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Windows of Sustainability Opportunities - Determinants of Techno-economic Time Windows and Conditions under which Environmental Innovation policy can utilise them*

Dipl.-Volksw. **Jan Nill**, research fellow at the Institute for Ecological Economy Research (IÖW), Potsdamer Str. 105, D-10785 Berlin, and PhD student at the University of Kassel, Department of Economics, Nora-Platiel-Str. 6, D-34109 Kassel; phone +49-(0)30-884594-28, fax +49-(0)30-8825439, e-mail: Jan.Nill@ioew.de

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Abstract

Fostering innovation is often seen as most important for policies towards sustainable development. However, if appropriate policies involve the change of technological trajectories, they are far from easy. One reason is the institutional reinforcement of established technological paths, e.g. by (endogenous) lobbying investments. Some authors have emphasised the role of windows of opportunities for innovation policies (David 1987, Erdmann 1993, Kemp 2001). The paper argues that political opportunities for environmental innovation policies depend on the underlying techno-economic dynamics. While on one hand the institutional reinforcement of technological path dependencies may act as constraint for policies, on the other hand endogenous evolutionary techno-economic dynamics may facilitate them. Therefore a co-evolutionary political-economic approach is proposed which builds on the concept of different types of techno-economic windows and an integration of economic-political linkages. The approach is illustrated with two empirical cases: renewed competition of ironmaking technologies and the historical competition between catalytic converter and lean burn engine.

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1. Introduction

Fostering innovation is often seen as important for policies towards sustainable development. Yet, given the ambitious environmental targets implied by sustainability, it might not be sufficient to stimulate incremental innovations alongside well-established techno-economic trajectories. However, public choice theory as well as evolutionary economics give hints that due to economic and institutional path dependencies such policies aiming at innovations which might change those technological trajectories are fraught with difficulties.

Concerning appropriate policies, empirical research has established that a simple incentive-response relation between certain economic instruments and innovative effects does not hold generally, but is context specific (e.g. Klemmer et al. 1999, Jänicke et al. 2000, see also Kemp et al. 2000). The ongoing SUSTIME research project (see also Erdmann 2003, Nill/ Zundel 2002, Hemmelskamp 2001) on which this paper is based to a significant extent, is based on the hypothesis that time and the dependency of innovation dynamics on time might provide a promising systematic context for environmental innovation policy analysis.

Such an approach can start from recent evolutionary economic approaches to innovation research. Here, some authors have emphasised the role of (techno-economic) windows of opportunities and timing for an appropriate policy (David 1987, Arthur 1988, Erdmann 1993, Kemp 2001). The *first challenge* which will be explored in this paper is therefore, if and how these dynamic theoretical approaches for innovation studies can serve as fruitful framework for empirical research on *environmental* innovations and appropriate policies.

A *second challenge* which is dealt with in this paper is related to the interaction of the techno-economic and the political sphere. Some authors highlight institutional reinforcements of established technological paths as problems for path changes, e.g. by (endogenous) lobbying investments and regulatory capture (e.g. Berg 1995, Weber 1999, Unruh 2000). Hence, for a meaningful policy evaluation, it cannot be taken for granted that techno-economic windows for sustainability opportunities can be utilised by political actors. Instead, sometimes "policy windows" might be required (Kingdon 1995).

In this paper I will argue that policy not only influences technological innovation processes but in the reverse direction political opportunities for environmental innovation policies depend on the underlying techno-economic dynamics. The linkages are twofold: while on one hand the institutional reinforcement of technological path dependencies may act as constraint for policies aiming at path changing sustainability innovations, on the other hand endogenous evolutionary techno-economic dynamics may facilitate them. In order to clarify opportunities and obstacles for policies, this paper pursues a co-evolutionary perspective and explores a dynamic politico-economic approach building on the combination of phase models of technological change, a derived concept of different types of techno-economic windows and an integration of economic-political linkages. The paper presents interim results which are based on a synthesis of relevant theoretical literatures as well as literature-based empirical case-studies.

Section 2 focuses on the outline of a conceptual framework for analysing techno-economic dynamics and the role of environmental policy therein. Section 3 deals with feedbacks of techno-economic factors the political system. Section 4 applies the framework to two empirical cases: ironmaking and catalytic converter vs. lean burn engine. While normative issues are not yet covered, the final section gives an outlook on appropriate political time strategies.

2. Conceptualising Techno-economic Dynamics

2.1. A Short Overview of Techno-economic Phase Models

A distinction between stable and unstable phases of techno-economic processes is common in dynamic economic approaches. Evolutionary economic approaches to technical change highlight that technological change is path-dependent. In contrast to neoclassical approaches in which technology is perfectly malleable and reacts directly to changed factor prices etc., they highlight the local and cumulative characteristics of this process. Therefore, in evolutionary approaches a distinction between periods of radical and incremental change is considered of being important. Technological development is described as a structured interplay of radical innovations and incremental innovations. To describe this pattern Giovanni Dosi (1982) has introduced the notions of “technological paradigm” and “technological trajectories”¹. In line with Kuhn (1962), Dosi suggests the following definition: “... a technological paradigm can be defined as a ‘pattern’ for solution of selected techno-economic problems based on highly selected principles derived from the natural sciences” (Dosi 1988: 224). Such a paradigm is closely linked with one or several radical innovations and it generates coherence of the technological system. On the one hand it limits the possible changes. On the other hand, by forcing the involved actors to specialise, it brings about economies of scale and scope and is an important precondition for successfully exploiting the potentials of a basic innovation. The resulting development pattern is called technological trajectory. Such trajectories exhibit a certain stability due to cognitive and techno-economic factors until they are challenged by new paradigms. Further, Dosi (1982) distinguishes an emerging phase of competition between paradigms and trajectories and a mature phase of incremental oligopolistic competition.

Another theoretical approach, which can be also described as a phase model, are the increasing returns and path dependency models developed by Arthur (1988, 1989) and David (1985, 1987). In these models, similar technologies compete in a virgin market until “small historical events” lead to the dominance of one technology. The resulting inherently stable phase is sometimes called “lock-in” (Arthur 1989). The main driving forces are increasing returns, driven by scale, learning, and network effects. They may imply that a temporary first mover advantage becomes rather stable. As regards appropriate standardisation policies, David (1987) calls the unstable phase before one technology dominates “window of opportunity”.

Other evolutionary economic approaches, however, point also to factors which allow for escaping lock-in (e.g. Cowan/ Hultèn 1996, Witt 1997, Kemp et al. 2001). Actors, their preferences, and their demand are heterogeneous; new scientific insights and technological breakthroughs can establish new technological paradigms which replace old ones. Such technological substitution processes can be supported by the approaching end of investment cycles, decreasing returns to scale, and technological anomalies. Moreover, new firms and niche markets are important in the adoption phase, and a critical number of diffusion agents is necessary for the successful introduction of a new technology into the market.

A formal treatment of the conditions of phase shifts which also introduces the notion of windows of opportunity can be found in an evolutionary model by Erdmann (1993).

¹A similar conceptualisation was proposed by Sahal (1981) who distinguished “technological guideposts” and “innovation avenues”.

However, there is still an important gap between theory and empirical analysis. While these dynamic models provide important theoretical insights, they often do not deliver a well elaborated template to identify such phase changes in time empirically.

Nevertheless, there are also empirical industry and innovation studies which have come up with phase models of technological change, one key notion being the emergence of dominant designs (for a survey see Utterback 1994). Abernathy/ Utterback (1978) and Abernathy/ Clark (1985) mainly draw on work on the automobile industry. They develop a model in which first product innovations predominate over process innovations, while the latter take over after the establishment of a dominant design. In suite of the stabilisation of the dominant design, also the amount of process innovations slowly decreases. Anderson/ Tushman (1990) build on this work and on empirical studies of a broader range of industries. They develop and validate a phase model in which periods of continuity and periods of discontinuity follow each other. Discontinuities arise through the emergence of the dominant design or, at the end of the next phase, by further technological breakthroughs.

The overview has shown that there are quite a lot approaches which support a phase model of technological change. However, there is a rather broad range of approaches which emphasize different aspects. For a policy oriented empirical application of such phase models, a conceptual synthesis and steps towards an operationalisation are necessary.

2.2. A Suggestion for a Synthesis

We propose to organise a synthesis of the mentioned concepts along two axes:

- to distinguish two different types of a techno-economic competition
- to order the approaches along the phases of the innovation process

These distinctions then allow us to deduce several types of techno-economic windows.

The phase models mentioned point to rather different mechanisms which bring about stability and instability. Therefore, it is useful to distinguish analytically *two types of technological competition*: ("*New-new*") Competition between new technologies (such as in the models of Arthur) and ("*old-new*") competition between an incumbent technology on a well established trajectory and new technologies (such as modelled e.g. by Reichel 1998). Besides different economic driving forces, in the old-new case the (attempt of) institutional stabilisation of the old path has to be systematically taken into account (see below). In any case, a pure diffusion perspective concerning one particular technology without regard to the competing alternatives may often be inappropriate.

The technological paradigm and trajectory concept may serve for a highly stylised further integration of the approaches: Consider as starting point an old paradigm which becomes unstable. The reasons may be own technological drawbacks, new technological breakthroughs or changing functional requirements, such as new environmental demands (see below). As a result, a future old-new competition is possible, and a search for alternatives starts. When technological promises of solutions and a potential future market for them emerge, then we call this the start of a techno-economic new-new-competition. In the beginning, several technological paradigms might compete. At the same time, it is not sure that the old paradigm will be substituted, which yields two cases:

1. If a substitution can be assumed because either the old technology has unsurmountable limits or the new technology is far superior², the interesting dynamics reduce to a simple new-new-competition. In this competition, one technological paradigm may succeed and then competition between several possible trajectories may continue until a dominant design emerges. The outcome of this new-new competition is highly critical in time if increasing returns, e.g. caused by

- technology-*specific* learning effects,
- economies of scale and scope,
- network effects, caused by spillovers on the consumption side or interrelated infrastructure technologies, and
- coordination effects,

and thus *path dependence* play a significant role.

2. If, however, the superiority of the new alternative(s) is less clear, also the driving forces of *old-new* competition have to be taken into account. Four effects may be mentioned here:

- the role of (industry) sunk costs as a result of past learning, network and scale effects, with re-investment cycles as a key dynamic factor (a sort of past dependence),
- the uncertain learning prospects of the new technologies, as for example measured by learning curves,
- the *sailing ship effect* (Rosenberg 1972, Howell 2000), that is an innovative reaction by incumbent firms, which at least may delay technological substitution,
- finally a strategic blocking reaction/ creation of entry barriers by the incumbents, which points to an institutional feed-back mechanism (see section 3).

The more important these factors are, the more depends the outcome of old-new-competition dependent on certain opportunities and events, and the more critical is time. Moreover, here both types of competition might interact, either sequentially or even at the same time. Eventually, however, a new or a renewed paradigm might succeed, yielding new technological trajectories, which result again in a temporary stable phase.

Two types of techno-economic (time) windows

In terms of system dynamics, we can broadly define a window of opportunity or *time window* as a time period in which weak impulses can lead to a change of attractors. With respect to actors such as firms or policy actors, we can characterise it as a time period in which they have a greater opportunity to change the direction of technological development in a significant way than during stable periods of technological development³.

² Without relevant market imperfections this may be a normal case because as a consequence of the high risk involved with radical innovations they usually will be only pursued if the economic potential is very high provided that the innovation can be realised.

³ It should be noted that we restrict the notion of techno-*economic* windows to phases of instability in which economic driving forces, i.e. the commercialisation perspective, are already important. A future destabilisation potential of the old trajectory alone or an exploration of potential *technological* alternatives ("promises of solutions") will not yet be called a window.

According to the sketched conceptual model, we have to distinguish between two types of time windows in the techno-economic system:

1. Following the investigations of Arthur (1989) and David (1987) referring mainly to new-new competition, we refer to this type of techno-economic window as “Arthur-David-window”. This window is open in the early stage of competition between technologies of a similar development stage. This competition is time-critical if increasing returns to adoption due to the above-mentioned effects are important. Then the direction of technological development may be influenced by – at least from a purely techno-economic point of view - “small historical events” (Arthur) or strategic manoeuvres which give a first mover advantage to one technology which can then be sustained.
2. Following the investigations of Kemp (2001) and Reichel (1998) of old-new competition we call this type the “Kemp-Reichel-window”. This window is open when the end of investment cycles of old technologies is approaching and new promising technologies are available at that time.

A caveat: the above-mentioned driving forces point also to conditions under which technological competition need not be that time-critical from an system-immanent point of view. To mention but two conditions: if demand is very heterogeneous, selection pressure towards one technology is reduced and co-existence of several market segments served by different technologies may persist (Nelson 1995, Windrum/ Birchenhall 1998). This feature is one basis for the sometimes highlighted role of niches for escaping lock-in (Cowan/ Hult n 1996). Secondly, concerning the time-criticality of old-new-competition, perfect competition, i.e. low entry barriers reduce the role of sunk costs incurred by the incumbent. In many markets, however, scale effects and considerable entry barriers are important characteristics.

If and how such windows and their determinants can be empirically determined will be illustrated by the cases in section 4. Before that, we turn to the role of policy and politics.

2.3. Techno-economic Dynamics and (Environmental) Innovation Policy

The presentation up to now has abstracted from political factors. While this is already problematic for "normal" processes of technological change (e.g. Nelson 1994), it is particularly inadequate in the case of environmentally beneficial innovation. Given that these innovations exhibit a particular appropriability problem – due to positive spillovers the innovator is usually not able to appropriate the social benefits of the innovation, which is the dynamic consequence of the well-known static environmental externality problem – the political framework is generally important for such innovations. In a dynamic perspective, policies might considerably influence the patterns of time criticality, or even introduce time dependency politically. The potential impact can be assumed to be particularly important if there is already an endogenous techno-economic instability.

Relating environmental innovation policy influence to the developed framework, the case that a new cleaner technology is in itself that much superior to old technologies that substitution takes place quasi-automatically will be rare due to the reasons given above. At least in principle however, a strict environmental policy can determine new functional requirements which outrule the old technology. In that case, the dynamics of *new-new-competition* will be the relevant feature - and strongly shaped by the content and timing of policy, an extreme example are "technology forcing" policies. In particular, environmental policy may act as the "small historical event" in the selection environment being of importance in the increasing

returns models, e.g. biases competition, or strengthens, or even locks-in first mover advantages.

But the typical overall pattern in which policy is involved is influencing the framework of an *old-new* competition. Usually new cleaner technologies have to compete with well established dominant technological trajectories. Examples of the latter are the fossil-fuel based energy system, steel-based car bodyworks, internal combustion engines, chlorine-based chemistry, conventionally heated housing. Therefore the endogenous substitution forces might be limited. The old-new competition may be influenced politically in at least the three following ways:

- environmental policy may create expectations or – if for example certain substances are banned - even certainty that the old trajectory will reach its limits,
- environmental policy requirements delay investment cycles (retrofitting), thus increasing sunk costs, especially if end-of pipe treatment is involved,
- political support may contribute to the competitiveness of new technologies.

Concerning the *new-new* competition between potential alternatives to the old trajectory, policy may of course have an impact, too. The abovementioned mechanisms are particularly interesting if the expected environmental performance of the alternatives differs significantly.

Finally, in both cases policy is able to put an end to technological competition and effectively prescribe the adoption of a particular solution (forced diffusion, e.g. by a standard).

Hence, environmental innovation policy can have a significant impact on the emergence and shaping of both types of techno-economic windows. As a consequence, policy strategies can be distinguished according to their relation to these dynamics of techno-economic competition:

2.4. Conclusion: a Taxonomy of Policy Strategies

Techno-economic windows provide an opportunity for a more effective or lower cost environmental innovation policy. As demonstrated, they do not always emerge independently from political determinants. It is therefore useful to distinguish three types of time dependent environmental innovation policies:

- Policies which *take advantage of* or *utilise* techno-economic windows that have emerged or will emerge in the techno-economic realm - be it of the old-new Kemp-Reichel type or of the new-new Arthur-David Type - in the latter case "utilise" can also mean "keep open". A relatively small and perhaps even temporary political impulse might be sufficient.
- Policies which *prepare* the emergence of future techno-economic windows. This type is of particular relevance if old-new-competition is the relevant framework. Mechanisms may e.g. include the creation of niches for or the support of new alternatives.
- Policies which *create* time windows in the techno-economic system, in the old-new-case e.g. by making alternatives competitive or by the political determination of a new ecological functional requirement which opens a new-new-competition. This interaction dimension is usually neglected in the models of techno-economic dynamics.

Of course the distinction between these policy types is not always neat. Put differently, depending of dosage, shaping and timing, the same policy (instrument) may have quite different consequences. However, a precondition for appropriate policy strategies is the identification of the relevant features of techno-economic dynamics described in section 2.2. (see section 4).

At the analytical level, the mentioned mechanisms point to a systematic interaction between the political and the techno-economic system which has to be taken into account. However, such an interaction works also into the reverse direction. And actually, these interlinkages may seriously limit the political opportunities to pursue some of the mentioned strategies, it cannot be assumed that such policies are always feasible. This issue is dealt with in the next section.

3. Accounting for Techno-economic/ Political System Linkages

3.1. Conceptualisation of the Political System

A particular characteristic of the political system in democratic societies is that it is only partly autonomous: on one hand, it is supposed to be open for and to react to impulses from the socio-cultural and the techno-economic system. In this respect, the different interest groups as part of the political system play an important role. On the other hand, the political system is characterised by its own specific institutional and administrative structure, system dynamics and inertia. These mechanisms have an impact on the channelling of impulses. In other words: political systems exhibit a double-sided constitution of mechanisms of openness to external impulses and specific internal system dynamics⁴. An interesting theory of policy change which integrates both aspects of political systems is proposed by Kingdon (1995). In his policy window model, Kingdon differentiates between three levels ("streams") which he conceives as to a good extent independent:

- the "problem stream", i.e. the recognition of the problem by relevant actors,
- the "policy stream", i.e. the existence and awareness of a suitable technical or organisational and politically acceptable solution or development thereof by experts, and
- the "politics stream", i.e. the political rules of decision-making that are strongly influenced by both political culture and interest groups.

In a way, these streams contain intra political system dynamics as well as change impulses from other subsystems. For example, the problem stream mirrors impulses from the cultural system. Kingdon argues that the number of suggestions for policy change which really appear on the political decision-making agenda is limited, so that policy changes need a "policy window" in order to be successful. Kingdon (1995: 174) defines a policy window as the "opportunity for action on given initiatives" which results from the merging of opportunities within all three streams. For the purpose of the present paper, I will concentrate on the techno-economic-political linkages, i.e. the stabilising and destabilising impulses from the techno-economic system and their channelling. While Kingdon mention these linkages but does not concentrate on them, some researchers, who applied the Kingdon model, emphasized that

⁴ Recent political science literature suggests that increasing returns and path-dependence might be even more important phenomena for describing dynamics of the political system (Pierson 2000).

economic factors should be included explicitly (Fisher-Vanden 1997, Lober 1997). Elsewhere, I propose a modified integrative policy window concept which accounts for intra-political dynamics, too (Nill 2002).

The economic-political linkages are twofold: while on one hand the institutional reinforcement of technological path dependencies may act as constraint for policies aiming at path changing sustainability innovations (stabilising impulse in the political stream), on the other hand endogenous evolutionary techno-economic dynamics may facilitate them (change impulse in the solution stream). Both linkages are further explored in the following sections.

3.2. Institutional Path-dependencies Co-evolving with Techno-economic Dynamics - Linkages in the Politics Stream

There is a growing political-economic or "public choice" literature which approaches economic-political linkages theoretically. The focus is on lobbying and rent seeking behaviour of economic actors and how this influences political outcomes. Some authors have linked this perspective with phase models of technological change (Berg 1995) and lock-in (Unruh 2000). They highlight that there may be an important and systematic spillover from the resulting dominant trajectories to their institutional environment including the political system. The dominance of certain technological trajectories may lead to institutional path-dependence which works as further stabilising factor. Therefore in transition problems indeed certain external change impulses may be blocked or only be effective in a biased form in the political system. This may be an important systematic determinant at least of old-new competition.

A broad account of this spillover process and the institutions involved is given by Unruh (2000). However, a vital determinant is the influence of economic actors of the dominant technological path. This may result in a systematic bias in favour of established technologies in the competition with new technologies, which can be already demonstrated with a simple political-economically expanded investment calculus of the actors (Berg 1995, also see the similarly-argued theories of endogenous protection, e.g. Brainard/ Verdier 1997). Within mature sectors, in which technological opportunities and economic self-reinforcing mechanisms tend to expire, investments in the development of favourable institutional framework conditions may be more profitable than investments in additional technological innovations. This particularly holds whenever capital-intensive and specific investments are concerned – that is, when important sunk costs are involved. Economic investments may then depend on accompanying political “safeguards”.

Nevertheless, the validity of the argument is bound to some conditions. Requirements cited in the literature include

- sufficient resources in order to be capable to act as a political actor and non-excessive period-fixed lobbying costs in order to maintain stability of the interest group influence (Brainard/Verdier 1997)
- internal organisational capabilities of the sector/ dominant path, of which a not too large group size is an important determinant (Olson 1965),
- as well as sufficient chance of success in political terms. The latter may depend e.g. on the economic importance of the sector as well as the importance of information asymmetries related to information needed for regulation (a point highlighted by Martimort 1999).

Many of these conditions may be rather fulfilled in the case of incumbents than of new actors.

One result of such co-evolution processes may be a bias of standards and regulation in favour of the established path or even a "regulatory capture" of bureaucracies: According to dynamic life cycle models of bureaucracies and due to asymmetric information and repeated interaction, the views of initially independent (regulatory) authorities may converge over time with the interests of the dominant path (Martimort 1999).

Therefore under certain conditions – at least in the case of old-new competition –, the political uptaking or reinforcing of techno-economic opportunities may require also suitable opportunities for change within the political system. While these mechanisms are described in detail elsewhere (Nill 2002), one such impulse may be changes in the influence and balance of interest groups. In countries such as Germany, in which corporatist structures are vital to some sectors and other political factors weaker, such change impulses may be particularly important. In the United States systematic long term cyclical elements with regard to the influence of economic interest groups have been found (McFarland 1994).

3.3. Techno-political Linkages in the Solution Stream

At least in the context of innovation policy, solutions delivered by the techno-economic system are one important precondition for survival of policy solutions in the "policy stream". Kingdon mentions the importance of technical feasibility and acceptability but does not further emphasize this point. Our contention is, that expected techno-economic windows as described in section 2.2. might be open opportunities for change in the solution generating stream. Thus, at least in the case of innovation policies, impulses for policy windows might also start from this stream. Our emphasis is in line with some other policy studies which claim the importance of available technically and economically feasible solutions for a political decision on new or ambitious environmental policies (e.g. Prittwitz 1990, Jacob 1999).

3.4. Conclusion: Political Conditions of Political Time Strategies

The analysis has pointed out two main linkages between techno-economic and political system which point in different directions. While the institutional feedback might be an important obstacle to path changes, the latter might be supported by the new solution feedback. In a policy oriented perspective, the important question is when and to what extent these linkages may lead to constraints on politically feasible environmental innovation policies. Our contention is that if these mechanisms are important, e.g. the old path is deeply institutionally embedded, they have a different impact on the three abovementioned policy types:

- In the case of *window-creating* policies, the linkages probably work as systemic constraint. which, if ever, can only be overcome by important other impulses for change in the political system, e.g. windows in the political and problem stream (Nill 2002). In this case usually a dominant trajectory has to be overcome (old-new) or its direction has to be changed (new-new). Also in the latter case, for the occurrence of a new technology competition based on new (ecological) functional requirements often a significant policy change towards stricter environmental policies is needed. This process can and probably will be influenced by representatives of the old path - being it political actors or economic interest groups.
- In the case of *window-preparing* policies, the economic-political linkages are probably of less importance - except if the policies are expected by relevant actors of the dominant path to be in fact window-creating policies. However, c.p. the result may be rather a re-

striction of feasible instruments than of the policies as such: While policies with direct negative impact on dominant path actors might be difficult to achieve, policies which rather support new alternatives should remain feasible - also the influence of new path actors may help.

- In the case of *window-utilising* policies, both linkage mechanisms will be at work. One policy facilitating condition being fulfilled it is of particular interest so that in the following the focus will be laid on this case. Here, a further distinction of three subcases is helpful:
 1. old-new, disruptive for old path actors
 2. old-new, non disruptive for old path actors
 3. new-new.

If in the *old-new* competition a techno-economic window has opened or its emergence is anticipated, the utilisation by policy is supposed to be subject to political-economic constraints only under particular conditions. The criterion proposed is a *disruptive impact* of window utilisation on actors of the old path. This may be the case if the exploitation implies (a) a probable decision of the technological competition (and not only the ensuring of window openness), and (b) this decision would have a significantly negative impact on politically important economic actors, for example due to competence- or cost-based constraints to utilise the techno-economic window successfully themselves. Due to these (expected) disruptive effects, a blocking of the political stream might result so that a political opportunity to utilise the techno-economic window is supposed to be tied to other change facilitating conditions in the political system (destabilising factors in the political or window in the problem stream). The competition in ironmaking technologies will illustrate the importance of these factors (see section 4.1). A case in which other opportunities for change in the political system have shaped policies is the intended German cease of nuclear power production (Nill 2002).

If an environmentally beneficial techno-economic Arthur-David window endogenously arises, the system linkages might not lead to systematic constraints on policies. One reason is the missing of systematic stabilising factors due to a similar techno-economic state of the technologies. The political exploitation of technical-economic Arthur-David windows consists mainly of assuring that in an open phase in competition the best technologies in ecological and economic terms have the chance to be selected. Under some conditions, it may be necessary to extend the duration of the economic window by means of political intervention (subsidies etc.) (David 1987). The main concern is rather extending the decision-making period, even if possible solutions (albeit perhaps sub-optimal ones) already exist. This may increase political pressure by pro-change actors such as environmentalists but also new economic actors, but the influence of “old path” interest groups in the policy stream may rather support a delay of decision and thus work as counterbalance to a too early choice. An exception may be if the early solution is potentially sub optimal but closer to the interests of the old path actors, leading to a coalition in favour of an early choice.

If these hypotheses prove relevant, the conditions for effective environmental innovation policies differ considerably, depending on the state of the relevant techno-economic subsystem. Techno-economic windows might be of high relevance because they do not only lower the costs of appropriate policies but might also provide the opportunity that such policies are politically feasible. (Only) If this is the case, an analysis of the techno-economic system can

be considered sufficient for policy relevant conclusions. In other cases, policy suggestions have also to be based on an analysis of destabilising factors in the political system (Nill 2002).

4. Applying the Framework to Empirical Case Studies

A precondition for appropriate policy strategies is the identification of the relevant features of techno-economic dynamics described in section 2.2. In the SUSTIME project, a comprehensive list of indicators for dynamics in the techno-economic and also political system is developed. For reasons of scope this paper will not reproduce such a list but rather illustrate the effects of the different dynamics and constellations with two empirical cases:

- The case of competing ironmaking technologies is an example of the overall case of old-new competition, but also with some interesting aspects of new-new competition. Here, a techno-economic Kemp-Reichel window arises to a good extent endogenously in the techno-economic system, policies did not play the key role. Thus, the driving forces of techno-economic dynamics can be illustrated quite well. Moreover, the usefulness of the differentiation of sub cases 1 and 2 of window-utilising strategies can be shown.
- The competition between catalytic converters and lean burn engines is an example of a new-new competition which has been decisively influenced by policies and politics. Here, in the beginning of the 1970s a techno-economic window of the Arthur-David type has been created by US policies. This was an important exogenous impulse for the emergence of a techno-economic window in Japan, too. Hence, the case can serve as an example for sub case 3 of window-utilising strategies, too.

The cases serve as illustration for the usefulness and applicability of the introduced theoretical concepts and also point to some refinements and qualifications.

4.1. Competition of Ironmaking Technologies

Steel production is one of the most energy and environment consuming industrial activities. Today steelmaking is dominated by two production routes based on different technologies. The still dominant *coke oven - blast furnace - basic oxygen furnace route* and the originally by and large complementary *scrap - electric arc furnace route*. The first two steps of the dominant route (*coke oven - blast furnace*) is up to today the far dominant ironmaking trajectory. The whole process takes place in so-called integrated steel mills at a quite high production scale while the second route is typical for so-called minimills, which work on a much lower scale. In the last years the ironmaking stage as well as the stage subsequent to crude steel production have seen important invention and partly also innovation processes.

Luiten (2001) puts forward the hypothesis that smelting reduction technology (SRT), a new process of ironmaking which skips the coke oven stage and substitutes for the blast furnace, leading to environmental benefits such as reduced emissions and less energy use, is locked-out from commercialisation by the dominance of the blast furnace route in integrated steel mills. SRT is considered to be one of the very important energy efficiency increasing process technologies in industry (e.g. Martin et al. 2000: 5). This example looks like a typical case of competition between an *old* and a *new*, environmentally beneficial, technology. For the utilisation in integrated steel mills, SRT has to compete with the traditional blast furnace route of

ironmaking. However, a closer analysis shows also interesting aspects of competition *between new technologies* (for a detailed analysis of the iron and steel case see Nill 2003).

Sources of techno-economic dynamics

The stability of the cokeoven - blast furnace - integrated steel mill route was mainly due to the realisation of enormous economies of scale and learning effects. However, some limits had been reached in this respect and in the wake of the oil and first steel crisis in the first half of the 70s, the disadvantages of such a trajectory, high costs of one plant and capital intensity/inflexibility were perceived as a potential future limit. Theoretical alternatives to the ironmaking stage such as directly reduced iron or smelting reduction technology have been already known since the 1950s, serious research efforts, however, only started in the middle of the 70s. For integrated steel producers, main incentives for research activities have been lower capital investment (by avoiding coke ovens and agglomeration plants and replacing blast furnaces) and the replacement of expensive metallurgical coals as input by normal coal. The threat of environmental regulations usually delivered an additional, but alone not sufficient incentive. The anticipated instability was of course also an incentive for suppliers and partly also outsiders such as mining companies to engage in certain research efforts.

A main driver introducing dynamics into these R&D processes since the middle of the 80s was the anticipation of a *window of opportunity* for innovation in the sense of market introduction because in integrated steel mills (ISM) *obsolete coke ovens and blast furnaces* had to be replaced. Coke ovens are reported to have a depreciation period of 40 years which was almost run off in the 80s. For example, in the Netherlands as well as in Japan, important replacement necessities of coke ovens or even blast furnaces (in Japan up to 40% of the installed capacity) were anticipated for 2000 to 2005 (Hogan 1994, Moors 2000). SRT is technically radical process change requiring large amount of process automatisation and training (Worrell et al. 1997), thus a long term time horizon for R&D was important. In most industrial countries general R&D efforts in the steel industry were supported by governments (in the European Community of Coal and Steel financed by a levy on steel prices). In the SRT case, these *window-preparing* policies generally played a supplementary but sometimes substantial role, often leading to additional research (Luiten 2001: 191). At the end of the 1980s and the beginning of the 1990s relevant prototypes ("hot models") emerged and the construction of small pilot plants of several SRT types was the next step performed.

Reaction of the old trajectory and delay of the window materialisation

However, the dominant trajectory did not stand still. The existing capital stock was being continuously improved and upgraded and thus its lifetime extended and sunk cost rose again so that the need to replace the existing coke ovens became less pressing. One impulse for this was environmental regulation. Moreover, the incremental innovation of direct pulverised coal injection in the blast furnace, combined with the increasing availability of coke imports, reduced the need for coke production (EC 2001: 319). And finally, cleaner coke ovens were developed. All in all, the cost advantages of SRT became smaller and smaller and some producers reinvested into the traditional route, thus losing interests in alternatives (Martin et al. 2000, Luiten 2001). This seems to be another illustrative example of the above-mentioned so called *sailing ship effect* induced by increased or renewed technological competition, in these cases strengthened by regulation. Hence, the anticipated window did not materialize (yet).

Emergence and political utilisation attempts of an early techno-economic window

The rather successful development of pilot processes demonstrated technical feasibility and clarified the conditions of economic feasibility. Thus one precondition for an instable phase of technological competition, i.e. a techno-economic window, was reached. Moreover, the very important economies of scale of ironmaking in integrated steel mills make a commercial demonstration plant costly. Therefore from a business perspective a decision to invest in such a plant depends on expectations that a window utilisation, i.e. the successful commercialisation of the new technology, will be possible. Thus, there is a time-critical instable techno-economic phase of "old-new" competition even before the potential new technology is commercially available.

However, also the reinvestment prospects changed, so that at least in some countries no instable phase occurred. Uncertain market demand and increasing world market competition, but sometimes also institutional embedding, led to delayed reinvestments or even the abandon of reinvestment plans. What had been anticipated by some firms as substitution process with a rather clear timing now became an open competition. As a result, only in two countries, the Netherlands and, albeit to a lesser extent, in Japan, the conditions lead to an instable phase of technological competition between blast furnace and smelting reduction technology in integrated steel mills. An indicator are the planned SRT commercialisation activities of Hoogovens and NKK.

In the *Netherlands*, steel industry is largely identical with the integrated producer Hoogovens. From 1996 on, the firm planned a demonstration plant on an industrial scale, i.e., 700,000 tons a year. The costs were estimated at 125 million US \$, which is above the costs of an *isolated* replacement of a blast furnace which is reported to cost 100 Mio US \$ (Hogan 1994: 186). After efforts to find a cooperative investor to supplement its own SRT technology had failed, Hoogovens went for its own. In 1997, the Dutch government announced the so-called National CO₂ Reduction plan in response to the Kyoto Protocol, which involved substantial budgets. Hoogovens applied for government support for a demonstration facility and was awarded 30 million US \$ which was about 25 per cent of total expenditures. In this example of *window-utilising* policies there was no relevant economic-political constraint because the proposed policy, i.e. a subsidy scheme, had no disruptive effects. And at the firm level, the change of technologies, even if radical in terms of processes, is not competence destroying but indeed competence-enhancing for the main economic actor concerned. So there is not too much stickiness towards the old path and an adaptation to the new solution is feasible – thus also a political blocking of a change of technological trajectories was not the preferred solution.

A further factor critical factor cited in the *Japanese case*, where only one firm attempted the commercialisation of a jointly developed SRT process, is the loss of technology specific (tacit) knowledge (Luiten 2001, p. 194). But after some attempts via extended demonstration in the small scale pilot plant and a promising feasibility study, the worsening economic situation of Japanese integrated steel producers led to a commercialisation stop (Kitagawa 2000).

The *German case* gives some hints that an economic-political feedback can be an important constraint on window-utilising policies. German integrated steel producers were only involved in the beginning of SRT research processes but did not further pursue this path. One reason might be a much greater stickiness to the old coke oven - blast furnace path, resulting e.g. from Government sponsored long-term agreement with the coal industry (the so-called Hüttenvertrag) to buy a certain amount of coke which was valid until the end of 1997. Due to the nearly total exemptions for energy extensive producers, the German eco-tax did not generate much further incentives. And unlike in the US, where government provided substantial support for a demonstration project even

though using foreign technology, German policy makers do not push into this direction. Given the path entrenchment, and especially the regional importance of coal and steel industry in particular in the biggest German Land Nordrhein-Westfalen, this is not surprising.

Closure of the techno-economic window in industrial countries

In the Dutch case, Hoogovens intended to provide the same amount as the government, 25 per cent, but failed to find another investor for the remaining 60 million US \$. The firm was not willing to invest more, given the rather high risk of the project. There was no steel expansion phase, and the firm decided instead to first invest in thin slab casting technology that was also new. Despite government support, Hoogovens thus first postponed and two years later, in 1999, stopped development due to financial reasons (Moors 2000, p. 244). In between, there has been a merger with British Steel, further reducing the reinvestment needs. Thus in spite of political support the techno-economic window was not utilised by the economic actor, and later on restricted by deteriorating economic prospects. There is some contention that if the development process had been a bit quicker and some other partners had remained in the project, in the economically better mid 1990s' situation perhaps the early techno-economic window could have been utilised (Luiten 2001: 177). Now Luiten expects at least a delay of five to ten years.

That in fact the techno-economic window was not utilised laid not in the hand of policy but seems to be a reasonable element of contingency, leaving market forces the last decision about the outcome of the competition. Concerning window-utilising policies in this case in general, there is no example that a demonstration plant failed due to lack of political support.

Success of one SRT technology in emerging countries: the importance of market niches

Since the 60s, the world steel market has undergone important structural changes. As a consequence there was a change in market structure, softening up the rather close oligopolies resulting from the huge economies of scale. This was driven by the rise of the minimills which allowed for steel production on a much smaller scale by the combination of another steel production technology, electric arc furnaces on the basis of scrap, with new casting technologies. Moreover, a demand for smaller steel mills emerged especially in newly industrialising countries with rather small local markets. Both created a stronger market segmentation and in effect also provided market niches for one SRT technology. Some SRT development processes were not initiated by integrated steel producers but by suppliers and mining companies. And one of the first SRT developers, the Austrian technology supplier VOEST, could make use of a market niche for the commercialisation of its first generation SRT process (COREX) already at the end of the 1980s. The partner was a South African minimill steelmaker. The market niche was mostly driven by the particular South African conditions: a dynamic local market, providing the incentive for a new steel plant, and the non-availability of technical alternatives due to limited access to metallurgical coal as well as scarcity of scrap (Luiten 2001). In fact, this window of opportunity was rather space than time dependent. After finally successful market introduction and the solution of a range of rather important technical problems, a range of further plants have been built or commissioned in India, Korea and South Africa. However, while an adoption in integrated steel mills is possible, up to now it is restricted to newly constructed steel mills. Due to the off-gases, a replacement of blast furnaces is not (yet) feasible.

Environmental benefits due to the skipping of a coke oven played a role, too, while the non-existence of advantages concerning CO₂ emissions – in effect the actual COREX route is blamed

as having even higher CO₂ emissions (EC 2001, p. 323) – was not (yet) of relevance. However, due to this successful use of a market niche by one SRT technology, perhaps also the dynamics of *new-new*-competition between several smelting reduction technologies will be of environmental relevance. Here the COREX design is not considered the most promising option.

4.2. Catalytic Converter vs. Lean-burn Engine: the Japanese Case

The introduction of catalytic converters in cars as a technique to abate air pollution is often considered as one of the most telling examples of a strict environmental policy. The USA and its Clean Air Act of 1970 was the frontrunner concerning the first announcement of such strict emission standards. It is one of the first examples of a „technology forcing“ policy, e.g. the setting of standards which cannot be met by available technologies yet. However, at that time the catalytic converter was only one promising solution to meet strict standards. And it was heavily criticised on economic grounds (e.g. NAS 1973: 5832). And a decade later also in Europe this solution was criticized with similar arguments in comparison to the lean burn engine as promising alternative (Moreau 1997, Faucheux 2000). Nevertheless the catalytic converter won the technological competition and is now the dominant pollution control technology for spark ignition engines in all industrial countries.

This case is a good example for a "new-new" competition between several new or improved technologies to significantly lower emissions of cars. Here, time criticality was mainly induced politically. Among the techno-economic factors, network effects due to the dependence of the catalytic converter on the availability of lead-free petrol as well as learning effects are worth mentioning. The example of the impact of the Clean Air Act in the US 1970 on innovation dynamics in Japan is taken to study the new-new case of window utilisation.

In the United states, the strictness of the standards as well as the reviving influence of auto industry on policy implementation severely restricted the range of possible technical solutions. Its preference for incremental solutions which seemed to be closest to the old trajectory in combination with the short time frames proposed initially quickly resulted in the dominance of the catalytic converter technology as the only viable solution (Nill 2002).

Emergence of the techno-economic window in Japan

The decisive starting point of competition between several pollution control technologies can be seen in the sketched changes in the US market as external policy induced impulse. The Japanese automobile industry depended on the export market USA, so they had to search for solutions to comply with the standard. Another important factor was the innovativeness of the Japanese industry. Some innovative smaller automobile firms considered the environmental challenge as chance for increasing market shares (Nishimura/ Sadakata 1989: 121). Already in 1972 they presented technologically different prototypes which fulfilled the US 1975 standards (Sakiya 1982). The range of competing alternatives introduced into the market or intended to commercialise consisted of variants of a lean burn engine, conventional engines with catalytic converters, and, initially, the rotary engine (Sakiya 1982). Another important factor was the early political decision in 1970 to introduce lead-free petrol until 1975. This was subsidised and opened the way for the catalytic converter, of which the introduction and diffusion depended on the availability of such petrol at the network of filling stations, to become one viable solution. Hence the range of possible solutions was further increased.

Window-utilisation policies

The resulting techno-economic window coincided with increasing environmental problem awareness and thus public demand for strict environmental regulation (Heaton/Maxwell 1984: 28-29). The Japanese Government utilised the window to set up a Pollution Control Law with similar standards as in the US in 1973. In this decision environmental and economic considerations converged because the standards avoided that the producers had to produce different cars for different markets (Moore/Miller 1994: 46; Genter 1990). Thus neither the influential Ministry for International Trade and Industry (MITI) nor the established actors of the automobile industry dared to publicly object to the proposed strictness of the standards (Hashimoto 1989: 39).

However, the way the new ecological functional requirements were shaped in the regulation heavily influenced the outcome of the competition. Both alternatives were not functionally equivalent concerning their environmental performance, which was at the centre of the political debate. While the lean burn engine promised better fuel economy performance, the catalytic converter showed more potential to reduce nitrogen oxide emissions. Together with the petrol regulation, the NO_x standard of the pollution control law gave in fact a big advantage to the catalytic converter solution, especially due to the short time horizon between passing of the law and enforcement. It appeared that most of the alternatives could not fulfil the envisaged NO_x standard for 1976. According to Grad et al. (1975: 299) the US 1976 standards could have only been met without catalytic converters by increasing the consumption of the engine by around 20%. After the implementation in the US had been delayed, the Japanese industry began a debate if it could be fulfilled at all (Genter 1990). The innovators, however, confirmed that the standards were technically feasible. Nevertheless, the enforcement of this standard was delayed, leaving the technological competition still open.

Two factors relevant in the political system, a political scandal concerning close government industry, thus reducing credibility of important economic actors and the MITI, and increasing environmental problem pressure, led to the decision in 1976 to put the Japanese standard into force in 1978. Hence, the techno-economic window was closed because only the three-way catalytic converter was able to fulfil the regulation.

4.3. Conclusions from the Empirical Cases

In general terms, the *ironmaking case* fits quite nicely to the proposed conceptual framework. Techno-economic windows seem to be important at several stages and the old-new competition in ironmaking technologies by integrated steel producers of industrialised countries shows some important time critical aspects. Nevertheless there are also endogenous forces which bring about change and can be utilised by policies.

On a conceptual level, in *old-new-competition* investment cycles and market entry barriers (due to sunk costs, investment scale or else) seem to be constituent for *time dependent* windows. Given this importance of scale, time windows can be important already before market introduction takes place. However, the time criticality of old-new-competition decreases with:

- dynamic market growth (e.g. steel mills in emerging countries),
- reduced market entry barriers (e.g. role of minimills)

In *new-new competition*, even if direct network effects are absent, scale and learning effects may provide for the relevance of windows. Yet time-criticality may decrease with

- demand segmentation and

- different and binding input requirements.

In the case *catalytic converter vs. lean burn engine*, the new-new competition is highly determined politically, while economic self-reinforcing mechanisms, in this case learning and network effects, work to a lesser extent. Concerning *window-utilising* policies, on which the focus was laid in this paper, the case show that political maintenance of the window is a difficult task if problem pressure is high and an acceptable solution exists whilst alternative solutions are fraught with uncertainty. A techno-economic first-mover advantage might therefore be of high relevance even if it is not yet economically self-reinforcing.

5. Outlook on Political Time Strategies and Further Research

(section still to be fully developed)

The developed framework highlights that at critical times the impact of policies on environmental innovations can be considerable but problematic, too. The design of appropriate time strategies is therefore an important but not easy task.

Selected Crucial Points of Political Time Strategies

- the way instruments will be implemented may have an important impact on innovation (e.g. future CO2 policy)
- importance of co-evolution of technological path and political-institutional environment for the available options and shaping of appropriate policies
- policy may have important effects – but also responsibility, e.g. technology forcing strategies; important role of time horizon

Outlook on further Research

- refinement and further check of data availability of relevant indicators
- empirical ex-ante in-depth study in cooperation with industry and policy actors
- normative issues, e.g. dynamic evaluation criteria for policies

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