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Environmental and Eco-Innovation: Concepts, Evidence and Policies

Joint Meetings of Tax and Environment Experts

This paper was written by Prof. Paul Ekins, University College London, and Dr. Roger Salmons, Policy Studies Institute, as a contribution to the project on Taxation, Innovation and the Environment of OECD's Joint Meetings of Tax and Environment Experts.

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FOREWORD

This paper was written by Prof. Paul Ekins[1] and Dr. Roger Salmons[2], as a contribution to the project on *Taxation, Innovation and the Environment* of OECD's Joint Meetings of Tax and Environment Experts.

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TABLE OF CONTENTS

Figures

ENVIRONMENTAL AND ECO-INNOVATION: CONCEPTS, EVIDENCE AND POLICIES

1. Introduction

1. This is intended to be what might be called ‘a think-piece with empirical and case study evidence’ on environmental and eco-innovation for the OECD project on *Taxation, Innovation and the Environment* (*i.e.* one of the “2-4 more theoretical papers” mentioned in OECD 2007, p. 6). According to the Background Statement for the OECD Global Forum on Environment on Eco-innovation[3] in November 2009: “Most OECD countries consider eco-innovation as an important part of the response to contemporary challenges, including climate change and energy security. In addition, many countries consider that eco-innovation could be a source of competitive advantages in the fast-growing environmental goods and services sector.”

2. Certainly this is true of the European Union, which has embraced eco-innovation and adopted the Environmental Technologies Action Plan (ETAP)[4] in order to promote environmental technologies or ‘eco-industries’, with the goal of achieving a reduction in resource use and pollution from economic activity without reducing economic growth. In May 2007 the European Commission published a report (CEC 2007) on trends and developments in eco-innovation in the European Union, which confirmed the strong growth of eco-industries, while emphasising that the state of the environment and climate change call for the take-up of clean and environmentally-friendly innovation “on a massive scale”[5], and proposing “a number of priorities and actions that will raise demand for environmental technologies and eco-innovation”.

3. The scale of the innovation cited indicates that what seems to be envisaged is what the innovation literature calls ‘a technological transition’. This paper begins with a review of a number of theories of innovation and technological transitions (Section 2), followed by some thoughts as to how eco-innovation can be measured (Section 3). On the basis of three of these measures – environmental improvement, the size of so-called ‘eco-industries’, and environmentally related patents – an overall trend of environmental and eco-innovation is assessed, which suggests that one or both processes has indeed taken place in recent years (Section 4). This then leads into consideration in Section 5 of the extent to which this might have been brought about by environmental policy in general, and environmental taxes in particular. Section 6 presents some overall conclusions from the paper.

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[3] Some of the issues addressed in this paper were also covered in the OECD Global Forum on Environment on Eco-Innovation, held 4-5 November 2009 in Paris. Papers presented at the Forum can be downloaded from the Forum website: www.oecd.org/environment/innovation/globalforum

[4] See the ETAP website at http://ec.europa.eu/environment/etap/actionplan_en.htm

[5] See http://ec.europa.eu/environment/news/brief/2007_04/index_en.htm#ecoinnovation

2. Theories of innovation and technological transitions

4. Core to the concept of innovation is change, most importantly technological change. Following Schumpeter (1942), the process of technological change is typically broken down into the following three stages:[6]

- invention – *i.e.* the first development of a scientifically or technically new product or process;
- innovation – *i.e.* the commercialization of the new product or process;
- diffusion – *i.e.* the adoption of the product or process by firms and individuals.

5. However, technologies do not exist, and new industries and technologies, are not developed in a vacuum. They are a product of the social and economic context in which they were developed and which they subsequently help to shape. Over time, processes of innovation may lead to profound transformation of both the technologies in use and the social context in which they are embedded. These transformations are often referred to in the literature as 'technological transitions', a term which implies much more than the substitution of one artefact for another. It connotes a change from one techno-socio-economic system (or 'socio-technical configuration' as it is called below) to another, in a complex and pervasive series of processes that may leave little of society unaffected.

6. There is now an enormous literature on technological change and the broader concept of technological transition (a significant portion of this literature is reviewed in Geels, 2002a), only certain elements of which can be highlighted here.

2.0 Technology Readiness Levels

7. A static view of different stages of innovation is given by the concept of 'Technology Readiness Levels', which is being increasingly used to identify the stage of innovation at which funding is being applied. There are 9 Technology Readiness Levels, ranging from 1 (basic research) to 9 (early deployment of near-commercial technologies). Of course, innovation does not stop there but may continue into full deployment and market diffusion as is clear from the dynamic theories of innovation briefly considered next.

Table 1. Description of Technology Readiness Levels (TRL)

Stage	Description of Activity
TRL 1-3 Basic Research	Activity driven by a desire to broaden scientific and technical knowledge, and is not explicitly linked to industrial or commercial objectives. It typically includes investigating the underlying foundations of phenomena and observable facts, and typically takes place almost entirely in the academic community.
TRL 3-5 Development	Research with a more direct commercial application, driven both by scientific enquiry (with a degree of public good in the outcomes) and commercial opportunity (with research areas driven by expertise in spotting market opportunity), and is seen as an opportunity to build and develop links between industry and academia increasing the likely success and pull through of ideas from the academic community.
TRL 6-7 Demonstration	Large-scale pre-commercial demonstration of technologies, designed to test and improve longer term operational reliability, develop and improve full scale designs, establish and reduce operating costs and take the technology to a stage where the technology becomes a potential commercial investment. Work is undertaken by the private sector, typically with some academic involvement.
TRL 8-9 Early deployment	Technologies have been shown to work on a large scale, but are not yet competitive in the market, require a policy and market framework that supports their deployment. Development is undertaken by companies in the private sector.

Source: Frontier Economics (2009), Table 3, p. 10; based on ETF (2008), p. 13.

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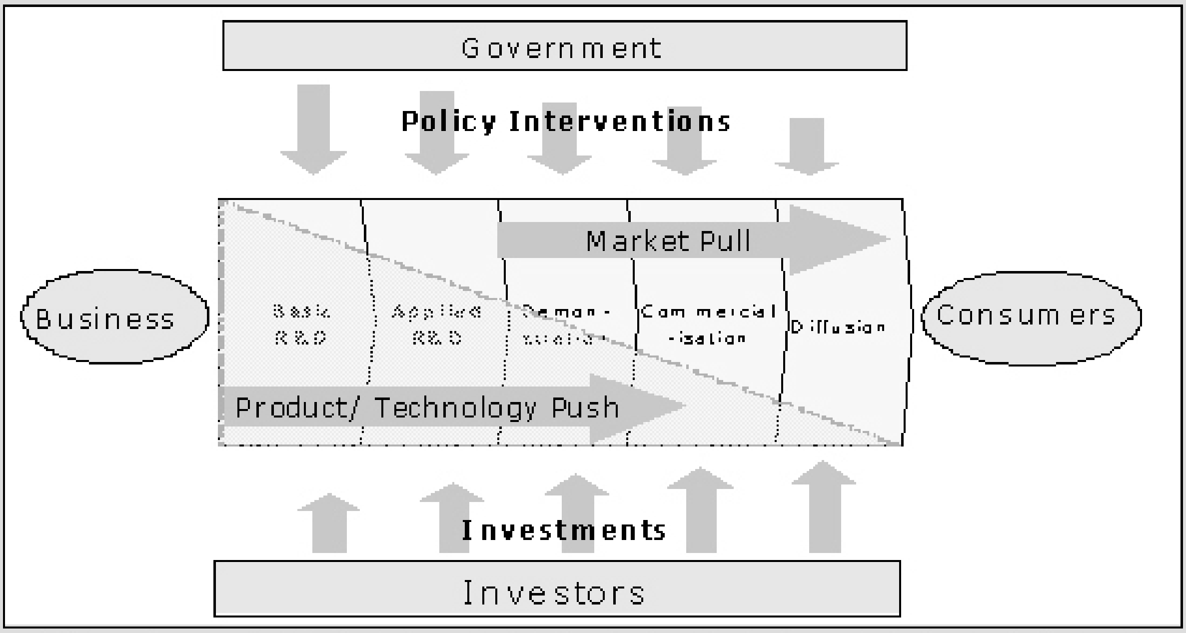
[6] Some authors break down the innovation stage into two: the application of inventions in demonstration projects; the development of niche applications and markets (*e.g.* Christiansen & Skjærseth, 2005).

2.1 Technology Push and Market Pull

8. One of the commonest descriptions of the way technologies are developed and diffused in society is in terms of ‘technology-push/market-pull’, as illustrated in Figure 1. This suggests that technologies are developed through basic and applied research and development (R&D), to demonstration and commercialisation and thereby diffused into society.

9. The first, pre-market phases of the process are described as ‘technology push’, because the principal drivers are the business and policy decisions, including government investment in R&D and the activities and interests of scientists and engineers, that cause the technology to be developed. The commercialisation and diffusion processes are much more driven by consumer demand-pull in the markets which have been targeted or into which the technologies will by then have penetrated to some extent. Clearly, as shown, both sets of drivers are present to some extent in all phases: even at the earliest phases of technology R&D potential market demand is a major interest, and even during diffusion research-driven technological change may occur. For the process to take place successfully, continuous learning from and feedback between these processes are required.

Figure 1. Roles of Innovation Chain Actors



- The innovation process involves the development and deployment of new technologies, products and services by business in order to meet the needs of consumers. To achieve this, funding is required from a variety of investors, such as insurance companies, banks, private equity houses and angel investors.
- In the early stages of the market, take-up is largely driven by the product/technology push. As consumer awareness builds, the rate of deployment is accelerated as consumer demand grows.
- Government can make various policy interventions at various stages of the innovation chain to overcome barriers to the development of various technologies, products and services.

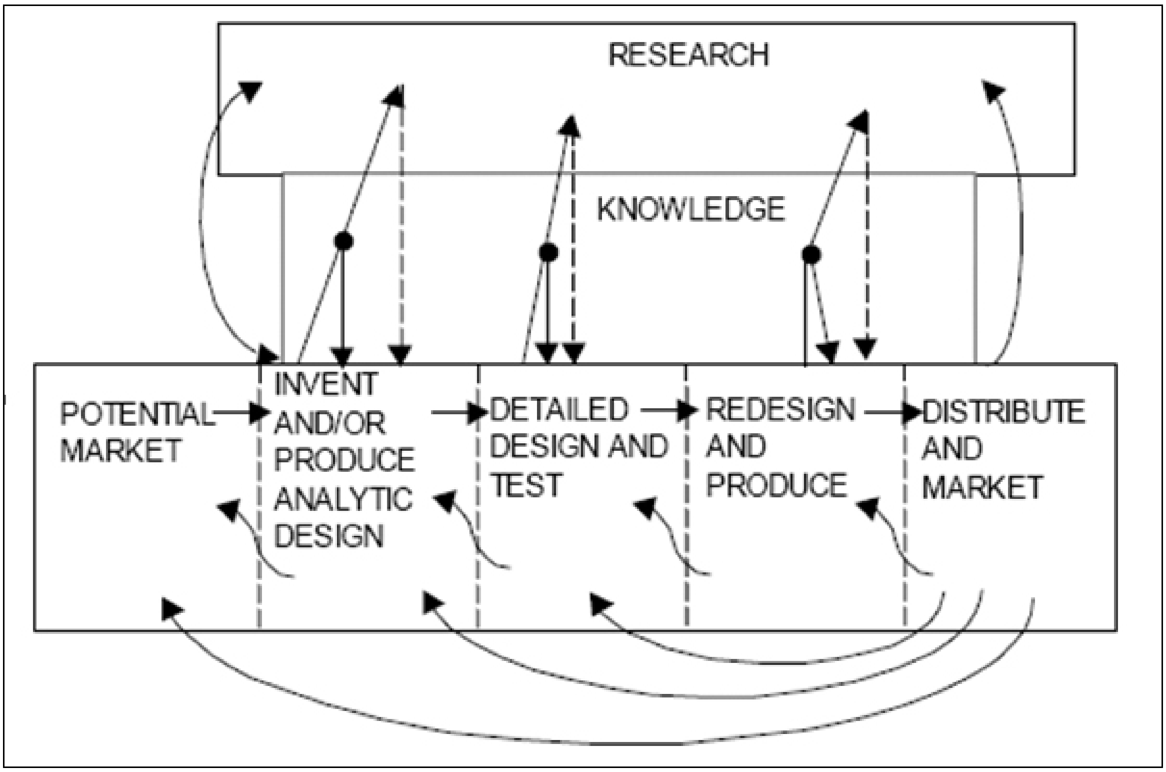
Source: Foxon, 2003, p. 18, after Carbon Trust 2002.

10. Each stage of the process may require, or be subject to, private investments or policy interventions (which may include government investments). At the R&D stages, at least for technologies which are thought to be of major potential public benefit, policy interventions are likely to be relatively important (shown by the length of the arrows). From demonstration onwards private investments are likely to be relatively important. However, especially for technologies of potential public benefit but uncertain

market demand (of which hydrogen technologies may be a good example) it is likely that public support and policy interventions will be necessary both to help the technology from the demonstration to commercialisation stages (a risky transition sometimes called the 'valley of death' (*e.g.* Wessner, 2005), because of the business casualties and the demise of potentially good ideas, technologies and innovations, which it often induces), and even right through to the diffusion stage.

11. The linear nature of the technology-push/market-pull model has been criticised by Kemp & Foxon (2007), who recommend instead the more interactive 'chain-linked' model developed by Kline & Rosenberg (1986), illustrated in Figure 2, in which research and knowledge creation takes places throughout the innovation and product development, design and marketing stages. Such a model is certainly consistent with *Mokyr* (2002)'s investigation of the inter-relationship between propositional (basic scientific) and prescriptive (technical know-how) knowledge of.

Figure 2. A chain-linked model of the innovation process



Source: Kline & Rosenberg, 1996.

12. While technology-push and market-pull may be important aspects of technological change, they contain no element of the social context in which such change is taking place, and therefore are clearly insufficient concepts by themselves to explain the much more widespread changes that are implied by the term 'technological transition'. This requires an approach which takes a much wider view of the social and economic system in which technologies are embedded and which provide the context in which they thrive and decline.

2.2 Co-evolution of social sub-systems

13. Fundamental changes in technology are now understood to be processes that are rooted at the deepest level in the social contexts in which they occur. For example, the evolutionary approach to technological development adopted by Freeman & Louça (2001, p. 121) proposes that such development

requires the co-evolution of five ‘semi-autonomous’ social subsystems: science, technology, economics, politics, culture. They are semi-autonomous because, although the five variables are linked and interact, they also have autonomous elements. Fundamental technological changes (such as, for example, the development of a low-carbon energy system) are possible when, and only when, the co-evolutionary direction of change of all five variables is basically supportive of such change.

14. Freeman and Louça themselves do little to explore the implications of their insight into the necessary co-evolution of the five sub-systems, but it seems useful to useful here to distinguish between, and elaborate somewhat, the physical and socio-economic sub-systems, as follows:

- **The Physical Dimension**, which deals with the physical issues involved in the production/ storage/distribution/end use of hydrogen, and has the following components:

– *Science*	the physically possible
– *Technology*	physical realisation of the physically possible
– *Infrastructure*	physical (including technical) support and diffusion of the physical realisation

- **The Socio-Economic Dimension**, which deals with the interests and drivers that push technical change along: entrepreneurs (and profits), consumers (and preferences), and public policy pressures, and has the following components:

– *Economics*	issues of allocation, distribution, competition
– *Institutions*	legal, financial, regulatory, planning frameworks
– *Political Drivers*	social perceptions driving political priority (security of supply, environmental issues) and the planning system, and the policy instruments through which these perceptions are implemented
– *Culture*	social perceptions driving social acceptability and consumer demand

15. These categories help to clarify that a major technological transition will only begin in earnest when some combination of entrepreneurs, consumers and public policy pressures generates both the investment in science, technology and infrastructure that physically permits environmental technologies to be widely deployed, and the economic, institutional and cultural conditions that make their widespread diffusion economically competitive and institutionally and socially acceptable.

2.3 Socio-technical landscapes and regimes, and technological niches

16. Another (though not contradictory) approach to technological transitions is taken by Geels (2002a, b), who adopts a three-tier “multi-level perspective”, the three levels of which are:

- The socio-technical landscape, material infrastructure and “widely shared cultural beliefs, symbols and values that are hard to deviate from” (Geels 2002a, p. 102);
- The socio-technical regime, the institutional and mental structures (“knowledge base, engineering practices, corporate governance structures, manufacturing processes and product characteristics”, Geels 2002a, p. 98) that provide the framework for any pervasive technology; and
- The technological niche, spaces insulated from the competitive challenge from mainstream technologies, in which innovations can survive and, perhaps, develop. Such niches may evolve into market niches, where, because of particular characteristics or functionalities, the innovative technologies can survive through market processes without need of insulation from mainstream technologies.

17. Geels' concept of sociotechnological regime is an extension of the 'technical regimes' discussed by Rip and Kemp (1998) and Nelson and Winter (1982). According to Geels (2002b, p. 1260), socio-technical regimes include not only the organisational and cognitive rules and routines adopted and followed by engineers and firms, but also the routines influencing the behaviour of "users, policy makers, social groups, suppliers, scientists and bankers etc.". The stability and persistence of a regime, and the widespread recognition of its function and purpose, derives from the fact that there is coherence between the incentives, rules and routines of these different actors: "The activities of these different groups are aligned and coordinated." (Geels 2002b, p. 1259). Thus the socio-economic actors in the same regime share an overall common aim – the fulfilment of the regime function. Each actor in the regime has an incentive to co-operate, as they would be worse off if they took an action putting the existence of the regime at risk. Innovation under such circumstances, when it occurs, tends to be incremental and to result in improvements to (and reinforcement of) the existing regime, rather than a transition to a new regime. Edgerton (2006) confirms the importance of incremental innovation to historical technological change in the UK, and it seems likely that the wide range of technologies used in 'eco-industries' will be as much if not more likely to be introduced incrementally as through more radical technological disruption.

18. It may not always be straightforward to demarcate clearly the boundaries between different socio-technical regimes, while some elements of one regime might also belong to another. Hughes (1987, p. 53) considered that a defining characteristic of technological systems is that they solve problems or fulfil goals, using whatever means are available and appropriate, where the problems have to do mostly with reordering the physical world in ways considered useful or desirable, at least by those designing or employing a technological system. More simply, Rip and Kemp (1998) define regimes as "configurations that work", a definition which Geels (2002a) makes clear refers to fulfilment by a regime, in an economically and socially acceptable way, of a *function* that is considered useful or desirable by some actor in the regime. There is consideration of how eco-innovation may be considered in terms of enhanced environmental and economic functionality in Section 3.

19. Identifying the main attribute of a regime as related to its functionality makes it easier to identify its core, if not precisely to delineate its boundaries: substantially different functions will be associated with different regimes (however, it is also clear that the functions defining a regime can evolve over time). Going beyond function, Geels (2002b, p. 1262) identifies the seven key dimensions of a socio-technical regime as technology, user practices and application domains (markets), symbolic meaning of technology, infrastructure, industry structure, policy and techno-scientific knowledge. Although these dimensions change through their own internally generated impulses, they are also linked and co-evolve in the same way as Freeman & Louça's social sub-systems described above. The stability of the regime comes from the coherence of and linkages between the dimensions. Regime change arises when this coherence or the linkages weaken.

20. Regime stability also derives from the process of technological 'lock-in', which Arthur (1988, p. 591) identified as deriving from five factors, which, once they are operational in favour of a particular technology, tend to give it a competitive advantage against which it is increasingly difficult for competing technologies to counter. The five factors are:

- *Learning by using*, which accelerates technological improvement
- *Network externalities* – the more widely a technology is used, the more applications are developed for it and the more useful it becomes
- *Economies of scale*, which reduce the unit price
- *Increasing informational returns*, linked to learning by using, whereby the increased numbers of users, knowing more about the technology, makes it easier for others to learn about the technology

- *Development of complementary technologies*, which both reinforce the position of the technology and make it more useful.

21. The concept of technological lock-in is often used to describe the persistence of sub-optimal technologies (the QWERTY keyboard is the most often quoted example, see David 1985), but these processes are actually characteristic of all successful technologies, sub-optimal or not. If there is to be a transition to the hydrogen economy, hydrogen technologies will need to be subject in large measure to all these processes.

22. There is also the issue of how broad a regime needs to be in order to qualify as such. Regimes may be seen to be 'nested' within each other. Berkhout *et al.* (2003, p. 9) ask whether the fundamental shift in pesticides brought about by the banning of DDT amounted to an agricultural regime change, or whether it left intact the wider regime of a chemical-intensive agriculture.

23. At a higher level than the regime, Geels (2002b)'s socio-technical landscape provides an external "structure or context for interactions among actors" (Geels 2002b, p. 1260) in a regime. This landscape contains a set of "heterogeneous factors, such as oil prices, economic growth, wars, political coalitions, cultural and normative values and environmental problems. The landscape is an external structure or context for interactions of actors. While regimes refer to rules that enable and constrain activities within communities, the 'ST-landscape' refers to wider technology-*external* factors" (Geels, 2002b, p. 1260, emphasis in original). A similar definition describes landscapes as composed of "background variables such as material infrastructure, political culture and coalitions, social values, worldviews and paradigms, the macro economy, demography and the natural environment, which channel transition processes and change themselves slowly in an autonomous way" (Kemp & Rotmans, 2001, cited in Berkhout *et al.* 2003, p. 6).

24. The internal/external distinction between regimes and landscapes seems more useful than another distinction used by both Kemp & Rotmans and Geels, relating to speed of change: "landscapes do change, but more slowly than regimes" (Geels, 2002b, p. 1260). This is by no means obvious. The external factors which belong to landscapes can in fact change very quickly. Oil prices, which historically have been very volatile, are one example. So are the geopolitical circumstances that can affect (perceptions of) energy security. So are the political perceptions of the priority of an issue like climate change. Changes in any or all three of these examples of landscape factors might be important in stimulating a technological transition towards far great use of environmental technologies. Through these examples it can be seen that changes in the socio-technical landscape can be the means whereby the stability and internal coherence of a socio-technical regime can be undermined.

25. Another distinction between the factors belonging to regimes or landscapes might be the extent to which they can be influenced by the socio-economic actors involved in the regime. Clearly, this varies among different actors. For example, the oil price can hardly be affected by individuals, but governments can have more effect. A rule of thumb for distinguishing between regime or landscape factors might be: if socio-economic actors can influence the direction, the timing or the rapidity of the change in a factor more than the extent to which they are influenced by it, this factor is likely to be part of the regime; in the opposite case that element will belong to the landscape. But the degree of influence is likely to vary for different actors and in different situations, so that it is not a hard and fast distinction. Such considerations suggest that, rather than being clearly differentiated, landscapes and regimes at different levels merge into each other by displaying some common, but other clearly differentiated, elements and characteristics that are all subject to change.

26. In the final analysis, because of the wide-ranging nature of the concepts of socio-technical landscapes and regimes, it probably needs to be accepted that no taxonomy is likely to distinguish unambiguously between different regimes, and between the elements belonging to the regime and those

belonging to the landscape. More distinct is the third element of Geels' multi-level perspective, the concept of the niche.

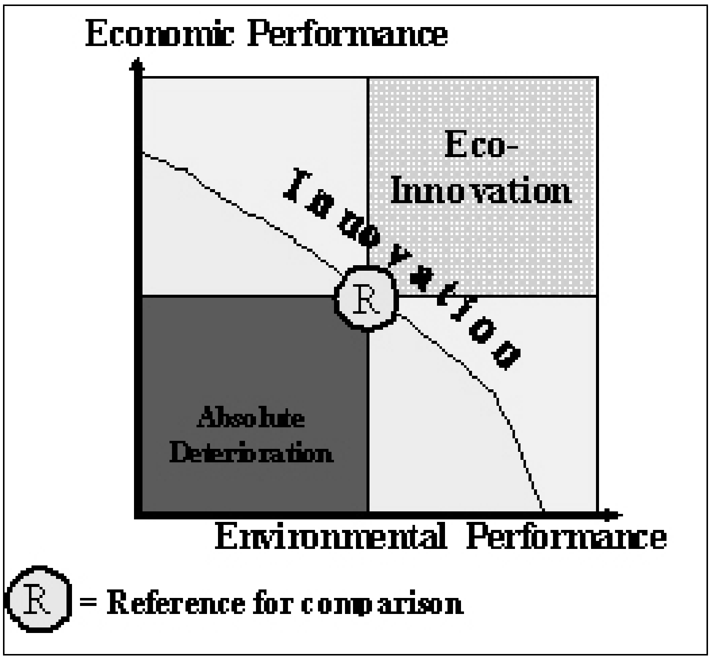
27. The niche is in fact a longstanding theme in relation to the diffusion of innovations and technological change (see for example, Foxon 2003, Kemp *et al.*, 1998, Wallace 1995), focusing on such issues as the importance of the size of the niche market, the technical and financial capabilities of suppliers, and stable investment conditions as key for successful diffusion. In the context of hydrogen fuel cells, Adamson (2005) defines niche markets as "small protected market[s] that a new disruptive innovation enters before it reaches the mass market" (Adamson 2005, p. 343), and Geels (2002a,b) seems to share that perception, seeing a fundamental property of niches that they "act as 'incubation rooms' for radical novelties", and offer some protection from normal market selection in the regime (Geels, 2002b, p. 1261). However, it is not clear why only disruptive innovations should inhabit niche markets, as seems to be implied by Adamson (2005). It seems quite possible for non-disruptive innovations also to be found in niche markets although they may not have the potential to break into the mass market and may exist in their niche for a considerable period of time. Nor is it clear why technologies in niches need necessarily to be protected from competition with technologies in the mass market (they may contain valued functional characteristics that distinguish them from such technologies). In fact niche markets may more simply be viewed as small, focused and targetable portions of a larger market, comprising a group of actors whose needs for products or services to perform particular functions are not being addressed by mainstream providers. Niche markets may function as incubators for new technologies, and that this can occur in the absence of protection from market competition in the regime, when the new technologies in question have functionalities (such as improved environmental performance) that are desired by a (small) group of consumers, such as, for example, 'green' consumers who seek out environmentally superior goods and services. Clearly an ETR (a landscape change) can narrow the price difference between such niche markets and comparable mainstream markets with goods and services that are inferior environmentally, thereby making it more likely that more consumers will purchase the environmentally superior goods and services, and allowing the niche to expand until, eventually, it may become the dominant technological regime. In this way the three levels of Geels' multi-level perspective can be brought together to show how jointly they can explain technological transitions.

2.4 Environmental and Eco-Innovation

28. As noted above, innovation is about technological change, where such change is broadly conceived as any change in the nature, process or organisation of production, but entails more than simple adjustments in output to relative prices. Moreover, in the economics literature innovation always means positive change, change which results in some defined economic improvement. Similarly, in respect of the environment, environmental innovation means changes that benefit the environment in some way. In the ECODRIVE project (Huppes *et al.* 2008) the now much-used term 'eco-innovation' was defined as a sub-class of innovation, the intersection between economic and environmental innovation, *i.e.* "eco-innovation is a change in economic activities that improves both the economic performance and the environmental performance of society" (Huppes *et al.* 2008, p. 29). In other words, whether or not eco-innovation has take place can only be judged on the basis of improved economic and environmental performance.

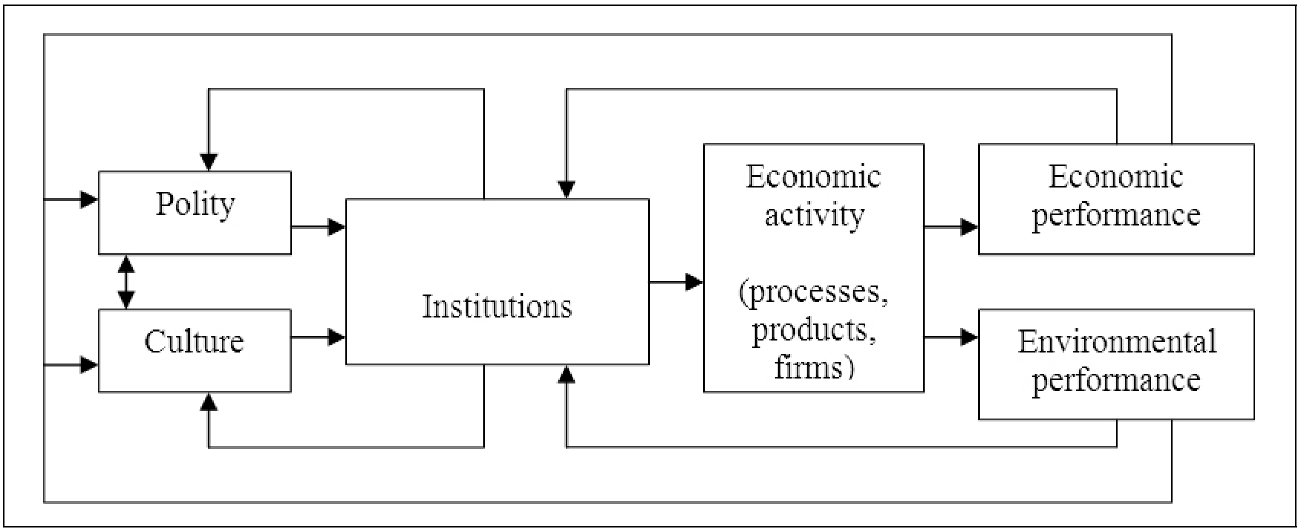
29. This is illustrated in Figure 3. Innovation (compared to the reference technology R, which defines the current economy-environment trade-off along the curved line) that improves the environment, environmental innovation) is to the right of the vertical line through R and the curved line. The light-green area shows where improved environmental performance has been accompanied by deteriorating economic performance. Similarly, economic innovation is the horizontal line through R and above the curved line. The light-green area in this case shows where improved economic performance has been accompanied by environmental deterioration. Eco-innovation is the dark-green area where performance along both axes has improved.

Figure 3. Eco-innovation as a Sub-class of Innovation



30. This approach can be extended to incorporate the socio-economic and cultural dimensions, in line with the 'sub-systems' approach of Freeman and Louça (2001), as shown in Figure 4. This shows that the outcomes of economic activity of interest in relation to environmental and eco-innovation are economic and environmental performance. Economic activity is driven by institutions, the framework of laws, norms and habitual practices that define how markets and other economic structures (*e.g.* public sector, households/families as sources of production). These institutions in turn derive from an interaction between polity and culture. There are multiple feedbacks between the boxes as shown and the whole socio-economic cultural construct should be thought of as a system in dynamic evolution.

Figure 4. The Socio-Economic Cultural System in Dynamic Evolution



31. The drivers of eco-innovation are, in the first place institutions, and in the second place the polity (which produces policies that feed into, or become, institutions) and culture, (*e.g.* social values), which also feed into or create new institutions. Both polity and culture are affected both by institutions, and by the

economic and environmental performance of economic activities. *Oosterhuis & ten Brink* (2006) show that there is widespread agreement in the literature that environmental policies have the potential to exert a strong influence on both the speed and the direction of environmental innovation. Rather than being an autonomous, 'black box' process, technological development is nowadays acknowledged (as illustrated in the previous section), to be the result of a large number of different factors that are amenable to analysis. Environmental policy can be one of these factors, even though its relative importance may differ from case to case. The policies which might promote environmental innovation and eco-innovation are the subject of Sections 5 and 6.

32. However, it is by no means straightforward to measure whether eco-innovation has taken place on the basis of improved performance, either in environmental or economic terms, because of interactions and feedbacks within and between economic and environmental systems at all levels. The next section considers how the two dimensions of eco-innovation may be measured.

3. Measuring environmental and eco-innovation

33. Measurements of innovation can be grouped under three broad headings: those that measure the inputs (or resources) devoted to the innovation process; those that measure the outputs from the process; and those that focus on the impacts of the innovations that are generated (Johnstone *et al.*, 2008).

Measuring Environmental Innovation

34. While there are now well developed frameworks for the measurement of innovation in general, such as the European Innovation Scoreboard[7], which is reported on an annual basis, the same is not true for environmental or eco-innovation, although the OECD now has in hand a programme of work in this area, described in OECD (2009), which seeks to develop "indicators of innovation and transfer in environmentally sound technologies (EST)". OECD (2009) reviews a number of possible indicators of EST innovation and indicators of international transfer of EST, concluding that the most promising approach in both areas is the use of suitably selected and structured patent data. Some of its early work on patents as an indicator of environmental innovation is reported in OECD (2008).

35. Another approach to measuring eco-innovation was taken by the so-called MEI European Framework 6 research project[8]. This adopted a different definition eco-innovation from the ECODRIVE project, defining it as "the production, application or exploitation of a good, service, production process, organisational structure, or management or business method that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of resources use (including energy use) compared to relevant alternatives." (Kemp & Foxon 2009b, p. 4). Close inspection of this reveals that the only difference between this and the ECODRIVE definition is that it does not insist on improved economic as well as improved environmental performance. In other words, it is what is called above 'environmental innovation', the light as well as the dark green areas in Figure 2.3 to the right of the vertical line through R and the curved line (the 'relevant alternative'). Both ECODRIVE and MEI identify that a requisite of eco-innovation is improved environmental performance or results.

36. The MEI project derived both a useful list of the determinants of eco-innovation and a list of possible indicators of it. The determinants were:[9]

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[7] See www.proinno-europe.eu/index.cfm?fuseaction=page.display&topicID=5&parentID=51.

[8] See www.merit.unu.edu/MEI/.

[9] Kemp & Pearson 2008, p. 7.

- Inputs: financial and human resources, R&D expenditure supporting the technological capabilities of a firm;
- Environmental policy framework (*e.g.* regulatory stringency, different environmental policy instruments such as technology-based standards, emission taxes or liability for environmental damages);
- Existence of environmental management systems, practices and tools;
- Demand pull hypothesis: expected market demand, profit situation in the past;
- Appropriation problem: competition situation (*e.g.* number of competitors, concentration of the market), innovation cooperation;
- Influence of stakeholders and motivations for environmental innovation (*e.g.* public authorities, pressure groups such as industry or trade associations);
- Availability of risk capital;
- Availability of high-skilled labour force.

37. It will be noted that the second of these bullet points identifies environmental policy, including taxation, as a determinant of eco-innovation. This is returned to later in the paper.

38. Table 2 gives a proposed list of eco-innovation measures (using the MEI terminology). It may be seen that the indicators cover a wide area, including products, firms, skills, attitudes, costs and policies. However, it may be noted that the MEI proposed indicators actually focus on the predisposing conditions for environmental improvement rather than on whether the environmental improvement has actually taken place. There are no indicators of environmental performance *per se*. There is presumably an assumption that the areas covered are likely to have a positive relationship with environmental performance. Moreover, in line with MEI's exclusively environmental definition of eco-innovation, it gave no attention to economic performance or results at all.

Table 2. List of proposed eco-innovation indicators, MEI project

	Indicator	**Data Source**
	The Firm	
1	R&D expenditures for environmental protection in industry	STATCAN currently collects this information
2	% of firms with EMAS or ISO14001	Numbers collected by German Federal Environmental Agency
3	% of firms with environmental mission statements and/or officers	Would need to survey for this
4	Managers opinion of eco-innovation	Possibly for inclusion in CIS
	The Conditions	
5	'Green Tax' as a percentage of government budget	OECD data
6	Government expenditures on environmental R&D as: % of total R&D expenditure or as % of GDP	GBAORD data
7	Uptake of environmental subsidies for eco-innovative activity	Government data
8	Financial support for eco-innovation from public programmes	OECD data
9	Demand for eco-innovative products	Measure demand using survey techniques
10	Environmental expenditure in college/university research	National Science Foundation collects this for US. EU source unknown
11	Number of environmental graduates, MScs or PhDs	EIS & IRCE report
12	Waste management costs (landfill tariff etc)	Government data
13	Executive opinion on environmental regulation (stringency and transparency)	For possible inclusion in CIS
14	Attitudes towards eco-innovation	Eurobarometer data
	The Linkages	
15	Frequency of eco-innovation workshops/conferences and number of people attending	Web based searches

16	Value of "green funds" made available by financial institutions for innovating companies	SRI fund service data
17	Managers perception of overall quality of environmental research in scientific institutions	For possible inclusion in the CIS
	Radical/incremental innovation indicators	
18	Ratio of eco-start-ups to incumbents in the market	Companies house data or European business register
19	Frequency of new entrants to the market	Companies house data or European business register
20	Diversification activities of incumbents, investment in smaller operations outside core business	EUROSTAT entry and exit data
21	Seed and start-up venture capital for eco-innovative firms (investment per 1000 GDP)	IRCE report or interpretation of EVCA data
	Overall performance indicators	
22	Eco-patents in triadic patent families per million population	US EU and Japan Patent offices
23	Material productivity of eco innovative firms (TMR per capita or GDP)	IRCE report
24	Share of eco-innovative firms as a percentage of all firms (may need to divide into manufacturing and services)	CIS. May need to be reanalysed

Source: Kemp & Pearson (2008), pp. 14-15.

CIS: Community Innovation Statistics. Collected by EUROSTAT available from:
http://epp.eurostat.ec.europa.eu/portal/page?_pageid=1090,30070682,1090_33076576&_dad=portal&_schema=PORTAL
EIS: European Innovation Scoreboard. Collected by the European Commission available from: http://trendchart.cordis.lu/
Eurobarometer. Available from: http://www.gesis.org/en/data_service/eurobarometer/
EUROSTAT: EUROpean STATistics. Available from:
http://epp.eurostat.ec.europa.eu/portal/page?_pageid=1090,30070682,1090_33076576&_dad=portal&_schema=PORTAL
EVCA: European Venture Capital Association. Available from: http://www.evca.com/html/home.asp
GBAORD: Government Budget Appropriations of Outlays for R&D. Collected by EUROSTAT, available from:
http://epp.eurostat.ec.europa.eu/portal/page?_pageid=1073,46587259&_dad=portal&_schema=PORTAL&p_product_code=KS-NS-06-017
IRCE: Impact of RTD on Competitiveness and Employment. Available from: http://cordis.europa.eu/era/benchmarking.ht
SRI: Socially Responsible Investment. Available from: http://www.eurosif.org/sri
STATCAN: STATistics CANada. Available from: http://www.statcan.ca/

Measuring Eco-innovation

39. The ECODRIVE project proceeded from the perception that eco-innovation needs to deliver improvements in both economic and environmental performance and therefore sought to determine how this joint outcome could be indicated.

40. There is much discussion in Huppes *et al.* (2008) of various methods of measuring environmental performance, across different environmental themes, and stressing the importance of taking into account all impacts on a life-cycle basis. There methods are well developed, but very complex, and will not be further detailed here.

41. The measurement of economic performance, also discussed in detail in Huppes *et al.* (2008), from which the following is taken, is no less complex, but rather less well developed, with possible distinctions between products, firms and different economic levels.

42. The purpose of economic activity is to deliver functionalities that meet human needs and wants, at a cost consumers (which may be individuals or businesses) are prepared to pay. In Figure 5, the functionalities are delivered by processes and products (including services) produced by firms, which may be classified as belonging to economic sectors, and which have supply chains consisting of firms which may belong to different sectors. The sectors will belong to a national economy.

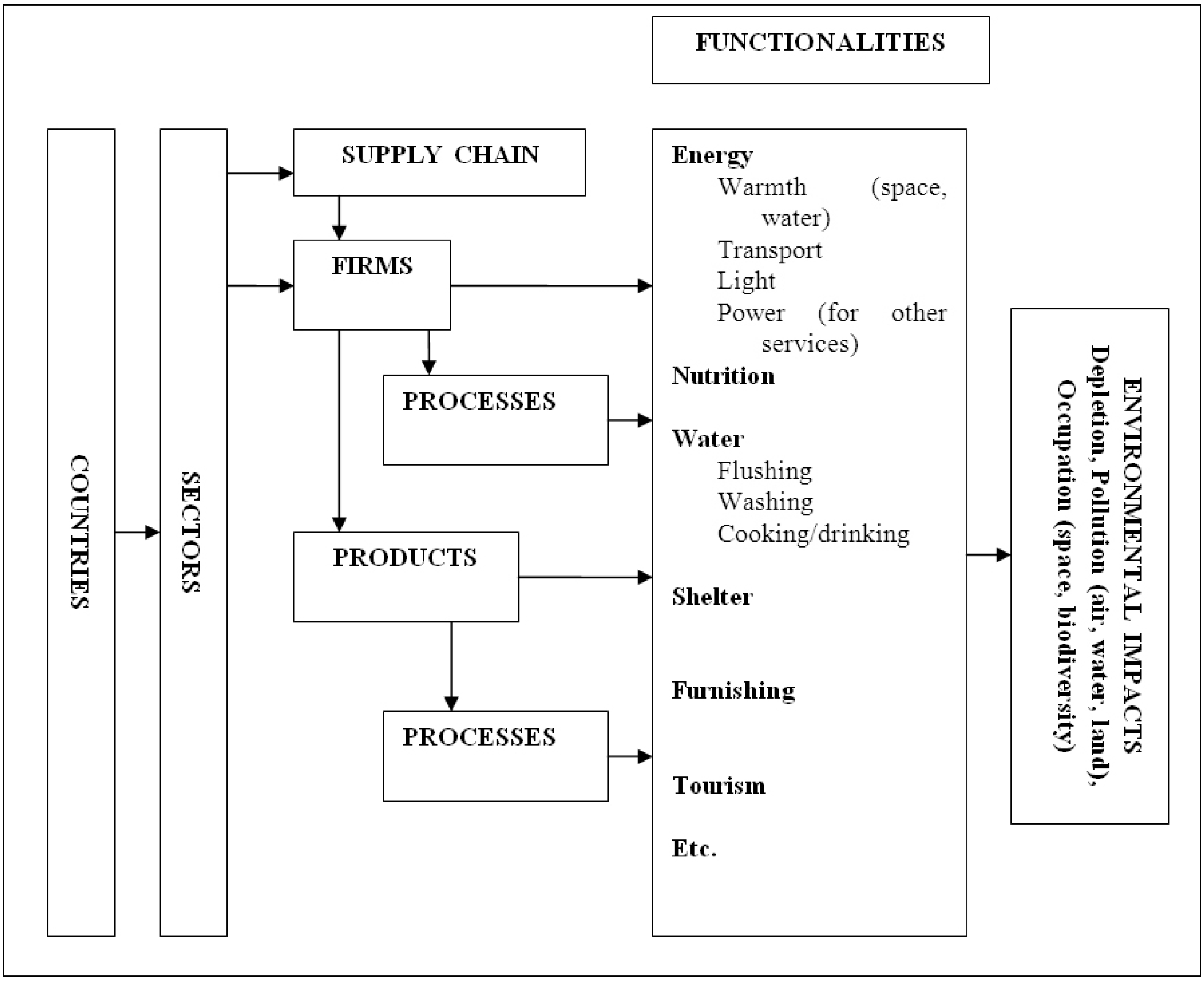
43. The most basic measure of improved economic performance for products and processes is therefore one which can show that greater functionality is being delivered for the same cost, or the same functionality is being delivered for reduced cost. The basic measure is therefore Functionality/Cost, where

functionality may be measured in a wide variety of different ways, depending on the product or process under consideration.

44. For example, in the case of transport, the unit of functionality may be vehicle-km, and the cost to the owner will be the life-cycle cost of acquiring, operating and disposing of the vehicle over the period of ownership. However, it should be borne in mind that many products have multiple functionalities, so that in comparing the functionalities of different products, one must be careful to compare like with like. For example, cars have many functionalities apart from the delivery of vehicle-km (an obvious one is conferring status, or making a social statement), so that it is important when comparing products like cars that they are as similar as possible in terms of other functionalities. The 'eco-innovative product or process' will then be one which delivers cheaper functionality and improves environmental performance.

45. Products and processes are produced or operated by firms. Clearly a firm may have different products and processes, delivering different functionalities, so a complete view of its performance will require some aggregation across these different outputs. Normally this aggregate is expressed in money terms, so that measures of a firm's performance will often be some measure of economic (money) output compared with economic inputs (*e.g.* value added, profitability, labour productivity), sometimes compared with other firms (*e.g.* market share). The 'eco-innovative firm' will then be one which improves its economic performance while also improving its environmental performance. Firms are conventionally grouped into economic sectors, obviously introducing a higher level of aggregation. Many of the measures of sectoral economic performance are the same as for firms and will consist of an aggregate, or average, of the sectors' firms' performance. And then sectors are aggregated into national economic statistics.

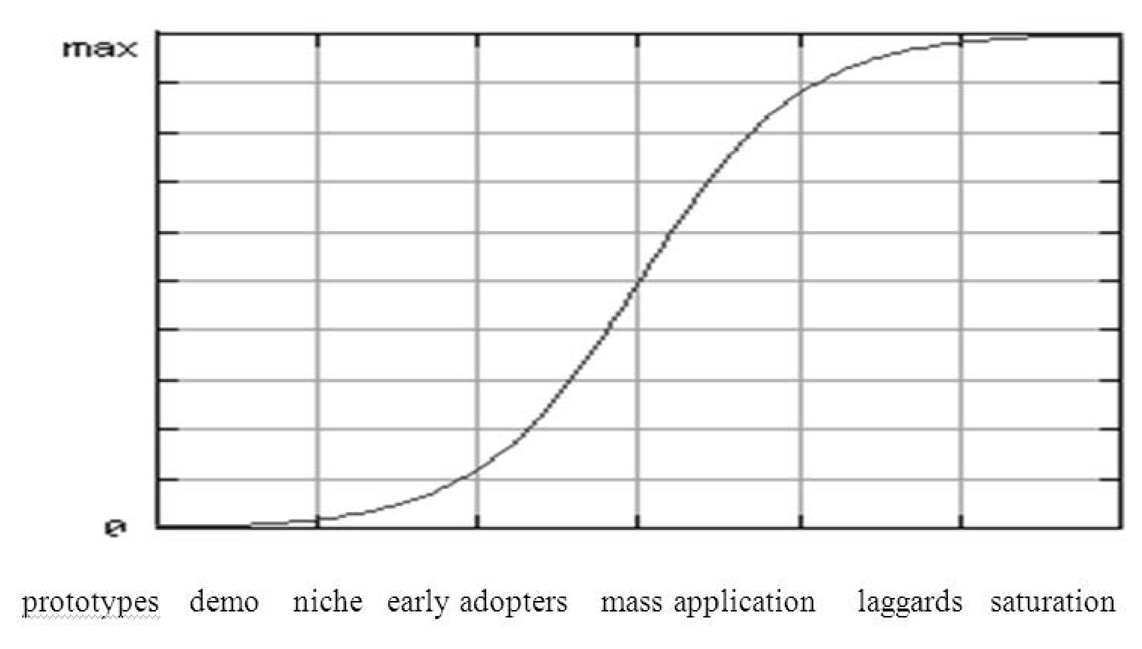
Figure 5. The Delivery of Functionality in an Economy



46. One critical issue in the consideration of economic performance is time. Economies are inherently dynamic, and the consideration of timescale will be crucially important to a judgement as to whether or not economic performance has improved. Many new technologies, and new firms, are not ‘economic’ to begin with (*i.e.* they deliver lower functionality per unit cost than incumbents). There is always a risk in investment that it will not pay off, and different investments pay off, when they do, over different periods of time. In any evaluation of economic performance, the timescale over which the evaluation has been conducted should therefore be made explicit.

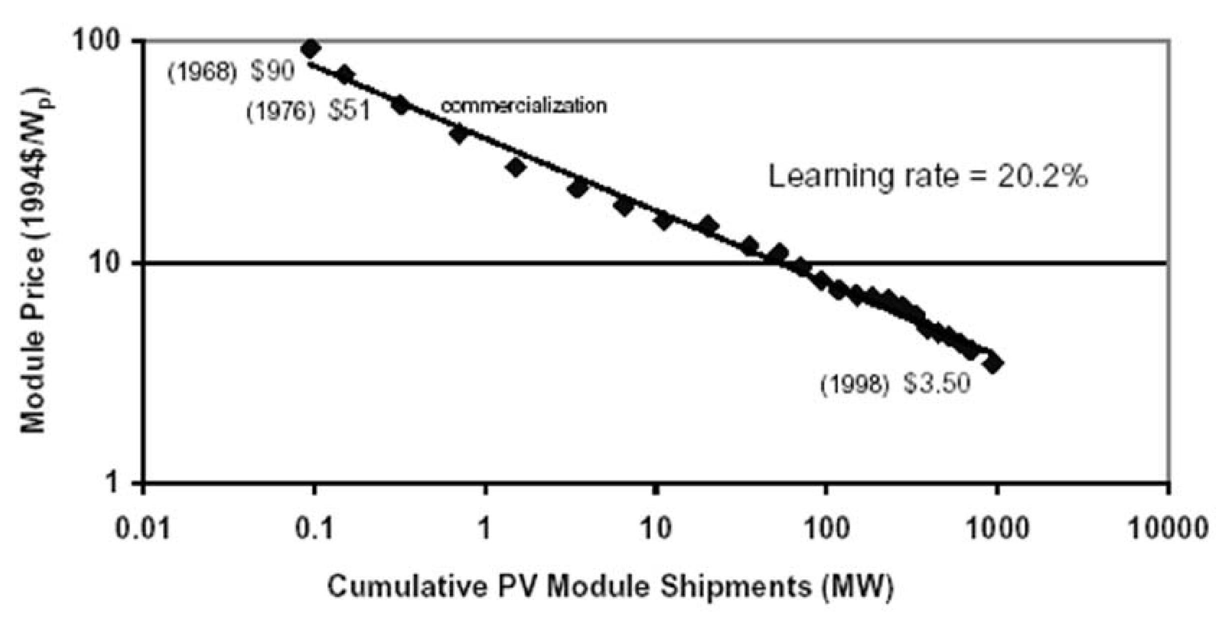
47. Furthermore, technology costs do not stay constant over time, but change with their diffusion into markets. *Oosterhuis & ten Brink* (2006) note that new technologies, when they are successful in being applied and finding their way to the market, often follow a pattern in which the uptake starts at a low speed, then accelerates and slows down again when the level of saturation approaches. This is reflected in the well-known logistic or S-curve (see Figure 6).

Figure 6. Stages in the introduction of a new technology; the S-curve



48. The acceleration in uptake is not only due to the fact that the technology is becoming more widely known, but also to improvements and cost reductions occurring in the course of the diffusion process due to economies of scale and learning effects. Cost reductions as a function of the accumulative production (or sales) of a particular technology can be represented by 'learning curves' or 'experience curves'. Figure 7 shows a learning curve for photovoltaic energy technology. The 'learning rate' is the percentage cost reduction with each doubling of cumulative production or sales.

Figure 7. Learning curve of PV-modules, 1968-1998.



Source: Harmon (2000).

49. *IEA* (2000) has assessed the potential of experience curves as tools to inform and strengthen energy technology policy. It stresses the importance of measures to encourage niche markets for new technologies as one of the most efficient ways for governments to provide learning opportunities. *McDonald and Schrattenholzer* (2001) have assembled data on experience accumulation and cost reduction for a number of energy technologies (including wind and solar PV). They estimated learning rates for the resulting 26 data sets, analyzed their variability, and evaluated their usefulness for applications in long-term energy models. *Junginger* (2005) applied a learning curve approach to investigate the potential cost reductions in renewable electricity production technologies, in particular wind and biomass based. He also addressed a number of methodological issues related to the construction and use of learning curves.

50. An example of policy that seeks to induce both S-curve diffusion and learning curve effects is the 'feed-in' tariffs which a number of countries have introduced to promote renewable energy. At present most such energy is not economic (*i.e.* it is more expensive per kWh delivered than a non-renewable alternative). That is why it needs the subsidy of a feed-in tariff. In the short term, therefore, it does not deliver enhanced economic performance and therefore, despite its enhanced environmental performance, it is an environmental innovation, rather than an eco-innovation, as the terms are used here.

51. However, this situation may change. Mass deployment of renewable energy technologies through feed-in tariffs may engender learning by doing or economies of scale, reducing unit costs (this has already happened to such an extent with wind power that onshore wind turbines in the best sites are now competitive with other means of generation). The costs of competitors (*e.g.* the price of fossil fuels) may rise. Other countries may decide to deploy these technologies, generating export markets.

52. Several studies have been carried out to assess the quantitative relationship between the development of costs of environmental technologies and time. A *TME* (1995) study pioneered this, and *RIVM* (2000) further explored the consequences of this phenomenon. Several other studies address this issue (*e.g. Anderson*, 1999; *Touche Ross*,1995).

53. Both RIVM and TME conclude that the reduction of unit costs of environmental technologies goes faster than the – comparable – technological progress factor that is incorporated in macro-economic models used by the Netherlands Central Planning Bureau. In these models the average factor is about 2% annually. The results of both the RIVM and TME study for the annual cost decrease of environmental technologies are presented in Table 3.

Table 3. Annual decrease in costs of applying environmental technologies

Technology / Cluster	Annual cost decrease		
	Min	**Average**	**Max**
Dephosphating sewage	3.8%		6.7%
Desulphurisation of flue gas at power stations	4%		10%
Regulated catalytic converter	9%		10.5%
Industrial low NO_x technologies	17%		31%
1. High Efficiency Central Heating		1.4%	
2. Energy related technologies		4.9%	
3. End-of-pipe, large installations		7.6%	
4. End-of-pipe, small installations (catalysts)		9.8%	
5. Agriculture low emission application of manure		9.2%	

Source: *TME*, 1995, p. vi; *RIVM*, 2000, p. 13, cited in *Oosterhuis*, 2006, p .26.

54. Both studies show comparable results: the annual cost decrease is mostly between 4 and 10%. Therefore, when modelling environmental costs for the longer term, some form of technological progress needs to be taken on board in addition to what is assumed in the macro-economic model.

55. In the TME and the RIVM study no attempt was made to differentiate between two types of technological progress (see *Krozer*, 2002):

- gradual improvements of already existing technologies (for which Krozer assumes that these will mainly lead to cost-savings and not so much to increased reduction potential);
- innovations (or “leap technologies”) for technologies which are new and can compete with existing technologies in both efficiency (lower costs) and effectiveness (larger reduction potential).

56. This distinction is important, especially concerning the development of the reduction potential, because this will enable in the future a greater reduction in pollution than currently thought.

57. The evidence in Table 3 on waste water treatment and low NO_x technologies in industry actually shows both developments:

- increasing reduction potential (to almost 100% theoretical) in a period of about 30 years;
- decreasing unit costs.

58. So from the empirical point of view both developments are important enough to be separately considered when estimating future costs of environmental technologies.

59. All these developments are likely to take time. Provided that economic performance is computed over that time, it may well be that an environmentally-improving new technology (*i.e.* an environmental innovation) which in the short term was an economic cost actually turns out to deliver enhanced economic performance, and therefore to be an eco-innovation.

60. For any product or process which delivers improved environmental performance, there are therefore three possibilities:

- It immediately delivers improved economic performance as well (*e.g.* compact fluorescent light bulbs, some home insulation), in which case it is unequivocally an eco-innovation.
- It does not deliver immediately improved economic performance, in which case it is only a *potential* eco-innovation which
  - Becomes an actual eco-innovation when its economic performance improves and it is widely taken up (a process which may take decades or even centuries);
  - Never becomes an eco-innovation because its economic performance never improves adequately.

61. The boundary within which economic performance is considered is also a relevant consideration. For example, although the feed-tariff is currently a net economic cost for the German economy as a whole (because the energy produced is more expensive than non-renewable energy), for the producers of renewable energy it may result in highly profitable businesses. If the boundary of the calculation of ‘economic performance’ is just those businesses, clearly the economic performance picture will be positive. If it is the national economy, and the German renewable energy businesses are focused on the German market, a different picture will emerge, and the overall change in economic performance may be negative. If, again, the German renewable energy industries generate significant exports, this may make their overall effect on the German economy positive.

62. Another example relates to the market boundary being considered. Many markets are highly imperfect and exhibit many market failures, especially in respect of environmental impacts. An economic activity may be highly successful in market terms (*i.e.* deliver a certain functionality at low cost, and result

in profitable businesses), but generate environmental costs which actually exceed the market benefits. Similarly, an environmentally preferable activity may seem to be uneconomic in market terms, but actually be socially desirable because of the environmental benefits it delivers. It is obviously important that analysis takes the full picture (all the market and external costs and benefits) into account, but because of uncertainties in the monetary valuation of external costs and benefits it may not be possible to say definitively whether they change the picture as revealed by markets.

63. Because of the existence of market failures like environmental externalities, environmental innovations may be socially desirable even if they are not eco-innovations, if the social judgement is that the environmental benefit outweighs their economic cost. For example, it may well be that, because of their reduction in carbon emissions, renewable energy technologies are highly desirable socially, even if at present they are not eco-innovations (though over time they may become so, as discussed above). Eco-innovations are always socially desirable (because they are win-win across the environmental and economic dimensions).

64. Devising measurement techniques to identify and distinguish between environmental and eco-innovation in these circumstances is likely to be difficult. Ideally one would wish to measure the impacts (both environmental and economic) relative to a counterfactual that represents the situation without the innovation. For example, while economic performance measures such as output or value added may still exhibit growth post innovation, this may be lower than would have been the case without it. However, in practice it may be difficult to establish such a counterfactual and therefore it may only be possible to measure performance relative to a base year (or period).

65. The ECODRIVE project came up with numerous suggestions for how economic and environmental performance could be measured, at different economic and spatial levels. It also derived predictive institutional, policy and cultural indicators (including those based on societal values) that might be used to show whether eco-innovation was likely to take place. For these suggestions see Huppes *et al.* 2008.

66. The purpose of indicators is of course to show whether eco-innovation has in fact taken place. The next section briefly reviews three very different indicators – of environmental performance, or the growth of eco-industries, and of the number of environmentally related patents – to see whether this is likely over recent years to have been the case.

4. Trends in eco-innovation

67. A range of potential indicators for measuring eco-innovation were identified in the preceding section. Here we consider the trends in three key indicators. As has been argued above, eco-innovation leads to improvements in both environmental and economic performance. Therefore, at the macro level, strong (or absolute) decoupling between economic growth and environmental degradation provides an important "impact indicator" of eco-innovation.[10] It may be surmised that, of crucial importance to delivering improved economic and environmental performance is the sub-set of economic activity (shown in Figure 2.4) that is explicitly concerned with environmental outcomes – the numerous firms and sectors grouped under the heading of 'eco-industries'. Thus, the growth in eco-industries provides an output indicator of eco-innovation. Of course, a necessary requirement for eco-innovation is the development of

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[10] Weak (relative) decoupling occurs when there is a decline in environmental impact per unit GDP. Strong (absolute) decoupling requires in addition that the environmental impact decline is absolute terms.

new environmental technologies (*i.e.* environmental innovation). Consequently, an increase in the number of environmentally related patents provides another "output indicator" of eco-innovation.[11]

4.1 Decoupling

68. *OECD* (2005) publishes ten 'key environmental indicators' relating to the issues of climate change, the ozone layer, air quality, waste generation, freshwater quality and freshwater resources, forest resources, fish resources, energy resources and biodiversity, where the first five relate to pollution, and the second to natural resource issues. Table 4 summarises developments in relation to these issues over the past twenty or so years and identifies where decoupling has occurred.

Table 4. Environmental Performance of OECD Countries across Ten Environmental Issues

Environmental Issue	Trend
Pollution	
Climate Change	In most OECD countries, and overall, carbon dioxide and greenhouse gas emissions have continued to increase, albeit slower than economic growth, *i.e.* there has been weak decoupling.
Ozone Layer	In North America, EU-15 and Japan consumption of CFCs has fallen to zero, and has greatly reduced for other ozone depleting substances. Over the 1990s this halted the depletion of the ozone layer for most countries.
Air Quality	Since 1990, both SO_x and NO_x emissions have fallen across the OECD as a whole, showing a strong decoupling from GDP.
Waste Generation	Total waste generated in the OECD, and waste generated per person, have grown more or less continuously since 1980, but less fast than private consumption.
Freshwater Quality	Installation of waste water treatment plants has reduced oxygen-depleting pollution loads from municipal and industrial point sources, but improvement in surface water quality in most countries is not obvious, perhaps because of the contribution from erosion and pollution from diffuse sources. Nitrate concentrations have also mainly stabilized rather than been reduced.
Resources	
Freshwater Resources	Total water abstractions have increased, though less fast than population. However, totals may conceal unsustainable abstractions at sub-national levels.
Forest Resources	OECD use of roundwood has largely stabilised over the 1990s, and the average harvest is around 55% of annual growth, with all countries being below 100%.
Fish Resources	OECD fishing fleets tend to fish globally. More than two thirds of marine fish stocks are exploited at or beyond maximum sustainable limits.
Energy Resources	Since 1990 overall energy, and fossil fuel, supply across the OECD have increased, though less fast than GDP. Energy supply per inhabitant has also increased.
Biodiversity	While the number and extent of protected areas have increase significantly since1980, but habitat loss and fragmentation outside protected areas is not being reduced and the percentage of threatened species remains high.

Source: OECD 2005.

69. Table 4 shows that the overall environmental performance of OECD countries over the past 20 years has been mixed; with improvements in some areas (notably in relation to the ozone layer and air quality), but deterioration in others (notably in relation to climate change, waste generation and fish resources). Strong decoupling has occurred in only two areas – ozone layer depletion and air quality.

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[11] While this is a necessary indicator for eco-innovation, it is not sufficient as there is no guarantee that the technologies covered by environmental patents will generate economic benefits as well as environmental improvements.

4.2 Eco-industries

70. While it is plausible that eco-industries contribute to environmental improvement, there is no guarantee that they will also lead to improved economic performance. Many environmental technologies, especially end-of-pipe technologies, add to rather than save costs, and so, in purely monetary terms, may incur an economic penalty. Eco-industries are therefore likely to come about through a mixture of environmental innovation and eco-innovation.

71. Classifying 'eco-industries' - also called the environmental, or environmental goods and services, industry - is not straightforward. Enterprises engaged in many different types of activities are involved, making it difficult to identify environmental protection products and services within the standard international classification of industrial activities (ISIC). An OECD/Eurostat Informal Working Group on the Environment Industry was established in 1995 to address the issues and develop a common methodology. The working group agreed on the following definition of the environment industry:

> '*The environmental goods and services industry consists of activities which produce goods and services to measure, prevent, limit, minimise or correct environmental damage to water, air and soil, problems related to waste, noise and eco-systems. This includes cleaner technologies, products and services that reduce environmental risk and minimise pollution and resource use.*' (*OECD/Eurostat*, 1999)

72. Environmental industries thus fall into three main groups:[12]

- **Pollution management group:** Includes Air pollution control; Wastewater management; Solid waste management; Remediation and clean-up of soil and water; Noise and vibration abatement; Environmental monitoring, analysis and assessment
- **Cleaner technologies and products group:** Activities which improve, reduce or eliminate environmental impact of technologies, processes and products (*e.g.* fuel-cell vehicles)
- **Resource management group:** Prime purpose of activities not environmental protection (*e.g.* energy saving, renewable energy plant)

73. As was noted above, eco-industries are widely dispersed across the various sectors of the standard industrial classification. To give an example, Table 5 lists the share of environment industry production in total industry production by standard industrial activity for Germany. The largest shares are found in the machinery sector and instruments and machinery sector where more than 8% of activities are attributed to the environment industry.

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[12] A more detailed list can be found in Annex 1 and Annex 7 of 'The Environmental Goods and Services Industry: Manual for Data Collection and Analysis' (*OECD/ EUROSTAT*, 1999).

Table 5. Distribution of environment industry by standard industry activity: Germany, 1992

Industrial activity	Share of environment industry production in industry total (%)
Non-metallic mineral products	1
Foundry products	n.a.
Production of continuous steel forming	1.1
Fabricated metal products	3.5
Machinery	8.8
Vehicles	0.8
Electronics	4.6
Instruments and Machinery	8.1
Iron, steel and metals	0.6
Chemicals	0.7
Ceramics	5.2
Glass	n.a.
Wood products	n.a.
Pulp and paper	0.7
Plastics	3.1
Rubber	2.7
Textiles	1.1

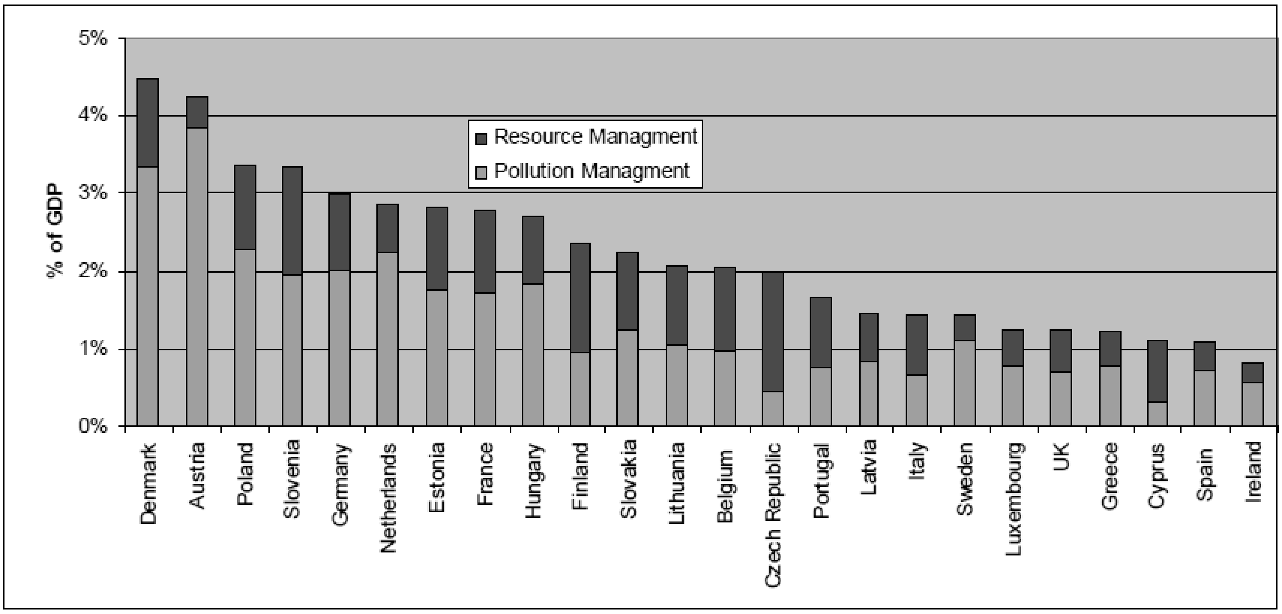
Source: OECD/ Eurostat, 1999 (Annex 6)

74. Because of the difficulties involved in classifying the environment industry, only a very limited amount of data on the size of this industry can be retrieved from standard national statistical sources. In recognition of this data gap the European Commission (DG Environment) published a comprehensive study: '*Eco-industry, its size, employment, perspectives and barriers to growth in an enlarged EU*' (*European Commission*, 2006). The study is based on data on environmental protection expenditures provided by Eurostat and a number of interviews with representatives of the industry and administration. This section of the report is based mainly on the DG Environment study. Other sources for tables and figures are noted where applicable.

75. The estimated total turnover of eco-industries in 2004 in the EU-25 is EUR 227 billion, with the largest industries being solid waste management and wastewater treatment (both around EUR 52 bio.) and water supply (EUR 45 bio.). By 2004, the eco-industries provided around 3.4 million jobs (full-time equivalent, direct and indirect employment); over two-thirds of which fell into the pollution management category. Reflecting their share of total turnover, the three largest employers were the solid waste management sector accounting for just over 1 million jobs, followed by wastewater treatment (800 thousand) and the water supply sector (500 thousand).

76. Pollution management activities accounted for 64% of total turnover in 2004, with the other 36% relating to resource management activities. However, there were some significant differences between countries (see Figure 8), with pollution management accounting for 90% of the total in Poland, but only around 20% in the Czech Republic.

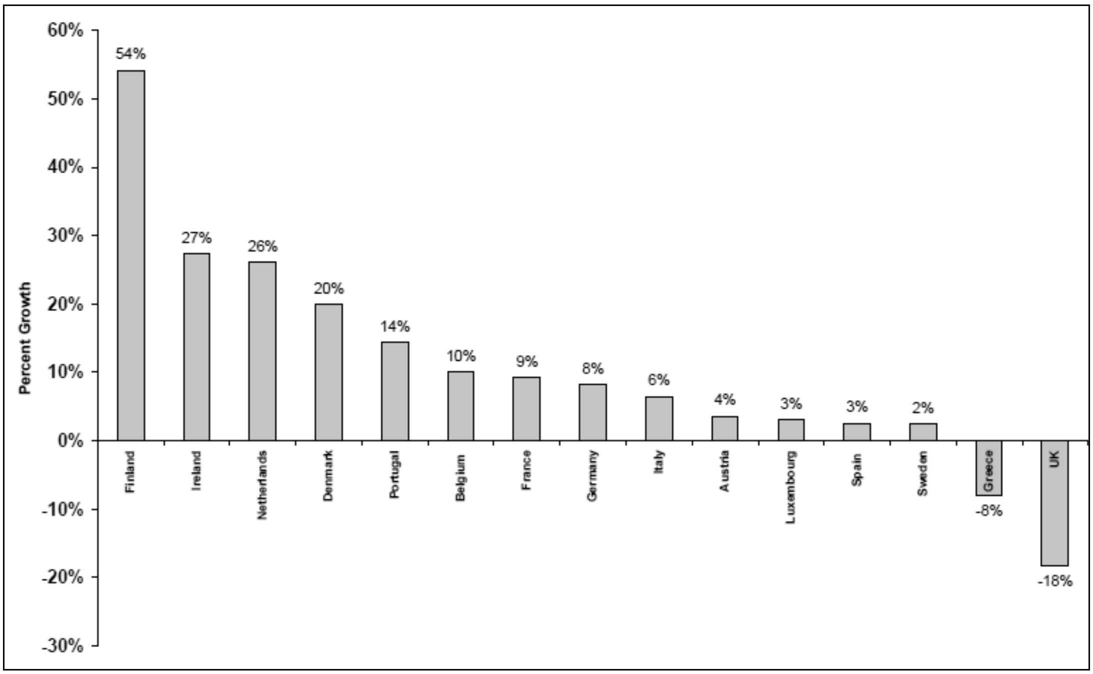
Figure 8. Eco-industry turnover as % of GDP by EU-25 country, 2004



Source: European Commission (2006), Figure 20.

77. On average the eco-industry turnover in 2004 represented around 2% of GDP. As one might expect, the countries with the largest eco-industry sectors were Germany (EUR 66.1 bio.) and France (EUR 45.9 bio.), followed by the UK (EUR 21.2 bio.) and Italy (EUR 19.2 bio.) However, as can be seen in Figure 8, relative to GDP it was Denmark and Austria that had the largest eco-industry sectors (both over 4% of GDP); while the UK and Italy were towards the bottom of the league (both below 1.5% of GDP).

Figure 9. Eco-industry turnover growth by EU-15 country (constant €), 1999-2004

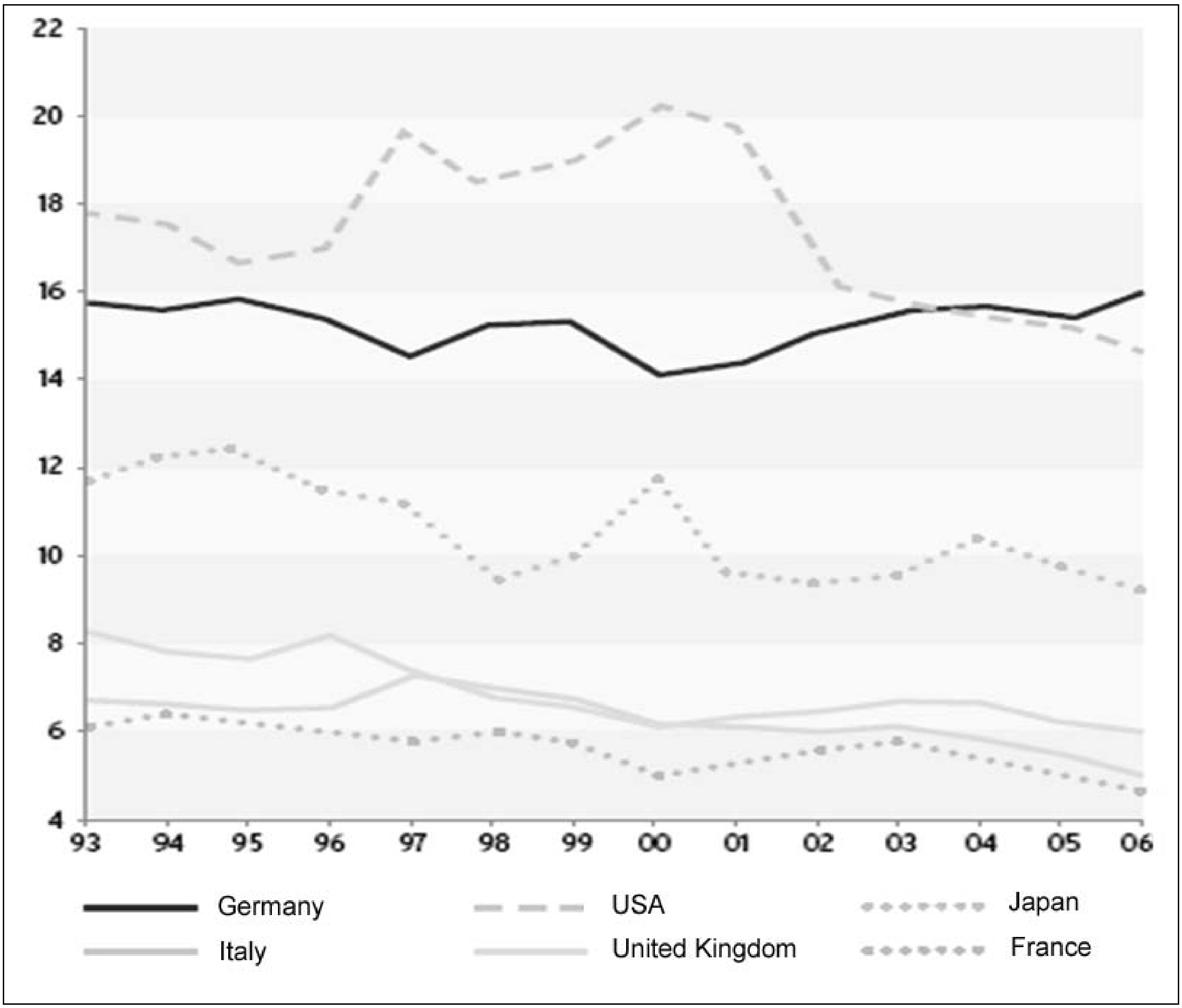


Source: DG Environment (2006), Figure 15.

78. Across the EU-15 the eco-industry grew by around 7% (in constant €) between 1999 and 2004 (*DG Environment*, 2006, p. 33). However, the growth rates for different countries varied widely (see Figure 4.2). The highest growth occurred in Finland (over 50%), followed by Ireland, the Netherlands and Denmark (all over 20%). The eco-industry in Germany grew by 8%, implying that it maintained its share of the European market; while in the UK it actually declined by 18% over the period, due largely to a decrease in the wastewater treatment sector.

79. Over the same time period, EU-15 GDP grew by around 11% in volume terms. Only in four countries did the increase in eco-industry turnover significantly outstrip the growth in GDP: Finland (54% vs 16%); The Netherlands (26% vs 9%); Denmark (20% vs 8%); and Portugal (14% vs 8%). For Germany, France and Italy, the increase in eco-industry turnover was broadly in line with the growth in GDP. Market share figures estimated by *BMU/UBA* (2007) show that Germany also maintained (or slightly increased) its world market share over the time period, while Japan and the USA both suffered significant losses (see Figure 4.3). This implies that the growth rate of eco-industries was less than 8% for these two countries.

Figure 10. Environmental Industry: World Market Share of OECD Countries



Source: BMU/UBA (2007).

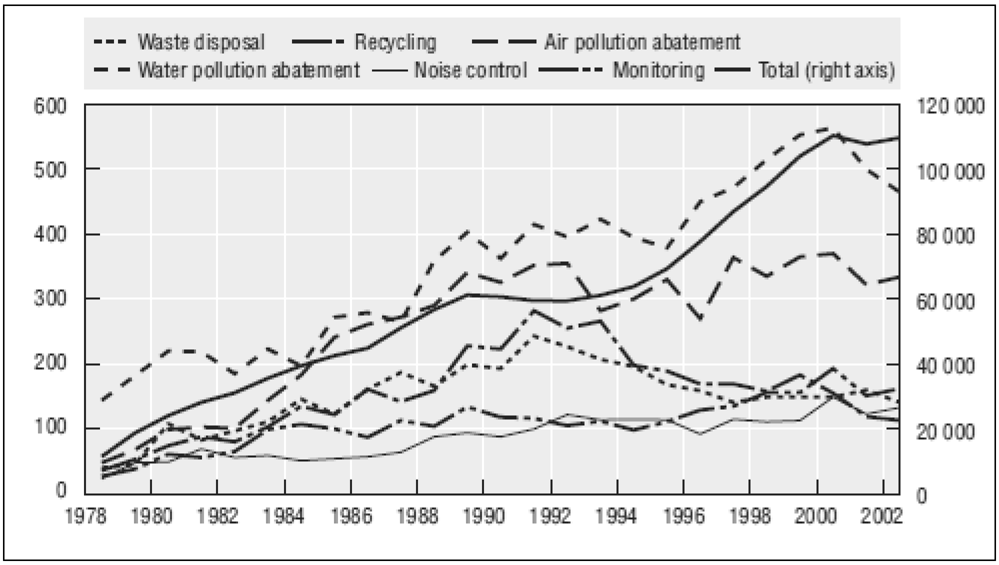
4.3 Environmental patents

80. Environmental technologies are often characterised in terms of the mechanism by which the environmental impact is reduced, with a distinction being made between:

- 'end-of-pipe' technologies that isolate or neutralize polluting substances after they have been formed;[13]
- 'process-integrated' technologies (also known as 'integrated' or 'clean' technologies) that change production processes, leading to less pollution, resource and/ or energy use;
- product innovations, in which (final) products are developed or (re)designed that contain less harmful substances, use less energy, produce less waste, etc.

81. The International Patent Classification (IPC) system identifies the technology classes and subclasses to which the patent applies. This facilitates the identification of those patents that potentially have environmental benefits (*i.e.* "environmental patents). For end-of-pipe technologies this may be relatively straightforward, with particular sub-classes relating entirely to environmental technologies. For changes in production processes and product characteristics however, it is necessary to use search algorithms based on keywords to identify relevant patents. Even with sophisticated algorithms, it is unlikely that all relevant environmental patents will be identified. Consequently, to the extent that process-integrated and product innovations are becoming more prevalent over time, the identified trends in environmental patents are likely to understate the true tends.[14] Notwithstanding this divergence, trends in environmental patents can give a reasonable indication of the growth in environmental innovation.

Figure 11. Number of EPO "Environmental" patent applications and total EPO patent applications



Source: OECD (2008), Figure 1.6.

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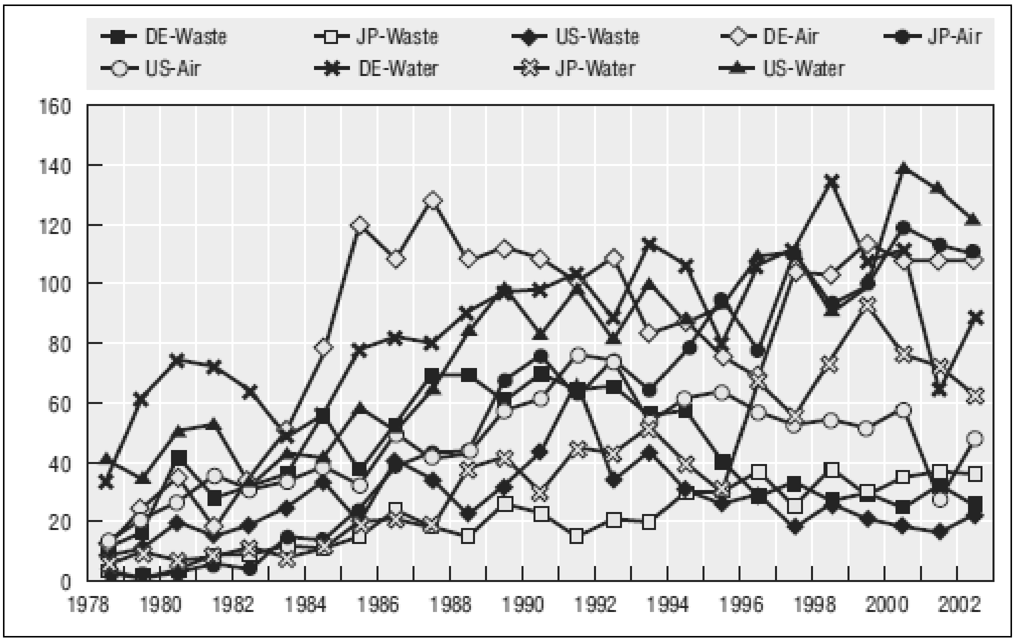
[13] End-of-pipe technology is often seen as undesirable because it may lead to waste that has to be disposed of. However, this is not necessarily the case. For example, reducing nitrogen oxides at the end of a smokestack or car exhaust produces the harmless substances nitrogen and oxygen, which are natural components of the air (although even then particles from the platinum catalyst from the vehicle's catalytic converter may cause pollution).

[14] This is exacerbated by the fact that many process-related innovations will not be patented.

82. Figure 11 shows the trends in environmental patent applications made to the European Patent Office (EPO) between 1978 and 2002, together with the trend in total patent applications.[15] While there are some differences between policy areas, there was a general increase over the period, with air pollution patents showing the greatest growth (a seven-fold increase). Waste disposal and recycling patents peaked in the early 1990s and declined thereafter. Overall, the number of environmental patents experienced a four-fold increase over the 25 year period. This was significantly less than the growth in total patents, which experienced an eleven-fold increase. Even allowing for the likely underestimation of the growth of environmental patents, it would appear that environmental innovation grew more slowly than other forms of innovation over this period.

Figure 12. Number of EPO "Environmental" patent applications



Source: OECD (2008), Figure 1.7.

83. Figure 12 shows the trends in environmental patent applications for the three OECD countries that account for the majority of environmental patents – Germany, Japan and the USA. This shows some interesting differences between the countries. In Germany and Japan, air pollution was the area with the greatest growth (an eleven-fold increase), although the trajectories over the period were very different: Japan showing a relatively steady increase; Germany showing a rapid increase in the early 1980s and a levelling-off thereafter. In the USA, water pollution experienced the greatest growth, with the number of patent applications in 2002 being three times greater than in 1978.

5. Policies for environmental innovation

84. There are a wide range of policy instruments which can be employed to implement environmental policies. These differ in many different respects. However, essentially they can be grouped under four generic headings (*Jordan et al.* 2003):

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[15] These were derived in a recent OECD study on the use of patent data to measure environmentally related innovation (*OECD*, 2008).

- *Market / Incentive-based* (also called economic) instruments, including "emissions trading, environmental taxes and charges, deposit-refund systems, subsidies (including the removal of environmentally-harmful subsidies), green purchasing, and liability and compensation" (*EEA* (2006, p. 13).
- *Command and Control regulation instruments*, which seek to define legal standards in relation to technologies, environmental performance, pressures or outcomes.
- *Voluntary* (also called negotiated) *agreements* between governments and producing organisations (*see ten Brink*, 2002, for a comprehensive discussion).
- *Information / Education-based instruments*, such as eco-labels, etc., which may be mandatory or voluntary.[16]

85. In recent years, it has been increasingly common to seek to deploy these instruments in so-called 'policy packages' or 'instrument mixes' (*OECD*, 2007), which combine them in order to enhance their overall effectiveness across the three (economic, social and environmental) dimensions of sustainable development.

86. All four types of instrument have the potential to stimulate environmental innovation (and potentially eco-innovation) by changing the investment / return equation in favour of environment-improving innovation, relative to profit-improving innovation, or no innovation at all. Market-based instruments change the equation directly, by changing the relative prices and costs of inputs or processes in favour of those with less environmental impact. Command and control instruments change the investment / return ratio by imposing penalties on actors who fail to meet the standards (*Kemp*, 1997). Under voluntary agreements, it is the threat of potential market-based instruments or regulation that changes the ratio in favour of environmental innovation. They can also lead to greater awareness of technological possibilities for eco-innovation that increase profitability as well as improving environmental performance.[17] Finally, information-based instruments may change the investment/return ratio by promoting more eco-efficient products to consumers.

87. There is a relatively large (and growing) literature on the relationship between environmental policy interventions and technological change – both theoretical and empirical, covering a wide range of policy instruments (*i.e.* command and control regulations, environmental taxes, investment incentives, permit trading schemes and voluntary agreements).[18] This literature has been the subject of a number of reviews, including a comprehensive synthesis by *Vollebergh* (2007) for the OECD Joint Meetings of Tax and Environment Experts, and it is not our intention to replicate these. Rather, we will provide brief summaries of some of the *predictions of theoretical models* regarding the effectiveness of different instruments in stimulating innovation and of the *empirical assessments* of the actual impacts of various policy instruments that have been implemented in the past, before focusing in slightly more depth on some *case-study evidence* comparing experiences across countries using different policy instruments.[19]

88. As was noted at the beginning of Section 2, the process of technological change is typically broken down into three stages: invention (*i.e.* the first development of a scientifically or technically new product or process; innovation (*i.e.* the commercialization of the new product or process); diffusion (*i.e.* the

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[16] Eco-labels are identified by *Jordan et al.* (2003) as the main example of information-based instruments. However, there are others.

[17] See *Ekins & Etheridge* (2006) for a discussion of this in relation to the UK Climate Change Agreements).

[18] This literature is restricted to technological change and does not consider more fundamental technological transitions (see Section 2).

[19] Other reviews include *Hemmelskamp* (1997), *Jaffe et al* (2002), *Kemp* (2000), *Popp* (2005) and *Requate* (2005).

adoption of the product or process by firms and individual). However, in practice, most studies do not distinguish between the first two stages (often just referring generically to R&D) and hence these stages have been combined for the purposes of this review, so that the only distinction is between technology development and technology diffusion; while the term innovation is used to represent the entire process of technological change.

5.1 Theoretical predictions

89. As is often the case with theoretical analyses, the specifications of the models and the underlying assumptions can have a significant bearing on the conclusions. Notwithstanding this, there is a reasonable degree of consistency between the findings of the various studies that have considered the impact of environmental policy instruments on innovation. These studies can be classified into two broad groups:

- those that explicitly analyze innovation, either in its entirety, or focusing on a particular stage of the process (*e.g.* technology diffusion);
- those that implicitly consider particular stages of the innovation process by analyzing an individual firm's decision regarding its investment in environmental technology (*i.e.* diffusion) or its expenditure on environmental R&D (*i.e.* development).

90. It should be noted that even in the first group, innovation is represented as a simple two-stage linear process of technology development and diffusion (and sometimes regulatory response), that does not reflect the complexities and subtleties of the innovation process discussed in Section 2, nor the social, political and cultural contexts. Furthermore, the analyses do not consider the dynamics of innovation (*e.g.* the speed of diffusion), focusing rather on the relative magnitudes of the potential benefits of innovation under different policy instruments (and hence the likelihood of innovation occurring), or the equilibrium outcomes after diffusion is completed.

91. The studies in the first group conclude that under conditions of perfect competition, emission taxes and auctioned permits provide greater incentives for innovation than direct controls or freely allocated permits. However, there is some disagreement over the relative impacts of the two instruments. Under the assumption that the innovator appropriates a fixed (exogenous) proportion of the gains accruing to the technology adopters, *Milliman & Prince* (1989) conclude that auctioned permits provide the greatest incentive, although the government may find it easier to adjust emission taxes in response to the resultant downward shift in marginal abatement costs. However, when the proportion is determined endogenously – as a market equilibrium royalty payment – *Fischer et al* (1998) find that either auctioned permits or emission taxes can provide the greater incentive, depending on the extent to which the technology can be imitated and hence, the extent to which the developer can appropriate the gains accruing to the other firms in the form of royalty payments. If imitation is easy, then auctioned permits provide the greater incentive. However, if imitation is difficult, then the emissions-tax provides the greatest incentive.

92. In both of the above analyses, the authors assume that all firms in the industry adopt the new technology (*i.e.* there is complete diffusion) and only consider the ability of the firm that develops the technology to appropriate the gains from diffusion. In contrast, *McGinty & de Vries* (2009) explicitly analyse the diffusion of a clean production technology. Using a product differentiation model of imperfect competition, they show that the provision of an emissions subsidy for the reduction in unit emissions of the clean technology (relative to the old dirty technology) will increase the equilibrium level of diffusion.[20] However, the impact depends on the degree of substitutability between clean and dirty products;

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[20] McGinty & de Vries (2009) actually model a subsidy applied to the unit production cost of the clean technology. However, in their model this can be interpreted as a subsidy payment for the reduction in emissions of that technology versus the incumbent dirty technology.

diminishing as the products become more differentiated. While the authors do not consider the impact of an emissions tax on the diffusion of the clean technology, it is clear from their results that this would only have the same impact as the subsidy if the clean and dirty products were perfect substitutes.

93. The studies looking at an individual firm's decision also show that an emissions tax can stimulate innovation and diffusion. *Jaffe & Stavins* (1995) consider explicitly the firm's decision criterion for investing in a new abatement technology and show that, by changing the benefit-cost balance in favour of the new technology, the introduction of either an emissions tax or an investment subsidy will bring forward the timing of its adoption by existing firms and make it more likely to be used by new entrants.

94. Other studies consider the firm's choice of optimal "abatement effort" in the context of maximizing its total profits, or minimizing its total cost of emissions reduction. This effort can take the form of R&D (development) or expenditure on abatement equipment (diffusion); the decision problem being the same in each case – *i.e.* to choose the optimal level of effort. *Kemp* (1997) assumes that the firm seeks to minimize its total cost of emissions reduction – implicitly assuming that its output level is fixed – and demonstrates that the optimal abatement effort is lower under direct regulation than under an equivalent emissions tax; with the relative level under tradable permits depending on whether the (exogenous) permit price is higher or lower than the tax rate. He also considers the impact of subsidizing the cost of the firm's R&D effort and shows that increasing the subsidy rate causes a rise in pollution-control R&D. More interestingly, the impact of the subsidy is greater if it is combined with an emissions tax than with an equivalent emissions limit. *Millock & Nauges* (2006) consider a firm's profit maximization problem – allowing output to vary – and show that while increases in an investment subsidy (expressed as a percentage of the gross investment cost) unambiguously increases abatement effort, the impact of increases in an emissions tax rate depends on the relative magnitudes of the direct impact and the indirect impact (via changes in output levels) on the marginal benefit of abatement effort. If the latter dominates, then an increase in the emissions tax rate leads to a reduction in the optimal level of abatement effort.

95. *Montero* (2002) extends the analysis of firm's choice of environmental R&D expenditure to compare the impacts of different policy instruments in a situation of imperfect competition and finds that the ranking depends on the nature of the competition.[21] Under Bertrand price competition in the output market, the results are comparable to those under perfect competition (*Kemp*, 1997): the relative ranking of auctioned permits and taxes is ambiguous, but both provide greater incentives for technology development than emission standards and freely allocated permits. However, under Cournot quantity competition, any of the instruments, apart from freely allocated permits, can provide the greatest incentive, depending on the model parameter values.

5.2 Empirical assessments

96. Empirical studies of the relationship between environmental policy interventions and innovation can be classified into two broad groups:

- those that assess the impact on the development of new technologies – typically using patent data as a measure of development activity;
- those that assess the impact on the diffusion of new technologies – either directly, or by assessing the impact on the likelihood of adoption.

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[21] Montero's model does not include diffusion. However, it does include spillover effects, where R&D by one firm reduces the abatement costs of the others.

97. Some of the studies consider the relationship between the overall stringency of environmental regulation and environmental innovation in aggregate. Others assess the impacts of individual policy instruments and specific technology areas – spanning energy efficiency (both product and process), renewable energy, air and water pollution abatement. Given the relative scarcity of environmental taxes in the past, there are few explicit studies of this policy instrument. However, a number of studies consider the impacts of changes in energy prices, which give an indirect indication of the potential impact of taxation.

98. A number of studies have assessed the relationship between technology development and the overall stringency of environmental regulation, using pollution and control expenditure (PACE) data as a proxy for the latter.[22] Based on simple graphical analyses for Germany, Japan and the USA, *Lanjouw & Mody* (1996) identify a relatively clear correlation between expenditure and patents over the 1970s and 1980s, with a time lag of 1-2 years. They also find some indications in the data that patenting in one country responds to increasing stringency of environmental regulation in the other two. *Jaffe & Palmer* (1997) evaluate the impact of PACE on two different measures of innovation – total private expenditures on R&D and the number of successful patent applications by US manufacturing industries. Unlike the previous study, they undertake formal econometric analysis of the data (controlling for industry-specific effects) and find that while there is a statistically significant positive relationship between PACE and R&D expenditures, there is no significant impact on patenting activity. However, this is not entirely surprising given the fact that their data is for all types of patents, not just those relating to environmental technologies and products. *Brunnermeier & Cohen* (2003) also assess the impact of PACE on patenting activity by US manufacturing industries. However, unlike the previous study, they use only environmental patent applications in their analysis. They find that PACE has a positive and statistically significant impact on patenting activity; as do industry size, concentration and export intensity. However, the magnitude of the coefficient (which represents the semi-elasticity of patents with respect to PACE) is only 0.0004. Thus, *ceteris paribus*, an increase in abatement expenditure of USD 100 million results in an increase in the mean number of patents of only 4%.

99. While there are obvious pragmatic reasons for using PACE data as a proxy for the stringency of environmental regulation (*i.e.* availability of data), the validity of the approach may be open to question. As *Brunnermeier & Cohen* (2003) note, expenditure may be affected by factors other than environmental regulation, such as external pressures from interest groups, or a desire to promote / maintain "green credentials" with customers. Furthermore, the reported data may not cover all pollution abatement costs and activities (particularly process related activities) and may be prone to over-statement by reporting firms for strategic reasons. However, to the extent that the reported PACE data is correlated with the stringency of environmental regulation, the analyses suggest that the latter does have an impact on innovation (at least in the USA), although the scale of the impact appears to be small.

100. Other studies have used patent data to evaluate the impact of specific environmental policy interventions on technology development. *Popp* (2002) finds that energy prices had a highly significant impact on energy-efficiency developments in the USA between 1970 and 1994; with a short-run price elasticity of 0.06 and a long-run elasticity 0.354.[23] The estimated mean lag is less than 4 years, leading the author to conclude that the imposition of a carbon / energy tax would lead to a fairly quick shift towards

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[22] However, the studies do not all use the same definition of PACE. *Lanjouw & Mody* (1996) include (real) investment expenditures, regulation and monitoring costs, and research and development by all levels of government, and by private manufacturing and non-manufacturing firms. *Jaffe & Palmer* (1997) and *Brunnermeier & Cohen* (2003) both use compliance cost data for private manufacturing firms (at the industry level) only. However, while the former use capital cost data in their analysis, the latter use operating cost data.

[23] Thus, a 10% increase in energy prices would be expected to increase the number of energy efficiency related patents by around 3.5% in the long run.

environmentally friendly innovation. *Johnstone & Hascic* (2008) assess the impact of a range of environmental policy instruments on patenting activity in the field of renewable energy, differentiating between price-based and quantity-based "clusters" of instruments and voluntary programmes.[24] They find that the (statistical) significance of the clusters varies across technologies. The price-based cluster is (highly) significant for solar, biomass and waste-to-energy; while the quantity-based cluster is significant for wind technologies. The authors surmise that this may be due to the different economic characteristics of the technologies. For example, the significance of investment incentives for solar and waste-to-energy may reflect the capital intensity of these technologies with large up-front investment costs. *De Vries & Medhi* (2008) investigate the relative importance of environmental regulations and fuel prices on innovation in automotive emission control technologies, distinguishing between post-combustion devices and engine re-design technologies. The results of their analysis suggest that the relative impacts of regulation and market forces differ between the two types of technology. For post-combustion technologies, both regulations are significant, while fuel prices have no significant impact. In contrast, the opposite is the case for engine re-design technologies; with fuel prices having a significant impact, but regulation having no discernable effect.

101. Turning to technology diffusion, *Jaffe & Stavins* (1995) assess the impact of energy prices, installation costs and building regulations (*i.e.* relevant building codes) on the diffusion of thermal insulation in new home construction in the United States, using state-level panel data for the years 1979-88. They estimate separate equations for ceiling, floor and wall insulation, and find that while the coefficient for energy prices is positive in all three equations, it is only significant for floor insulation. The coefficients for installation cost (which are all negative as expected) are around 2-3 times greater in magnitude and of comparable significance; while the regulation coefficients are consistently insignificant (and of varying sign), indicating that building codes had minimal impact on household energy efficiency levels over the period. The authors use the estimated models in a simulation to compare the effects of a 10% increase in energy prices (*i.e.* an energy tax) with those of a 10% reduction in installation costs (*i.e.* a investment subsidy) – with each being applied over the whole ten-year period. While the tax increases diffusion by between 2%-6% by the end of the period, the technology subsidy increases diffusion by between 4%-15%.

102. *Kemp* (1997) assess the impact of water effluent charges on the diffusion of biological water treatment technology in the Dutch food and beverage industry over the period 1974-91, using a rational choice threshold model of technology adoption decisions. The estimated coefficients are all significant and of the expected sign and magnitude, and the model provides a very close fit to the actual diffusion of waste-water treatment technologies over the period. This leads the author to conclude that the effluent charges were a significant positive factor in the diffusion of treatment technologies. Indeed, he estimates that only around 4% of plants would have installed waste-water treatment equipment by the end of the period if the charge had remained at its (low) 1974 level, compared to the actual figure of over 40%.

103. *Kerr & Newell* (2001) assess the relative impacts of permit trading and regulation on the diffusion of isomerization technology in the US petroleum industry in response to the lead phase-down regulations introduced in the 1970s and 1980s, using a duration model of technology adoption.[25] They find that the adoption of isomerization technology was driven almost entirely by the increasing stringency of the regulation over the period – with a 10% increase in stringency leading to a 40% increase in the likelihood of adoption. Permit trading had a significant impact on the cost efficiency of diffusion; with low

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[24] The clusters are price-based instruments (investment incentives, tax measures and tariffs), quantity-based instruments (obligations and tradable certificates) and voluntary programmes.

[25] Lead trading was allowed up until late 1979 and from late 1982 through the end of 1987. Outside of these periods, refineries were subject to individual performance standards. This switching between instruments allows the impact of permit trading to be assessed relative to the command regulation.

abatement cost refineries (*i.e.* sellers of permits) being significantly more likely to adopt the technology than under the performance standard, and high-cost refineries (*i.e.* buyers of permits) being significantly less likely to adopt. While the authors do not consider the impact of permit trading on the overall rate of adoption across all refineries, the estimated parameter values and relative proportions of high-cost and low-cost refineries suggest that the likelihood of adoption was slightly higher under permit trading than under the performance standards.

104. As part of their analysis of the impacts of the French tax-subsidy scheme for NO_X and SO_2 emissions, *Millock & Nauges* (2006) estimate the impact of the emission taxes on a plant's decision to install end-of pipe abatement equipment. Using panel data for 226 plants in three industries (iron and steel, coke and chemicals) for the period 1900-98, the authors find that the total value of emissions taxes paid by the plant (*i.e.* for both pollutants) has a positive impact on its decision to invest in abatement equipment. However, the magnitude of the effect varies considerably across the sectors and is only significant for the iron and steel sector.

105. An alternative approach to evaluating the drivers of innovation is adopted by *Newell et al* (1999), who use a product characteristic model to estimate the impact of energy prices, energy efficiency standards and other factors on the energy efficiency of three types of electrical consumer durables (room air conditioners, central air conditioners and gas water heaters) in the USA between the 1970s and 1990s. In this framework, innovation is represented by movements of and / or movements along a "transformation surface" that relates the bundle of product characteristics to real cost of producing that bundle; with the authors distinguishing between shifts in the surface towards the origin (*overall technological change*); changes in the slope of the surface (*directional technological change*); changes in the mix of products along a given surface (*model substitution*). They find little evidence that either energy prices or energy efficiency standards had any impact on overall technological change. However, energy prices had a significant impact on directional technological change for both room and central air conditioners.

5.3 Case studies

106. In addition to the formal econometric assessments of the impacts of environmental policy interventions on innovation, there have been a number of case studies that have compared experiences of across countries in order to gain some insights regarding the relative effectiveness of different policy instruments and approaches. Here we consider five such studies, spanning a range of different environmental policy areas:

- CO_2 emissions from upstream petroleum production
- Vehicle fuel efficiency / CO_2 emissions
- Energy efficiency of ICT equipment
- Solar photovoltaics
- Substitution of hazardous chemical substances

107. It is, of course, not possible to draw general conclusions from individual case studies. Consequently, a synthesis of the five studies is provided in an attempt to identify some general messages. Four of the case studies are taken from a recent project undertaken for DG Environment of the European Commission on the impact of environmental policy on innovation, to which one of the authors of this report contributed.[26]

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[26] Innovation dynamics induced by environmental policy (contract # 07010401/2005/424497/FRA/G1). A summary of the project is provided by *Ekins & Venn* (2009).

a) Upstream petroleum production

108. *Christiansen & Skjaerseth* (2005) undertake a comparative analysis of the impacts of climate change policies on the upstream petroleum sectors in Norway and The Netherlands during the 1990s.

- In Norway, upstream petroleum operations have been subject to a CO_2 tax since 1991. In addition to the tax, the sector has been subject to a portfolio of other measures comprising publicly-funded R&D support schemes, gas flaring permits and mandatory Environmental Impact Assessments.
- In the Netherlands, the control of CO_2 emissions from the petroleum sector was addressed through a series of voluntary agreements between the sector and the government. In 1995, the oil and gas industry signed a Declaration of Intent which included quantified targets the improvements in energy efficiency and reductions in CO_2 emissions by the year 2000. This was translated into a Long Term Agreement (LTA) on energy efficiency in the following year, with an improvement target of 20% over the period 1989-2000 - but without targets for CO_2 reductions. In 2001, a new LTA was signed which committed firms to implementing energy efficiency measures with a positive NPV at a 15% discount rate or a five year payback period.

109. Both approaches appear to have been effective, in that CO_2 emissions per unit production fell by around 22% between 1990 and 2001 in Norway, while energy efficiency improved by around 35% in The Netherlands over the same period. However, there were marked differences between the two countries in terms of the nature of the innovation that occurred. In The Netherlands, technological change was incremental, reflecting a steady diffusion of available (*i.e.* known) technology. In contrast, the authors find evidence of more radical innovations and adaptations by the Norwegian petroleum sector – including the development of energy-efficient gas turbines, installation of waste heat recovery units, process modifications and improved utilization of process heat. While the authors acknowledge the impossibility of proving a causal link between policy intervention and innovation (in the context of their case study), they conclude that the CO_2 tax played a key role in the development and implementation of these radical innovations; with the benefits of reduced tax payments providing an important incentive. However, they also conclude that the impacts of the two instruments were conditioned by the political contexts in which they were applied and the problem characteristics in the respective countries (*e.g.* the economic significance of the sector, size of installations, etc.).

b) Car fuel efficiency / CO_2 emissions

110. *Kuik* (2006*)* compares the impacts of policy interventions to improve the fuel efficiency of passenger vehicles in Europe, Japan and the USA.

- In Europe, the European Commission entered into a series of voluntary agreements with the automobile industry to reduce CO_2 emissions from passenger cars and to improve fuel efficiency. Separate agreements were concluded in 1998 with the European Automobile Manufacturers' Association (ACEA), the Japan Automobile Manufacturers Association (JAMA), and the Korea Automobile Manufacturers Association (KAMA).[27] The agreements specified an industry-level target for new passenger fleet average CO_2 emissions of 140 g CO_2/km, to be reached by 2008/9; together with an indicative target of 120 g CO_2/km for 2012.[28]

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[27] For simplicity, these are collectively labelled as the ACEA agreement.

[28] The target year is 2008 for ACEA and 2009 for JAMA and KAMA. Other elements include fuel-economy labelling for passenger cars, and the promotion of car fuel efficiency by fiscal measures (EC, 2005).

- In Japan, the car manufacturing sector is one of many sectors covered by the Top Runner Programme that was introduced in 1999 as part of the revision of the Law on the Rational Use of Energy (Naturvårdverket, 2005). Under the programme, the most energy-efficient product (*i.e.* the "Top Runner") becomes the basis of the regulatory standard in 3 to 12 years time, taking into account the potential for technological innovation and diffusion. The standards in the Top Runner Program are also used in the green purchasing law and the green car tax scheme. Additionally, there is an annual award for the most energy-efficient products and systems.
- In the USA, the Corporate Average Fuel Economy (CAFE) programme was initiated by US Congress in 1975 as a measure to conserve petrol and to reduce US reliance on imported oil (Gerard and Lave, 2003). The CAFE standards set mandatory average fuel economy standards for car manufacturers for passenger cars and light-duty trucks. For passenger cars, the standards were increased from 18 miles per gallon (mpg) in 1978 to 27.5 mpg in 1985, but have not been raised since.

111. The ACEA agreement and the Top Runner programme have been more successful than the US CAFE program in inducing innovation. *Kuik* (2006) concludes that this is due to differences in the fuel-efficiency standards, with the standards in Europe and Japan being significantly more stringent. Furthermore, while the CAFÉ programme is mandatory, it has various legal loopholes and the penalties for non-compliance are relatively small. However, even under the European and Japanese interventions, the focus appears to have been on the diffusion of already available technologies and incremental innovations, rather than radical or break-through innovations.

112. While significant improvements in fuel efficiency were achieved under the ACEA agreement, the industry failed to meet the 2008 target of 140 g CO_2/km by a considerable margin.[29] Consequently, the European Commission introduced legislation in April 2009, setting a mandatory target of 130 g CO_2/km for 2012 (and an indicative target of 95 g CO_2/km for 2020), with various flexibility mechanisms.[30]

c) Energy efficiency of ICT equipment

113. *Oosterhuis* (2006a) compares experiences of attempts to improve the energy efficiency of Information Communications Technology (ICT) equipment in the USA, Japan and Europe.

- In the USA, computers and monitors were the first products to be included in the Energy Star labelling scheme introduced by the USEPA in 1992. In the following year, President Clinton signed an Executive Order requiring Federal agencies to purchase computer equipment, specifically personal computers, monitors and printers that met the Energy Star requirements.[31] This was reinforced by extensive promotion efforts to all government levels, the provision of tools to demonstrate cost and greenhouse gas emission savings, and integration within government procurement catalogue.
- In Japan, ICT equipment has been included in the Top Runner Programme since its introduction in 1999 (see the previous case). The ICT energy efficiency standards were incorporated into the

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[29] In 2007, the latest year for which data has been reported, average fuel efficiency for EU25 had declined to 158 g CO_2 per km (COM(2009) 9 Final).

[30] Regulation (EC) 443/2009. The target is being phased in over a three year period. Only 65% of each manufacturer's new car registrations must comply with the standard in 2012, rising to 100% from 2015 onwards. Manufacturers may form "pools" in order to jointly meet the standard.

[31] Executive Order 12845. This was replaced in 1999 by Executive Order 13123—Greening the Government Through Efficient Energy Management.

Law concerning the Promotion of Public Green Procurement (Green Procurement Law, when it came into force in 2001. There are currently 12 ICT product groups covered by both the Top Runner Programme and the Green Procurement Law.

- In Europe, policies to encourage improvement in the energy efficiency of ICT equipment have been less coherent, with a greater emphasis on voluntary approaches. The voluntary Energy Star scheme for ICT equipment was introduced in 2002 following an agreement with the USA in the previous year to co-ordinate energy labelling programmes. However, while the European Union supported the use of energy efficiency criteria in public tenders, it was not until the adoption of a revised Energy Star Regulation in January 2008 that energy efficiency criteria were made mandatory for public procurement of ICT equipment.[32]

114. The Japanese and US policy interventions were both highly successful in improving the energy efficiency of ICT equipment. Indeed, in Japan, computers were taken off the list of green procurement items in 2004 because all of the computers in the market at that time met the set energy efficiency criteria, although they have subsequently been reinstated following the introduction of new more stringent Top Runner standards. In the USA, the Executive Order was crucial in creating awareness and the public market for Energy Star products, particularly office equipment (*Siemens*, 2001). As a direct result of the Order, 95% of monitors, 85% of computers and 99% of printers sold in 1999 were Energy Star compliant (*Webber et al*, 2000). In contrast, the voluntary approach adopted in Europe was much less successful in driving improvements in the energy efficiency of ICT equipment (*Oosterhuis,* 2006).

d) Photovoltaics (PV)

115. *Ten Brink et al* (2006) compare the impacts of policy interventions to promote the diffusion of solar photovoltaics (PV) in Japan, Germany and the United Kingdom. A detailed review of the policies adopted in Japan and Germany is also provided by *Sawin* (2004).

- In Japan, the “solar roofs” programme (later to be known as the “70,000 roofs” programme) was launched in 1994 to promote PV through low-interest loans, a comprehensive education programme and rebates for grid-connected residential systems. Rebates started at 50% of installed costs and declined gradually over time. The programme was expanded substantially three years later, with its annual budget peaking at USD 219 million in 2001. In addition, many local governments provided PV subsidies and low-interest loans. Solar PV was included in the Renewable Portfolio Standard (RPS) that was introduced in 2003, which required electricity suppliers to source a given percentage of their sales from renewable sources. However, since the RPS only aims to increase the share of all renewables to 1.35% by 2010, it is not expected to have a significant impact on the diffusion of PV.
- In Germany, feed-in tariffs (guaranteed payments for power output above market rates) have been the main instrument used to encourage the diffusion of PV since 1991. The tariffs are guaranteed for 20 years and are based on the real costs of generation. In addition, the federal government has refinanced low-interest loans offered by the major banks, provided tax credits for investments in renewable energy projects and funded R&D activities.
- In the United Kingdom, the diffusion of PV has been promoted through funding of demonstration projects and the provision of installation subsidies through the Energy savings Trust. Along with other renewable electricity sources (*e.g.* wind power, etc.), PV was included under the

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[32] Regulation (EC) 106 / 2008. The Regulation requires that all EU institutions and central Member State government authorities use energy efficiency criteria no less demanding than those defined in the Energy Star programme when purchasing office equipment.

Renewables Obligation Order that was imposed on electricity generators in 2002 (similar to the RPS in Japan), and was exempted from the Climate Change Levy (a business energy tax) that was introduced in 2001.

116. The policies adopted in Japan and Germany have both been extremely successful in promoting the diffusion of PV, making these countries the world-leaders in the technology. In Germany, PV installations grew at an average annual rate of almost 47% between 1992 and 2003, while PV capacity in Japan increased by more than 43% per annum over a similar period (*Sawin*, 2004). The feed-in tariff was particularly effective as it guaranteed sustained above-market payments for the relatively costly PV technologies - *e.g.* in 2005 the guaranteed feed-in tariff for PV electricity was around six times higher than the tariff for wind-generated electricity (ten Brink et al, 2006).

117. In both countries, the rapid increase in installed capacity led to improvements in the technology and produced economies of scale that yielded dramatic cost reductions. The installed cost of residential grid-connected systems in Japan halved between 1995 and 2003, while the cost of PV systems in Germany declined by almost 40% (*Sawin*, 2004; *ten Brink et al*, 2006); although in the latter case, some of the decrease was attributable to increased competition from foreign producers rather than cost reductions resulting from innovation (*BMU*, 2003).

118. In contrast, policy support for either innovation or diffusion of PV technologies in the United Kingdom has been relatively weak, leading the *Carbon Trust* (2002) to conclude that the UK had arguably “missed the boat” in developing conventional PV systems. The Renewables Obligation Order has done little to promote PV as it does not differentiate between the technologies at different stages of development, and tends to promote those closest to the market (such as wind power). The impact of the investment subsidies provided by the Energy Savings Trust has also been relatively small. *Ten Brink et al* (2006) conclude that the UK policy approach of using the Renewables Obligation and exemptions from the Climate Change Levy, have been more expensive per unit of renewable power produced and less effective than other policy mechanisms used in other countries.

e) Substitution of hazardous chemical substances

119. *Oosterhuis* (2006b) compares the impacts of policy interventions regarding the replacement of chlorinated solvents by less hazardous alternatives in Sweden, Denmark, the US and Germany.

- In Sweden, the substitution principle was first introduced into chemicals legislation in 1973 (Löfstedt, 2003). Since 1999 it has been known as the ‘product choice principle’, forming one of the cornerstones of the Swedish Environmental Code. Under the principle, the use of trichloroethylene (“tri”) which was prohibited in 1996, although exemptions from the ban were allowed for industries where substitutes were not available.
- In Denmark, occupational health and safety legislation, enacted in 2001, requires the replacement of hazardous substances or materials by less hazardous ones, even if the effects of the hazardous substances are insignificant. However, the law provides for exemptions if substitution is technically impossible or prohibitively expensive. In addition, the Danish Environmental Protection Agency has published a ‘List of Undesirable Substances’, for which substitution is encouraged. Substitution of hazardous chemicals is also promoted by means of economic instruments, with environmental taxes being levied on pesticides, chlorinated solvents, CFCs, nickel-cadmium batteries, soft PVC and phthalates.
- In the USA, the Massachusetts Toxics Use Reduction Act (TURA), introduced in 1989, requires that manufacturing firms using specific quantities of approximately 900 industrial chemicals undertake a bi-yearly toxics use-reduction planning process. This forces firms to consider why

they use a specific chemical and how it is used in the production process, and requires them to conduct a systematic search for and comprehensive financial, technical, environmental, and occupational health and safety analysis of viable alternatives. The act also requires firms to identify ways to redesign production processes and products and provides six different methods that 'count' as toxics use reduction (Tickner *et al.,* 2005). The TURA program has designated tri as one of five high priority substances that are to receive special attention, with the aim of attaining significant reduction in use. In 2004 a project was started, targeted at smaller businesses using tri, who do not have direct access to pollution prevention information and resources (TURI, 2006).

- In Germany, the Hazardous Substances Ordinance (*Gefahrstoffverordnung*), introduced in 2004, states that employers should prevent or minimise the dangers to the health and safety of their employees caused by hazardous substances, preferably by substituting the relevant substance.[33] While the Ordinance does not require substitution, a decision not to substitute a hazardous substance must be justified. The approach differs from the other three countries in that it focuses on risk reduction through the introduction of 'closed' systems for the use of chlorinated solvents rather than seeking a reduction in the use of the hazardous substances *per se*.

120. Thus, only in Sweden and Denmark did environmental concerns provide a significant motivation for the adoption of polices to replace chlorinated solvents. In the other two countries, substitution was based primarily on occupational health and safety considerations.

121. The policies adopted in Denmark, Germany and the USA have all been effective in reducing the use of chlorinated solvents. In particular, Germany not only achieved substantial decreases in solvent use, but also became a leading exporter of high-quality closed-loop degreasing equipment (*Sterner*, 2004). There is also evidence that the environmental taxes which were levied on hazardous chemicals in Denmark were effective (*Ecological Council*, 2002); with the tax on chlorinated solvents contributing to a decrease in the use of these substances by 60% (*Sterner*, 2004). Evidence from a Danish cable producer, which replaced PVC with phthalates by halogen-free polymers in some of its products, suggests that the taxes on PVC and phthalates helped to lessen the price difference (*Ecological Council*, 2006).

122. In the USA, between 1990 and 2000 some 550 firms that continuously participated in the TURA program reduced the use of the targeted toxic chemicals by 40% (*Tickner & Geiser*, 2004, Appendix A). According to *O'Rourke & Lee* (2004), mandatory planning, new mechanisms of accountability and improved processes of learning have all been critical to TURA's success in motivating firms to innovate for the environment. Spin off programmes with the aim of widening participation, can be seen as being a testament to the successful nature of the TURA programme.

123. Compared to the other three countries, the Swedish tri ban was less effective, due largely to the number of exemptions to the ban that were granted. As a result, the specific emissions of tri per euro of value added in the metal industry in Sweden is now ninety times higher than in Germany, whereas in 1993 it was only nine times higher (*Birkenfeld et al.*, 2005). This suggests that imposing chemical substitution by means of a general ban with exemptions may lead to less environmental innovation than stimulating substitution through the use of financial incentives or regulations aimed at limiting exposure and emissions.

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[33] Article 9(1).

f) Synthesis

124. Table 6 provides a summary of the five case studies in terms of the countries covered and the types of policy instruments used. It also provides a subjective assessment of the success of the respective policy interventions in terms of inducing innovation, and indentifies the type of innovation that occurred. Where packages of policy instruments have been used, the primary instrument(s) are shown by **X** and the secondary instruments by (X).

Table 6. Summary of cases studies (a)

Case Study	Country or Area	Policy instruments used				Success in inducing innovation	Type of innovation		
		Incentive / Market-based	Command and Control	Voluntary	Information Based		End-of-Pipe	Process Integrated	Product Innovation
1	Norway	**X**	(X)			Good		X	
	Netherlands			**X**		Medium		X	
2	Europe	(X)		**X**		Medium			X
	USA		**X**			Poor			X
	Japan	(X)	**X**		(X)	Good			X
3	Europe			**X**	**X**	Poor			X
	USA	**X**			**X**	Excellent			X
	Japan	**X**	**X**		(X)	Excellent			X
4	Germany	**X**				Good			X
	Japan	**X**	(X)			Excellent			X
	UK	**X**	**X**			Poor			X
5	Sweden		**X**			Medium			X
	Denmark	**X**	**X**			Good			X
	USA		**X**			Good		X	
	Germany		**X**			Excellent		X[34]	

Key for policy instruments used: **X** Primary instrument(s) (X) Secondary instrument(s)
(a) Adapted from Table 14.2, *Ekins & Venn* (2009)

125. It is clear from Table 6 that a wide range of different environmental policy instruments has been used; either in isolation, or in combination. Market-based and command and control instruments are the most commonly used; with the former being the primary instrument in seven instances, and the latter in eight cases. For the seven instances of market-based primary instruments, two are environmental taxes (case 1, Norway; case 5, Denmark); two are green procurement requirements (case 3, Japan and USA); and three are subsidy schemes of some form (case 4). Apart from a greater use of voluntary approaches in Europe, there is little difference in the mixes of policy instruments used in Europe, Japan and the USA. However, it is not possible to draw any general conclusions about differences in policy approaches from only five case studies.

126. Both market-based and command and control instruments have been effective in inducing innovation; with the former having six "good" or "excellent" assessments; and the latter, five. In contrast, the three examples of voluntary approaches do not appear to have performed very well, receiving only "medium" or "poor" assessments. It is dangerous to draw any conclusions about the relative performance

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[34] Although there has been product innovation, a main success of the policy has been the eco-innovation of new processes and capital stock together with a reduction in the use of hazardous chemicals.

of the different market-based instruments on the basis of these case studies. However, the two green procurement schemes appear to have been particularly successful – both receiving excellent assessments.

127. A clear message to emerge from the case studies is that the stringency of the policy intervention (or alternatively the scale of support provided) is a key factor in its impact on innovation. In all three of the "poor" outcomes, either the stringency of the intervention (case 2, USA and case 3, Europe), or the scale of the support provided (case 4, UK) was simply inadequate to drive changes in the market. In contrast, all the "excellent" outcomes have been induced by strong policies; whether mandatory public procurement (case 3, Japan and USA), in Japan's case combined with increasing standards; strong market incentives combined with large R&D budgets (case 4, Japan); or stringent regulation (case 5, Germany). In respect of PV (case 3), Germany seems to have matched Japan's market incentives, but not the R&D support, which may go some way to explaining Japan's leadership in manufacturing.

128. In terms of the type of innovation that occurred, this was largely determined by the choice of case studies. In most cases, the innovation was product-related (though the changes in products may also have involved process changes). However, process integrated innovation occurred in relation to the upstream petroleum sector (case 1) and in the substitution of hazardous chemical substances (case 5). No evidence emerges from the case studies as to whether certain types of instruments are more likely to bring about certain kinds of innovation. However, the case studies do illustrate the possible contributions and combinations of 'technology-push' and 'market-pull' in inducing innovation, discussed in section 2.

129. In the ICT case study (case 3), while energy efficiency was already improving in the USA, the Executive Order signed by President Clinton in 1993 acted as a catalyst for faster change, with the government policy acting as a 'market pull' force on the technology. In the same case study, the Green Procurement Law introduced in Japan in 2001 also provided a 'market pull' force. However, in this case, it was supplemented by knowledge that the standards would be increasingly tightened through the Top Runner programme, giving an impetus to 'technology push' through R&D as companies sought to get their products into the favoured Top Runner position. Despite its later start than the USA, this is considered to be one reason why Japanese ICT companies have strong positions when it comes to environmental performance.

130. Similar forces were at work in Japan in the PV sector (case 4). Financial support was initially focused on the basic R&D stage ('technology push'), and this lasted a long time before the new technology was ready for wide deployment. More recently the 'technology push' has been supplemented by ambitious 'market pull' deployment programmes, which have enabled Japanese companies to achieve the cost reduction shown in the learning-curve graphs.

131. Finally, in the case study on the substitution of hazardous chemicals (case 5), the German ordinance on hazardous chemicals resulted in the development of new processes, such as high quality closed loop degreasing equipment. In the model outlined in section 2 (see Figure 2.1), this innovation would appear to have started at the applied R&D stage; achieving market success (and investment mobilised by 'market pull') once successful 'closed loop' processes had been developed. As a result, Germany has not only achieved substantial decreases in solvent use, but has also become a leading exporter of high-quality closed-loop degreasing equipment – a classic example of the Porter hypothesis (*Porter & Van der Linde*, 1995).

5.4 Discussion

132. The studies reviewed in the preceding three sub-sections suggest that environmental regulation in general, and market-based policy instruments such as environmental taxes, tradable permits and investment subsidies in particular, can (in theory) and do (in practice) have a positive impact on both the development

and diffusion of environmental technologies. However, the supporting empirical and case-study evidence is not universal and the effectiveness of specific instruments would appear to vary across different sectors and different types of innovation.

133. To a certain extent, such differences can be explained by the theoretical models. In particular, the impact of environmental taxes (relative to other instruments) is predicted to depend on the competitive structures of the markets in which the regulated firms operate and on the ability of innovator firms to appropriate the benefits accruing to other firms during diffusion. However, a number of other potential factors have been identified in the literature which may affect the impact of price-based policy instruments on innovation.

134. *Jaffe et al* (2002) caution that the impact of price-based policy instruments on technology diffusion may be adversely affected by a number of potential market failures, including information failures, principle-agent problems (*e.g.* landlord-tenant), capital market failures and positive adoption spillovers. In addition, while not market failures as such; uncertainty over future returns and the (associated) use of high discount rates for investment decisions can also undermine the effectiveness of price-based instruments in stimulating diffusion. However, as was noted above, the findings from the case study of the ETR in Germany suggest that an environmental tax may actually reduce the level of uncertainty over future returns provided that it is of sufficient magnitude and longevity.

135. *Skjaerseth & Christiansen* (2005) emphasize that the relationship between policy instruments (of all types) and technological change is extremely complicated. They argue that account must be taken of the political / industrial context in which policy instruments are introduced, and the nature of the environmental problem that they are intended to address. In particular, they make a distinction between "malign problems" where technological change involves net costs for target groups, and "benign problems" where there are widespread "no-regret" opportunities for change. Based on a comparative analysis of four different case studies, they conclude that mandatory policy instruments (including environmental taxes) are more effective in promoting short-term technological change when the problems are malign, but that low legitimacy (with the target group) may undermine long-term technological change. However, when problems are benign, or when long-term change requires cooperation, voluntary policy instruments are likely to be more effective.

136. *Johnstone* (2005) questions the focus of the theoretical and empirical analyses on the impact of environmental policy instruments on the rate of technological change; arguing that the direction of technological change is as important – if not more so. It is not just the quantity of innovation that is important. It is also important that innovation is socially-optimal in the sense that it minimizes the cost of attaining a particular environmental goal in the long term. Inappropriate innovation today may result in "lock-in" to a sub-optimal technological path for the future.

137. With this in mind, he identifies a number of issues that can adversely affect the direction of innovation, and that should be taken into account when selecting and designing policy instruments: technological market failures[35]; missing markets for certain environmental attributes of innovation; policy incidence; and joint production of emissions. Most studies of the innovation effects of environmental policy instruments assume that the only missing market is that for the environmental good (bad). However, in practice there may be other markets that are missing (or incomplete), which can adversely affect transmission of innovation incentives. This is particularly so in the area of waste / resource management, where instruments applied at the end of the product lifecycle may have little or no impact on product design innovation. Even if all markets are complete except for the environmental externality, the point of incidence of the policy intervention may be more important for the direction of innovation than the choice

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[35] These are the same market failures that are identified by *Jaffe et al.* (2002).

of particular policy instrument. For example, a limit or standard applied directly to the emissions of a pollutant may be more effective in promoting optimal innovation than a tax applied to a proxy input variable. Finally, when there is joint production of pollutants (*e.g.* CO_2 and air pollutants from vehicle engines), there is a danger that if policy instruments (of whatever type) are applied to one pollutant in isolation, the resultant innovation may reduce emissions of that pollutant at the expense of increases in the others.

6. Conclusions

138. Technologies are a product of the social and economic context in which they were developed and which they subsequently help to shape. Innovation involves technological change (broadly conceived) that is in some sense beneficial.

139. A distinction can be made between environmental innovation that improves environmental performance without regard to the economic impact (which may be positive or negative) and eco-innovation which improves both environmental and economic performance. Eco-innovation is thus a sub-set of environmental innovation. Eco-innovation in response to environmental policy is the outcome postulated by the Porter hypothesis (*Porter and van der Linde*, 1995).

140. A distinction can also be made between technological change that takes place, or simply responds to changes, within a given social economic context, and technological transition that interacts more deeply with and influences changes in the context, as well as being driven by them.

141. Technological change comprises a number of stages – from basic R&D through to diffusion – with "technology push" drivers being more important for the early stages and "market pull" drivers being more important for the latter stages. While policy interventions are particularly important for the early development stages, they can also play an important role in the commercialization and diffusion of technologies – although the nature of the interventions is likely to differ.

142. Technological transition is much more complex, requiring the co-evolution of scientific, technological, economic, political and cultural sub-systems. Common interests of actors and technological lock-in tend to reinforce the stability of socio-technical regimes. Consequently, innovation tends to be incremental (*i.e.* technological change), remaining compatible with if not actually reinforcing the existing regime, rather than radical (*i.e.* transition to a new regime).

143. Technological change has been sufficient to meet previous environmental challenges, such as local air and water pollution. However, it seems unlikely that it will be sufficient to meet the more fundamental challenge of substantially reducing greenhouse gas emissions in order to mitigate climate change – technological transition will be required. Furthermore, policy makers are hoping that eco-innovation will allow the challenge to be met without compromising economic growth and may even open up new economic opportunities.

144. Unfortunately, most of the available indicators and the literature on environmental policy and innovation relates to incremental technological change (rather than transition) and to environmental innovation (rather than eco-innovation).

145. Consequently, while it is possible to discuss "eco-transition" in conceptual terms – identifying the potential factors that may facilitate or inhibit it – and there is a considerable literature that analyses technological transitions *ex post*, it is difficult to provide any hard evidence regarding the extent to which it may be occurring, or the effectiveness of different polices (and instruments) in driving it.

146. Measuring eco-innovation requires the measurement of both environmental and economic performance. In each case, it is important to use an appropriate time frame, system boundary and counterfactual. In particular, innovations that are un-economic in the short term (*i.e.* impose economic costs) may provide economic benefits in the longer term as learning reduces costs. Ideally one should compare the outcomes under the innovation with those that would have occurred without the innovation. However, in practice this may not be possible and it may be necessary to compare them with the actual outcomes in a base period.

147. Necessary conditions for eco-innovation to have taken place are that environmentally beneficial technologies have been developed; that there existed firms providing environmentally beneficial products and services; and that there have been improvements in both economic and environmental performance. Consequently, three important indicators for eco-innovation are:

- the growth in eco-industries (relative to other industries)
- increase in the number of environmentally related patents (relative to other patents)
- strong (or absolute) decoupling between economic growth and environmental degradation

148. The evidence presented in this paper suggests that, while eco-innovation may have occurred in particular areas/countries, it cannot be concluded that it is general or widespread. Eco-industries account for only small proportion of economic activity and have grown more slowly than GDP in most countries. Notable exceptions are Finland, Denmark, and the Netherlands. While the number of environmental patents has increased, it has grown more slowly than other types of patents – with the possible exception of air pollution technologies in Germany and Japan. Finally, while strong decoupling between environmental impacts and economic activity has been observed in relation to ozone layer depletion and air quality, it has not yet occurred for the pervasive environmental impacts, such as climate change or biodiversity loss, of most concern. The economic implications of achieving this strong decoupling are unclear.

149. There is a growing body of evidence that environmental regulation in general, and market-based policy instruments such as environmental taxes, tradable permits and investment subsidies in particular, can (in theory) and do (in practice) have a positive impact on both the development and diffusion of environmental technologies.

150. At the macro-level, there is evidence that the overall stringency of environmental policies – as measured by aggregate pollution and control expenditure – has a positive impact on the development of new environmental technologies. This is backed up at the micro-level by case studies which demonstrate that the stringency of a specific policy intervention (or the scale of the support provided for new technologies) was a key factor in driving innovation.

151. Price-based policy instruments (such as environmental taxes and R&D / investment subsidies) and auctioned permits appear to be particularly effective in stimulating innovation. However, there is some variation in the effectiveness of these instruments between industries, technology areas and type (*i.e.* end-of-pipe versus process-integrated) stimulated. In some cases, regulation can be more effective. Interestingly, the theoretical studies suggest that freely allocated (*e.g.* grandfathered) permits are one of the least effective instruments when it comes to stimulating innovation. There is a general lack of evidence in relation to the policy effects on the *direction* of innovation, rather than just the rate, although this is likely to be just as important for improving environmental outcomes.

152. Consequently, while it would appear that environmental taxes can be effective in stimulating both technology development and diffusion in many cases – at least in terms of the rate of technological change, there may be situations in which other policy instruments may be more appropriate. In general, the

stringency and point of incidence of an environmental policy intervention may be more important than the choice of a particular policy instrument in determining both the rate and direction of innovation.

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