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The Emergence of Lead Markets for Environmental Innovations

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1 Introduction

The diffusion of innovations varies considerably from country to country. Some countries adopt a specific innovation earlier, while other countries are late. For instance, the breakthrough of the Internet started earlier and the diffusion is now more complete in the United States than in any other country. The same has been the case with cellular phones in Finland or the facsimile machine in Japan. An explanation that takes into consideration solely the properties of the innovation will not suffice to explain these differences. Supporting factors in the respective countries must also be taken into account. Countries which not only adopt innovations early, but also shape world markets by the demand they create, can be described and analysed as *lead markets*.

Lead markets are "geographic markets, which have the characteristic that product or process innovations, which are designed to fit local demand preferences and local (...) conditions, can subsequently be introduced successfully in other geographic markets as well and commercialised world-wide without many modifications. In the model of international diffusion of innovations, a lead market is the core of the world market where the local users are early adopters of an innovation on an international scale" (Beise 1999: 4). This definition focuses on two characteristics of lead markets. Firstly, they are pioneering countries in the development and marketing of innovations. Secondly, innovations that arise in these markets subsequently diffuse world-wide. Both phenomena call for analysis and explanation.

We expect in these mechanisms a considerable potential for an encompassing ecological modernisation. Ideally, lead markets affect competition in other market regions, trigger appropriate responses and adaptations, and thereby lead to the international diffusion of the new technology. We are particularly interested in policies which facilitate or are constitutive to lead markets. We aim to analyse both the emergence of pioneer markets and the mechanism of international diffusion of environmental innovations.

At first glance, lead markets are often countries with the following features (Meyer-Krahmer 1999):

- High per capita income
- Demanding, innovative buyers and high quality standards
- Problems creating pressure for change and innovation
- Flexible regulation and innovation-friendly basic conditions for producers and users
- Product standards acknowledged in other countries

It can be expected that these factors are characteristic of lead markets for *environmental* technologies as well, but that there are also additional factors at work here, arising from the particular context in which environmental innovations are developed, both at the national and international level. Environmental innovations are not only stimulated by the higher environmental standards of consumers in a country as compared with those in other countries, but also by special promotional measures, or by political intervention in the market (Klemmer et al. 1999; Jänicke et al. 2000). Furthermore, environmental innovations provide marketable solutions to environmental problems that are usually encountered worldwide, or at least in many countries. Thus, technological solutions to environmental problems inherently lend themselves to adoption in international or global markets.

Lead markets may fulfil a range of functions. From an *international* perspective, they provide marketable solutions to global environmental problems. Lead markets in high-income countries are able to raise the necessary funds for the development of innovations. This may assist new technologies through their teething troubles. In demonstrating both technical and political feasibility, they stimulate other countries and enterprises to adopt their pioneering standards.

From a *national* perspective, ambitious standards or support mechanisms may create a first-mover advantage for domestic industries. Furthermore, ambitious policy measures can attract internationally mobile capital for the development and marketing of environmental innovations. Finally, economic advantages legitimate the national policymakers, and a demanding policy provides them with an attractive role in the global arena.

On the other hand, the international diffusion of environmental innovations is constrained by the national specifics of its origin. Environmental innovations are usually induced by national environmental regulations and subsidies and it is not immediately rational for firms in countries without the same regulation or governmental intervention to adopt them. Therefore, either the international diffusion of environmental innovations must be accompanied by international policy diffusion, or the adoption by other countries of the induced innovations must be economically reasonable. This paper aims to identify policy patterns that stimulate internationally successful environmental innovations while avoiding nationally idiosyncratic innovations.

The main subject of this paper is the international diffusion of environmental innovations, i.e. the emergence of lead markets out of pioneering markets for environmental innovations. We want to determine which actors (governments, NGOs, economic actors) and their respective strategies have the potential to facilitate lead markets.

Our analysis consists of three distinct steps. First, theories of innovation economics, environmental economics, management sciences and policy sciences are reviewed with regard to their contribution to an explanation of lead markets. Second, cases of lead markets as they are described in literature are reviewed and compared. The final step seeks to build on the first two to develop an analytical framework.

2 Theoretical Approaches

2.1 Lessons from innovation economics

The main question the lead market theory must address is why countries follow a lead market in adopting an innovation, even if these markets have previously favoured different environmental innovation approaches or designs. An innovation design is a technical specification of an innovation idea. An environmental problem can be solved by a variety of innovation designs. Different countries usually prefer different innovation designs for a given problem, as the initial market contexts pose different technical requirements. Not just strong needs and the demand for a particular innovation, but also the ability to transfer nationally specific innovations or preferences abroad is a condition for a lead market. A variety of lead effects are responsible for this internationalisation of an innovation design. The lead or leverage effect is the mechanism by which a design adopted by the lead market spreads to lag markets, supersedes initially preferred alternative designs in these markets, and becomes the globally dominant design. There are several factors that can explain this internationalisation pattern. Basically, lower prices and certainty of the benefit of an innovation design can compensate for internationally varying market conditions. Secondly, an international trend that is most advanced in the lead market brings about an internationalisation of needs (or preferences), and thus the adoption of innovations which respond to these needs by more and more countries. Beise (2001) has reviewed these and other explanations of the lead market phenomenon. On the basis of these results, a system of five groups of lead advantages of a country has been derived:

1. Price advantage. National conditions that result either in relative price decreases of a nationally preferred innovation design compared to designs preferred in other countries, or in the anticipation of international factor price changes.
2. Demand advantage. National conditions that result in the anticipation of the benefits of an innovation design emerging at a global level.
3. Transfer advantage. National conditions which increase the perceived benefit of a nationally preferred innovation design for users in other countries, or by which national demand conditions are actively transferred abroad.
4. Export advantage. National conditions that support the inclusion of foreign demand preferences in nationally preferred innovation designs.
5. Market structure advantage. National conditions that increase the level of competition between domestic companies and facilitate low market entry barriers for new ones.

Demand advantage

National demand advantage results from local conditions which facilitate the anticipation of the benefit of nationally preferred innovation designs in foreign markets. This mechanism allows the internationalisation of innovation designs and is dependent on a global trend in which specific innovations become increasingly beneficial or preferable to most countries. This trend can be, for example, a demographic trend, an environmental trend, or simply an increase in per capita income. A trend can also mean a time lead in building up infrastructure complementary to the innovation. Lead markets are at the forefront of the international trend. Various factors can put users in a country at the forefront of a trend: high income, as in the case of Vernon's (1966) product life cycle; a national context that foreshadows global environmental changes; an advanced accumulation of collateral assets, such as infrastructure. When other countries catch up, they demand the innovation already in use in the country at the forefront of the trend.

Price advantage

Countries may gain a price advantage if the relative price of the nationally preferred innovation design decreases, so that differences in demand preference to foreign countries can be compensated. This price mechanism is the centrepiece of Levitt's (1983) globalisation hypothesis, in which the consumers in foreign markets "capitulate" to the attraction of lower prices and abandon their initial selection of goods. Price reductions are mainly due to cost reductions based on static and dynamic economies of scale. The two nation-specific factors of economies of scale are market size and market growth. Another price advantage emerges from anticipatory factor prices; the lead market demands innovations induced by factor price changes which later occur world-wide. A factor that is more expensive in the lead market than in other countries, e.g. petrol, induces innovations causing the factor to be used less, e.g. more fuel-efficient cars. When the factor becomes expensive in other countries as well, the same innovations are adopted in these lag countries. In such a case, the lead-market country anticipates a world-wide price trend. The same price advantage results from price changes of goods complementary to the innovation design.

Export advantage

National conditions that support the inclusion of foreign demand preferences in nationally preferred innovation designs constitute a national export advantage. One can derive three factors of a national export advantage: domestic demand that is sensitive to the problems and needs of foreign countries; long-time export experience of domestic companies; and the similarity of local market conditions to foreign market conditions. Firstly, even if a country is not at the forefront of a global trend in terms of domestic environmental issues, domestic users may be more sensitive to global problems and needs than potential adopters in countries where the problem is more advanced. This sensitivity of demand can provide incentives for domestic companies to adopt a global perspective and increase their ability to meet global problems ahead of companies in other countries. For instance, consumers in a given country may be sensitive to the effects of world-wide climatic change, even if their domestic environment is not as seriously affected as that of other countries.

Secondly, firms in a given country have an advantage over foreign competitors if their innovations can be exported more easily. Innovations can be exported more easily if (1) the environmental and market conditions of foreign countries are similar to the market for which the innovation was designed, and (2) a design includes features that make it suitable for a variety of contexts. The reduction in the variety of nation-specific designs is faster, because it is easier for a country to turn to a foreign design if the loss of benefit is small. Dekimpe et al. (1998) support the hypothesis already proposed by Vernon (1979) that the higher the similarity of cultural, social and economic factors between two countries, the greater the likelihood that an innovation design adopted by one of two countries will be adopted by the other country as well. Companies can gain an export advantage if knowledge of the benefit of innovations to users in foreign countries is applied in the design of their innovations. Knowledge of foreign market conditions enables an innovator to design his innovations to fit the local as well as foreign markets by incorporating additional features. With such "dual-use" or "robust" innovation designs, a company can catch up with foreign firms' innovations in their home markets at an early stage, so as to pre-empt the international competition for nation-specific technologies. A country's context, including its users, suppliers and national institutions, can support or pressure companies to design innovations which can be exported. Small countries' firms are often pressured into developing innovations for both domestic and foreign environments, because the domestic market is too small to justify the necessary R&D investment.

Transfer advantage

When users in a given country adopt an innovation design, this can increase the perceived benefit of the design among users in further countries, thus influencing their adoption decisions. The perceived benefit increases when information on the usability of the innovation design is made available. Information about the innovation not only raises awareness of the innovation design, but also reduces uncertainty surrounding new products and processes. A country can have a transfer advantage if its market context supports increases in the perceived benefit of a nationally preferred innovation design for users in foreign countries. Diffusion theory suggests that the international diffusion of durable goods depends on the intensity of communication between two countries (Takada/Jain 1991). The lead market could therefore be the country that has the strongest communication ties with other countries. Lead countries are those that are generally watched by many other countries, for instance countries that are intensively covered by mass media or whose lifestyles are often present in television series and motion pictures. In the international innovation diffusion context, the "demonstration effect" (Mansfield 1968) becomes an international "lead effect" (Kalish et al. 1995). Potential adopters in a second country observe the success of the innovation in the first market earlier than the success of innovations adopted in other, not so keenly watched countries. The reputation and sophistication of a user can be a signal for the quality of an innovation design. As Porter (1990) pointed out early on, it is not only the quantity, but also the *quality* of the home demand that determines the international competitive advantage of a nation. Therefore, even a small country with a small market size can achieve a competitive advantage in certain segments. The quality of home demand can be interpreted as information on the specification of an innovation, based on the users' competence, know-how and prior experience with related products or processes.

International network externalities constitute a further transfer advantage. The Internet has gained international appeal because it connects all countries in a standardised transmission protocol. The preference for a design can likewise be actively transferred abroad. A country transfers demand for innovation design abroad through multinational companies, using the innovation in their foreign subsidiaries.

Market structure advantage

Innovations may be adopted internationally simply because, among all alternatives, they are the most beneficial to the most countries. The reason users in one country adopt an innovation before users in other countries is sometimes that the market pushes local companies to innovate, making the innovation available earlier in that country. Faster development and more market-oriented innovations can be supported by competition. From Posner (1961) to Dosi et al. (1990), the degree of competition and entrepreneurial effort in the domestic market has been described as one of the main determinants of international patterns of innovations. Even in the case of Japan, Sakakibara/Porter (2001) found that the higher the domestic competition, the bigger the country's export success. Firstly, buyers tend to be more demanding when the producers face competition than when they are tightly regulated or hold a monopoly (Porter 1990). Secondly, competing companies are more strongly pressured to follow those who have already adopted a new technology (Mansfield 1968: 144). Thirdly, and perhaps most importantly, more innovation designs are tested in a competitive market than in a monopolised market. As a result, a competitive market is more appropriate for finding a design that is not only the best within the domestic environment, but in all national environments. Fierce domestic competition facilitates the tapping of an internationally homogeneous latent consumer demand for innovations.

2.2 Lessons from policy analysis

The international diffusion of clean(er) technologies is frequently supported by the diffusion of their supporting policies. Recent comparative research on the spread of environmental policy among countries reveals a remarkable international convergence in the development of national policy patterns (Kern 2000; Jörgens 1996; Jänicke/Weidner 1997). Standard solutions from pioneer countries diffuse world-wide, thus bringing about a substantial convergence in policy formulation at the national level – irrespective of often considerably different capacities for action. Unlike in the 1970s, when the USA or Japan had a major innovative function in global environmental policy, today innovations in environmental policy emerge strikingly often in small EU countries that are tightly integrated in the global market (Jänicke 1998).

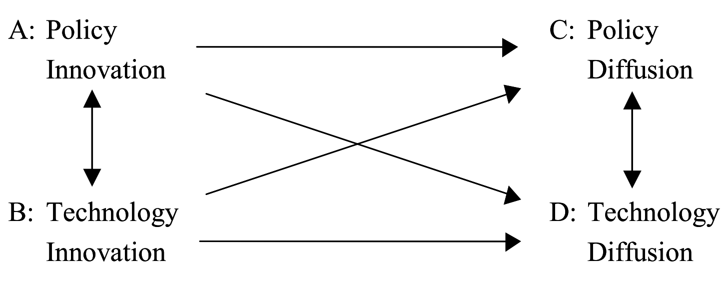
The – reformed – institutional fabric of the EU seems comparatively favourable both for innovations and for their diffusion (Héritier et al. 1994). Firstly, the EU must accept, at least in principle, a "high level of protection" in member states. Secondly, it must seek to harmonise innovations in environmental policy implemented at the national level. Pioneer countries, for their part, often have an interest in anchoring their policy innovations within the EU framework in order to minimise necessary subsequent adaptations to European policy. It is to their advantage to "Europeanise" national pioneering measures which favour the particular country's domestic industry. Policy diffusion within the EU, however, takes place not only by way of EU harmonisation, but also from country to country. In the latter case, the policy innovation in question often must first be introduced by one of the more influential EU countries before achieving the necessary widespread impact. The adoption of the CO_2/energy tax by Germany's red-green coalition government in 1998, after its introduction in the Netherlands and the Scandinavian countries in the early 1990s, is an example of "horizontal" diffusion. It has yet to be established as a European measure.

The diffusion of innovations in environmental policy thus takes place both directly from one country to another, i.e. by way of imitative policy learning or "lesson drawing" (Rose 1993) and by way of international institutions (e.g. international regimes), organisations (OECD, UNEP, World Bank, Greenpeace), or expert networks (e.g. the International Network of Green Planners). Environmental ministries have, in a period of less than 30 years, strongly asserted their position in more than 130 countries. Just ten years after the Rio Conference (1992), environmental plans, as defined under "Agenda 21", have been adopted almost world-wide – albeit in extremely disparate quality. In other cases (e.g. soil protection legislation), however, the diffusion rate is clearly curbed by the tenacity of the underlying problems.

From this type of research, three assumptions about the process of innovation and diffusion can be derived:

1. A high *capacity for environmental policy* is necessary for both policy innovation and the adoption of innovations. The OECD defines this broadly as "a society's ability to identify and solve environmental problems" (OECD 1994: 8). While the terms capacity and capacity building were used previously by numerous institutions such as UNEP, FAO, World Bank and OECD in connection with less developed countries only, they more recently have been fruitfully extended to apply to industrialised countries as well (Jänicke/Weidner 1997; Weidner/Jänicke 2001). Capacity refers to the structural preconditions for successful environmental policies and encompasses the collective actors (especially environmental institutions and organisations). The structural preconditions include (a) the institutional set-up (e.g. open and effectively integrated political institutions, administrative competence); (b) the system of creation, transfer and application of knowledge; and (c) the economic-technical basis.
2. The process of innovation and diffusion depends on the type of policy innovation and on the type of underlying problem. In general, technology-based policies diffuse faster than policies aimed at structural change. Pioneering national environmental policy is more likely to diffuse if it addresses environmental problems which are highly visible and on the international agenda, e.g. climate protection. Policy innovations which are naturally able to assert themselves, e.g. distributive instruments (subsidies) or informational instruments, diffuse more rapidly than regulatory instruments (e.g. command and control) or redistributive policies (e.g. taxes).
3. The diffusion of policies is frequently supported by international organisations. By spreading information about best practice, even weak organisations, which merely provide an international arena for national actors, rather than being international actors themselves (Underdal 2001), have an opportunity for effective action. For example, the OECD continuously evaluates, compares and benchmarks national policies, and in so doing successfully supports a convergence in policymaking without having any formal legitimacy of its own.

Figure 1: Stage Model of the Diffusion of Environmental Innovation



Policy induced diffusion

- Technology forcing $A \Rightarrow B \Rightarrow C \Rightarrow D$
  e.g. US-car emission standards (1970)
- Political initiative $A \Rightarrow B \Rightarrow D \Rightarrow C$
  e.g. cadmium substitutes
- Political dominance $A \Rightarrow C \Rightarrow B \Rightarrow D$
  no example yet ?

Technology induced diffusion

- Technological initiative $B \Rightarrow A \Rightarrow C \Rightarrow D$
  e.g. wind energy
- Technological dominance $B \Rightarrow A \Rightarrow D \Rightarrow C$
  e.g. CHP technologies
- Autonomous diffusion $B \Rightarrow D$
  e.g. incremental improvements of energy efficiency

Source: Jänicke (2000)

The interplay between the diffusion of environmental policy measures and environmental technology can take a wide variety of possible sequences. Figure 1 depicts a stage model of policy and technology invention and policy and technology diffusion. Theoretically, it is possible to distinguish between the following diffusion scenarios, depending on the factors leading to the political and technological innovations:

- *Technology forcing* (A⇒B⇒C⇒D): A national environmental policy innovation in one country forces a technological innovation which diffuses if the policy innovation also diffuses (e.g.: catalytic converter technology in cars).
- *Technological initiative* (B⇒A⇒C⇒D): An existing environmental technology induces a political innovation whose diffusion in turn encourages the diffusion of the technology (e.g.: wind energy in Denmark).
- *Political initiative* (A⇒B⇒D⇒C): A national environmental policy leads to technological innovations whose diffusion in turn encourages diffusion of the policy innovation (e.g.: cadmium substitute). [1]
- *Technological dominance* (B⇒A⇒D⇒C): An innovation in environmental technology is successfully diffused and as a result receives political support both nationally and internationally (e.g.: combined heat and power in industry). [2]
- *Political dominance* (A⇒C⇒B⇒D): The innovation in environmental policy is successfully diffused before a corresponding technology is available (this scenario is symptomatically very rare in ecological modernisation).
- *Autonomous technological development* (B⇒D): An innovation in environmental technology is successfully diffused without political influence; this case, beyond incrementally increasing energy efficiency in companies, seems to be rather rare.

The mechanism of international diffusion of policy innovations is favourable for the creation of lead markets for environmental innovations. On the one hand, the convergence of standards and regulations implies – in the case of technology-based policies – a widening of the market for technologies. On the other hand, the availability of technical solutions makes the diffusion of the corresponding policy innovation more likely.

Technological innovations provide additional options for policymakers. Once their technical and economic feasibility have been proven, supporting policies are more readily adopted. In other cases, policy factors have been the major driving forces in the stimulation of environment-friendly technical innovations. Technology forcing has, however, been the exception in environmental innovation (cf. Conrad 1998; Jacob 1999). The other extreme – the autonomous emergence and diffusion of innovations in environmental technology – is the exception rather than the rule and such developments usually yield only limited incremental increases in efficiency.

Technologies with advantages beyond environmental relief (e.g. cost reductions or users' higher willingness to pay) are more likely than EOP technologies to be successful abroad, even in the absence of policy diffusion. There is evidence, however, that EOP technologies, in combination with supporting regulation, diffuse in very similar manner. The technologies should address environmental problems of an international nature, i.e. problems that are on the international agenda or at least occur in different regions of the world. We expect technologies developed under competitive market structures to be more successful. Industries already operating in world markets are most likely to yield successful innovations.

In addition to the factors mentioned above, we expect lead markets to originate in countries which have proven their technological competence at least in the particular field in question, are highly integrated in the world market, are good overall economic performers, and have an established reputation as a pioneer in environmental policy.

2.3 Pioneering policy from the perspective of environmental economics

The influences derived above as determining lead markets for environmental innovations imply that the pioneering country is the innovator not only of the technology, but also of the policy measures taken to stimulate the innovation and support its adoption. It is therefore crucial to understand why countries may be progressive in their environmental policy regulations, and under which circumstances these policies are successful in increasing the share of domestic companies in international markets and thus increasing national employment and incomes. A causal relationship between a strict pioneering environmental policy and a competitive advantage is the core of the Porter hypothesis, which became

[1] The use of cadmium was regulated in Sweden in the early 1980s, with their standards for substitutes being adopted by European industry. Not until the early 1990s, however, were these standards made binding by the European Commission (Bätcher/Böhm/Tötsch 1992).

[2] Combined heat and power (CHP) in industry spread largely autonomously, even though regulatory measures were intended to encourage its use in public power stations.

prominent in the 1990s and is supported by a large body of case studies.

Modern game theory-founded environmental economics supports the view that a strict environmental policy implemented in advance of other countries – even while increasing costs to regulated companies – can improve the competitiveness of domestic enterprises under certain conditions (Ecchia/Mariotti 1994; Fees/Muehlheusser 2001; Fees/ Taistra 2001; Taistra 2000; Ulph 1996; Ulph/Ulph 1996). Several different mechanisms are suggested as being responsible for this.

Firstly, environmental policy can incite companies operating on oligopolistic international markets to behave more aggressively by pressuring them to make credible commitments to expand their market share. Foreign firms – if not supported by their governments – may then reduce their production in order to avoid having to lower prices.

Secondly, if economies of scale exist for suppliers due to learning, or for users of environmental technologies due to network effects, and the environmental policy diffuses to foreign countries, domestic firms can gain market share. It is important that foreign environmental policy neither follows too early, i.e. before economies of scale have become effective, nor too late, in which case domestic enterprises will bear higher costs than their foreign competitors over an extended period. Companies manufacturing environmental products are more likely to improve their competitiveness if foreign environmental policy is strict and foreign demand for environmental technology reacts strongly. For domestic users of environmental technology it is essential that foreign demand for their products does not strongly react to prices.

Thirdly, if innovation offset exists, i.e. if the cost of compliance is offset or more than offset by cost savings through innovation, the environmental policy stimulating such innovation creates a cost advantage relative to foreign competitors, but only so long as environmental policy abroad does not follow. It is not always apparent why environmental policy is necessary to motivate companies to invest in profitable innovations. One possible reason is conflict between owners and management.

Fourthly, greater willingness to pay for environmentally sound process technology or goods produced by environmentally friendly means leads to increased competitiveness for suppliers or users of such technologies, respectively.

2.4 Companies and strategic management

To explain the emergence of innovations and their international diffusion, it is not enough to examine country-specific factors or properties of an industrial sector alone, when only few companies compete internationally. The characteristics of firms must additionally be taken into account. Two approaches from management sciences which explain the strategic management of companies may be utilised in this context: on the one side, Porter's strategic positioning school and, on the other, the resource-based view (from static to more dynamic views). Strategic positioning builds on theories of industrial organisation, whereas the resource-based view builds on several research traditions, including, for example, evolutionary theories. Furthermore, the resource-based view may be interpreted as one part of a traditional SWOT analysis (strengths and weaknesses) and the strategic positioning school as representing the other part (opportunities and threats) (Spanos/Spyros 2001; Rugman/Verbeke 1998). The following hypotheses build on these traditions, as well as on some lessons of the case studies.

1. The strategic choices of a company take into account its positioning within a market, as well as the development of capabilities of the firm in a dynamic context.
2. With regard to the environment, the strategic choices of companies must take into account the environmental policy of the home base, the national environmental policies of other countries and of the international arena, and the action of other societal and supranational actors in a dynamic framework.
3. Companies therefore must decide either to develop "green" capabilities to comply with policy or, in the case of non-enforcement, not to react. The specific environmental policy and institutional context must be considered in this decision. Therefore, a general rule may not exist. The following matrix shows some possible interdependencies.

Figure 2: Corporate Strategy with National and International Environmental Pressures

Resource-based response to international environmental pressures \ **Resource-based response to national environmental pressures**	weak	strong
strong	1 International-based capabilities	3 National and international capabilities
weak	2 Compliance not capabilities	4 National-based capabilities

Source: Rugman/Verbeke (1998).

4. From a dynamic perspective, the creation of a lead market might start in quadrant 4 with the development of nationally based capabilities and then – with the diffusion of environmental policies – move to quadrant 3, where national and international markets and capabilities are created.
5. Environmental policy is not independent of company action. National environmental policymakers usually take into account the position of the firms in their country when negotiating international environmental agreements or the development of supranational environmental policy, e.g. in the European Union.
6. Further differentiation is necessary with regard to environmental innovations created in a pilot market. Is this development mainly driven by market forces, as suggested by the lead market theory, or by regulatory measures? In both cases, the strategic situation of firms must be taken into account.
7. Multinational enterprises with production locations in various countries must comply with different policy patterns and societal behaviour, and must react to these different challenges. They must make strategic choices; they have the possibility of learning from the varying circumstances, creating special corporate capabilities and thus playing an important role in the diffusion of technological as well as organisational innovations, and may further create "green" corporate capabilities. It must be taken into account that the context of "green" innovations (especially the creation of a lead market) might not be the place of production. One main reason for this is the transferability of innovations between contexts, especially by multinational companies.

3 Towards an Integrated Model of the Lead Market for Environmental Innovations

The emergence of lead markets for environmental innovations cannot be explained by a single disciplinary approach. All of the distinct theoretical approaches, defined by their methodologies and their respective subjects of research as described above, contribute to the analysis of this phenomenon. In this paper we attempt to integrate the approaches in a multi-level analytical framework (Figure 3).

The framework, however, is not a deterministic one. The factors which can influence lead markets for environmental innovations, as derived from the theoretical discussion above, are expected to be positively correlated statistically with the emergence of a lead market. The statistical validation is not examined in this paper. Instead, we report the results of several case studies to illustrate the national factors responsible for the international diffusion of the environmental innovations analysed.

This new model of international diffusion of environmental innovations should explain the internationalisation of environmental innovations compared to national adoption without international diffusion. We utilise the lead market factors as the main explanatory factors for the internationalisation process.[3] The reason for this is that international diffusion, in contrast to national diffusion, cannot be directly explained by policies, but only by economic or political reasoning, as no actor or policy has the power to pressure all companies world-wide to adopt an innovation. The theory integration is accomplished by integrating the additional arguments for environmental innovations into the lead market factors (policy diffusion, Porter effect) and modelling the impact of actors and policies on the lead market factors.

The policy level consists of actors and policies. It comprises a range of different national and international actors. It includes governmental and economic actors, as well as NGOs and their respective international organisations. The role of multinational companies in the international diffusion of environmental innovations by the various means described above is located at this level. All actors, their interests, their specific resources, and their corresponding strategies form a policy pattern (Blazejczak et al. 1999). This encompasses instrumentation (such as emissions control legislation, tax regimes, subsidies for specific technologies, etc.), policy style, and the configuration of the involved actors. Our case studies, which we describe below, confirm the need to look beyond single policy instruments and to consider the framework in which the policy measures are applied.

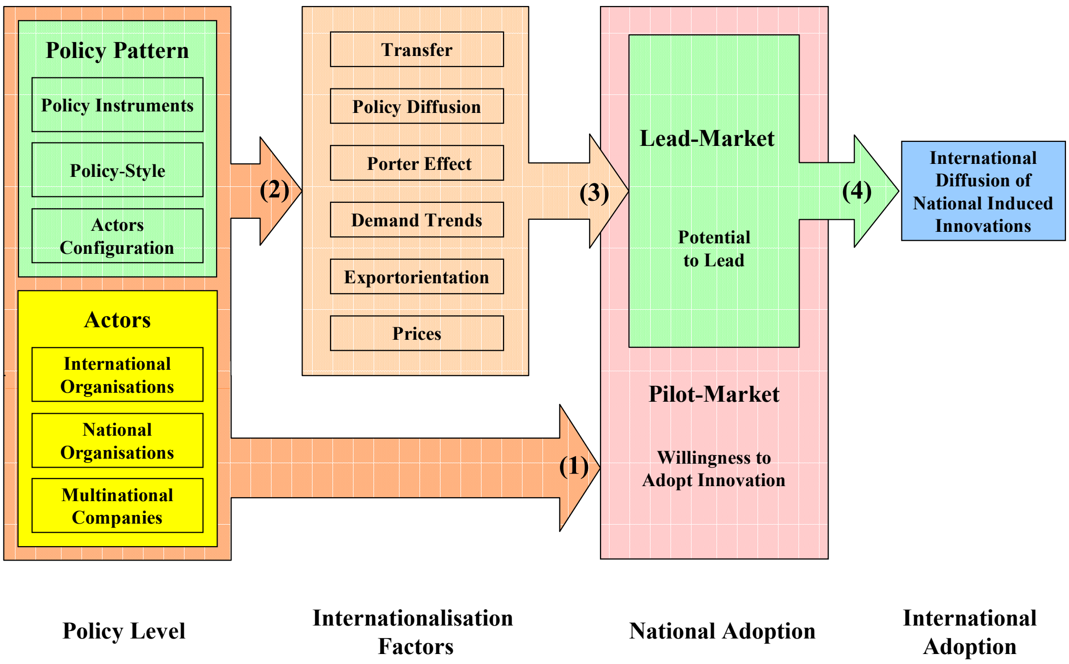
The elements of the policy level can have a direct influence on the willingness of a country to adopt innovations. This relationship is marked with (1) in Figure 3. Our analysis of the relationship between a policy pattern and the willingness to innovate builds on the results of a preceding research project (Klemmer et al. 1999). The Klemmer project focuses on the likelihood that innovations occur at the national level. Yet it does not elaborate under which circumstances an international diffusion of innovations occurs. The traditional impact

[3] The stage model in figure 3 is a complementary taxonomy that includes the sequence of policy and innovation diffusion but is not explanatory.

of policies on the adoption of innovations in a country (1) is not sufficient to account for the distinction between lead markets and idiosyncratic innovation markets that adopt innovations not adopted by other countries. This can be achieved only by the inclusion of the lead market factors. Our further analysis should reveal to what extent policy patterns and actors have an influence on the internationalisation factors of environmental innovations (marked as (2) in Figure 3).

The internationalisation factors constitute the second level of the model. We argue that the environmental policy-specific arguments can in principle be assigned to the five lead market factors elaborated in innovation economics and described in section 2.1. The analysis within innovation economics has focused on the relationship between the lead market factors and the potential of a country to lead the adoption of a specific innovation design internationally (marked as (3) in Figure 3). These factors are likely to improve the chances for an innovation to diffuse internationally (marked as (4) in Figure 3). To apply the model for environmental innovations, the lead market factors are adapted to the specific context of environmental innovations. The fact that policies diffuse between nation states or are harmonised in international organisations provides an additional strong factor in favour of the internationalisation of environmental innovations. Policy diffusion internationalises other innovations as well, such as pharmaceuticals or product safety improvements. The traditional lead market model integrates the arguments for international policy diffusion as a transfer advantage (Beise 2001: 102). The regulatory context of countries seen as pacesetters in the development of environmental policy is often transferred to other countries that are risk-averse. Such a pacesetter position may be gained either through innovativeness or through an important role in international organisations. In environmental innovations, policy diffusion plays such a prominent role that we add it as an extra internationalisation factor.

Figure 3: Framework for Analysing the International Diffusion of Environmentally Responsive Innovations



The market structure advantage, which describes competition as the most important factor in pushing innovations, is interpreted in the context of environmental innovations as the “Porter effect”. The Porter effect is the main argument in environmental economics to explain why, in the absence of policy diffusion, national regulation leads to global innovations. The main idea of the market structure advantage is that there are innovation opportunities hidden in the technological opportunity space and that market forces push companies to discover those opportunities. The greater the competition, the more likely it is that companies will discover profitable innovation opportunities. Porter and van der Linde (1995) argue that environmental innovations can also be profitable, but that, due to complacency, companies often do not pursue them. Environmental innovations, however, are driven less by competition than by regulatory means. To denote these differences, we refer to the market structure advantage as the Porter effect. The open question is what kinds of regulations can push companies to develop innovations that are profitable in foreign countries as well as in the domestic market.

The internationalisation mechanisms are based on country-specific attributes. They can, however, be influenced by various political and public actors and policies. For example, a tax regime can actively change factor prices for energy, pushing a country to the forefront of an international factor cost trend. Multinational companies can have a large impact on the international transfer of innovations and policy diffusion; international organisations can spur policy diffusion, which contributes to lead effect.

The framework illustrated in Figure 3 can be used to analyse the impact of policies on the lead market role of countries in environmentally responsive industries. It complements the traditional relationship between the policy level and the national adoption of innovations. The determinants of the lead market role of a country are modelled as a function of its lead market factors (relationship 3 in Figure 3). The lead market factors themselves are determined by the policy level (relationship 2).

The framework can be used to analyse the effects of policies and actors on the adoption and international diffusion of innovations. Its advantage over former studies of environmental regulation is that it makes a clear distinction between national and international adoption. With the help of the lead market concept of the international diffusion of innovations, this distinction can be theoretically substantiated. The original concept put the reasons for the international success of innovations down to theoretical attributes of countries. The traditional policy analysis focused on the effect of policies and styles on national innovation development and adoption. Our reformulation within the framework of environmental innovations emphasises the role of policies and actors on the internationalisation of innovations. Relationships (1), (3) and (4) are not only validated by theoretical reasoning, but supported by a rich literature, as well as by the results of our case studies. If these relationships are accepted, the next steps in research can concentrate on relationship (2). From the causal relations observed, we are particularly interested in drawing conclusions as to how policy patterns can be designed which are likely to stimulate environmental innovations that diffuse to other countries.

4 Case Studies of Lead Markets from Literature Studies

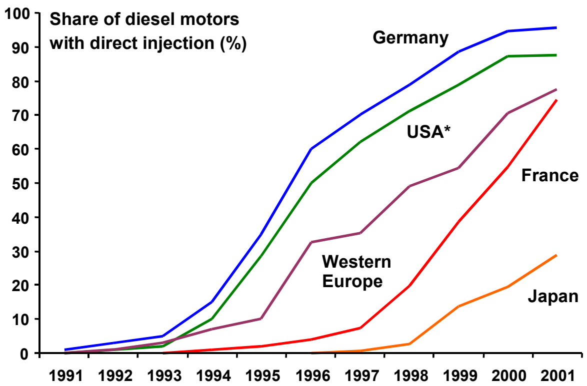
From these distinct theoretical perspectives, altogether 13 cases of environmental technologies and organisational innovations in the literature were explored with regard to their pioneering and lead markets. The selection criteria for the case studies were mainly pragmatic. The cases had to be well documented in the literature, they had to represent marketable environmental innovations, and a wide variety of sectors and countries had to be included. The case studies followed a common questionnaire asking for: (1) a description of the innovation design, the lead market, the regulatory measures taken in the pioneering country, and the actors involved; (2) an analysis of the lead market factors of the *country*; (3) the lead market factors of the *innovation*; and (4) the lead market factors of the *policies* supporting innovation and diffusion. In the following, a summary is presented of those case studies in which the phenomena of lead markets are most obvious.

4.1 Fuel-efficient passenger cars

Fuel-efficiency is a means of reducing the emission of greenhouse or other harmful gases. Fuel-efficient passenger cars are cars that consume a low level of fuel per 100 km. They are powered by petrol or hydrogen, or are equipped with both petrol and electric engines (hybrid cars). In Germany the most fuel-efficient cars are known as “3-Liter-Autos”, meaning that they consume less than 4 litres per 100 km. In the 1990s this limit was a realistic goal for most car manufacturers in the context of European driving habits and design preferences, and policies such as favourable tax treatment were introduced to support it. Since the end of the 1990s, there have been several German car models that are within this low consumption limit.

Modern fuel-efficient passenger cars use a bundle of technologies aimed at reducing fuel consumption. The most effective technologies in reducing fuel consumption are the use of low-weight materials, the enhancement of the aerodynamics of the car body, and the optimisation of the combustion process. The latter has been the development path most frequently taken, partly because it is the most efficient and partly because of market preferences. Indeed, cars have become heavier over time and body design must follow safety as well as aesthetic criteria (Franke 1998). Among motor technologies, high-pressure direct injection, and in particular the common-rail injection system, has been the most successful since the 1990s. High-pressure injection improves combustion and lowers the emission of exhaust gases while increasing the car's performance, notably its acceleration. In diesel engines high-pressure injection became almost standard during the 1990s (Figure 4 International Diffusion of Diesel Pressure Injection). The modern injection systems were developed by several car companies in Europe and Japan. Germany was the lead market. The US and Japanese markets lagged in this technical change, since the proportion and reputation of diesel-powered cars are much lower in these countries (Petersen/Diaz-Bone 1998).

Figure 4: International Diffusion of Diesel High Pressure Injection



** USA: predominantly light trucks*
Source: Bosch/ZEW

There are only few policy instruments in the automobile industry that directly stipulate the fuel consumption of cars. The US introduced a fuel economy rule (CAFE) for new cars in 1975, and is the sole country to have passed such legislation. For all companies selling cars in the US, it sets as a minimum fuel-efficiency requirement the average consumption of all cars sold in one year, or 8.77 litres per 100 km. Up to now, this rule has not been adopted by other countries. In Europe, a voluntary fleet consumption reduction plan by the European Automobile Manufacturers Association prevented its establishment in legislation. One of the reasons that this regulation has not diffused internationally is that it has proven ineffective. Its main weakness is that it does not affect demand. Firstly, automakers have the option of violating the rules and paying fines if demand favours less fuel-efficient car designs. Secondly, there is a loophole in the law that coincided dramatically with a market trend in the US. Light trucks, which became the most successful models in the US, were granted a much higher limit (11.63 litres per 100 km). Light trucks now account for more than 50% of all sales and 41% of oil consumed. The effect of CAFE on fuel consumption has therefore been low or even negative, since the market share of light trucks has increased dramatically. US cars still consume fuel at the highest rates in the world. There are few incentives for consumers to buy fuel-efficient cars. Correspondingly, there is no demand for fuel-efficiency and no incentive for car producers to lower average fuel consumption below the threshold (Bommer 1996).

Legislation in the auto industry is mainly aimed at reducing exhaust gases from passenger cars. Specific regulations vary from country to country, however, with the effect that different engine technologies have proven most efficient, depending on the given emissions requirements. In the United States, emissions-reduction policies specifically target harmful gases such as NO_x, while in Europe regulations focus on CO_2, the gas primarily responsible for the greenhouse effect. Since CO_2 emission is directly proportionate to the volume of fuel consumed, a reduction in CO_2 is only possible through higher motor fuel-efficiency. NO_x, on the other hand, can be reduced by catalytic converters and improved combustion processes without decreasing fuel consumption. The European regulation therefore applies direct pressure for higher automobile fuel-efficiency. Another effect of these differences is that diesel engine technology was boosted by European legislation, while the US rules discourage the adoption of diesel cars. Diesel engines are the most economic combustion motors today. The limit of three litres of fuel per 100 km is only achievable through modern diesel technology. However, diesel engines have higher NO_x emissions than comparable petrol engines. Diesel engines are therefore not an attractive technology for US car manufacturers aiming to follow US emissions regulations with as little R&D as possible. Yet, as diesel engines are the most promising technology to reduce fuel consumption in the short term, European automakers have concentrated intensive R&D effort on refining diesel engines to achieve reductions not only in CO_2, but in NO_x as well.

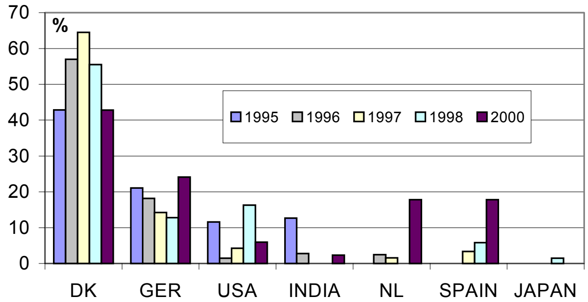
What factors made the fuel-efficiency innovations adopted in Europe more successful? Firstly, Europe has the highest fuel prices in the world, making such innovation most beneficial there. Yet, while there is a global trend of increasing petrol prices, the differences, especially between some European states and the US, are still so great that fuel-efficiency alone cannot persuade US consumers to adopt the innovation. The only innovations to have diffused internationally are those that do not just reduce fuel consumption, but also enhance other attributes of the car in keeping with global passenger car design trends. Over time, cars have become heavier, more luxurious and more powerful. High-pressure direct injection has proven to be a great improvement in diesel engines, which previously suffered from low performance. The main reason for the international success was neither the fuel-efficiency legislation, nor the other environmental factors that make fuel consumption more economical, but the general lead market attributes of the European market, which is often at the forefront of vehicle technology. Since the benefits of fuel-efficient technologies for the car owner are still low in the US, only innovations that offer additional benefits diffuse world-wide. This internationalisation mechanism is close to the Porter hypothesis: Pressure for environmentally responsive innovations in a market context that is most demanding, sophisticated and has a good international reputation leads to the development of technologies that appeal to users in other countries, even in the absence of an international diffusion of policies. Fuel-efficient technologies are employed not only in small or micro-compact cars, the prototype of a fuel-efficient car, but also in large luxurious cars such as Mercedes-Benz. These cars are more successful internationally than any other type, and it can be expected that the most successful fuel-efficient car will be a midsize sedan rather than the 3-litre cars currently available.

4.2 Wind energy

The world market for renewable energies and especially wind energy has increased rapidly over the past decades, due to the oil crisis in the 1970s and the ensuing discussion of environmental impacts due to fossil fuels. This developing world market is dominated by two countries: Denmark, the pioneering country in wind-generated electricity, and Germany, the market with the largest installed wind energy capacity in the world. Denmark is the world's largest exporter of wind turbine generators, as is shown in Figure 5. As the comparison of the import and export markets of the two countries shows, Germany exports only a small part of its wind turbines to other countries (DEWI 2000). Whereas Denmark's wind energy industry is world market-oriented, its German counterpart depends more on domestic demand and regulation (Denmark: 81% exports, 19% imports; Germany: 10% exports, 90% imports).

International Diffusion of Wind Energy shows the penetration rate of wind energy use in different countries (measured as exploitation of wind potential) and identifies Denmark as the lead market.

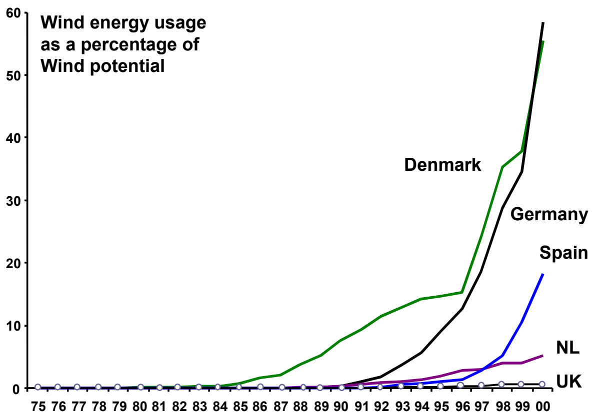
Figure 5: World Market Share of Wind Energy Industry by Country



Source: BTM Consult http://www.btm.dk/Statistics.htm

Denmark looks back on a long history of technical development of the wind mill. As early as 1918, 120 Danish energy utilities had a wind mill with a typical size of 20 to 35 kW, accounting for 3 percent of the country's total electricity production. The "Danish concept" is traditionally characterised by three rotor blades. Beginning in the 1950s, direct current generator plants were replaced by generators producing alternating current (the corresponding modern version is the asynchronous generator). The third typical feature, the modern wind energy converter, was also developed before the oil crisis. Today's converting systems are equipped either with pitch or active stall regulators, two different techniques for increasing flexibility of response to changing wind forces.

Figure 6: International Diffusion of Wind Energy



Source: IEA/OECD (2002), Lehmann/Reetz (1995)

While wind energy was long regarded as too expensive to compete with fossil fuels, the situation changed during the oil crisis. Several countries began to install big wind power plants of one megawatt or more, such as the GROWIAN in Germany. The plants failed, however, as they were economically inefficient. The main criterion in the technological development of such large wind power plants was their compatibility with the existing system of large, centralised fossil and nuclear energy plants. Energy utilities had no incentive to undermine their established system by developing a decentralised alternative system of renewable energies. Today GROWIAN is often cited as a project undertaken by actors who wanted to demonstrate the unfeasibility of wind energy, an indicator that wind energy development in Germany was not guided by economic reasonableness. In contrast, the technological development of wind energy in Denmark was characterised by more variety and flexibility. Although some experiments with large wind power plants were undertaken, the industrial and economic breakthrough was achieved through the continuous improvement of smaller converters. The new class of 55-kilowatt wind turbine generators developed in 1980-81 reduced costs by about 50 percent. In the 1980s many technology support programmes were set up all over the world, e.g. in California. Thousands of Danish Micon 55-kilowatt wind turbines were exported to Palm Springs. The Danish producers had the first-mover advantage, which they had gained when they started industrial production of wind turbines five years earlier than their competitors (http://www.windpower.dk). Since the 1980s, the size of wind turbines has increased continuously. This is the globally dominant technical trajectory and may lead to generators as big as GROWIAN. But at all times, the generator predominantly used in the Danish market has also been the most commercially successful design world-wide. The Danish market took a realistic and economically rational approach to wind energy.

In Europe, three different strategies for supporting wind energy can be observed (Langraf/Kellner 2000; Haas et al. 2000):

- renewable energy feed tariffs (REFITs),
- bidding systems, and
- tradable permit systems for renewables.

Some countries have implemented systems with additional incentives, such as tax reductions or specific depreciation privileges for renewable energies.

Renewable energy feed tariffs (REFITs) have been implemented in Germany, Denmark, Spain, Italy and Austria, and have also been used temporarily in Ireland (until 1994) and the Netherlands (until 1995). This system introduces fixed prices for green electricity bought by energy utilities from producers of renewable energy. Thus, the system can be described as a subsidy for wind energy. The REFITs system has fallen under criticism, since it is in conflict with the current trend of liberalising energy markets. Its main advantage is the low risk for investors, which has lead to a wind energy boom in countries with REFITs systems. On the other hand, this is also a disadvantage, since the competitive pressure on producers is low, too. This may lead to a system with higher costs for wind energy compared to a more competitive system.

Bidding systems have been implemented in the United Kingdom, France and, since 1995, Ireland. Competition among electricity producers is created by calls for tender from an agency representing the government. Energy utilities are obligated to buy a fixed amount of renewable energy per year from different sources. The quantity is set by the authority, and suppliers with the lowest price are selected to produce it. Energy utilities are compensated for additional costs by a national levy on energy which must be paid by all energy consumers. The bidding system leads to high competitive pressure and low costs and prices. In 1997 average wind energy prices in Germany were twice as high as in the United Kingdom. In the bidding system, only the best wind locations have a chance of succeeding. The prices of the REFITs system are higher, since they are oriented to estimated average costs of wind energy. One problem with bidding systems is the high risk for investors, compounded by an application process that is often characterised as expensive, time-consuming and bureaucratic. A further problem is the lack of continuity, since bidding conditions are subject to frequent change. Consequently, no significant wind industry could be established in any country with a bidding system.

Up to now, systems of green tradable permits for renewable energies have been introduced only in the Netherlands. Other countries, such as Denmark, are planning to switch from the REFITs system to tradable permits in the near future. Tradable permits combine the efficiency gains of bidding systems with the advantages of REFITs systems (achieving environmental goals by means of fixed targets for renewable energy development). The state sets quotas for renewable energies and issues certificates to companies producing the kind of green energy desired. The certificates can be traded on the market. Energy utilities are obligated to hold a certain percentage of renewable energy in their portfolio, i.e. they must either buy a certain amount of renewables certificates on the market or produce green electricity themselves.

Substantial differences can be identified when the regulation systems are related to the development of a national wind industry (Haas et al. 2000). In countries with the REFITs system, the wind industry developed rapidly, namely in Denmark, Germany, Italy, Austria and Spain, and, up to 1994 and 1995, respectively, also in Ireland and the Netherlands. In countries with bidding systems, wind energy use has developed very slowly, independent of existing wind resources. In France, the United Kingdom and Ireland the wind industry is poorly developed, despite an abundance of coastal regions with high wind potentials. Finally, the system of tradable permits for green electricity is still too young for an evaluation of its impact on the wind industry.

4.3 Substitutes for CFCs in domestic refrigerators

CFCs are chemicals used as, among other things, coolants in refrigerators and blowing agents for insulating foam. In the late 1970s they came under the suspicion of damaging the ozone layer. This led to the steady development of an international regime aiming to phase out and replace these substances. There are three primary substitutes available: 1) partially chlorinated HCFCs, 2) non-chlorinated HFCs, with HFC 134a as the most prominent chemical, and 3) natural gases such as butane or propane (HCs).

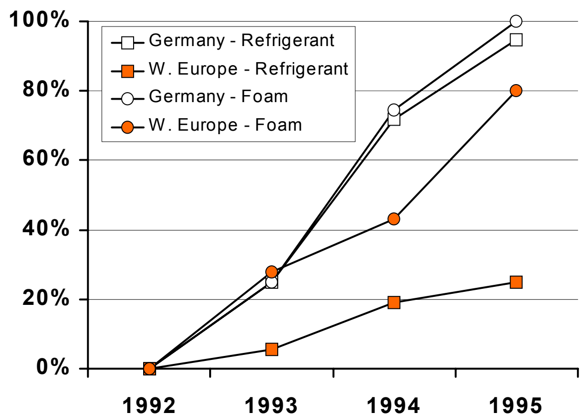
The first class of chemicals, partially chlorinated HCFCs, have a small remaining ozone depletion potential (ODP) and are therefore considered to be a viable alternative only for a transitional period. In the long term, amendments to the ozone regime require the phasing out of these chemicals as well. The second option, HFCs, was favoured by the chemical industries in both the US and, initially, Europe. This class of chemicals has been known since the 1950s. Considerable research efforts have been undertaken and advances in production technologies made under threat of regulation and, especially in the US, the fear of expensive skin cancer liability cases. The US-based corporation DuPont has been a leader in this area. The driving force for the search for substitutes was the early commitment of the company to stop production, should the suspected damaging potential of CFCs be confirmed. The company's search for alternatives is reflected in the rising expenditures for R&D in this field (Grundmann 1999: 254) and the large share of related patents held by the company (Oberthür 1997: 93). The US was also the first country to prohibit the use of CFCs as propellants. Taken in 1977, this measure gave momentum to the search for an alternative for other applications as well.

The prospect of a technically and economically feasible alternative for CFCs accelerated the negotiations of the global regulations laid down in the Montreal Protocol of 1986. DuPont supported global regulation of CFCs from 1986 on, while European manufacturers such as Hoechst opposed it, since European producers lagged behind in the development of substitutes. But the European position changed gradually from the mid-1980s onwards. As a result, the world production of CFCs has declined steadily.

Whereas the US favoured the second class of substitutes, HFCs, the third alternative, HCs, became dominant in Europe. While HFCs do not harm the ozone layer, they do hold considerable global warming potential, and are therefore criticised by environmentalists. At the beginning of the 1990s, Greenpeace Germany initiated the development of a refrigerator which employed hydrocarbons (HCs) as coolants and blowing agents. The major refrigerator manufacturers initially resisted this technology due to the combustibility of the gases. However, shortly after a small producer, in collaboration with a university institute, developed a prototype which met safety standards and Greenpeace started a public campaign in support of this company, the major German manufacturers adopted this technology (e.g. Lohbeck in 1999). German manufacturers converted to HC technology at their foreign production sites as well. Bosch-Siemens, for example, now produces on an HC basis in all of its subsidiaries. Electrolux switched to HC technology for the European market. Meanwhile, this technology has also been adopted by low-cost producers such as the Italian manufacturer Candy, which switched in 1999. Other manufacturers that have converted to HC technology are based in countries as diverse as Sweden, Denmark, France, Japan, Turkey, India, China and Cuba.

Currently, all three refrigerator coolant alternatives are on the market: CFCs are still produced in developing countries such as China and India; HFCs have gained a large market share in North America, Japan and Southern Europe; and HCs have become the dominant chemical for refrigerators for domestic use in Northern Europe. In Germany, the market share of HC technology is reported to have already reached 100% (World Bank et al. 1996). In Japan HFC has become the predominant technology for refrigerants, but HC is utilised as well. As of 2000, approximately 40% of blowing agents used in refrigerator production were based on HFCs, while 60% utilised HC (Little 2002). The jury is still out as to whether one of these two alternatives will become globally dominant, but HC has strong potential to become the global choice.

Figure 7: Market Share of HC Refrigerators



Source: Authors' calculations based on data and estimates of Sicars (1995).

There is a lack of current data on the market penetration of HC technology. Its diffusion between 1992 and 1996 in Germany and Europe as a whole, the countries leading the international development, is shown in the following graph. It should be noted, however, that the German data is included in that of Europe. There are many signs that HC market penetration in other countries has also advanced considerably by now, and that a diffusion is taking place, particularly to less-developed countries (e.g. World Bank 1996).

In the mid-1990s, HC technology had made few inroads outside of Western Europe. Minor applications were reported from Eastern Europe, Japan, China and Oceania, whereas most producers in Central and South America, Africa and Asia continued to use CFCs (UNEP 1998). In recent years, however, the share of HC-based refrigerators has grown significantly. According to a Greenpeace study, in 2000 there were more than 55 million HC refrigerators in operation world-wide (Maté n.d.). This represents a share of roughly 10%. Lohbeck estimated the 1999 world-wide production to be about 15 million units annually, or a market share of around 20% (Lohbeck 1999).

A considerable increase is owed to a conversion made by large Chinese manufacturers. It is reported that two Chinese manufacturers (Kelon and Haier) have almost completely switched their annual production of 2.5 million units to HC technology. This gives China the largest share of HC technology outside Europe (Lohbeck 1999). The conversion in China was supported by the German and Swiss governmental development agencies, by Greenpeace, and by the German manufacturer Liebherr.

Other German development assistance projects were started in India to develop a plant based on HC technology which was planned to be finished in the late 1990s (Sicars 1999). Campaigning by Greenpeace and Friends of the Earth also took place in African countries and in Australia. The Swiss/German development projects were supported by the World Bank and were part of the “Multilateral Fund” (MF) that was set up in the framework of the Montreal Protocol to finance conversion to CFC-free technologies. Countries in the South are particularly interested in HC technology, because there are no licence fees to be paid as there are for the patented HFC technologies.

Despite the early lead in the conversion from CFCs, in the US the HC campaigning has not been successful. A recent study comparing the HFC and HC technologies argues that the US producers are unlikely to adopt this technology because US manufacturers are concerned that even a small risk of accidents due to the flammability of HCs may result in large financial claims and product liability insurance cost could increase significantly (Little 2002). The predominant type of refrigerator in the US is not only considerably larger, but also has an automatic rather than manual defrost system, which would lead to higher safety requirements if HC technology were applied. Furthermore, it is more difficult to meet the mandatory energy-efficiency standards with HC technology. The same study argues that the overall contribution of HFCs to global warming is only of minor importance as compared to CO_2. This view of important barriers in the US market is countered by other authors, mainly based on the European experience, with almost no accidents, improvements in energy efficiency, and a switch to automatic defrost as well (overview in Lorentzen 1995).

Despite Greenpeace’s campaign in favour of HC technologies and the above-mentioned government projects to support their adoption in developing countries, there are few countries with policies that discourage the use of HFCs or favour HC. Although HFCs are affected by the Kyoto Protocol due to of their global warming potential (GWP), specific policies are rare. The Danish Environmental Protection Agency published a plan to phase out their use, along with that of other fluorinated gases, by 2006. French climate change strategy covers HFCs and proposes voluntary agreements for their reduction, as well as an extension of the planned CO_2 tax in accordance with their GWP. The UK draft climate change programme states as a general principle that HFCs should be avoided wherever acceptable alternatives are available. The Netherlands specifies a reduction target of 23%. In other countries (Germany, Belgium, Austria), subnational regulations are in place to reduce the use of HFCs. Ecolabels are planned in Austria, and are implemented for refrigerators in Germany (Anderson 2000).

The main driver for innovation in the lead country, Germany, has been the campaigning by Greenpeace. Their activities have also been important for the diffusion of HC technology in Europe and in developing countries. This diffusion was promoted by development aid projects sponsored by the Multilateral Fund, and by the adoption of this technology by German producers in their foreign subsidiaries as well as at home. It is too early to tell whether this technology will be adopted in the US as well, but European experience and NGO activities in the US make this conversion more likely.

4.4 Chlorine-reduced pulp production

In the process of producing pulp from woodchips one major problem is to reduce the lignin content of the pulp as much as possible (delignification). This has an immediate impact on the pulp quality. The brightness of the resulting paper (or cardboard) depends on the percentage to which the lignin parts have been separated. At the same time, the strength of the pulp should not be reduced. By far the largest amount of the lignin content is separated out during the so-called cooking, a thermo-chemical step in the pulp production process. The lignin content is further reduced in an additional step called bleaching.

Up to the 1980s, the production of pulp was (predominantly) based on the use of elementary chlorine in bleaching. In the mid-1980s it became known that the use of elementary chlorine leads to the generation of environmentally highly problematic chlorine compounds, such as dioxin.

When awareness increased of the danger of organochlorines – which can only be reduced through in-process technologies – Scandinavian mills were best able to adopt these technologies, as they were not locked in to secondary waste water treatment facilities. Additionally, their experience in developing in-process technologies to reduce overall waste streams put Scandinavian suppliers of pulp production technologies in a favourable position to respond to the demand for equipment to reduce chlorinated organic emissions.

The improvement in the competitiveness of Scandinavian suppliers has not been detected in analyses of trade data, however (Scholz/Stähler 1999). One possible interpretation offered by the authors is that in the pulp and paper industry the diffusion of innovations occurs via imitation rather than through trade of equipment. It can also be argued, however, that trade data on equipment for pulp and paper production thus far investigated are too aggregated to detect improvements in individual segments of the equipment market.

Several technologies with the potential to reduce chlorinated organic emissions have been developed and are applied in large-scale production facilities.

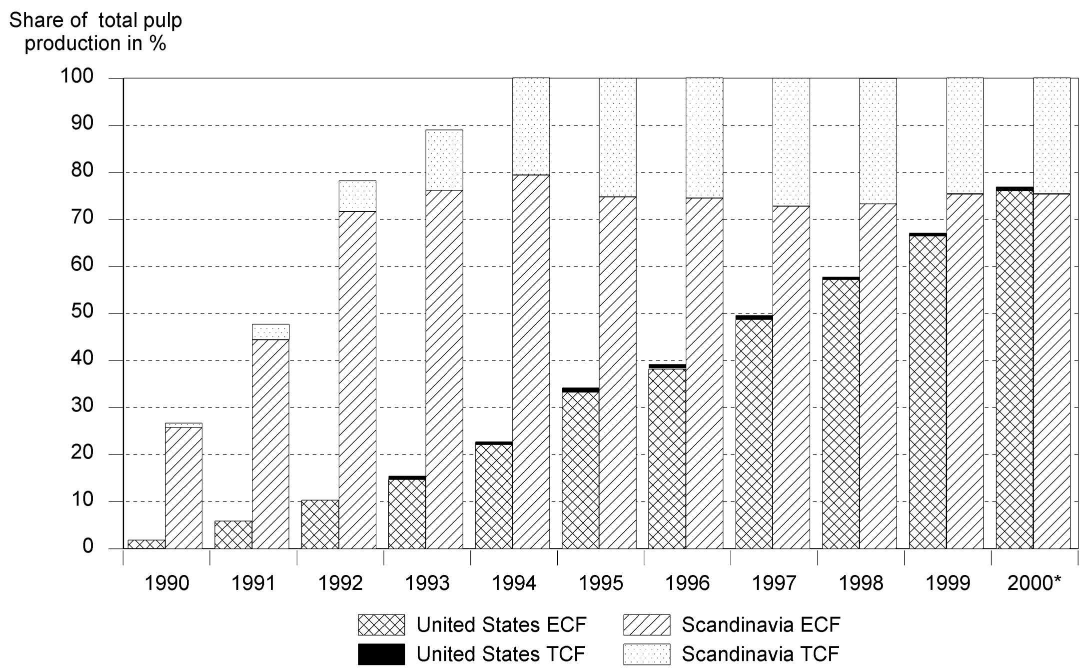
- In the technology for e*xtended delignification,* additional lignin removal is achieved by lengthening the cooking process. Pulping chemicals, which are largely recovered, are used here as functional substitutes for bleaching chemicals, which have to be disposed of. The technology was developed in Sweden by the research institute STFI and commercialised by Kamyr/Kvaerner (Sweden) for the – more common – continuous cooking processes and by Beloit (US) and Sunds Defibrator (Sweden) for the – usually older – batch processes. Retrofitting existing plants is possible in most cases, but involves high capital costs. The process results in reduced operating costs compared to conventional processes.
- *Oxygen delignification* technology uses an additional oxygen reactor between the pulping and bleaching step, to remove additional lignin in an alkaline environment. This technology can be integrated with extended delignification in one process line. Kamyr/Kvaerner (Sweden) and Sunds Defibrator (Sweden) developed and manufactured much of the technology. It is also characterised by high capital costs and reduced operating costs. Although retrofitting is possible, the introduction of the technology is more profitable when used in building up new capacity. One disadvantage is a reduction in pulp quality due to strength degradation. The supply of cheap oxygen in Japan encouraged diffusion of oxygen delignification in that country. In the US, the advantage of reduced levels of BOD, which is connected with this technology, could not be exploited, as most facilities were already equipped with biological treatment systems (due to former strict regulation of water emissions).
- *Ozone delignification* technology uses ozone as bleaching agent. Ozone has to be produced on-site, which accounts for a significant part of total capital cost. The process results in very low emissions, because all effluent can be recycled. It was developed by the pulp and paper company Union Camp (US) to meet regulatory demands under specific natural conditions for its Franklin mill. The technology was marketed in a joint venture with Sunds Defibrator (Sweden). Its installation requires high capital costs and results in reduced operating costs, especially for softwoods. Integrated with oxygen and/or extended delignification upstream, the technology allows the production of TCF pulp.
- The s*ubstitution of chlorine dioxide for chlorine* at a higher rate is a proven technology to reduce the formation of chlorinated organics. The technology is comparatively cheap and easy to retrofit. It results in moderately increased operating costs, because chlorine dioxide is more expensive than chlorine. Chlorine dioxide must be produced on-site. The problem of generating by-products in excess of plant needs has been reduced by new solutions. Installation in the US is driven by increasingly strict regulation. The highly corrosive chlorine compounds limit the potential for effluent recycling and conflict with the long-term prospect of a zero-emission or eco-cyclic pulp mill.

The complete substitution of chlorine dioxide for elementary chlorine results in elementary chlorine-free, or ECF pulp. A combination of technologies for extended cooking, oxygen and/or ozone delignification is the basis for producing totally chlorine free, or TCF pulp. The first TCF pulp was produced in Sweden in 1990 by a small producer. Large-volume producers soon followed suit.

The diffusion of pulp production technologies can be described by looking at the production volumes of pulp differentiated by chlorine use in production. In the US, diffusion started only in 1990, but has increased steadily since then. As can be seen in figure 8, the diffusion of chlorine-reduced technologies started much earlier in Scandinavia and had already reached 100% of production by the mid-nineties. The role of Scandinavia as lead market for chlorine-reduced pulp production is underpinned by these data.

With regard to the distinction of ECF and TCF pulp, it is obvious that TCF plays a significant role in Scandinavia but not in the US. The share of TCF pulp did not increase from 1995 even in Scandinavia. The early diffusion of TCF was supported to a large extent by Greenpeace campaigns which resulted in strong demand for chlorine-free paper in Europe, especially in Germany (indirect demand effect). Since these campaigns levelled off, incentives for a further diffusion of TCF have seemed to be missing.

Figure 8: International Diffusion of ECF and TCF Pulp (Location of Production)



* Estimate based on 1999 production volumes.

Source: Alliance for Environmental Technology (http://www.aet.org/science/aet_trends_2000.html).

In the 1970s the US led environmental regulation of the pulp and paper industry. Regulation required that manufacturers adopt BAT to avoid the release of conventional pollutants, such as suspended solids and oxygen-demanding organic materials. These requirements could only be met by the installation of primary and secondary waste water treatment facilities, which was very costly.

In Scandinavia, specifically in Sweden, requirements with respect to conventional pollutants came later and were more lenient. Compared to the US, comparatively few mills were required to install secondary treatment of effluents. This was due to the high assimilative capacity for conventional pollutants of the large bodies of water into which mills discharged in Sweden. It was possible to meet the Swedish requirements through in-process modifications, which reduced overall waste streams. Swedish environmental regulations are shaped by the country's participation in international agreements, such as the Helsinki Convention (Baltic Sea Convention) signed in 1974.

Once secondary treatment was installed, the benefits of TCF processes such as oxygen and ozone bleaching were reduced to avoid the release of chlorinated organics; the additional benefits of reduced conventional pollutants – through lower waste loads, which emerged out of the possibility of recycling chlorine-free waste streams – did not pay off.

In the mid-1980s, the release of organochlorines became a concern that could be addressed only through process changes. At that time, Scandinavian equipment suppliers had won a strong market position for these technologies. This was reinforced by the long period (more than a decade), required to bring a technology to commercialisation in this field, while US firms were required to rapidly address the problem of organochlorines. In addition, US producers of pulp were forced to make a second major investment.

The development of in-process modifications to reduce or eliminate the release of organochlorines was promoted by NGOs. In particular, Greenpeace put pressure on publishing houses in Germany to use paper manufactured from TCF pulp. This had repercussions for their Scandinavian suppliers of paper and pulp. Some early movers were able to capture higher prices for TCF paper. One impact was an increased spread of information on environmental problems, as well as their solutions throughout the world.

In the US, the threat of litigation from water sports organisations had an influence on the decision of manufacturers to adopt ECF pulping technologies. The further diffusion of chlorine-reduced technologies to newly industrialised countries, namely in Southeast Asia, was financially supported by aid agencies. An important role was also played by leading consulting firms, predominantly based in Scandinavia, who advocated the use of the most advanced technologies in the build-up of new production capacities in these countries. The few suppliers for these technologies act world-wide and are interested in selling the most advanced solutions.

The case of ECF/TCF pulp production demonstrates the advantages of regulations which encourage a reduction of the entire waste stream, thus curbing the release of yet unrecognised problem materials.

The result of this case study is inconsistent with the hypothesis that moving ahead with stricter regulation will invariably promote international competitiveness. Rather, it becomes obvious that the flexibility of the Scandinavian regulations was responsible for the good starting position of suppliers in these countries when the release of organochlorines was recognised as a problem of pulp production.

The importance of flexibility of environmental regulations has not been investigated in theoretical environmental economics models yet.

4.5 Introduction of the catalytic converter for cars

In the 1950s automobile exhaust emissions were identified as a main source of smog. This led to the adoption of air quality and auto emissions standards in California in 1959, imposing requirements for the reduction of HC by 80% and CO by 60% by 1966. Through this and later legislation, California established itself as the pacesetter for US policy.

At the federal level, the Clean Air Act was passed in 1970, calling for a reduction of 90% in HC and CO within five years, and in NO_x within six years. These ambitious standards were set against the backdrop of a presidential campaign which saw the candidates (Nixon and Muskie) competing in the field of environmental policy.

This was the first time that Congress had set environmental targets, which were meant to be technology forcing, since the car manufactures claimed there was no existing emissions control technology able to meet the new standards. The automobile industry, however, was not convinced that the standards would be enforced in the long term. Indeed, the EPA delayed their implementation until 1978, while in the 1977 amendments to the Clean Air Act, Congress again relaxed standards for NO_x.

The automotive industry in the US might be characterised as an oligopoly, as it effectively avoids price as well as non-price competition. In the 1970s, after the oil price shock, the sector came under heavy pressure by Japanese and European imports, especially in the small cars segment.

The requirements for emissions control were a new challenge for this industry. There were different strategies available to meet these standards: (i) modifications of engines and control systems, as well as emission control devices and (ii) the investigation of alternative power trains for automobiles. US automakers co-operated in investigating technologies they considered likely to be successful. Co-operation in this area began as early as 1954. It continued until it was finally prohibited in 1969 as the result of a lawsuit brought by environmentalists arguing that the industry denied public access to technological findings concerning emission controls.

Another case of (international) co-operation, the Inter-Industry Emissions Control Program (IIEC), was initiated at the beginning of the 1960s. This body included Ford, several oil companies, and import manufacturers such as VW and Toyota. GM and Chrysler did not participate because of the antitrust law.

R&D efforts regarding the catalytic converter began at the end of the 1950s at GM. At the same time, efforts were made in the development of alternative power train technologies, in particular electric, petrol, electric hybrids, as well as Stirling, steam power, fuel cell and gas turbine systems. In 1967 the Department of Commerce reviewed these alternative engines, concluding that they had not been adequately studied and there was a need for further research.

More strenuous efforts in research on the catalytic converter did not start until the end of the 1960s. GM established a task force in 1969 which was asked to evaluate the potential of catalytic converters for automobiles. This task force of high- anking individuals indicates that the problem of emissions control had become a priority within the strategy of GM.

The catalytic converter became the dominant technical strategy to reduce emissions for two main reasons. Firstly, it did not affect basic engine design[4], and secondly, it could be abandoned if there were a change in the law by Congress.

The market for catalytic converters for mobile sources did not exist before the enactment of the US regulation. Catalytic converters for stationary sources were produced by a small number of companies, all of which were present on the American market at this time. Three firms in particular achieved success in developing and marketing catalytic converters for mobile sources: the British-based company Johnson Matthey, and two American companies, Engelhard and Corning. Both of the US companies entered this field only after the passage of the Clean Air Act in 1970. The suppliers who were active and successful on the US market at the beginning of the 1970s are still the dominant producers worldwide today. In 1998 Engelhard (US) controlled 30% of the world market, Johnson Matthey (UK) 25%, Degussa-Hüls (Germany) 17%, and Delphi Automotive Systems (US) 15%. Along with NGK (Japan), Corning remains the major supplier of carrier materials for catalytic converters.

The Japanese automotive industry focused early on the US emissions regulations. While Japanese automakers modified their export models as early as 1963 to meet the emissions standards set by New York and California, they did not comply with their own government's request in 1963 to build domestic models with lower emissions. In 1971 the Japanese government adopted the emissions standards of the 1970 Clean Air Act, setting a target date of 1975 for full compliance. A policy supporting lead-free gasoline had been adopted in 1970, motivated equally by industrial policy ("benefit of trade") on the one hand, and the need to address domestic environmental problems on the other.

A range of technical solutions to meet these standards were developed, such as catalytic converters, improved combustion control technology (lean burn combustion, the compound vortex combustion chamber or CVCC, and stratified combustion), as well as the incineration of toxic emissions by thermal reactors. However, in order to meet the NO_x standards and adapt to global markets, the Japanese government chose the three-way catalytic converter as its preferred strategy in 1978.

Even when the US relaxed its air quality standards against the background of the energy crisis and the difficulty of the automobile industry in complying with the legislation, Japan maintained a strict pro-environment policy, mainly because of successful lobbying and lawsuits brought by some cities in their fight against air pollution. A report on the technical feasibility of catalytic converters supported the EPA's decision to put the standards into force in 1978 with little delay.

Compared to the US car market (big three), the automobile industry in Japan was much more competitive.

With regard to regulatory style, there has been a much more co-operative structure between industry and government in Japan compared to the situation in the USA. The government supported the introduction of tax incentives for low-emissions cars.

The European emissions standards were mainly driven by concerns about European harmonisation. Companies that exported to the US (such as Mercedes, Saab and Volvo) had to meet these standards and had incentives to promote their adoption in Europe. Sweden had adopted the American standards in 1976, with other countries following in 1985.

The development of more stringent regulations in Europe was rooted in the German regulation limiting the lead-content of petrol (1978) and in the debate on acid rain (Waldsterben) in 1983. This led to regulatory initiatives of the German government at the European level.

However, the German manufacturers were divided. On one side were the exporting producers who had experience with catalytic converters, and on the other the manufacturers producing mainly for the European market. Ironically, it was

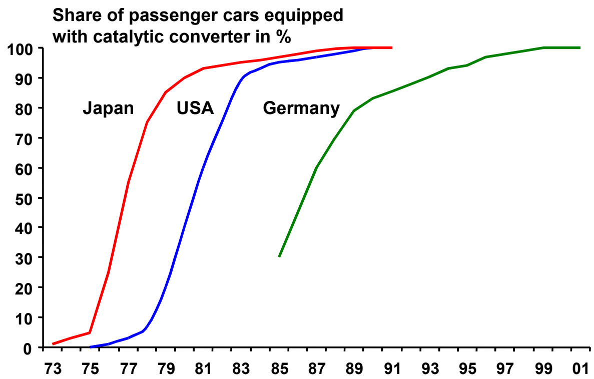
[4] Although the catalytic converter is usually considered an add-on device, it cannot function alone as such, but must be incorporated as a component in an overall emissions control system which requires lead-free gasoline, a change in the design of existing technology as for example electronic engine control technology, and engines with lowered compression ratios and upgraded valve seats. Therefore the catalytic converter technology is not a simple add-on technology instead there was a need for technological adaption and in this context occurred network effects.

the subsidiaries of two American producers, Opel and Ford, who were least prepared to introduce the catalytic converter.

The 1984 European Commission proposal for emissions standards did not stipulate any specific technology. The issue divided the member states into two opposing groups. Countries without automobile industries, such as Denmark and the Netherlands, joined Germany, home both of major car exporters to the US and of Bosch, the main supplier of electronic automotive equipment. The opposing camp, which included France and the United Kingdom, focused its efforts mainly on the development of clean engines. French car manufacturers, especially, argued that there should not be a decision in support of the BAT – which at this time was the catalytic converter – but rather that time should be left to develop alternative technologies.

Finally, the European Community adopted a directive in June 1985 which imposed different emissions standards according to engine type. As a result, unleaded petrol became available throughout the EU and high-powered cars had to be equipped with three-way catalytic converters. This standard was later tightened such that low-powered cars also had to be equipped with three-way catalytic converters from 1993 onwards. According to some commentators, some German automakers were able to achieve a temporary competitive advantage over the French car industry.

Figure 9: International Diffusion of Catalytic Converters for New Cars



Source: ZEW Estimation

Driven by the environmental problems mainly in the cities of developing countries, the diffusion of the catalytic converter is still in progress, as, for example, in India or China. International institutions such as the World Bank, along with various organisations, are important supporters of the diffusion.

5 Conclusions

On the basis of the presented case studies, as well as several studies that have not been presented due to limited space, it is possible to draw some preliminary conclusions regarding innovation processes and the international diffusion of environmental technologies.

Figure 10: Lead Markets for Environmental Technologies

An environmental lead market is the core of the world market for a product or process and is characterised by the following:
• National policy or non-governmental influences successfully create a structure of incentives for users to adopt an innovation relating to a (manifest or latent) international environmental problem. • The international dimension of the problem creates a potential demand in other geographic markets as well as the domestic market. • Environmental lead markets are frequently initiated by national policy innovations (e.g. standards) which potentially diffuse to other countries. Policy innovation/diffusion and technical innovation/diffusion are closely interrelated. • The diffusion of environmental policy innovations is supported both by horizontal imitation (“benchmarking”, “lesson-drawing”) and by international organisations. • The international diffusion of environmental innovations can be facilitated by a range of mechanisms other than policy diffusion, including cost reductions, export orientation and innovation superiority.

We understand lead markets for environmental technologies as regional or national markets which – stimulated by demanding preferences for environmental goods in a given country, by specific supporting measures, or by policy interventions – influence markets in other regions, triggering adjustments that lead to an international diffusion of the new technologies. We take into account here that *environmental* innovations must be largely attributed to governmental (or NGO) activities.

There are *demand*-driven lead markets (i.e. nations with higher environmental standards), which lead to a widespread adoption of environmentally friendly technologies. Examples of this phenomenon include the California exhaust gas standards for automobiles and the Swedish regulations on the use of cadmium (Jacob 2002). Other lead markets are driven by a *supply* of innovative technologies. Frequently, the producers of technologies seek to extend their markets and therefore lobby for international support for their technologies.

Regarding the pioneering countries that have successfully established their innovations in world markets, the following conclusions can be drawn: The pioneer country demonstrates the feasibility of its standards and regulations. Subsequently, the innovative regulation is adopted by other countries. A diffusion of the regulations is more likely if a country has a reputation as a pioneer. A very small number of countries today, mostly member states of the EU, serve as the benchmark for the environmental policy development. Our cases confirm once again the leading role of the Scandinavian countries in this respect. The frequent success of these countries in establishing lead markets underlines that great market size is not necessary. Even very small countries like Sweden may push the international market to adopt their standards.

All of the countries identified as lead markets are highly integrated in world markets and demonstrate good overall economic performance. They are seen to have a high degree of technological competence, at least in the particular field of the innovation concerned.

The pioneer market, with its demanding environmental regulations can, however, also send out signals to the supply side beyond the domestic market. In such cases, competitive companies can advertise their ability to supply such demanding market areas as a sign of their technological competence. If there are scale effects, it can be cost-efficient to orient production to the highest standards.

With regard to the types of innovations that are likely to diffuse internationally, the following is worth mentioning: The cases we have presented encompass process innovations as well as product innovations, and thus run counter to the view prevalent in the literature that only product innovations lend themselves to global diffusion (e.g. Scharpf 1999). All process technologies, however, can also be regarded as products. For the technologies and countries examined, peculiarities of factor prices or complementary goods do not seem to be of great significance, which may enhance the transferability of these technologies.

Lead markets depend on policies and regulations, and therefore government agencies are frequently important actors in the process of innovation and diffusion. However, in two cases (chlorine-reduced pulp production and CFC/HFC-free refrigeration) NGOs, above all Greenpeace, took over the role of policymaker to a large extent. For the three-litre car and the promotion of wind energy, environmental NGOs were at least important players. The significance of multinational companies in the process of innovation is less clear, however. Several studies have stressed their importance for the diffusion of innovations. International organisations sometimes do play a role in diffusion, but are insignificant as to the innovation in the pioneer country. Learning and adoption also takes place in the form of country-to-country learning.

The underlying environmental problems are both local and global. Those that are local have parallels in other regions of the world. In most cases, the problems are on the international agenda. Except for the case of the catalytic converter, the solutions adopted to the problems were not EOP solutions, but rather integrated technologies. Therefore, the technologies do not simply impose additional costs, but have at least the potential for additional advantages.

In most of the cases, subsidies were paid in the pioneering country, either directly – by reducing the costs of the innovation or its complementary goods – or indirectly – by increasing the benefit of an innovation. Energy taxes were important as a background variable in several cases. For the chemicals (phosphates, CFCs and cadmium), early prohibitions in the respective pioneering countries were important driving forces. Explicit political strategies to support the diffusion of policies as a means of extending markets are rare. The dependence of environmental innovations on political strategies should not imply that there is a causal relationship in which regulators force the adoption of a specific technology. Instead, policies usually take up existing technologies and support their diffusion. Regulations were tightened when substitutes were successful. In general, the policy style is characterised by flexibility and an orientation to innovation. Frequently, the lead countries have the image of a pioneer in environmental policy. Industry therefore might expect the diffusion of the policy innovations. Indeed, all cases confirm a demonstration effect of the policy measures on other countries. The adopted policies are transferable to other countries without many modifications. In general, regulations stimulate diversity rather than demanding a specific technical solution.

The economic risks for innovators and the risk reduction for adopters vary among the technologies, depending on the one hand on the necessary investments and on the other on possible subsidies that reduce the costs of adoption. Most of the case studies demonstrate that strict and early regulations hold the potential of advantages in exports, or at least that they bring no serious additional costs for pioneering.

Network externalities were important only in two cases (biomass CHP, where the availability of a district heating grid is an important factor for a high degree of market penetration, and catalytic converters, which require lead-free petrol). For other technologies (hydrogen- or electricity-powered cars), the lack of an appropriate infrastructure explains the failure of diffusion.

Whether the analysis of lead markets can be applied fruitfully to innovations in the stage of development or introduction to the market is an open question. By identifying emerging lead markets for environmental innovations, the stimulating and supporting policies could be optimised and R&D efforts could be adjusted more precisely. Forthcoming studies by the authors aim at analysing such emerging markets.

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