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Evolutionary approaches for sustainable innovation policies: From niche to paradigm?[☆]

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ABSTRACT

Fostering technological innovation is considered as an important element of policies towards sustainable development. In the past 10 years, evolutionary policy approaches have been increasingly advocated. For several reasons, they seem well equipped to underpin sustainable innovation policies. They focus on dynamics of change and their drivers, they allow for a substantive perspective on technologies beyond mere input–output relations, taking into account trajectories and different characteristics of innovation, and they are able to describe circumstances under which established technologies might persist even when they are to some extent inferior to their new competitors (lock-in). However, the policy effectiveness of evolutionary approaches in cases in which radical or systemic changes are involved is not yet proven. In this paper we assess the theoretical rationale, instrumental aspects and the coping with policy constraints of three evolutionary policy approaches which have also been used in empirical studies: strategic niche management, transition management and time strategies. Each approach has its strengths and specific problems and all three have to be further developed and tested out but they hold promise for contributing to non-incremental change with economic and environmental benefits, by shaping processes of variation, selection and retention, with the outcomes feeding back into policy. They may also be used in other areas in which innovation direction is important, for instance health care or food.

1. Introduction

Fostering technological innovation is often considered as an important element of policies towards sustainable development. It is increasingly acknowledged that a focus on incremental innovation along established paths does not suffice for achieving demanding environmental sustainability goals such as mitigating climate change. A need for radical technological change or even system innovation has been expressed (e.g. Carrillo-Hermosilla, 2006; Freeman, 1992; Smith et al., 2005; Weaver et al., 2000). This raises the question of an appropriate policy framework for sustainable innovation policies which takes up this challenge. Its necessary scope goes clearly beyond a simple extension of an (neoclassical) environmental policy framework to account for environmental innovation. The neoclassical externality and market failure framework is useful for thinking about innovation policy, too, but as pointed out by critics one cannot define actual policies on this basis. It provides a general rationale for innovation support but it is inherently imprecise in its detailed prescriptions (Metcalfe and Georghiou, 1998). Moreover, it is basically static and abstracts from the dynamics of specific technologies.

In dealing with issues of innovation support, policy makers have often adopted a systemic view in which attention is giving to the "system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts that define new technologies" (Metcalfe, 1995, p. 38). Actual policies following from this are oriented towards improving the "national system of innovation" through the support for industry–university collaboration, training, with some of the support targeted to areas in which innovation is viewed to be needed. Concrete policies have evolved with experience, with the help of evaluation studies. They are partly theory-based, and partly experience-based. Smits and Kuhlmann (2004) speak of the co-evolution of innovation practice, intervention strategies and theory. The theory behind modern innovation policy is broadly indicated, e.g. by Mytelka and Smith (2002). It can be said to be a combination of market failure and system failure, where system failures have to do with the facilitating structure, which may be ill-developed for innovation in general or unhelpful for certain types of innovation, causing problems of adaptation and problems in the creation of novelty. Even when innovation

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policy tries to correct for market failures there is a clear commitment to markets as a mechanism for coordination, precisely because of the evolutionary process that is involved—of variation and selection of ideas, technologies, product designs, routines and institutional arrangements, with an important role for trial-and-error because optimal designs cannot be determined ex ante (cf. Nelson and Winter, 1982).

It seems therefore correct to say that broadly speaking a systemic-evolutionary view is behind actual innovation policies. Recently an interest in evolutionary aspects surfaced in actual innovation policies related to sustainability goals, too. This is most evident in the Dutch transition management policies for fostering a transition in energy technologies in an evolutionary manner, by supporting variation within a broad portfolio chosen by platforms involving business actors, government officials, academics and one environmental NGO (see Kemp and Loorbach, 2005; Loorbach, 2007).

The term evolutionary policy is new and in need of definition. In theory outside biology, the term evolutionary is often coined in relation to innovation and change (e.g. Nelson and Winter, 1982). It may refer to gradual change or to the evolutionary mechanism of variation, selection and retention (inheritance). With evolutionary policy, we mean an adaptive policy approach that is concerned with the dynamics of variation, selection and retention. The analytical foundation and scope of an evolutionary perspective on policy, however, are not straightforward. A dynamic perspective renders the dominant theoretical policy framework of static neoclassical welfare economics inappropriate (e.g. Metcalfe and Georghiou, 1998; Witt, 1996), in which the diagnosis of market failures is endogenously linked with the derivation of optimal or at least welfare-improving policies (this issue is further dealt with in Section 2). Given that a comparably specified evolutionary policy framework is still lacking, different approaches to cope with this challenge have been developed. From the mid-1990s the first tentative applications of elements of an evolutionary framework to policy issues related to environmental sustainability could be observed (Cowan and Kline, 1996; Erdmann, 1993a; Goodstein, 1995; Kemp, 1994; Schot, 1992; Schot et al., 1994). Reichel (1998) combines neoclassical and evolutionary elements in a policy framework focusing on the overcoming of barriers to the market introduction of new environmental technologies.

In recent years, three relatively well-developed evolutionary sustainable innovation policy approaches have been proposed which attempt to integrate the insights gained in innovation policy practice. The approach of "strategic niche management" highlights the importance of protected spaces and of user involvement in early technological development to create new paths which are able to replace unsustainable technologies (e.g. Hoogma et al., 2002; Kemp et al., 1998; Raven, 2005; Van der Laak et al., 2007). These insights informed the approach of "transition management" with its broader scope on system changes and system innovation, and reliance on evolving adaptive portfolios (e.g. Rotmans et al., 2001; Kemp and Loorbach, 2005). More recently, the concept of "time strategies" has been proposed which focuses on the political preparation and utilisation of time windows of opportunities in unstable phases of technological competition (e.g. Nill and Zundel, 2001; Zundel et al., 2005a).[1] All three approaches have been used as analytical framework for the empirical analysis of policies in range of empirical cases in the domains of transport, energy, construction, iron and steel production, chemicals and waste management. Also first attempts to integrate some insights from the different approaches can be observed (Foxon et al., 2005; Kemp and Zundel, 2007).

The effectiveness, however, of evolutionary policy approaches in stimulating radical or systemic sustainability innovations is not yet proven. The uptake in sustainability-oriented policy making is still moderate and mainly conferred to policy niches such as the use of transition management in the Netherlands to foster sustainable (system) innovations. Nevertheless, based on the existing analyses and an evaluation of first policy experiences, it is possible to assess their strengths, complementarities and remaining weaknesses systematically. By comparing and contrasting these three approaches, we are able to illustrate how the approaches have been conceived theoretically and how they can be or have been applied in the policy context. The purpose of the paper is to start this process of integration of the three approaches and set the agenda for other scholars to engage with as well as for further research. As contributors to the development of the three approaches we feel to be in a good position to do so.

The remainder of the paper is structured as follows. Based on the literature review, Section 2 sets out the framework and criteria of the assessment. Subsequent sections cover the three main themes of the assessment, which are: the appropriate matching of policy objectives with problem analysis in the three covered approaches (Section 3), appropriate and empirically meaningful criteria for policy evaluation (Section 4) and the coping with policy constraints with regard to information constraints and the political context (Section 5). It is shown that each approach has its strengths and specific problems and that their complementarities for contributing to radical and system innovation with sustainability benefits have not yet been fully exploited. Section 6 discusses the prospects of integrated evolutionary approaches to become a new paradigm for sustainable innovation policy and points out directions for further research.

2. An economic framework for assessing achievements and challenges of evolutionary approaches to sustainable innovation policy

An appropriate assessment framework for policy concepts needs to cover analytical soundness as well as empirical usefulness of policy approaches. We use the theory of economic policy as reference for the analytical dimensions of the assessment. Building on the seminal work of Tinbergen (1952), traditional approaches to the theory of economic policy have a normative and instrumental focus and can be described as decision-oriented "objective + means-approaches". They have been first developed in a macroeconomic context. Policy makers have the capacity to autonomously define objectives with regard to desired states of the economic system and choose corresponding means by using an explicative economic theory which contains the means as (exogenous) variable and the policy objective as endogenous variable. The economic objectives to be addressed are not determined a priori.

Neoclassical welfare economics grounded in microeconomics contributed elements of the combined definition of problems and objectives into the core of economic theory by demonstrating that under specific – and as we will see from an evolutionary perspective problematic – conditions an equilibrium attained in competitive markets exhibits desirable normative properties. The latter are contained in the concept of (Pareto-)efficiency, i.e. a state in which no economic actor can achieve a better situation without worsening the situation of other economic actors. Relevant economic problems arise and policies are only legitimate if these conditions are not met ("market failure"), e.g. if there are environmental and/or

[1] A fourth evolutionary framework for policy is offered by van den Bergh et al. (2007). It consists of evolutionary-economic principles for policy such as extended level playing field. The framework lays down a scheme for evaluating government policies (environmental, innovation and economic policy), which is applied to Dutch energy innovation policies. Lack of space prohibits us from including it fully in our discussion.

knowledge externalities. The endogenously derived policy objective is to re-establish the conditions for an ideal competitive market equilibrium (determining, e.g. the "optimal" amount of pollution or innovation). The welfare economic approach maintains that policy makers are supposed to have sufficient knowledge and hierarchical steering capabilities. Policy constraints were treated in the theory of economic policy as relevant dimension only later (for an overview see e.g. Mueller, 2003).

We argue that an analytically meaningful assessment of evolutionary policy approaches has to go beyond the objective and means dimensions and should be placed in a broader "problem + objective + means + constraints" framework (Nill, 2004a). Each of the four dimensions why?, what?, how? and what not? is important. The separation of the category "problem" from "objectives", which is common in political science, makes visible that rather specific assumptions are necessary for being able to directly derive policy objectives from the problem analysis. This has been described above for neoclassical welfare economics, which takes this direct link for granted. In a dynamic framework, explicit considerations are necessary how and to what extent such links can be theoretically defined.

The importance to consider policy constraints explicitly is also straightforward. In particular knowledge constraints are highlighted by evolutionary, in particular neo-Hayekian, policy approaches but also partly reflected as information asymmetries in neo-institutional economics. Constraints related to the political process are dealt with in a separate, non-normative approach to the theory of economic policy, public choice or economic theory of politics, which applies the economic theory of rational decisions to policy making.

Moreover, policy concepts need also to be empirically useful, i.e. categories need to be observable and applicable to practical contexts of policy making. Given the limited practical experiences with explicit evolutionary policy approaches, the assessment of this dimension cannot draw on policy evaluations but rather on the usefulness of the policy approaches as conceptual framework for the ex post analysis of empirical cases and policies.

The elements of the "problem + objective + means + constraints" framework lead to three main analytical challenges that need to be addressed by analytically underpinned policy approaches:

- Matching of policy objectives with problem analysis.
- Conceiving appropriate and empirically meaningful criteria for instrumentation.
- Coping with policy constraints with regard to uncertainty and the political context.

In the following subsections, these analytical challenges and corresponding assessment criteria are specified for the domain of sustainable innovation policies.

2.1. Matching of policy objectives with problem analysis

In neoclassical economics, problems related to the emergence and diffusion of sustainable innovations are described as double externality problem (e.g. Jaffe et al., 2005; Rennings, 2000). The policy objective is to internalise both environmental and knowledge externalities by environmental and innovation policy instruments. Beyond the well-known empirical problems to observe and measure these externalities, the analytical appropriateness of this policy framework is questionable (e.g. Hemmelskamp, 1999). For one, the problem description remains static. Moreover, in a dynamic perspective which allows for novelties, the usefulness of the Pareto criterion as norm diminishes significantly because Schumpeterian creative destruction affects some economic actors negatively (Witt, 1996). Some authors of the neo-Hayekian strand of evolutionary economics even claim that a normative evolutionary framework for policy interventions is hard to conceive (e.g. Pelikan and Wegner, 2003).

In an evolutionary perspective, relevant problems that could give rise to policy interventions are linked with dynamic features of innovation processes. As Nelson and Winter (1982) write:

> "[. . .] processes of change are continually tossing up new 'externalities' that must be dealt with in some manner or other. In a regime in which technical advance is occurring and organizational structure is evolving in response to changing patterns of demand and supply, new non-market interactions that are not contained adequately by prevailing laws and policies are almost certain to appear, and old ones may disappear. Long-lasting chemical insecticides were not a problem eighty years ago. Horse manure polluted the cities but automotive emissions did not. The canonical 'externality' problem of evolutionary theory is the generation by new technologies of benefits and costs that old institutional structures ignore" (Nelson and Winter, 1982, p. 368).

In particular the neo-Schumpeterian strand of evolutionary economics (building on the seminal work of Dosi (1982) and Nelson and Winter (1982)), allows for a substantive perspective on technologies, technological competition and socio-technical systems beyond mere input–output relations, taking into account trajectories and different types of innovation. Freeman and Perez (1988) bequeathed us the useful distinction between incremental and radical technological innovation and system innovation. The notion system may refer in this context either to large technological systems (Hughes, 1983) with a huge impact of the availability infrastructures for technology performance (e.g. energy production and distribution system and transport system) and/or systems or technological regimes of which the configuration is to a large extent shaped by institutions and social norms.[2] Also the role of path dependence in technological competition has been put to the forefront, and circumstances have been described under which technologies might persist even though they might be inferior to their competitors (a situation which Arthur (1988) termed lock-in). More recently, evolutionary-economic insights have been combined with socio-technical concepts to study technological transitions and the interaction of niches, technological regimes and other landscape factors therein (Geels, 2002).

The additional main common thread of evolutionary approaches for *sustainable* innovation policies is that they are in concerned with the problem of a lock-in of unsustainable technologies and related barriers to "major shifts of innovation direction". As Metcalfe and Georghiou (1998, p. 95) posit, these problems consist of a spillover between selection and variation that inhibits the chances of radical new technologies. Moreover, in the case of environmental innovations, some of the static environmental externalities highlighted by neoclassical environmental economics do not vanish over time but add to the forces leading to lock-in and barriers to technological regime shifts offering sustainability benefits (e.g. Ayres, 1991; Kemp and Soete, 1992; van den Bergh et al., 2007).

Cowan and Hultén (1996) and Cowan and Kline (1996) are early examples for still rather general applications of this line of

[2] Jacobsson and others take a somewhat different stance and describe the dynamics of new technologies as technological innovation systems, combining evolutionary insights with the innovation system literature. Their model involves analysis of a range of system functions for assessing their performance, and has been applied to study dynamics of environmental innovation in the energy sector (Bergek et al., 2006; Hekkert et al., 2007; Jacobsson and Bergek, 2004; see also the contribution of Markard et al., 2009). The focus is on a specific technology and how it may come into wider use, with less concern for technological competition.

thinking to the cases of electric vehicles and renewable energy.[3] For assessing if policies to overcome lock-in are justified from a societal perspective, Reichel (1998) combines the estimation of environmental externalities along neoclassical lines with the calculation of potentials for sustained cost reductions by learning and network effects to reach a self-reinforcing dynamics within a limited timeframe. He applies the framework, which he labels "lock-out efficiency", empirically to the case of renewable electricity, establishing that based on this criterion in Germany only an innovation-oriented support policy for wind energy is warranted while this is not the case for photovoltaic solar energy on a national level. However, the derivation of a clear empirical result is only achieved by setting the economic and political framework conditions as well as the environmental externalities constant, which is at odds with evolutionary approaches.

From an evolutionary perspective in which change creates its own set of problems, the idea of achieving predetermined outcomes does not make much sense, because it would assume that an optimal predetermined outcome (such as the level of emission reduction for which the marginal costs of further reduction equates the marginal benefits) can be calculated and can be achieved through the use of policy. Rather, in an evolutionary world of surprise and lock-in, the main task for policy is to concern itself with problematic processes of variation and selection, to ensure that their operation is advantageous for society at large and to adjust policies to new problems that can be expected. The need for policy support may disappear over time (when technical innovations benefit from learning economics or support from private actors). Besides a need for support, there is also a need for control (to contain the side-effects of new technologies) and for stimulating competition between various options. The corresponding *sustainable* innovation policy objectives are to mitigate and to escape environmentally harmful lock-in by modulating the dynamics of variation and selection.[4] While from this problem diagnosis process-oriented policy goals can be derived, not much can be said on the level of outcome-oriented objectives, e.g. with regard to the desirable state of the environment.

Assessment criteria for evolutionary approaches to sustainable innovation policy are hence

- the clarity and completeness of the problem analysis with regard to coverage of relevant innovation dynamics.
- the consistency and match of policy objectives with the dynamic problem analysis and
- the potential of the approaches for orienting innovations and innovation processes to sustainable development goals.

2.2. Conceiving appropriate and empirically meaningful criteria for policy design

Only in the static world of neoclassical equilibrium, the Pareto norm that frames the policy objective can also be used as distinctive criteria for policy design and instrumentation. In a heterogeneous world characterised by uncertainty, path dependence and co-evolution of technology and society, the Pareto norm is less relevant. Market selection based on short-term gains may lead to suboptimal outcomes. Of the new solutions available those that fit existing regimes have advantages over more radical innovations which require multiple changes. A common thread of evolutionary approaches with regard to design and instrumentation of sustainable innovation policies is therefore that political changes of relative prices alone, e.g. by environmental taxes, as advocated by neoclassical approaches, are limited in their effects on innovation (Erdmann, 1993a; Polenz, 2004). Other instruments and diverse contexts such as the status of technological competition and innovation dynamics need also to be considered. Cowan and Kline (1996) mention the role of regulation, R&D support and the creation of niche markets, e.g. by public procurement. Goodstein (1995) advocates time-limited direct support of new solutions and Könnöla et al. (2006) explore the potential of prospective voluntary agreements for escaping lock-in.

Explicit criteria that allow discrimination between different policy alternatives would be desirable. Neoclassical economics has recognised the limits of a static (Pareto-) efficiency criterion in the context of innovation processes. In neoclassical environmental innovation economics there have been attempts to substitute it by a criterion of "dynamic efficiency". However, under closer inspection this criterion boils down to a mere effectiveness criterion with regard to the innovation impact of policy instruments (low and high), as derived from abstract theorizing. However, up to now there is still a lack of an agreed normative evolutionary substitute of the Pareto-efficiency criterion.

Erdmann (1993b) proposes as criterion of "evolutionary efficiency" that a limited policy impulse leads to a durable switch to the environmentally less harmful technology. Foxon et al. (2005) rather propose to add three evolutionary criteria to a conventional neoclassical assessment of policy instruments: (1) overcoming lock-in, (2) contributing to niche development, and (3) promoting technological diversity. Also the evolutionary-economic criteria advanced by van den Bergh et al. (2007) are meant to complement the neoclassical criterion that prices should reflect social costs. However, these proposals only partly cover the time dimension and its implications. Implementation strategies need to strike the right balance between initial stimulation of not yet competitive variations with sustainability benefits to ensure and enhance diversity and the use of selection pressures to gear these to individual and collective needs. The often highlighted evolutionary principle that policy should stimulate variety and interactive learning (e.g. Rammel and van den Bergh, 2003; Foxon et al., 2005) is not yet a full-fledged implementation strategy and may even, as the time-strategic approach suggests (see below), not always be appropriate. Possible trade-offs need to be dealt with.

For policy design and instruments, assessment criteria for evolutionary approaches to sustainable innovation policy are therefore

- the balancing of support and competition in implementation and
- positive experiences with regard to empirical applications.

2.3. Coping with policy constraints with regard to uncertainty and the political context

If policy makers take up evolutionary insights and venture in a more process-oriented and context-adapted policy approach, they require knowledge for assessing the nature and extent of problems, determining objectives and choosing appropriate means. Some of this knowledge is unlikely to be readily available. Limitations of knowledge are at the core of evolutionary theories of economic and technological change and give rise to the dilemma of control (Collingridge, 1980) and "blind giant" problem (David, 1987).[5] Some evolutionary approaches in the Hayekian tradition take this issue

[3] See also Goodstein (1995) and Unruh (2000) for further applications to energy and transport.

[4] Policy may also concern itself with the nexus between variation and selection (Rip and Schot, 2002; Schot et al., 1994; Van den Belt and Rip, 1987). The approach of strategic niche management follows this line of thinking.

[5] Both concepts point out that political intervention is potentially very powerful in early phases of technology development, but that precisely in that phase the state is like a blind giant and lacks the necessary knowledge.

of systematic knowledge constraints as basis for a critical stance towards active innovation policies (see e.g. Wegner, 1997). Erdmann (1993b) bases his plea for the general duration limitation of policy interventions on the importance of knowledge constraints. An important corollary is that policy makers accept that in a dynamic world policy is fallible and therefore in need of adaptation.

But even if policy knowledge is sufficient for attempting a "probe and learn" oriented evolutionary policy making, there is also a second element, which is that policy is not separate from societal dynamics, including the dynamics of specific innovation trajectories, but is part and parcel of these dynamics. At a minimum it means that policy is not formulated independent from political agendas and business wants. It has to cope with distributed power (Voß et al., 2007). This means that policy needs opportunities for action to overcome opposition from established actors who stand to lose from such policies (see e.g. Unruh, 2002) but also to phase out policy support when such support is viewed no longer desirable. David (1987) speaks of the "angry orphans" who may mobilise political pressure for continuing support. As a partial remedy, the use of rules such as duration limitations for support policies is suggested to maintain adaptive flexibility of policies (see also Goodstein, 1995).

Assessment criteria for evolutionary approaches to sustainable innovation policy are thus

- to what extent they cope in theory with such policy constraints and
- how such policy constraints are dealt with in practical applications.

On the basis of the specified assessment criteria, the three evolutionary policy approaches strategic niche management, transition management as well as time strategies are assessed n the following with regard to the three analytical challenges set out above.

3. Matching of policy objectives with problem analysis

3.1. Strategic niche management

The idea of using niches for creating a transition path to a new technological regime is the basic idea behind "strategic niche management" (SNM). SNM is an evolutionary approach aiming at fostering innovations with sustainability benefits and the securing the sustainability of those innovations. Support and control (through selection pressure) have a role to play in this. The literature very much focuses on the use of societal experiments. Specifically, SNM is the creation and management of protected spaces (niches) for promising technologies by means of experimentation with the aim of learning about the performance, effects, economic viability and social desirability of the technology and to use this knowledge to inform private and public (support and control) policies that are needed for the further development and rate of application of new technologies and technology systems (Kemp et al., 2000, p. 170).

Policy support is needed and warranted because new technologies are often only promises. As the studies of Rosenberg (1982) and many others have shown, at the beginning of its development, a new product or new technology system is far from perfect and the environment may be ill-adapted to its use. The new technology has to be improved in term of meeting user needs; the producer must learn how to produce it efficiently and align their organisation to the new product. The innovation may also require complementary technology and new infrastructure for its production and use, adaptation of users as well as changes in the framework conditions. The case for SNM can be said to be firmly established for experiments and for innovations offering sustainability benefits, where there is a clear case for support (for more detailed arguments see Kemp et al., 1998; Weber and Dorda, 1999). For the evaluation of the latter, partly arguments of neoclassical environmental economics are used.

Protection may be offered by private and public actors: by suppliers, development and regulatory agencies, local authorities and/or users. SNM is a strategy to escape lock-in by fostering learning processes and processes of socio-technical alignment. The idea of SNM for new technologies comes from the literature on sequential decision making to deal with complexity (Simon, 1957), trial-and-error modes of learning, evolutionary theories of technical change (Nelson and Winter, 1982; Rip and Kemp, 1998), and studies on the critical role of users in innovation (von Hippel, 1988).

The main policy objectives are process oriented: learning and facilitating virtuous cycles for change. The policy objective is not to achieve a certain outcome in terms of technology use. The desirability of the innovation is something to be tested and cannot be taken for granted. Policy could assist in the generation and dissemination of lessons through the use of special programmes in which not only the market aspects of various configurations are investigated but also the sustainability aspects. These assessments should feed into the technology development process (as in the constructive technology assessment model of Rip et al. (1995)).

Strategic niche management is advocated as an evolutionary element for system-oriented transition policy by Kemp et al. (1998) and Hoogma et al. (2002) but criticised by Berkhout et al. (2004) for being too much of a bottom-up strategy. The criticism is also supported by the fact that some good niche strategies (e.g. Swiss electric cars) were not enough to reach a successful technological transition, causing doubt about the potential of SNM as a standalone tool for transition. Nonetheless, SNM can be viewed as useful for generating learning about needs, technology imperfections and strategies to overcome these (Hoogma et al., 2002; Van der Laak et al., 2007). It may help to build actor networks but appears insufficient to overthrow well-established stable regimes (see Raven, 2005; Smith, 2004). A specification of external determinants of niches and their growth beyond the emphasised internal dynamics would be helpful to clarify the possible application scope of SNM strategies.

3.2. Transition management

Transition management is a model for fostering sustainability transitions to deal with persistent problems that require system innovation (Kemp and Loorbach, 2005; Loorbach and Kemp, 2007; Loorbach, 2007; Rotmans et al., 2001). The problem diagnosis behind transition management is that persistent problems such as greenhouse gas emissions from combustion of fossil fuels require fundamental changes in the systems of production and consumption. The scope is thus on system innovation (in the area of energy supply these might consist of the widespread application of microcogeneration systems in homes and a large-scale hydrogen-based system). In early work (Rotmans et al., 2001) it was said that transition management is oriented towards system optimisation *and* system innovation, but in later work it was stated that transition management is a model for system innovation. The narrower focus was criticised by Smith et al. (2005) who argued that persistent problems might also be dealt with through system improvements: a greening of existing trajectories.

Transition management is a new steering concept that relies on 'darwinistic' processes of variation and selection rather than the 'intelligence' of planning (Kemp et al., 2007a). It makes use of "bottom-up" developments and long-term goals both at the national and local level and is not so much concerned with specific outcomes but rather with mechanisms of change. The basic philosophy is that of *goal-oriented modulation*: the utilisation of ongoing developments for societal goals, with the aim to achieve a societally desirable transition. Various transition paths are explored simultaneously to avoid lock-in to certain paths. A mechanism of self-correction based on policy learning and social learning is part of transition management. It offers a framework for policy integration, helping different political actors to collaborate. Key elements are (Kemp and Rotmans, forthcoming; Rotmans et al., 2001):

- Long-term thinking (at least 25 years) as a framework for short-term action.
- Thinking in terms of multiple domains (for example, energy, transport and waste).
- A focus on learning and a special learning philosophy (learning-by-doing and doing-by-learning).
- Learning about a variety of options (which requires a wide playing field instead of a level playing field).

The focus on sustainability goals and use of adaptive policies using dynamic portfolios makes it an evolutionary policy approach for fostering sustainability transitions. There is a great deal of attention to aspects of governance. The business interest in innovation and societal interest in sustainable development is exploited through the creation of special innovation platforms and support for selected transition paths. Transition management is a multi-level model of governance for shaping processes of co-evolution using visions, transition experiments and cycles of learning and adaptation (Kemp et al., 2007b). It is being used in the Netherlands by the national government as a model for sustainable innovation.

The very idea of the management of transitions has been criticised by Elzen et al. (2004) and Shove and Walker (2007), saying that transitions – as processes of co-evolution – cannot be managed. This is actually accepted by Dutch authorities, who see themselves as shapers of change processes rather than as transition managers; they are avoiding the term management: they talk about the transition approach instead of transition management.

3.3. *Time strategies*

The time-strategic evolutionary policy approach starts from the diagnosis of a possible lock-in problem that hinders the market introduction and diffusion of environmental technologies. In addition it takes into account that the extent of lock-in and path dependence may vary over time, and stable and unstable phases of technological competition alternate (see column "status of the techno-economic system" in Table 1). Correspondingly, political opportunities for environmental innovation policies depend on the underlying techno-economic dynamics. Building on David (1987) and Erdmann (1993b), the often loosely used notion of "windows of opportunity" is specified as guiding concept in a cooperative research project of several German research institutions and MERIT (e.g. Erdmann et al., 2007; Nill and Zundel, 2001; Zundel et al., 2005a). Given that this approach mostly developed in Germany is less known internationally, it is presented in the following in a bit more detail. Techno-economic windows (of opportunity) are defined as the unstable phases of technological competition in which an established technology path becomes unstable due to external factors or internal problems (e.g. discovery that it is not sustainable) and new solutions become competitive. In the case of environmental policy, usually old-vs-new technological competition is the general framework. New-vs-new competition driven by increasing returns to adoption, however, which is the focus of the concepts of David (1987) and Arthur (1988), may also be important in such unstable phases in technological evolution and may contribute to the shaping of techno-economic windows.

The time-strategic approach to environmental innovation policy attempts to exploit these uneven techno-economic dynamics in order to make transitions towards more sustainable technologies easier. It does not pretend to be applicable as such to system innovations. A taxonomy and a range of determinants to assess the stability of the techno-economic system have been developed. Three corresponding policy strategies are specified and briefly outlined below that are linked with adapted policy objectives in accordance with the diagnosed time-dependent states (see Table 1):

- window preparation,
- window creation and
- window utilisation.

Political interventions are better justified if techno-economic windows can be envisaged and hence evolutionary market forces can be built upon. Policy objectives are specified in relation to the state of the techno-economic system. For these strategies, dynamics in the socio-cultural and the political system and their interaction are also taken into account:

- If the situation is characterised by a stable old path, but the existence of at least one promising solution, *window preparation* policies are appropriate. These can extend market forces. The stimulation of a diversity of technological alternatives and of the development of promising solutions towards competitiveness are main policy objectives which contribute both to the preparation of and for techno-economic windows. However, the value of the support of enhanced diversity is seen as of limited use when a

Table 1
Taxonomy of techno-economic dynamics and related policy objectives.

Status of the techno-economic system	Status of technological alternatives	Kind of technological competition	Policy strategies and objectives
Stable	Only theoretical alternatives exist	Not applicable	Demonstration of technical feasibility
(Still) stable	Promising solutions	Only new-vs-new	"Window preparation": diversity and development
Stable (but strong social pressure for quick path change)	Promising solutions	Not applicable	"Window creation": handling of political pressure
Unstable (window)	At least one solution is competitive	Old-vs-new and new-vs-new	"Window utilisation": making transition easier and avoiding rush selection
Unstable (window)	Only one alternative solution is competitive, but other promising solutions for the future	Mainly old-vs-new	"Window utilisation": making transition easier
Unstable (window)	Several alternative solutions are competitive	Mainly new-vs-new	"Window utilisation": avoiding rush selection
Stable	Transition takes place	Not applicable	Restoring selection function of markets

Source: Zundel et al. (2005b, p. 329), adapted.

techno-economic window in the competition with established technologies is emerging, hence it is linked to the state of techno-economic dynamics.
- If in the same situation there is strong social or (international) political pressure to act, government may be forced to apply *window creation* policies. In this case the government has to deal with strongly opposing market forces. There is the danger that quick fixes are used that benefit add-on-technologies or the retrofitting of existing technologies instead of the development of more radical alternative solutions. Government must hence balance the social pressure for a quick solution needed for political support, which determines the length of the political window, and the time period needed for more far-reaching solutions.
- If the old path is unstable or at least a techno-economic window can be anticipated and at least one new solution becomes competitive to some extent, *window-utilisation* policies can be applied. Fundamentally a technological transition is now possible and the government's target may now be to facilitate this transition by appropriately influencing the selection environment. If there are other new and potentially more promising solutions that have not attained competitiveness yet, a rush selection of the solution of which the development is most advanced needs to be avoided. However, given the market forces towards selection, there may be a trade-off between diversity and facilitating transition.

However, elements of a substantive assessment of the sustainability of different competing technologies have only been partly conducted as part of the time-strategic framework. The existence respectively political or societal agreement about the underlying sustainability problem as such is taken as given, although some first steps towards a new framing of the normative debate have been undertaken by introducing the concept of "second order sustainability" (Sartorius, 2006) by which the adaptive flexibility of the techno-economic system is emphasised as necessary (but not sufficient) condition for an effective working of trial-and-error processes towards sustainability. The concept is still mainly qualitative. Finally, an ex ante test with regard to practical innovation policies is still lacking.

3.4. Comparative summary

All three approaches succeed in a dynamical problem conceptualisation which is matched with corresponding policy strategies which focus more on process-related than outcome-oriented objectives. Sustainability problems are mostly taken as exogenous starting point. Time strategies focus on the lock-in of a specific technology path and ways to enhance radical innovation to overcome such a lock-in and foster a transition between technology paths. Strategic niche management has been used both as tool for fostering radical technological change as well as contribution to overcome a lock-in which is rather located at the system level, while transition management addresses mainly the level of system innovations. In the case of SNM empirical insights gained so far confirm the usefulness of the approach as such but point to limits of pursuing it as a stand-alone policy approach, at least for fostering system innovation. Transition management and the time-strategic approach appear at least in theory more comprehensive with respect to escaping lock-in.

4. Conceiving appropriate and empirically meaningful criteria for policy instrumentation

4.1. Strategic niche management

A first important issue of SNM implementation involves the selection of technologies and project places. According to the literature, technologies are suited for SNM if they:

- have significant development potential and a synergy with ongoing developments (like the evolution of user preferences and societal values, policy developments, areas of rapid technical advances);
- are attractive to use for certain applications in which the disadvantages of the new technology count less and the advantages are valued high (Kemp et al., 2000).

The selection is to be done in a combined top-down and bottom-up manner, based on visions for system innovation and local interest in the new technology or system. It is important that there is also an industrial interest but the choice of the niche technology should not be exclusively based on industrial interest (Kemp et al., 1998). The place of experimentation could be chosen as part of an open selection process. By carefully choosing an appropriate domain, the costs may be kept low. Some places provide a natural niche for a new innovation, reducing the need for support. For instance, electric vehicles are attractive for use in polluted urban areas and within fleets where maintenance and short range are less of a problem. It also appears useful to undertake experiments in different settings because this helps to learn about conditions for success (Hoogma et al., 2002). Empirical experiences with the intentional selection of SNM experiments are still scarce. In the Netherlands, SNM is being used for energy technologies under the so-called "unique chances subsidy instrument" (UKR), a special scheme for transition experiments. To be eligible for support, the experiment has to fit an official transition path of the Dutch energy transition, it should be led by a market actor, and should contribute to greenhouse gas reductions.

The balancing of support for initial development and the maintenance of selection pressure is a key element of the implementation of strategic niche management. Support should be temporary and should be phased out over time. Selection pressures are needed for dealing with side-effects and for helping the technology to progress along the learning curve, which requires money and effort. If the case of Dutch wind power is analysed from a SNM perspective, the support was too generous, causing the Dutch manufacturers to stick with a suboptimal design (Kamp, 2002; Verbong et al., 2001).

Main criteria for the extension of an experiment into a niche are the confirmation of expectations, extent and breadth of learning, network formation and institutional embedding (Hoogma et al., 2002; Raven, 2005). Operational aspects for how to expand an experiment into a niche and how to organise protection as well as explicit criteria for implementation choices remain to be worked out (Caniëls and Romijn, 2008). Some useful heuristics for dealing with trade-offs in the management process are being offered by Weber and Dorda (1999) on the basis of an analysis of a range of experiments in the transport sector:

- Awareness of changing requirements in terms of network structure in the course of the progress and scaling-up of the experiment is required.
- It should be considered, which kinds of complementary policies could be conducive, necessary or detrimental to the niche technology/concept.
- The technology or concept needs to be adapted to mass users when the niche is growing.[6]

That this adaptation is not an easy process and depends a lot on the context of the regime or selection environment has been

[6] Van der Laak et al. (2007) offer similar conclusions based on an analysis of biofuels experiments and the literature review.

highlighted by recent contributions (e.g. Caniëls and Romijn, 2008; Raven, 2005; Smith et al., 2005).

An assessment of the balancing of support and selection pressures has been undertaken by Hoogma et al. (2002) for transport innovations and by Van der Laak et al. (2007) for biofuels. In the case of biofuels tax exemptions were granted up to a certain level. In one case tax exemption was temporary repealed. Sustainability aspects could have received more attention by the actors involved. In that sense, selection pressure was too weak but the projects had to deal with strong economic pressures. The balancing of support and selection pressure will remain a thorny problem, as this has to be determined on an individual basis in an ongoing way, which creates a problem for subsidy schemes working with fixed rules.

4.2. *Transition management*

Building upon ideas from SNM, transition management seeks to provide support for system innovations offering sustainability benefits. Actors interested in green system innovations are being brought together in special transition arena, which also involve experts and people from government and civil society. Within the arenas issues of sustainability and ideas for system innovation are being discussed, leading to the selection of transition paths, eligible for special support by policy. The transition arenas operate separate from regular policy arenas but the activities of the arenas should influence regular policy. There is competition in the platforms between various options and competition between the various paths. Initially the competition is weak: a broad portfolio is selected. But competition will become stronger, when money is to be targeted towards a smaller set of options.

It is interesting to analyse the policy developments in the Netherlands that occurred in the name of transition management. For the energy transition six platforms were created. For transition experiments a special instrument was created, the “unique chances subsidy scheme” (see Section 4.1). Government also supported the creation of transition coalitions. These things fitted with the transition management model. Protection afforded to actual transition experiment projects was relatively weak: the government funded up to 40% of the extra-costs of transition experiments. Market actors had to carry normal market costs and at least 60% of the extra-costs.

The number of official transition paths eligible for support is 30 (from 26 in 2006), a high number. The government wants to reduce this, because it cannot financially support so many paths. It tries to involve venture capitalists in the process, especially the institutional investors. The ideology is that the process must be market-led. Sustainability aspects are considered in the choice of paths and experiments but it is hard to deal with all relevant aspects on an ongoing basis. Carbon reductions are a criterion for the choice of transition experiments and probably will be used as an important criterion in future support policy.

Transition management should serve as a vehicle for policy integration, and indeed a first step into this direction is taken through the creation of the interdepartmental programme directorate (IPE) bringing together Director generals from six ministries, but it is hard to say how far the integration will go and what it will bring.

4.3. *Time strategies*

Instrumentation is covered in the time-strategic approach by two policy guidelines. One is that appropriate instrumentation is not so much conceived as a question of instrument choice, but of instrument design, intensity and timing with respect to techno-economic dynamics. A second policy guideline is that an assessment of the technological consequences of seemingly technology-neutral framework instruments is warranted, as far as possible on the basis of information available (Zundel et al., 2005a, pp. 343–344). In other words: the “dynamic efficiency” or innovation impact of policy instruments is also a function of evolutionary dynamics. Beyond economic and political feasibility, the main general criterion proposed is an appropriate balance between clear signals pointing to transition and adjustment flexibility. An instrument mix of the use of environmental policy framework instruments with a moderate intervention level and specific window-oriented instruments targeted at specific innovation dynamics is seen as appropriate time-strategic approach (e.g. Nill, 2004b).

Further aspects of instrumentation are conceived in tune with the different strategies described in Section 3.3. For *window preparation*, the creation of niches for or the support of new alternatives is advocated as one possible approach, with reference to strategic niche management (Zundel et al., 2005a). Unlike in SNM, market niches are treated as exogenous determinant, which can help in destabilising a lock-in when used properly, but niche dynamics are not conceptually reflected in much detail. Not the protection of alternatives but the conditions of its competitiveness with established technologies over time are put to the forefront. For *window utilisation*, instruments need to be flexible and open for fine-tuning. In some empirical cases, investment subsidies proved an adequate element. Also instruments aimed at altering the economic framework conditions (such as environmental taxes and emission trading) can be instrumental in this respect. They can also hinder window utilisation if incumbent technologies are exempted or if due to lack of stringency of the intervention mainly low-cost solutions are favoured. These considerations can be illustrated at the case of energy-efficient housing in Germany (see Box 1).

A time-strategic policy concept has been successfully applied as analytical device for the assessment of a range of empirical ex post case studies of policy interventions such as CFCs, chlorine-alkali-electrolysis, lean-burn-engine vs catalytic converter, combined-cycle gas turbines and iron production technologies (see the various contributions in Sartorius and Zundel (2005)). Detailed time strategies have been developed for three practical cases (see Nill, 2004b; Sartorius, 2007; Weiner and Zundel, 2004). Among other issues, the importance of “promising solutions” as a starting point for successful window preparation policies has been empirically demonstrated (Zundel et al., 2005a). Policies that tried to enhance path changes without the existence of such promising solutions failed (e.g. EDTA substitution).

Not much work has been done on the issue of the selection of supported technologies, which is of course linked to issues related to an appropriate sustainability assessment. It is, however, recognised that better and more robust criteria and tools are needed for dealing conceptually and empirically with the possible trade-off between diversity and specialisation. This holds in particular if public budgets are limited, which may temporarily threaten diversity if strong increasing returns are involved.

4.4. *Comparative summary*

The approaches highlight different issues with regard to policy instrumentation and implementation, e.g. concerning the balance between support and competition. The empirical studies of strategic niche management focus mostly on the early phases within niches and point to the need of both support and competition (selection pressure). Transition management builds on these insights and elements of an application are observable in the Netherlands. Positive empirical experiences with regard to later phases of niche dynamics are limited. Time strategies take competitive selection as a reference and develop a phase-dependent implementation strategy, limiting the importance of diversity creation to early phases in which no techno-economic window is approaching yet. However, while some empirical illustrations are

Box 1. Window preparation and window utilisation: the case of energy-efficient housing

In Germany, conventional housings have been gradually improved towards a kind of low energy standard, now defined by the energy saving ordinance of 2002 (70–110 kWh end energy per m^2 per year). But in parallel, at the innovation frontier much larger steps are in sight. In particular passive housing emerged as a potential new path, enabling much lower energy consumption (below 15 kWh/(m^2 a)) for heating at a reasonable cost, while also some more incremental innovations were boosted (for details see Haum and Nill, 2004; Nill, 2004b). The first commercial passive houses were sometimes supported at the State level. In 1999 there was a first boost of the new path. Policy supported the new solution by redirecting an existing premium loan programme for new private housings from low energy housing to passive housing, what can be called a *window preparing* policy. It supported more than 300 houses in 1999 and more than 500 houses in 2000 and thus supported stabilisation and expansion of the niche. It is worth mentioning that since 1999 in the framework of the so-called ecological tax reform also the tax on gas and heating oil has been raised to some extent. Expert interviews, however, accord more importance to the subsidies than the tax changes. In effects there were some elements of a niche management policy present, mainly carried out by the administrative part of the political system, which was open to the innovation dynamics.

In 2001 the building performance standards have been changed from end energy to primary energy use, creating more favourable conditions for the integration of renewable energy heating systems. Since then, also the more incremental new option of the so-called 3 l houses (30 kWh/(m^2 a)) is backed, albeit with less favourable interest rate conditions. In October 2002 the re-elected red-green German government stated the ambition to create an incentive programme for 30.000 passive houses and thus to *utilise* the emerging *techno-economic window*. Originally it was intended as capital subsidy. Due to budget constraints and administrative problems of creating a new scheme, it has been implemented only to a limited extent, by the way of changing the financial conditions of the premium loan scheme in May 2003. The incentive was now better than before, but with some State schemes being reduced at the same time and another capital subsidy being stopped, the effects remained below the ambition. What has been observable is a clear effect of the availability of subsidies also for less energy-efficient houses, which were reintroduced following demands of construction industry. In 2005 more than 6700 approved houses of the less ambitious standard nearly doubled the 3800 accommodation units of passive house standard or technologies reaching an equivalent primary energy use of 40 kWh/(m^2 a) based on renewable heating. From a time-strategic perspective it has been a questionable window-utilising policy, because it may reduce incentives for more ambitious new solutions. A credible transition strategy is still missing—with regard to the strength of the impulse as well as to time limitations of the instruments. Moreover, in the decentralised housing market, the critical phase of competition is diffusion beyond a niche, and for this subsidies are a quite expensive instrument. More stringent framework instruments like energy taxes would influence the old and new paths at the same time. However, for the latter no political window could be discerned.

promising, a true empirical test of the time-strategic approach is still lacking.

Robust criteria for the selection of target innovations and implementation choices are only partly developed yet. Maintenance of selection pressure and a decrease in the diversity of options over time are important elements. Costs of diversity are only partly taken into account (Jacob, 2007). Insights gained up to now seem by and large complementary. For example, SNM provides insights into internal success conditions for niche dynamics while time strategies provide a policy context when these dynamics might influence the wider selection process.

5. Coping with policy constraints with regard to uncertainty and the political context

5.1. Strategic niche management

An advantage of the SNM approach is that knowledge gaps can be directly addressed through the use of experimentation. Learning is an explicit goal of strategic niche management, which is based on a probe and learning approach, a strategy that proved very successful for non-environmental innovations such as mobile phones and computer axial tomography for 3D scans (Lynn et al., 1996). It aims to address systematic uncertainty about user needs, markets and sustainability benefits and risks. But learning does not occur automatically and may be partial or poorly transferred. This was the case in the experiments in the transport sector described in Hoogma et al. (2002, p. 191), where much was learned about user acceptance, technical imperfections and so on, but very little was learned about how policy makers and other actors could be enrolled in the process. The experiments furthermore learned little about wider system aspects (complementary innovations, how they could be sold as part of packages and skills and institutional changes necessary for wider use). The projects generally failed to build broad platforms for interaction and achieving societal embedding. There was too much of a technology push (Hoogma et al., 2002, p. 193).

Political will to support experiments is high and does not constitute a constraint but often they are undertaken as one-off events and there is a danger that policy attention ends when the experiment is finished (e.g. Hoogma et al., 2002). In view of political success conditions, the role of the experiments goes beyond a technology test. To be really successful it should set in motion processes of institutional embedding (create new or broader coalitions, gain support and acceptance and become part of actor's frames and every day practices, see Kemp et al., 1998). The experiment and system innovation of which it is part should be linked to the policy process at different levels (local, national and supranational).

Kemp et al. (1998) recognise that the elimination of support as part of SNM is politically difficult because it is strongly resented by business who want continued support for many years to safeguard investments (see also David, 1987). To limit opportunistic use of support, some guidance in the form of rules is needed, e.g. with respect to a limited duration as proposed in other above-mentioned evolutionary approaches.

5.2. Transition management

Transition management theorists state that transition management is developed as a policy approach for dealing with problems of uncertainty and complexity (Rotmans et al., 2001). Visioning should help to identify attractive system innovations and the commitment to transitions should help to create policy change. The empowerment of outsiders and experiences with transition experiments should help set in motion institutional change, including policy change. Something like this is indeed happening. Special transition platforms have been created and transition policies are being formulated. For discussing transition issues among various departments and to foster collaboration a directorate is created (IPE). The impulse for the directorate came from stakeholders involved in the energy transition who developed pressure on government to re-organise policies and combine them (Kern and Smith, 2007). The creation of such a directorate is an example of endogenous institutionalisation.

Several commentators expressed doubts about the possibility to deliberately shift technologies, practices and social arrangements onto a more sustainable track (Elzen et al., 2004; Jacob, 2007; Shove and Walker, 2007). Indeed this is not an easy task in the face of distributed power, diverging views, short-terminism on the part of politics, business actors and consumers. A more elaborate discussion of how the model of transition management can deal with dilemmas for steering is given in Kemp et al. (2007b) and Rotmans and Kemp (2008). Notwithstanding the suggestions given with regard to how to deal with constraints, it remains true that a further specification of transition management in particular with regard to knowledge and policy process-oriented constraints is needed (Beckenbach, 2007; Smith et al., 2005). It also remains to be seen whether it will be politically possible to apply transition management in its present conception in large countries and federal states, representing different political systems.

5.3. Time strategies

Appropriate time strategies need the assessment of a range of information concerning the techno-economic system and its dynamics. Hence monitoring of techno-economic dynamics and an emphasis on reversibility of time strategies are two of the guiding policy principles (Zundel et al., 2005a, pp. 343, 346). The empirical cases show that it seems to be possible not only for economic but also for political actors to discern technology paths and techno-economic windows and to act broadly consistently with these dynamics (e.g. iron and steel technologies in the Netherlands, housing in Germany, CFC substitutes). However, as it is not always possible to underpin this by a robust information base, a trial-and-error element will remain. Nevertheless, the information basis seems sufficient to avoid with considerable probability the pathological cases of evolutionary policy making under information constraints described by Wegner (1997), i.e. substitutive or innovative reactions of economic actors which contradict the policy objectives. These are promising answers to the doubt raised by Jacob (2007) concerning the ex ante recognition of windows.

Time strategies in environmental innovation policy are demanding in terms of the abilities of political and administrative actors to manage dynamic processes. Political capabilities to react to these dynamics are observable in the empirical cases, albeit considerable improvements can be envisaged (e.g. in dealing with the irreducible possibility of failure). And of course, successful time strategies depend on policy entrepreneurs to act upon the opportunities.

Moreover, the concept is able to conceive the dynamics of the political process not only as a restriction for time-strategic innovation policy. Political dynamics are also regarded as a resource for the strategy implementation against resistance of actors linked with old paths. The corresponding policy guideline is to use synergies with socio-cultural and political time windows (Zundel et al., 2005a, p. 345). The empirical studies show, however, that a full treatment of all systems requires quite extensive work. Robust information on dynamics within the political systems and political-economic constraints linked with the role of actors embedded in established technology paths are sometimes difficult to obtain. At least for window preparation policies, however, the latter constraints did not turn out as main obstacle, as for example the German case of low energy housing demonstrated (Haum and Nill, 2004).

5.4. Comparative summary

Policy makers need considerable knowledge about technology dynamics and their potential economic and environmental effects to implement evolutionary sustainable innovation policies. Some of this knowledge is not readily available even if monitoring systems are in place. However, these knowledge limits did not turn out to be key bottlenecks in the empirical cases presented. This might relate to the fact that mostly mature, less dynamic technology fields like energy, transport, iron and steel production or construction are dealt with. However, these are precisely those fields with the highest environmental impact (for an extensive analysis see e.g. Binder, 2001).

The political context for adaptive policy strategies has often not been treated in detail in the empirical studies. The time-strategic approach to discuss the role of political and social pressure in terms of interaction between different systems and windows might be a good starting point for doing so. The application of transition management and elements of strategic niche management in the Netherlands shows that policy-related constraints can be overcome in suitable contexts. However, more research on the preconditions in the political system for implementing adaptive policy and experimental strategies is warranted. First empirical results on the time-strategic approach and some applications of strategic niche management indicate that also in countries beyond the Netherlands and its “polder model” suitable contexts for appropriately adapted evolutionary approaches exist.

6. Prospects of evolutionary approaches to sustainable innovation policy

Evolutionary approaches to sustainable innovation policy as discussed in this paper have already successfully conquered a niche in policy analysis. Evolutionary arguments and elements are included into general studies and treatments on sustainable innovation policy (e.g. Foxon et al., 2005; Freeman and Soete, 1997; Hemmelskamp, 1999; Rammel and van den Bergh, 2003; van den Bergh et al., 2007) as well as in sector- and partly also instrument-specific analyses (e.g. the contributions in Klemmer (1999) and van den Bergh et al., 2007). Transition management, some elements of strategic niche management and implicitly also time-strategic elements, have been applied in environmental innovation policies. Evolutionary perspectives can be expected to gain importance in policy analysis when attention shifts either towards radical process and product technologies and/or to system changes as ways to work towards sustainable development.

For stimulating *radical technological change* there is a huge potential for an *integrated evolutionary approach* as paradigm for sustainable innovation policies, if it aptly builds and expands on the complementarities of niche management and time strategies, in particular by better specifying and addressing the interaction of niche dynamics and wider selection dynamics over time (for further elaboration, see Nill, 2009). The evolutionary models put into perspective the competition between those solutions favoured by regime actors and radical solutions often favoured by outsiders. Policy may nurture the niches and help them to grow in a world geared to regime technologies and practices. For dealing with barriers to the innovation trajectory, the integration of elements from the work on technological innovation systems (Jacobsson and Bergek, 2004; Hekkert et al., 2007) may prove useful. Reaching this competition phase, however, will depend on the performance level achieved by new technologies.

As long as promising radical innovations exist but have not yet reached a competitive performance level, window preparation strategies are the appropriate policy target and niche dynamics are the locus of technological dynamics. Strategic niche management is an appropriate strategy, if the selection environment affords some market pull. If the market pull is low, the importance of general environmental policy instruments like emission trading or environmental taxes increases.

An integrated evolutionary approach to sustainable innovation policy avoids technology forcing but builds and leverages on the dynamic forces of market competition. Information requirements do create problems but these do not always constitute insurmountable problems.

Especially in the case of sustainability problems in large technological systems and the need for *system innovation*, a further development of *transition management* by integrating insights of the other evolutionary approaches seems to be a promising prospect. A long-term perspective is crucial. Portfolio approaches help to create adaptive flexibility and avoid lock-in to new solutions. Sustainability aspects can be factored into the choice of these portfolios and the support given for individual solutions through the use of sustainability criteria. For strategic niche management, this integration into transition management has already taken place to a significant extent (see Loorbach, 2007).

More generally, evolutionary approaches may be suited for stimulating radical technologies and system change more widely. Their use may not be limited to systems and technologies offering environmentally sustainability benefits. Any sector characterised by lock-in of problematic innovation directions may benefit from an evolutionary approach. In the Netherlands, the transition management approach is applied in health care, in a programme for experiments aimed at providing patient-centred care.

Interestingly, policy officials sometimes appear to be ahead of academics in defining "evolutionary" policies beyond the current niche. It is time for academics to step in, to evaluate experiences and to further develop evolutionary approaches. In doing so four issues deserve special attention.

First, the normative basis for innovation policy needs to be reformulated in a world in which preferences change endogenously and in which established practices and technologies are hard to undo. Directions could include an extension and refinement of the second order sustainability concept (Sartorius, 2006).

Second, there is a need to develop sharper criteria for policy design and instrument choice for various contexts. Here we could further develop a time-dependent instrument assessment and build on the attempts of van den Bergh et al. (2007) on combining evolutionary concepts with the policy criterion of ensuring an "extended level playing field".

Third, the link between techno-economic and political systems, especially the co-evolution of these two systems, deserves more scrutiny. In the time-strategic approach, exploratory steps in this direction have been undertaken (see e.g. Zundel et al., 2005b). Progress involves further work concerning concepts and indicators of the dynamics of political systems and explicit accounting of and research into country differences.

Fourth, the international dimension of evolutionary sustainable innovation policies needs more consideration. The recent European debate of creating lead markets for strategic technologies (which include environmental technologies such as fuel cells), uses some arguments on timing and the need of early support for creating global first mover advantages which are similar to time-strategic and niche management approaches, but draws mainly on other conceptual sources, in particular on market dynamics and (technological) competition (Beise-Zee and Rennings, 2005; Jacob et al., 2005). Developing an evolutionary approach to lead market policies is in our view a promising endeavour.

Advances in the resolution of these issues would significantly enhance prospects of evolutionary approaches in achieving a paradigmatic status. It helps to confront the inherent limitations of subsidy schemes and regulation, both of which are at least as standalone instruments ill-suited to stimulate dynamic advances along new trajectories and for "managing" processes of co-evolution. The evolutionary perspective places the discussion of instruments into the proper context of knowledge constraints and politics.

As political scientists have shown, policy is produced within systems of governance—of science, environmental protection, and innovation policy. The systems of governance are rather separate, with poor links. Evolutionary approaches may help to better align these separate systems of governance towards radical innovation and system innovation with sustainability benefits. We are not saying it is easy to integrate fragmented systems into a system for innovation for sustainable development but the concepts discussed provide elements for progress in this direction. It adds extra-complexities to policy that may prevent it from becoming the new paradigm for environmental innovation policy. It is reassuring to observe, however, that policy makers as reflexive practitioners have already traversed into this direction, far deeper than theorists, and that a catch-up of the latter seems on the way.

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