governmental policies and managerial tools for pollution prevention became available, technology responses shifted away from pollution control technologies to production process changes and recycling, aimed at the prevention and reuse of waste material. With the emergence of green consumerism and development of ecodesign tools in the mid 1980s and the 1990s, products increasingly became the focus of attention. This lead to the development of eco-friendly products such as low-solvent paints and coatings. Regulatory attention towards prevention and the use of integrated approaches for dealing with environmental problems thus very much 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. Technical change was interlinked with institutional 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. Thus, this change process can not be understood solely in terms of changing costs and demand conditions.

The latter bears also relevance for the recent debate about the so-called Porter hypothesis. This hypothesis states that strict environmental regulations do not inevitably hinder competitive advantage against foreign rivals but they even often enhance it (Porter 1991). The underlying reason is that strict environmental regulations can enhance competitiveness by stimulating innovation (Porter and Van der Linde 1995). Although Porter et al. support their view with a number of empirical examples, the empirical foundation for the hypothesis is still weak. Anyhow, it is clear that the Porter-hypothesis challenges the standard behavioural model of rational agents, in which rationally is defined in term of maximising utility (profits). Why do firms need environmental regulation to enhance their competitiveness? Within the framework of mainstream rational modelling it is hard to fully explain why firms don't see those opportunities by themselves. Basically four arguments can be given by way of explanation. In particular the fourth argument implies a departure from the standard behavioural assumption underlying neo-classical modelling.

The first argument is that positive externalities do exists with respect to R&D. That means that environmental regulation is needed to compensate for insufficient R&D in environmental friendly technologies under laisez faire in terms of what is socially optimal, since private firms do not internalise positive spill-overs.

A second argument refers to the reducement of uncertainty with respect to future environmental policies. Strict and constant environmental regulation then may well enhance innovation (see Dixit and Pindyck 1994).

The third argument is that environmental policy enables firms to create a first-mover advantage by developing and adopting environmental technologies. This comparative advantage may be beneficial at the moment other countries also adopt a more stringent environmental policy[8].

The fourth argument is that strict environmental policy may reduce intrafirm inefficiency and will stimulate firms to operate on their production possibility frontier. This argument moves away from the standard model since it implies that firms do not always behave in a rational way, maximising their utility and taking optimal decisions. This argument refers to the so-called X-inefficiency, that is that firms do not maximise their possibilities due to an unknown (and non-allocative) factor X. The theory of X-efficiency is built on the assumption that although utility maximisation is consistent with rational behaviour, it is not a necessary ingredient of it (Leibenstein 1978). Evolutionary economic theorising may shed light on this issue in two ways. First, by taking into account behavioural differences among agents (see also Bergh et al. 1998). For example, systematic organisational failures with respect to corporate responses to environmental concerns relax the assumption of the business firm behaving in a rational utility maximising way and support the view that these responses are based, among others, on routines (Gabel and Sinclair-Desgagné 1998). Second, by embodying a contextualised view on technology in which technological, cultural and institutional factors are linked. Environmental regulation may trigger complex change processes which cannot be solely understood in terms of changing costs and demand conditions.

[8] note the importance of learning effects in this context

Niche development: the example of the gasturbine

It is to be noted that very often technological change knows an impact on the environment without specifically aiming to do so. Often there does not exist such thing as environmental technologies while the environmental effect of employing a (new) technology are significant. One example is the development of gasturbines (see figure...). The history of turbines is also a good example for hybridisation of technologies. It shows strong links with other developments of primary movers, such as steam engines/turbines and even the internal combustion engine (see Gille 1986, McNeil 1990, Islas 1997, 1999). Gas turbines for electricity generation running on natural gas are one application of the basic design principle. Compared to 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 w.r.t. SO_2. Islas (1997) has identified two main design trajectories leading to this type of application, an 'aero-derived' one, which depends on the fusion of knowledge from jet propulsion technologies, and an 'industrial' one, which depends on the combination of steam turbine and supercharging gas turbine technology.

The aero-derived GT is simpler, more compact, but also less efficient and reliable than the industrially derived one (Islas 1997, p.55-6). Still, the areo-derived versions allowed GT's to enter this market and provided a niche for learning on gas turbine technology from which industrial derived GT's in the combined cycle versions profited later. The advantage of both types of gas turbines, allowing to enter niches in the existing energy generation system were a rapid start-up time making it a good means to meet demand peaks.

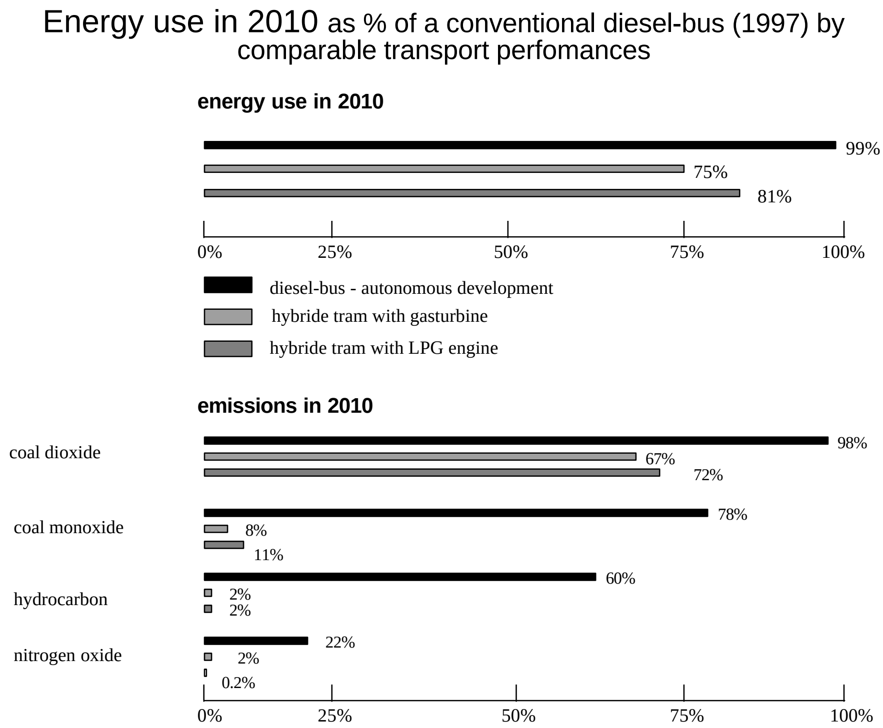
The first gas turbine was patented in 1791. Initially the concept did not compete successfully in terms of applicability against steam machines and internal combustion engines. In 1882 steam turbines were invented and relatively quickly diffused into electricity generation. The first real gas turbines 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 3%), compared to steam turbines and internal combustion engines. This lead to the abandonment of gas turbines as standalone solutions in electricity generation. Major research efforts into gas turbines were made in aviation.

The aero-derived gas turbine was initially conceived in the 1930s linked with the development of aerodynamics. The applications for electricity generation build on the experiences that were made in the development of jet engines in WWII and the following gasturbine in electricity generation is less clear-cut. The gas turbine principle was used in industrial applications (blast furnaces, mines, yeast production) and found a niche as auxiliary device in electricity generation. There are two types that have to be separated: simple cycle and combined cycle gas turbines. The latter make use of the cogenerartion principle, combining gas and steam turbine. The gas turbines developed at the beginning of the century were simple cycle ones. Although they diffused in the 1950s as auxiliary devices to meet peak load electricity demand (having low start-up times and lower unit costs), this type always remained below the efficiency of steam and later combined cycle gas turbines.

Starting from a supercharging addition to steam turbines at the beginning of the process in the 1920s, design moved to a gas turbine with an additional steam turbine in the 1950s to make use of the co-generation principle. After that, in the 1970s, development moved on to a genuine 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 socio-economic pressure towards environmentally (more) benign technologies and away from nuclear power (Islas 1999).

While the case of aero-derived gas turbines is a rather clear-cut linear development of the basic gas turbine principle depending on advances of knowledge, the 'industrial' gas turbine is characterised by an increasing role for the gas turbine component in a larger system. The combined cycle gas turbine, matches what Levinthal (1998) refers to as technology convergence in contrast to technology fusion. Two related technologies are merged in a domain of application, which is related to at least one of these technologies. This has happened in the case of the industrial gas turbine. Technology fusion (Kodama 1992) captures according to Levinthal the case, where formerly unrelated technologies are fused in a novel application.

One application can be found in electric hybrid propulsion in which an electric engine and an other source, for example, a gasturbine are combined. Within the STD project mentioned earlier in this paper (see section 2) a study has been carried out to investigate the environmental impact of a serial hybridisation of an electric engine and gasturbines in public transport. The gasturbines are supposed to produce the necessary electricity for the electric engine in a tram. Figure ... shows the result of the of the simulations.



Source: Klosterman et al. (eds.), Electric hybrid propulsion: feasibility gasturbine-aggregates for public transport, Helmond, 1997. in: in: STD 'key' Mobility, Den Haag 1997, p 43

The example clearly illustrates the significant effect of the application of formerly unrelated technologies on the emission level in the field of transport.

Policy implications

The added-value of evolutionary economics in the context of environmental policy lies mainly in the recognition of the way in which society is locked-in to particular technologies (see e.g. Cowan and Hulten 1996); how the market favours technologies that are within the hydrocarbon regime, and is biased against technologies that require a new infrastructure, skills, plant design, etc. When talking about environmental technological change, policy-makers face the challenge of escaping technological lock-in to environmentally unsustainable practices and triggering a 'lock-out' away from unsustainable systems. In other words, the relevant competition processes refer not so much to (two) similar introduced technologies (as in the 1988 Arthur model) but more to the relation between an existing (dominant) polluting technology and an introduced clean technology.

Of course, the internalisation of external costs („to let speak prices the ecological truth«) through, for example taxes or tradable permits will contribute to energy economising and a switch away from hydrocarbon-based energy technologies in an efficient way. Therefore it is obvious that a carbon tax and tradable carbon rights will have a role to play in the array of necessary GHG policies. However, it is not likely that such measures will be sufficient to bring about radical change in energy technologies and practices, unless they significantly and persistently raise the costs of using fossil fuels (see Kuper and Van Soest 1999), something that is highly unlikely in the political reality of today. To encourage renewable energy technologies that are not part of the hydrocarbon regime, or the development of alternative modes of transport, a kind of technology-specific transition policy is needed, a policy (package) that would make use of the cumulative and self-reinforcing character of technological change. Such policies would be aimed directly at the interactions of actors, shape these in way that contribute to the exploration and development of a new path. These policies would include the use of economic incentives but will not be limited to it. They would consist of research programmes, the use of prospective studies of alternative, more sustainable, futures (to inform RTD programmes), the formulation of goals and targets, and of building policy constituencies and technology constituencies for alternative technologies. Policy makers would act as a kind of socio-technical alignment actor and a modulator of socio-technical change rather than a promoter or regulator.

Such policies seems to fit better within an evolutionary than a neo-classical framework in which technology is embedded in institutional structures which are the context for learning and institutional change[9].

Strategic niche management for environmental technologies

At the end of this paper we will discuss in more detail a particular policy for achieving environmental gains, one that follows from our discussion that emphasises the importance of niches in the technological transitions. Strategic niche management (SNM) is a new approach, first suggested by Rip and further developed by Schot, Hoogma and Elzen (1994), (1997) and Weber, Hoogma, Lane and Schot (1999). It is a kind of process approach aimed at modulating the dynamics of socio-technical change through the creation and management of spaces for

[9] A more extensive discussion can be found in Rip and Kemp, 1996; 1998), Rip, Misa and Schot (1995) and Rip and Schot 1999).

the use of new technology. In the spaces the technology is partly protected from the normal selection pressures of business. The protection should be temporary and partial. Apart from protection there should also be selection pressure. SNM is about finding a balance between the two. Some protection may be warranted even when the technology is economic to use. This is especially true for environmental technologies of which the societal benefits are undervalued in the market place.

The spaces should be carefully selected. Important considerations are: first, the attractiveness of the technology in the local context and second, the extent to which the setting allows for learning processes (about the market for the technology and the best design configuration and support policies). The heterogeneity of the selection environment implies that there will always be spaces (application domains) for which the technology is attractive.

SNM thus consists of the real use of technologies, in selected 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. Strategic niche management also helps to stimulate the further development of these technologies, achieve cost efficiencies in mass production, promote the development of complementary technologies and skills, and stimulate changes in social organisation that are important to the wider diffusion of the new technology; to build a constituency behind a product (of firms, researchers, public authorities) whose semi-coordinated actions are necessary to bring about a substantial shift in interconnected technologies and practices.

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.

SNM is especially appropriate for so-called pathway technologies. Pathway technologies are technologies that 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 sustainable one. They may also be called enabling technologies. 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 light weight materials. Some examples of SNM-like experiments with more sustainable transport technologies - such as electric vehicles, individualised form of collective transport (such as dial-a-ride services), organised car sharing, bicycle pools - are described in Hoogma *et al*. (1999).

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 transport 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.

It is not a substitute for existing policies, but a useful addition, which helps to increase the variety of technology options and work towards more sustainable technology systems and thus come closer to the goal of ecological modernisation, which, as stated, goes beyond the control of particular pollutants and the adoption of eco-efficiency solutions. Patterns of co-evolution are explored and modulated without creating too great adjustment problems for the actors concerned by building upon ongoing developments, exploiting windows of opportunity at different levels. SNM may be used for system renewal rather than system optimisation. As argued in Janicke (1984), Ayres and Simonis (1994) and Kemp (1994), environmental sustainability requires eco-restructuring, that is the development of new technology systems (for example in transport, chemical industry, agriculture) offering magnitude environmental improvements. Policy interventions should be aimed at points at which leverage can be exercised on processes of socio-technical change, have a forward looking element, and be informed by real existing technological possibilities and desirable futures. We have argued for alignment policies with a clear technology element, aimed at the identification, exploration and creation of new paths. Even if these paths may not be optimal in the long term, there is a need to increase the range of technology options. Increasing the range of technology options also provides a hedge against shifts in the economic environment and against the revelation that a widely used technology poses a serious hazard. The question is then how much variety has to be created and maintained (Rip and Kemp, 1998). Evolutionary modelling provides some approximate answers but not a clear policy prescription such as the externalisation of external costs. A practical approach derives from the branched, niche-based character of technological development, which is to create semi-protected spaces for new technologies, especially pathway technologies that may lead to more sustainable trajectories. Environmental policy should not be limited to the support of environmental technologies or the control of non-sustainable ones but also be aimed at changing the current trajectories of production and consumption, bending these in more sustainable directions by exploiting identified windows of opportunity. Particular technologies and artefacts are part of larger systems, and elements of a socio-technical landscape. Policy should take into account these system elements, trends, and the strategic games that occur in society (within industry and between industry and NGOs). Evolutionary perspectives have something to offer here, but need to further developed to be of practical use.

4. 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. Since the seminal work of Nelson and Winter (1982) evolutionary approaches in economics revived and are also applied in the field of environmental economics. The added value of evolutionary approaches is that technologies are not defined in terms of a stylised input-output relationship but that technologies are ‘lumpy’ and linked with other technologies, economic activities and production and user practices and whole range of institutions that form a technological system or regime. 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

Most of 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. An important part of the evolutionary process of technological regime shifts consist of the role of niches. They act as an incubator for new technology and a stepping stone for further change--like the opening up of new domains of application and the development of a new regime in space and time. Niches are important 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.) that are necessary for the further development of a new technology or technology system. Niches help to create virtuous cycles that allow a new technology to escape lock in, by helping the technology to overcome initial barriers of high costs, the non-availability of complementary technologies and the non-alignment of a new technology to the external environment during the infancy period of a new technology when it has not yet benefited from dynamic scale and learning economies.

The added-value of evolutionary economics in the context of environmental policy lies mainly in the recognition of the way in which society is locked-in to particular unsustainable technologies. When talking about environmental technological change, policy-makers face the challenge of escaping technological lock-in to environmentally unsustainable practices and triggering a 'lock-out' away from unsustainable systems. In other words, the relevant competition processes refer not so much to (two) similar introduced technologies (as in the 1988 Arthur model) but more to the relation between an existing (dominant) polluting technology and an introduced clean technology.

Escaping lock-in into unsustainable technologies and technological systems requires policies that include the use of economic incentives but will not be limited to it. These policies would consist of an integral approach in which technological, economic, structural and cultural factors are taken into account. Such policies seems to fit better within an evolutionary than a neo-classical framework in which technology is embedded in institutional structures which are the context for learning and institutional change.

A particular policy for achieving environmental gains, that follows from the importance of niches in the technological transitions is Strategic Niche Management (SNM). It is a kind of process approach aimed at modulating the dynamics of socio-technical change through the creation and management of spaces for the use of new technology. 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. 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. It is not a substitute for existing policies, but a useful addition, which helps to increase the variety of technology options and work towards more sustainable technology systems and thus come closer to the goal of ecological modernisation, which, as stated, goes beyond the control of particular pollutants and the adoption of eco-efficiency solutions. Evolutionary perspectives have something to offer here, but need to be further developed to be of practical use.

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