Indicators for a Sustainable Technology Development – A Dynamic Perspective[1]

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1 Introduction

From the more technical perspective, the discussion of sustainable innovations is basically concerned with two questions. What is the underlying conception of sustainability and how do the innovations in question conform to the chosen conception? In this context, indicators of sustainable innovations primarily deal with questions of operability and comparability (see e.g. Pearce et al. 1989 and Rennings 2000 for an overview).

Inclusion of the economic perspective then leads to the question whether and under which conditions a sustainable innovation will also be marketable. Are its properties acceptable for the potential customers and can it be produced at an acceptable price? Once the innovation meets the conditions for successful market entrance, also its macroeconomic impact, particularly its welfare, employment and, possibly, social distribution effects, will be of interest.

Once it turns out that an innovation shows promising ecological and social properties but at least temporarily lacks economic competitiveness, it is a possible role of the state to support this technology until it can successfully compete with its less sustainable counterpart. Since the intervention of the state usually takes the form of a market regulation, the next question typically asks which instruments for such political interventions exist and which ones appear to be most suitable. Eventually it may turn out that even a mix of regulative measures is needed to properly account for the complexity of circumstances in which the innovation arises (Klemmer et al. 1999).

While, up to this point, the discussion of sustainable innovations has already reached a considerable degree of sophistication, one major point is still missing. Although, in the context of regulatory instrument mixes, the diversity and complexity of circumstances is well acknowledged, time as

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an important factor of influence is neither explicitly mentioned nor, all the less, systematically investigated. In fact, the neglect of time is a major omission because the circumstances change with time and the respectively most appropriate regulatory measures with them. Since each instrument causes to the state specific costs, it should also be clear that the necessary expenses will vary considerably with the changing circumstances and, of course, with time.

In this paper, time will be accounted for more thoroughly. In particular, it is assumed that along with the change in circumstances, periods of stability (where establishing a different technological regime requires much effort) alternate with periods of instability (where such a shift is more easily achieved). It is further assumed that in the search for the lowest possible cost of implementing an innovation, it is possible to identify and even strategically use the latter phases of instability. After a short discussion of the relevant concepts of sustainability and sustainable innovations in section 2, it will be shown in section 3 that the alternation between stability and instability exists and how it may be used to achieve better long-term sustainability. In order to account for this dynamic conception of sustainability, a broad set of relevant factors and the corresponding indicators will be developed and a proposal for their integration made in section 4. In section 5, the operability of this set of indicators will be illustrated in the light of a series of innovations following the phase-out of ozone-depleting CFCs in the 1980s and 1990s. Finally, section 6 will conclude.

2 Sustainability and its assessment

Sustainability is usually discussed as a state or, better, a development in which three kinds of (conflicts of) interests are met (or resolved) simultaneously: (i) the interest of the present generation to generally improve their actual living conditions (i.e. economic sustainability), (ii) the search for an equalisation of the living conditions between rich and poor (i.e. social sustainability), and (iii) the interests of future generations that are not to be compromised by the actual need satisfaction of the present generation (i.e. ecological sustainability). It is intuitively clear that particularly less developed countries show a stronger tendency to consider the (over)use of the environment as one of their more important potentials for earning a sufficient income and that therefore a very unequal distribution of resources is one of the major causes for environmental destruction. Since this issue is subject to intense political discussion and continued negotiations between most countries, the normative character of social (re-)distribution is readily accepted as an argument to exclude it from the scientific discourse. Although balancing the interests of succeeding generations is a normative issue as well, the lacking possibility of the future generations to participate in the corresponding political discussion is in this case taken as a justification and as a potential for science to make fruitful contributions. Consequently, the discussion of sustainability particularly among economists essentially focuses on the question how to allow for the strongest possible growth now without compromising the potential for growth to persist in the future.

2.1 Weak vs. strong sustainability

The main precondition for such equal treatment of successive generations is the preservation of a pool of natural resources and man-made capital that provides each generation with identical starting conditions, that is, with the opportunity to have its activities based on equivalent sets of man-made and natural capital. This conceptualisation of sustainable development as "non-declining wealth" (Pearce et al. 1989) finds two basically different expressions. On the one hand, economists in the tradition of Hartwick (1978) and Solow (1986) argue that a society using an exhaustible stock of resources could enjoy a constant stream of consumption over time if it invested all the rents from tapping on those resources, that is, if it held the overall capital stock constant. Evidently, this weak approach to sustainability is based on the implicit assumption that both natural and man-made capital are complete substitutes. While this assumption may be met in some cases, it does not hold in general. For many types of natural assets (e.g. an endangered species, a habitat or the ozone layer) technical substitutes do not exist. In general, the latter argument applies even more to the capability of the natural environment to assimilate the by-products of human activities than to its function as a mere supplier of input resources. It is for this reason that the central role of substitutability between man-made and natural capital is essentially questioned by the supporters of the concept of strong sustainability. According to the so-called 'management rules' (Daly 1990), for instance, proponents of the latter concept claim that (i) the harvest rates of renewable resources is not allowed to exceed their rate of regeneration, (ii) the rates of generation of by-products from the production, use, and disposal of goods should not exceed the respective assimilation rates of the ecosystem, and (iii) the exploitation of exhaustible resources has to be compensated through replacement with equivalent (renewable) alternatives. So, substitutability has to be proven rather than simply being assumed. With regard to the properties qualifying a technology as sustainable, the requirements in a context of strong sustainability are evidently much stronger than in a context of weak sustainability.

2.2 Sustainability indicators

The relation between weak and strong sustainability is also mirrored in the indicators used for their operationalisation. According to the weak concept, the development of a given economy is considered sustainable, if the total savings are higher than the combined depreciation of both, natural and man-made capital. Since the net investment into man-made capital and the damage to the environment are both measured (e.g. by green GDP accounting) and freely aggregated in terms of money, they are evidently treated like full substitutes (Pearce and Atkinson 1993).

Unlike weak sustainability, concepts of strong sustainability specify the natural capital in terms of its physical function rather than the costs of actual damage caused to it. The logic of this approach is based on the assumption that in order to continue to rely on certain essential functions of the environment (e.g. assimilation of waste or supply with resources), the ecosystem or at least certain parts of it have to be kept intact. Although this approach does not exclude monetisation in principle (e.g. in terms of the opportunity costs of the avoided or restricted use of the environment), the (however aggregated) monetary figure does not suffice to eventually specify the state of sustainability. Instead, it is necessary to follow the following three-step procedure and to (i) identify those elements of the natural capital that are essential for the maintenance of the ecosystem's stability or resilience, (ii) select those elements that are related to, and possibly endangered by, economic activities, and (iii) derive a set of indicators each of which reflects the actual condition of a specific aspect of the environment and puts it into relation to the sustainable state as determined by any suitable management rule (see Opschoor and Reijnders 1991).

Typical examples of the latter approach are Pressure-State-Response (PSR) indicators like the one employed by the OECD. Here, the causes of environmental problems ("pressure"), the actual state of the environment ("state"), and efforts to solve the problem ("response") are monitored and quantified in separate modules. Problems however exist with the assignment of counter-measures ('response') to specific pressures and states. While it is possible in the short run to quantify the effect of the latter measures in terms of a reduction of those processes or their side-effects that caused the corresponding pressure in the first place, many countermeasures later turn out to be themselves not without side-effects such that the relaxation of pressure in their target field may go along with the increase of pressures in other fields. This kind of uncertainty is characteristic not only for environmental innovations.

2.3 Critical loads and non-linearity

While a PSR-like indicator represents a first important step to the assessment of the causes and development of environmental problems, it supposes a correlation between pressure and response that is misleading for the following reason (Rennings and Wiggering 1997): The logic underlying the PSR approach implies that stronger (weaker) efforts to counteract an environmental problem by means of the best-available technology will generally lead to the alleviation (enhancement) of the pressure and, thus, to the improvement (deterioration) of the condition of the environment. Unfortunately, with regard to the environment, such a "linear" relation between causes and effects is not the rule. In contrast, effects like the following are frequently observed. Although in a certain agriculturally dominated region the intense use of mineral fertilisers was common practice for quite a while, contamination of the ground-water with nitrate could be observed only recently – with a strongly increasing rate. Due to the existence (and transgression) of carrying capacities or buffer capacities, such non-linear processes typically show sudden changes or even jumps. Returning to a sustainable state then not only requires the reduction of emissions below the respective critical load or critical level. Since the latter may itself be adversely affected by the harm, it additionally requires the repair of the damages that had so far been caused by the excess emissions.

3 Sustainable innovations in evolutionary perspective

It should have become evident at this point that innovations can usefully be integrated only into a concept of strong sustainability. Weak sustainability, by contrast, does not only fail to question the crucial substitution between natural and man-made capital; it also fails to differentiate which kind of technology or innovation is employed and whether innovative activities are shown at all.

But despite their significance in the context of sustainability, innovations also play an ambiguous role. On the one hand, they offer a potential to redress sustainability once it is lost; on the other hand, they are often also the cause for just this loss. After discussing some basic properties of sustainable innovations, the major part of this section will focus on two aspects of innovations that are extensively discussed in evolutionary economics: uncertainty and path dependence.

3.1 Innovations and sustainability

The usual (economic) understanding of the process of innovation is documented in the 'Oslo Manual' of the OECD (1997) and essentially distinguishes between process, product, and organisational innovation. While a process innovation basically refers to the (quantitative) relation between input factors and output commodities and a product innovation typically comprises a change in the (qualitative) properties of the output, organisational innovations can be associated with both, qualitative and quantitative changes (Rennings 2000). In all three cases, the term innovation refers to efficiency increases, that is, to changes in the production of goods and services that ultimately allow for a better satisfaction of certain needs and desires of the consumers with the same set of input factors or, equivalently, for the satisfaction of the same needs and desires with less input.

Sustainable innovations could basically be defined in the same way as ordinary innovations, however with the important restriction that the efficiency increase is not allowed to violate the chosen sustainability (e.g. Daly's management) rules. However, since it is evident that the current human way of life leads to transgressions of the sustainability boundary in many and profound ways and that the existing institutions (including codified rules, customs, habits, and social preferences) are broadly coherent with just this lifestyle, efficiency changes under the proviso of sustainability may sometimes be achieved more readily through institutional or social than through technical innovations. In the context of sustainability, it is therefore necessary to broaden the view from the merely technical towards the social and political aspects of innovations. In accord with these thoughts, Klemmer et al. (1999; see also Rennings 2000) broadly define the term 'environmental innovation' as all measures of relevant actors that lead to the development and application of new ideas, behaviour, products and processes and, thereby, contribute to a reduction of environmental burdens or to ecologically specified sustainability targets. This may include process and product innovations, organisational changes in the management of firms, and, on the social and political level, changes in environmentally counter-productive regulation and legislature, consumer behaviour, or lifestyle in general. This emphasis on social innovations is all the more important because unsustainable development itself is often the result of "technology outpacing changes in social organisation" (Norgaard 1994). Moreover, after an intense and extended discussion in environmental economics about the "right" instruments towards an environmentally sound, sustainable development, it more and more turns out that there is not a single suitable instrument. Instead, it seems to depend on the respective circumstances (e.g. the type of competition or information asymmetries), whether Pigovian taxes, markets for pollution rights, the setting of standards or even temporary subsidisation of promising innovations is the more effective instrument (Rennings 2000). Jaenicke (1999) even goes one step further by claiming that the relevance of instruments for environmental policy has generally been overemphasised. Instead, the discussion should focus on other elements of a successful environmental policy such as long-term goals, mixes of instruments, policy styles, and constellations of actors.

Altogether, the above emphasis on social and political aspects makes clear that the success of sustainable innovations depends on more than their mere technical (or even economic) superiority. This is all the more evident when, according to the following suggestions, sustainability is considered as the property of an entire system rather than being associated with a specific innovation.

3.2 Fundamental uncertainty

It is the wide variety and high complexity of interactions between human actors and between the latter and their natural environment that renders human (economic) activities as well as their environmental effects highly unpredictable particularly in the long run. However, the uncertainty accruing in this context is not just a matter of probability distributions within a known or assumed set of possibilities. Instead uncertainty is better characterised as ignorance in the face of novel, fundamentally unpredictable, events. So the question arises how to deal with this fundamental uncertainty. If complete knowledge about the set of available alternatives is lacking, actors cannot maximise the expected utility of alternative choices and, thus, rational decisions cannot be made. Moreover, rational choice theory assuming fixed sets of individual preferences that basically include all possible alternatives may simply turn out to be underdetermined in the face of real novelty.

Therefore, it may be advisable to look at the solution of (long-run) problems related to fundamental uncertainty and inflexible preferences from a completely different perspective: the one represented by Darwin's approach to evolution in nature. Like society, nature is characterised by the complex interaction between its constituents, the living organisms and their physical environment, and thus by the existence of fundamental uncertainty and non-linearity which together give rise to the formation of new species or the sudden extinction of major parts of the existing biosphere. In order to "manage" such unpredictable processes, nature relies on the principles of random variation and natural selection – with diversity created by random mutation and recombination within the existing genetic pool and selection resulting from continuous competition of species for a limited set of resources.

A further step toward an increased problem solving capability in nature and, ultimately, in man is based on the capability of an organism to undergo specific or individual adaptation to varying circumstances and to transmit the acquired knowledge to other organisms – that is to learn and communicate. While evolution on this level is based on social norms, individual values, and ideas rather than material genes, the basic principles nevertheless remain essentially unchanged (Sartorius 2003, especially ch. 4). Initially, the perception of a problem leads to the assessment of a variety of alternative approaches to its solution. Those approaches giving rise to a solution of the problem are selected; those that fail are rejected. The solutions with the best performance are further modified and tested in subsequent rounds of selection. The wider the variety of alternative approaches the higher is the probability that at least one of them may perform better than in the status quo. With respect to human behaviour, special use of evolutionary principles has been made by many proponents of evolutionary economics: Schumpeter (1934), for instance, emphasises the relevance of entrepreneurial creativity as a source of new problem solutions; Hayek (1978) interprets market competition as a process of selection (and detection) of superior goods by means of the willingness-to-pay on the demand side; and Nelson and Winter (1982) show how profit may serve as the selecting force that leads to the persistence of some innovations and to the vanishing of most others. A particular case of evolution leading to the solution of unprecedented problems is the selection of co-operation rules on the group level, a task that could never be fulfilled by individuals on the basis of their mere rationality (Hayek 1978; Sartorius 2002). In this context, (environmental) sustainability can indeed be interpreted as co-operation (i.e. as an expression of fair behaviour) between succeeding generations.

The relevance of fundamental uncertainty and the corresponding problem solving capability for sustainability is quite evident. Human activities frequently generate adverse environmental side-effects which, due to the complexity of their interaction with the environment, are often unforeseen. In the search for (long-term) sustainability indicators, it therefore makes little sense to exclusively rely on indicators that are related to specific environmental problems and their causing agents since they may be subject to considerable variation over time. This does not at all imply that the determination of critical substances and the application of critical thresholds do not make sense. Especially in the short run they are even indispensable. However, in the long run, that is in the time perspective in which the sustainability concept is usefully applied, an indicator for sustainability also has to account for the conditions under which the identification of problems as well as the search for the corresponding solutions and their translation into the appropriate measures takes place. Rather than referring to specific innovations whose characterisation as being sustainable can only be a temporary one, sustainability being the property of a system should be determined with reference to the system's general capability to bring about a variety of potentially useful innovations and, should the occasion arise, to allow for the ready implementation of the most promising alternative. In short, sustainability also, and from the evolutionary perspective predominantly, includes the flexibility and versatility of the entire system to allow for a quick and effective response to whichever environmental problems arise (see Erdmann 2000).

3.3 Irreversibility and path dependence

Beside fundamental uncertainty and the need for diversity following from the preceding argument, the complexity of multiple-interaction systems has another at least equally important consequence for the sustainability discussion. If the sequence of events within a complex system was described by means of several independent parameters, careful analysis would reveal non-ergodicity. That is, of all basically possible states only some are likely to occur in any single moment. Whether or not a given state is likely to arise, accordingly depends on the past or, more exactly, on the succession of states preceding the actual state – a phenomenon called path dependence. With regard to sustainability, path dependence plays a particularly important role in three respects. First, the wide variety of life forms in nature represents a large source of solutions for problems not only in the natural environment but also in the human sphere – for the assimilation of wastes, the production of food, and the design of pharmaceuticals, to mention just a few examples. Every species evidently represents a piece of knowledge that could potentially be useful for present or future generations. Against the backdrop of path dependence, however, it is also clear that the loss of any species leads to a loss of such knowledge that is irreversible. For every species is the outcome of a succession of phylogenetic stages in which the formation of every single stage is based on the existence of its respective predecessor – a fact that renders it impossible to reconstruct a species once it has been lost.

Second, even when knowledge is not directly acquired from models in nature, but derived through trial and error in the scientific process, this does not imply that all knowledge is equally accessible. Instead, technical knowledge generation is characterised by the formation of technological trajectories (Dosi 1982). Within such trajectories, knowledge acquisition occurs gradually – by the systematic small variation of single parameters and the selection of those variants showing the desired effect most markedly. Innovations proceeding along such a path are to some extent predictable but the marginal cost-to-effect ratio is subject to increase such that it becomes increasingly more difficult to make profitable innovations. An alternative route is the search for fundamental innovations leading to radical change between trajectories. While this approach has the potential for better profitability, it is characterised by a high degree of uncertainty representing a substantial burden for typically risk-averse people.

The third aspect of path dependence to be addressed here refers to the induced resistance-to-change and, thus, somehow relates to the second. It plays an important role in the discussion about technology development and is of central importance for the objective of this paper: the search of indicators for a sustainable technology development. Innovations and the introduction of new technologies often are the key instruments to the (temporary) avoidance or redressing of adverse environmental effects. However, even if negative external effects were completely internalised and the new technology turned out to be technologically and environmentally superior to the existing one, successful commercialisation and diffusion into the market cannot be taken for granted. A frequently quoted example for this kind of failure of a superior technology to prevail refers to the design of typewriter and computer keyboards (David 1985). Although the totality of users could benefit from the use of a better design that allows for a significantly higher writing speed, the traditional QWERTY keyboard is maintained because just for the first users of any new alternative, a deviation from the dominant design would cause costs that are much higher than the expected benefits. While network externalities are the relevant factor in the latter case, a variety of other effects will be identified in section 4 that lead to the lock-in of a conventional technology and, accordingly, to the lock-out of its superior challenger.

4 Indicators for second-order sustainability

In the preceding section, it was suggested that certain structural properties of a given technology can severely restrict the probability with which new innovations may become effective. The way in which these states of stability are sometimes discussed (David 1985) or modelled (Arthur 1988) in the literature could imply that such states of stability are omnipresent and, once they turn up, tend to persist for prolonged periods of time. Not surprisingly, some economists (e.g. Liebowitz and Margolis 1994) are convinced that positions like the preceding one crossly overstate the relevance of network externalities, as this would allow them to become the cause of almost ubiquitous market failure. In the latter debate, an intermediate position is taken by Witt (1997) who, while principally acknowledging the relevance of network effects, limits their general importance for the function of the market to certain restricted periods of time. So periods of stability tend to alternate with periods of instability where new networks can be formed. Such a period in which the direction of technological progress is flexible is referred to as a "window of opportunity" (Witt 1997). Disregarding these windows could severely hamper, if not completely inhibit, the introduction of any useful innovation. And even when, in the pursuit of sustainability, a new (sustainable) technology was successfully pushed by governmental regulation with no regard at the specific circumstances, the difference between stable and unstable phases would be worth a lot of money. It will therefore be the main objective of this section to identify all important factors and accordingly derive a set of indicators that allow political and other decision makers to make a well-founded judgement as to whether the preference for a potentially sustainable innovation is based on economic, social, and political feasibility.

The first set of factors will be economic ones. It will become evident in the following that the variety of relevant effects is wider and their respective time pattern more diverse than may have been implied by the repeated reference to network externalities in previous parts of this paper. Additionally, it is a special characteristic of many sustainable technologies that, beyond the competitive disadvantage frequently arising from their failure to internalise reduced external costs, the government typically plays a crucial role in overcoming existing barriers to competitiveness in the relevant markets. In doing so the government inevitably faces opposition from those whose interests are negatively affected: the incumbent industry and other groups paying the price for the measures taken. Typically, a government or policy makers in general are not inclined to neglect such an opposition unless the promoting forces from other parts of the society are sufficiently strong. More so, major techno-economic changes require a general openness or even a readiness to change (i.e. a phase of instability) on the part of the political system. For these reasons, the techno-economic factors will have to be supplemented by both, political and social factors. The selection of these criteria occurred on the basis of a priori theoretical plausibility considerations and ex post after the screening of relevant case studies (Sartorius and Zundel 2005). Due to the large number of relevant factors, it is not possible to present them here at length; for a more detailed discussion, the reader is therefore referred to Zundel et al. (2003, ch.1).

4.1 Determinants of (in)stability in the techno-economic system

Economies of scale. Economies of scale are due to the fact that the benefit arising from employment of a more sophisticated machinery can more than outweigh its higher overhead cost if only the quantity of output can be increased sufficiently. They are typically measured on the firm level in terms of average unit cost as a function of output rate. While economies of scale a cause of strong competitive (cost) advantage, they are particularly relevant for new technologies which, at the beginning of their life cycle, cannot immediately engage into large-scale production.

Economies of scope. Economies of scope account for the realisation of synergies between different production lines. This includes among other things the common use of certain resources, intermediate products, or production facilities and, thus, requires a high degree of co-ordination. While economies of scope lead to important cost decreases for the established industry, the mutual dependencies between existing production lines make it even more difficult for a potential market entrant or a new technology to become competitive.

Learning by doing. Unlike the cases of economies of scale and economies of scope, the cost decreasing effect of growing experience in designing, constructing ('learning by doing'), and using production facilities ('learning by using') is a function of the cumulative output of a given branch of production over its entire history. The learning effects relevant in this context arise from incremental technical progress and are typically expressed as the percentage of cost/price reduction per doubling of the cumulative production output. While learning effects provide any new technology with a large potential for further cost reductions, they confront it with a high cost disadvantage in the beginning.

Sunk cost. Investment into a new technology can cause significant sunk costs if this investment renders useless an old technology in the same firm prior to its complete depreciation. Since sunk costs represent opportunity costs of the new technology, they cause a systematic disadvantage for any new technology. While the latter argument does not come to bear in competitive markets, it is indeed relevant whenever market access is restricted by other causes. The rate of capitalisation in the relevant industry and data about the investment cycle can be used to assess sunk costs; however, the analysis needs to be supplemented by the competitive structure of the industry in question (see below).

Network externalities. Network externalities refer to the fact that the utility derived from the use of a given technology is positively correlated with the number of its users. Alternatively, a technology can be subject to network externalities if, rather than constituting a network itself, it relies on another technology that forms the network in its turn. Whether or not network externalities actually constitute an entry barrier for a new technology, depends on the dependence of the latter on an existing (technology) network and, if so, on their mutual compatibility. The weaker the dependence and the better the compatibility, the smaller the competitive advantage that can be drawn from network externalities by each competitor.

Market structure. In many markets, the number of market entries is limited by specific (declining average) cost structures or by governmental regulations, giving rise to natural or regulated oligopolies or monopolies. Although this does not exclude competition in principle, such market structures will provide the corresponding firms with strong incentives to maintain the existing market barriers, to engage into strategic interaction with other market participants for the realisation of monopoly rents, and to neglect innovative activities. Therefore, any non-competitive market structures will strongly stabilise the existing technology at the expense of potential competitors.

Potential versus risk. Marginal returns within any given technological paradigm tend to decrease in time. In order to replenish their earned innovation rent and, thus, maintain their current profit margins within a competitive market environment, entrepreneurs therefore have to complement their technological portfolios occasionally with more radical innovations. Since more radical innovations are associated with higher risk, an (expected) strong potential (including its regulatory conditions) will be decisive for the success or failure of a new technology to be adopted.

Demand. In order to be considered an economic substitute for an existing technology, a new technology will have to fulfil certain functions of the former that are crucial for attracting the attention and raising the specific demand of those consumers and investors that would otherwise buy the established technology. But this by no means implies that both technologies have to resemble each other in most or even all of their remaining properties. Since, after comparing two almost equivalent technologies, most people would probably buy the established version they are more familiar with, a new technology therefore has to fulfil as many extra-functions as possible to overcome this inertia.

Niche markets. If the entry barrier for a new technology is high, it may need a long period of subsidisation until general competitiveness is achieved. At the same time, partial competitiveness may be achieved under certain, for instance geographically or culturally specified conditions. Such an environment in which the new technology is economically viable despite its marked competitive disadvantages in the general market is called a niche market. The existence and the extent of niche markets can be decisive for reaching competitiveness of a new technology in general. In the same vein, artificial creation of such a niche market through governmental regulation can be an important approach to the successful implementation of a new technology.

4.2 Determinants of in-/stability in the political system

The basic characteristics of the political system generally play an important role in allowing a new, more sustainable technology to prevail. As a precondition for this to happen, the political system either must be in favour of the new technology from the beginning or it needs to be destabilised itself in the first place. While in the former case, structural characteristics of the political system play the most important role, both structural and procedural aspects are important in the latter. The following enumeration will begin with the structural factors and then shift to the procedural ones.

Institutional embeddedness. Many technologies, particularly those related to environmental protection, are subject to substantial political regulation that determines which external effects a technology is allowed to exert and which (and how) others must be avoided. In this context, the design of, and the mutual interaction between, the relevant institutions can greatly influence the competitive position of an innovation as opposed to the established technology. If, for instance, the regulatory restrictions specifically refer to an existing technology as the state of the art in solving an environmental problem, this technology is strongly stabilised as opposed to all innovations that approach the problem in a different way and, thus, have to pass approval and licensing procedures in order to conform with the regulation.

Interest groups. While it is a matter of political culture how influential corporate bodies or individual actors can be in principle (see e.g. the dependence of the government or the political administration on any kind of support from certain industries), it depends on the specific circumstances which effects they actually give rise to. Basically, the power of an interest group is known to be crucially dependent on the size of the group, the homogeneity of its interests, its organisation, and the resources it controls (Olson 1965). Other important factors are the economic relevance of the industry or its history and its cultural integration. Particularly in mature industries with strong market power, lobbying may even pay for single firms as from their perspective, investing in a useful regulatory institutional environment may be more profitable than investments in technological innovations (Berg 1995). As a consequence, most lobbying activities will tend to stabilise the established technology.

Asymmetry of knowledge. For the solution of environmental problems, governments and political administrations need external advice. So long as the problem has not attracted too much public attention, it is most convenient for the political administration to try to obtain the necessary information from the industry that caused the problem. According to the life cycle theory of bureaucracies, initially independent (regulatory) authorities will then successively merge their interests with those of the established industry (including the technological trajectory it represents) (Martimort 1999). This "regulatory capture of bureaucracies" often leads to quick and at most half-hearted solutions predominantly related to the dominant technology. By contrast, more radical changes can only be expected, if the necessary knowledge comes from more independent sources – notably state-financed scientific research.

Parliamentary majorities. Especially more radical changes are often not unanimously supported since the improvement of the situation of some people goes at the expense of others. Even if its basic attitude would tend to render a government or a political party supportive of this change, its actual realisation will ultimately depend on the strength and stability of the majority on which the politically acting group can rely. From this perspective, a large, stable majority basically opens the potential for more radical changes than does a minute or unstable one.

Election cycle. One of the most prominent stylised facts in political science states that more radical political changes usually occur at the beginning of an election period while incremental changes, if not political standstill, follow at the end (Troja 1998). With regard to environmental innovations this implies a potential for greater instability of the established technology (i.e. a political window of opportunity) in the post-election period. Unfortunately, empirical tests so far failed to confirm this effect of the election cycle (Horbach 1992). A special popularity of environmental regulation or an eminent problem pressure could be reasons for this. In

Germany, the temporal alternation between state and federal elections additionally renders the distinction between pre- and post-election periods obsolete. Finally, it has to be recognised that many aspects of environmental innovation policy are consensually negotiated and, therefore, unsuitable as topics for an electoral campaign.

Singular constraints. The costs and, thus, the scope of each regulatory measure is subject to a budget constraint. However, the latter is itself the result of negotiations between a variety of parties, each wishing to appropriate the largest share of the budget at disposal. While in many cases, the power of the interest groups behind technologies influences the allocation of governmental resources, this is not a natural outcome. In the end, it may depend on the social appreciation of environmental protection or the reputation of the involved parties whether the incumbent industry can defend its subsidies or has to share it with its more sustainable competitors. In this respect, a sudden change could also be brought about by singular (i.e. exogenous) events like political scandals and environmental or other catastrophes.

Decision-making procedures. Since it is not possible here to extensively analyse the entire political decision-making process, just a few criteria will be presented that may allow for a basic characterisation of the procedural aspects of a political system with regard to the stabilisation or destabilisation of a specific technology.

1. It is an important aspect of political culture whether the initiatives for regulatory acts typically come from single actors (e.g. president, members of parliament) or major bodies (government, parties, or the parliament). Individual-based initiatives tend to give rise to more radical (i.e. destabilising) changes than those of (more consensus-oriented) corporate bodies.
2. The relation between the legislative bodies and the executive administration determines whether a regulation is generally enacted by means of a law that has to pass a lengthy parliamentary approval procedure or whether this can be done by referring to an ordinance that is quickly adopted by the political administration.
3. Obligatory reassessment and the enactment of resubmission cycles ensure that the existing regulation does not lead to the stabilisation of the respectively benefiting technology.
4. Another important aspect of the political culture refers to the existence and influence of corporate structures (e.g. industry associations and labour unions); they typically refer to, and stabilise, established technologies.

5. Participation of larger parts of the society (e.g. NGOs, public research institutes) in the search for more sustainable solutions will not only facilitate the search for knowledge but also increase and widen the support for (often more radical) solutions.
6. Finally, it is important how a country is incorporated into supranational structures (e.g. EU, WTO). While this limits a country's possibility to implement innovations in an idiosyncratic manner, it broadens the scope and efficacy of many sustainable innovations.

4.3 Factors of change in the socio-cultural system

Public attention to a (perceived) problem and subsequent worry about its potential consequences play a key role in provoking political reactions directed to solving the problem or, at least, alleviating its consequences. This is all the more true in the context of environmental protection since due to their long-term relevance and public-good nature, environmental problems and their solutions are rarely issues that allow a politician to derive major benefits for himself. While awareness and concern by a considerable part of the population is neither sufficient nor necessary for political action to be initiated, their lack will usually lead to a failure or, at least, major delay in acting accordingly.

Mass media play an important role not only as transmitters for the corresponding information but also for the assignment of meaning and valuation to the underlying problem. The relation between the media and their readers, listeners, or watchers is characterised by mutual interaction giving rise to positive and negative reinforcement The scientific verification of an environmental problem which often stays at the beginning of such an 'issue attention cycle' (Downs 1972), is identified through scanning the scientific literature for relevant keywords and trying to identify seminal publications through the tracing back of references. On the other hand, public concern about these problems can be measured to some extent by counting relevant articles in newspapers and reports in other mass media. Additionally, it may be necessary to account for the more qualitative aspects of concern and valuation, as the authors of relevant articles often differ in their basic attitude towards a given environmental problem. It is also important to realise that the attention of mass media to any given problem usually tends to decline more rapidly than the attention of the public in general.

Table 1. Factors determining the stability or instability in each of the three subsystems and the indicators used for their operationalisation

Effect	**Indicators**	**Operationalisation**
Techno-economic system		
Economies of scale		cost (or price) development as a function of actual output
Sunk costs	average capitalisation of the industry	statistical data
	identification of investment cycles	recurrent phase-shifted cycling of prices and investment
	political regulation	cost of retro-fitting after regulation, delayed investment due to expectation of uncertain measures
Economies of scope	pattern of interactions between production lines	number and relevance of interactions between the old (new) technology and the entire production network
Learning by doing		cost (or price) development as a function of cumulative output
Network externalities	direct competition with (an)other network(s)	market share(s) of the competitor(s), availability of gateway technologies
	need for compatibility with complementing infrastructure or periphery:	
	• existence of public standards	which requirements are met?
	• availability of an adapter	cost of the adapter, legal admission possible, payable royalties
Market structure	degree of competition as a function of market concentration	market share of the biggest firm(s), Herfindahl-index, legal regulations
Potential vs. risk	riskiness ↔ availability of capital	marginal interest rate, capital share of venture capitalists
	problem solving capacity ↔ realisation of an innovation rent	technical properties, associated costs
Extra-demand	readiness to pay for extra-functions	market research
	existence of natural niche markets	higher prices, non-applicability of the established technology
	creation of artificial niche markets by means of regulation	(eco-)taxes, tradable certificates, cost of retro-fitting the old technology

Table 1. (cont.)

Effect	**Indicators**	**Operationalisation**
Political system		
Institutional embeddedness	Subsidies	financial support, tax breaks
	Protection	duties, other barriers to trade
	norms and standards	specificity of specification
Interest groups	resources under control (power)	number and economic importance of represented firms/sector
	structure of the basis; degree of homogeneity	market shares, concentration index
	influence; earlier success	(qualitative)
Asymmetry of knowledge	influence of (incumbent) industry in hearings	(qualitative)
	number of industry-independent research institutions/projects	number, financial support, number and size of commissioned projects
Parliamentary majorities	stability of majorities	size of majority, stability of constituting coalition (number and relation of parties)
Election cycle	distance to the next election	ditto
Singular constraints	political scandals Catastrophes	deception by possible interest holders accidents, unexpected discoveries
Decision-making procedures	probability of legislative initiatives	number and relevance of potential initiators, number of actual cases
	legislative vs. administrative regulation	number of laws referring to ordinances, actual number of ordinances
	reassessment and resubmission cycles	deadlines, frequency, possible consequences
	corporate structure	number, size, and frequency of political involvement of corporate organisations
	Participation	frequency and extent of incorporation of political "outsiders" (e.g. NGOs) into the decision process
	supranational structures	share of regulation that is not subject to national legislation

Table 1. (cont.)

Effect	Indicators	Operationalisation
Socio-cultural system		
Scientific verification of threat to sustainability	relevant publications in scientific literature, contributions to conferences	number of relevant articles (keyword search) in journals or conference proceedings and monographs; identification of seminal articles and quotation circles
Public concern about lack of sustainability	relevant articles in newspapers, reports in broadcast	number of articles/reports over time
Public acceptance of possible solutions	formation of major protest campaigns	number and size of campaigns

4.4 Integration of the indicators

After elaboration of a large, comprehensive set of indicators in the preceding parts of this section the question naturally arises as to how an integration of these indicators can be achieved. The first restriction to the achievement of this goal comes from the fact that most but not all indicators can be assessed in quantitative form. To determine their effect on the stability or instability of the established technological regime, it is necessary to compare the latter with its more sustainable alternative and to figure out the meaning of this difference. Here, a small difference in terms one property can be more important than a large difference in terms of another. So, representation of the entire comparison by a single pair of numbers is impossible.

The latter problem also applies to all those indicators that are indeed available as single figures. Even if these figures are expressed in the same dimension (e.g. monetary value), their meaning for the ultimate goal is quite different (compare sunk costs and size of niche market). As a consequence, any comparison can in the end only be of qualitative nature.

The next problem refers to the aggregation of the different factors. In the techno-economic sphere, all factors essentially work in parallel. High sunk costs add to the stability of the incumbent technology as well as does extended learning. Niche markets for the new technology on the other hand destabilise the incumbent. None of these factors relies on another one to become effective. So, even if one effect became zero, the other factors would remain unaffected. This mode of aggregation is called additive.

By contrast, in the socio-cultural system, (scientific) verification of an environmental problem is a necessary (but not sufficient) prerequisite for the formation of public concern. So, without discovering the problem, there will not be any concern. Conversely, public concern alone sometimes is little effective until the exact causes for an environmental problem are scientifically verified. So, both factors work in sequence with the combined effect yielded by multiplying the single constituents.

In the political system, both effects are found. While structural and procedural factors in general appear to complement each other in a multiplicative way, the specific structural (or procedural) factors tend to work in parallel.

With regard to the relationship between the entire systems, the political system not surprisingly is of central importance because in the end, it brings about the regulation. However, the political system hardly works on its own; it needs impulses from the other systems: destabilising impulses (for the existing technological regime) come from the society disapproving the lack of sustainability and/or from the new, more sustainable technological or institutional alternatives; opposite stabilising impulses come from the incumbent industry that caused the environmental problem and the loss of sustainability in the first place. Figure 1 summarises how the composite indicator of sustainable technology development is constructed from its constituents.

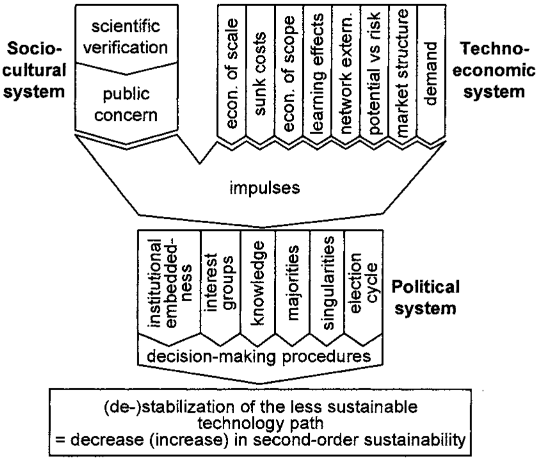

Fig. 1. Reconstruction of a comprehensive indicator for the successful implementation of sustainable innovations from its constituent factors in the techno-economic, political, and social sphere

5 Application of the new indicators: the phase-out of CFC

The indicator of sustainability or, more precisely, sustainability-directed technology development that has been developed in the preceding section, significantly differs from other indicators in referring not so much to the environmentally relevant properties of specific technologies, but to the entirety of the system properties that allow those technologies to become effective by entering the market in the first place. In order to use this indicator strategically, it would be necessary to first check all its components for relevance in a given context of an unsustainable technology and its potential substitute(s). Then all significant aspects would have to be assessed in terms of stabilising or destabilising effects and their changes in time. Finally, after specifying the mode of interaction between the relevant components, aggregation would yield a kind of time profile of in/stability reflecting the ease of transition from an established to a new technological path. Since at least some of the components are subject to influences by the political system, the whole analysis provides useful hints to the design of a policy that reaches sustainability targets most effectively.

Though under way, such ex ante studies are not yet completed. So, in order to illustrate the operability of the proposed method of analysis, I will refer to the ex post analysis of a rather successfully regulated technological transition that took place during the last quarter of the 20th century: the phase-out of ozone-depleting chlorofluorocarbons (CFCs)[2].

In the beginning of the 1970s, a small group of scientists became concerned about the environmental effects of the emission of chlorine compounds into the higher atmosphere. Among the major impacts of this group was Molina and Rowland's (1974) detection of a chemical mechanism potentially leading to the depletion of stratospheric ozone by chlorine atoms originating from CFCs. Ozone molecules were known to be essential for blocking UV radiation from entering those parts of the atmosphere where they would cause harm to organisms including humans. Although these results lacked validation in nature for several years, this community of environmentally concerned scientists succeeded in conveying their findings to environmental protection groups which reacted by initiating a campaign against the use of CFCs as aerosols in spray cans. Many consumers complied by not buying spray cans before a law prohibiting this usage of CFC was enacted in 1978. This led to a temporary reduction in CFC emissions

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[2] For a more comprehensive analysis of this case and for other case studies refer to Sartorius and Zundel (2005).

which was soon compensated by the increasing use of CFC in uses other than as aerosols (Meadows et al. 1992).

Enacting a law against CFC in spray cans did not require too much pressure after it turned out that the substitution for CFC even led to cost savings. Another reason for this success was the particular reliance of U.S. politicians on scientific arguments. But in order for the U.S. government to take more extended measures to reduce CFC emissions, the evidence in nature for the Molina-Rowland hypothesis was simply too weak and the opposition against such measures was too strong. As a case in point, a DuPont executive testified before Congress in 1974 that the "chlorine-ozone hypothesis is at this time purely speculative with no concrete evidence to support it." However, "[i]f creditable scientific data ... showed that any chlorofluoro-carbons cannot be used without a threat to health, DuPont will stop production of these compounds." (Meadows et al. 1992). At the same time, it was quite clear that the USA would be the major stake-holder in all measures concerning CFC since they were both the biggest producers and the biggest consumers of CFC. Due to significant differences even within the Reagan administration, however, it was not clear until the second half of the 1980s what position (positive or negative) would eventually be adopted in this respect. It was the U.S. Environmental Protection Agency (EPA) and the U.S. state department's bureau of Oceans and International Environmental and Scientific affairs (OES) that tended to adopt the critical scientists' position. On the other hand, interest groups and governmental offices related to chemical industry tended to adopt the viewpoint that important and far-reaching governmental regulation in the field could not be justified, not to mention the Reagan administration's general attitude was against any kind of regulatory intervention.

Then, in 1984, the first evidence for a big 'ozone hole' over Antarctica was found. Scientists of the British Antarctic Survey measured a 40 percent decrease in ozone in the stratosphere over Antarctica. While it took until later in 1987 that the causal relation between CFC emission and the ozone hole was finally established, the existence of the ozone hole was sufficient to initiate a powerful movement that eventually led to the ban of CFCs. Internationally, an important role in the latter process was played by the UN Environment Programme (UNEP) which organised a series of big international conferences intended to make a rigorous assessment of the remaining uncertainties of, and provide solutions to, the relationship between ozone depletion and CFC emission. When, as a result, evidence of the ozone-depleting effect of CFC had finally become strong enough to serve as an argument in favour of CFC regulation, especially two events led to a successful agreement in 1987. First, DuPont honoured the pledge it had made more than a decade ago and came to share the critical scientists' concern about CFC-caused ozone depletion. This "change in mind" of the biggest producer of CFC in the U.S. and world-wide led to a collapse of the U.S. industrial opposition against CFC regulation. Second, as a consequence of the discovery of the ozone hole and of other negative ecological impacts (e.g. the accidents in Schweizerhalle and in Chernobyl), green parties particularly in Germany became more influential. Together with a change in the presidency of the European Commission, this gave rise to a turn in the EU attitude that originally opposed CFC regulation.

In the end, international agreement on the Montreal protocol led to a two-step reduction of CFC production of 20% by the year 1993 of a total of 50% by 1998. Three years later (1990) in London, an amendment was ratified by 92 countries yielding a complete phase-out by the year 2000 and another two years later (in the Copenhagen amendment) the phase-out was advanced to 1996. This total ban of these chemicals within a single decade is all the more surprising in view of the economic relevance of CFCs (the USA alone produced almost one million tons of CFC each year).

With regard to the analysis in terms of stability and instability, the CFC story can be divided into two parts terminating in the ban of CFC-containing spray cans (in 1978) and in the Montreal protocol (in 1987) and its successors, respectively. In each part, the political system played a central role in the ban of CFC since without the basic readiness of the political system (and the corresponding window of opportunity being open), regulation would not have taken place. However, in both cases, additional support from the social system (i.e. an open window there) was useful, if not essential, in several respects. First, the scientific community played a crucial role in the social system by discovering the environmental problem associated with CFC emission and directing people's awareness and concern to it (Grundmann 1999). Second, a strong impulse pro regulation from the social system was necessary (though not always sufficient) to counterbalance contra regulation impulses coming from the economic system. This effect was even enhanced by the demonstration of a significant proportion of society that the environmentally harmful goods or services are indeed unwelcome. Third, the open window in the social system served as a legitimisation and incentive for policy makers to pursue regulatory measures against opposing forces from within the political system. Altogether, the social window of opportunity the opening of which was caused by the discovery and confirmation of the ozone-depleting effect of CFC, in its turn gave rise to an opening of the political window in the first place.

The following factors were crucial for the readiness to change of the political system. While the majority for the Democrats had been responsible for the enactment of the Clean Air Act and the ban of CFC in spray cans in the first phase, it was the initiative of individuals like U.S. chief negotiator Richard Benedick and a scandal in the EPA that led to the reconstitution of a pro-regulation regime despite the Republican government after 1983. Since the interest group contra regulation consisted only of a few chemical manufacturers with DuPont representing the biggest player, they were powerful enough to prevent major regulation before 1987; however, the alliance immediately collapsed after DuPont changed its attitude in 1986. Finally, the increasing role of environmental policy in some European countries and special ambitions of the former German chancellor Kohl in the EU led to a change in the supra-national actor constellation that allowed for the agreement in the Montreal protocol. By contrast, other factors like institutional embeddedness or knowledge asymmetries did not exert a significant effect.

Whether or not, at last, the economic window of opportunity was open for a regulation crucially depended on the cost-benefit calculus employed. Here it is important to distinguish between effects on the level of the economy which were more directly relevant for the response of the political system and effects on the firm or industry level that were crucial in terms of the pressure exerted on the political system. In the latter case, the most important costs of a regulation of CFCs were the sunk costs associated with the then obsolete production facilities (for CFCs) and the risk associated with the introduction of substitutes whereas the decisive benefit resulted from avoiding potential liability suits of those people that would eventually turn out to suffer from CFC-related skin cancer. Other techno-economic factors like economies of scale, economies of scope, learning, and network effects did not play such a crucial role as substitutes for CFCs were readily available with regard to production as well as demand[3]. Eventually, it was the confirmation of the direct link between the emission of CFC on the one hand and the break-down of the ozone layer and the concomitant increase in the irradiation of the earth's surface with ultraviolet light on the other, that forced the CFC producers to give up their opposition. While a variety of different substitute technologies was engaged in competition with CFC, it could be shown that those CFC substitutes supplied by the chemical industry initially benefited from first-mover advantages, that is, from the fact that they were in place first. Due to the regulation method employed (i.e. CFC emission trading), however, this advantages did not give rise to the displacement of other substitutes. Thus,

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[3] It was certainly in support of the phase-out process that substitution took place in several steps with HCFCs first replacing CFCs, then HFCs replacing the latter two, and finally, at least in some applications, hydro carbons, CO2 or ammonia replacing HFCs.

the techno-economic window could be kept open to increase the number of alternatives among which selection was supposed to take place.

In the end, the successive destabilisation of the CFC regime (and opening of the corresponding windows of opportunity) in each, the social, techno-economic, and political system has led to one of the most prominent cases of successful innovation policy towards sustainability.

6 Conclusion

In particular radical innovations can be important means to the achievement of improved sustainability. Due to the existence of path dependencies, however, the transition from one technological trajectory to another, more sustainable one is often impeded by significant barriers. Fortunately, these barriers are by their nature subject to substantial changes; so, it makes sense to carefully distinguish between periods of stability (with high barriers) in which the given trajectory can hardly be left and periods of instability (characterised by low barriers) where a new trajectory can be reached more easily. With respect to sustainability, the latter distinction is particularly important for two reasons. First, more sustainable innovations often rely on governmental regulation. In periods of instability, the economic burden arising from this regulation will be much lower than in periods of stability; so, a given budget will yield a much better sustainability effect in the former case than in the latter. Second, due to the complexity and changes in their respective environments, innovations are generally associated with fundamental uncertainty such that it becomes impossible to predict the degree of sustainability resulting from specific innovations in the long run. Under these circumstances, it is essential to allow for rapid change with the possibility to select between a variety of different trajectories within a process of trial and error. Sustainability as viewed from this evolutionary perspective may therefore better be understood as the general capability to readily change between different technological trajectories.

In order to undergo successful diffusion, most sustainable innovations rely on regulatory measures especially in the beginning of their (economic) lifecycles. When looking for the factors determining periods of (in-)stability, the political system enacting this regulation therefore is of central interest. However, while basically allowing for the convergence of both technological progress and sustainability, the political system itself can neither give rise to the search for sustainability nor bring about the appropriate innovations in the first place. This is where the socio-cultural and, of course, the techno-economic sphere itself enter the focus of attention as emitters of positive impulses. Additionally, negative impulses like those coming from the incumbent industry need to be taken into account. After all, a series of factors (and corresponding indicators) could be identified which after proper weighting and prioritisation allow to make an estimation whether, and possibly when, the incumbent industry is sufficiently destabilised and the political system rendered sufficiently favourable to the new, more sustainable technology such that a transition to the preferred trajectory is possible without too much effort.

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