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Environmental innovation and industrial dynamics: the contributions of evolutionary economics

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The general purpose of the DIME Working Package on Environmental Innovations is to extend theoretical and empirical knowledge on environmental innovations and on their impact upon industrial dynamics and competitiveness. The research focus is on the characteristics, determinants and indicators of environmental innovations, as well as on the role of environmental policy instruments. These issues also challenge the existing analytical frameworks that dominate environmental economics literature.

Environmental innovation and industrial dynamics: the contributions of evolutionary economics

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Abstract

The purpose of this article is to discuss the contributions of the evolutionary theory of innovation on the micro and meso dynamics of environmental innovations. We argue that the evolutionary literature on innovation, and more particularly on technological regimes, provides a relevant framework in order to analyse the various determinants of environmental innovations and the double externality problem in an industrial dynamics context. The article starts with an overview of the empirical literature on environmental innovations with a focus on their determinants and specificities. In section 3, we discuss the contributions of the evolutionary literature on technological regimes and argue that it can provide a relevant framework for a sectoral approach of environmental innovations. In section 4, we concentrate on the role of demand side dynamics and highlight the implications of technological competition models on the role of demand conditions in the diffusion of environmental technologies. Finally, section 5 is devoted to the implications of the evolutionary theory of innovation on the question of the transition towards more sustainable technological systems.

Keywords

Environmental innovations, industrial dynamics, evolutionary theory, technological regimes

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Environmental innovation and industrial dynamics: the contributions of evolutionary economics

Vanessa OLTRA

1 Introduction

In spite of the increasing concern on the role of technological change and innovation as factors of environmental sustainability, environmental economics has paid little attention to the understanding of environmental innovation. Until recently, scholars working in environmental economics consider environmental innovation as induced by regulation. Within this perspective, one of the main research questions is the incentive effect upon innovation of different environmental policy instruments. This question is often tackled in quantitative terms searching to evaluate which policy instrument creates the highest incentive to innovate. In the literature, the focus is more on the design and the implementation of various policy instruments, than on the explanation of the innovation process itself. In such a policy oriented approach, an explicit and thorough representation of the innovation process is often missing, which creates a strong bias in the analysis of policy effects. As a matter of fact, environmental innovations cannot be reduced to a systematic response to environmental regulation, but should be considered as the result of a complex and interactive process. As shown in the empirical literature on the determinants of environmental innovations, the innovative strategies of firms are driven by a set of determinants and objectives. With the development and the adoption of environmental innovations, firms try to combine their objectives of productive efficiency and product quality with environmental performances. As a consequence, we argue that the literature on environmental innovations should focus more on the complex interactions between their various determinants and on the relationship between competitiveness and environmental performances of firms. By providing a theoretical framework dedicated to the analysis of technological change and industrial dynamics, evolutionary economics can provide relevant contributions for a better understanding of the process of environmental innovation within an industrial dynamics perspective.

The purpose of this article is to discuss these contributions. The article starts with an overview of the empirical literature on environmental innovations with a focus on their determinants and specificities. In section 3, we discuss the contributions of the evolutionary literature on technological regimes and argue that it can provide a relevant framework for a sectoral approach of environmental innovations. In section 4, we concentrate on the role of demand side dynamics and highlight the implications of technological competition models on the role of demand conditions in the diffusion of environmental technologies. Finally, section 5 is devoted to the implications of the evolutionary theory of innovation on the question of the transition towards more sustainable technological systems.

2 Literature review on environmental innovations

In the existing literature, we can find different terms - i.e. eco-innovations, environmental innovations, eco-technologies - and definitions of environmental innovations. But whatever the term, environmental innovations are generally distinguished from innovation in general and so studied separately. Why such a distinction? Is it just because environmental innovations have initially been studied by researchers coming from the field of environmental economics? Or is it motivated by a real specificity of environmental innovations which calls for specific concepts and analytical tools? The answer to these questions requires a clarification of the definition of environmental innovations, as well as a thorough analysis of their properties and determinants.

2.1 Definition

In a very broad sense, environmental innovations can be defined as innovations that consist of new or modified processes, practices, systems and products which benefit the environment and contribute to environmental sustainability (Rennings, 2000). Obviously, the positive environmental impact of innovation is the core element of the definition. But this environmental impact may be intentional or not, local or global, and more or less significant compared to current or conventional technologies. Empirical studies on environmental innovation generally focus on intentional, or environmentally motivated, innovations since they generally concentrate on a selected and well-defined sample of environmental technologies which are *ex ante* labelled “environmental”. For example, the intentional character of the environmental impact is straightforward when studying what is called the 'eco-industry'[2], in which environmental innovation is the core business. But when we want to

[2] i.e. The industry engaged in "the production of goods and services to measure, prevent, limit, minimise or correct environmental damage to water, air and soil, as well as problems related to waste, noise and

study more generally how environmental constraints and objectives are integrated within the innovative strategy of industrial firms, we should opt for a broader definition including all the innovations that have a positive environmental impact, this latter being intentional or not, direct or indirect. The positive environmental effect might be a side effect of an innovation initially not driven by an environmental purpose. Empirically, unintentional environmental innovations are very difficult to identify and thus to evaluate, since the environmental gains of 'normal innovations' have never been the object of systematic study.

What is at stake here is the very concept of environmental innovation and the frontiers of its definition. As a matter of fact, while being the distinguishing feature of environmental innovations, the environmental impact is difficult to assess. Many criteria may be used to evaluate the environmental impact of an innovation: greenhouse gases emissions, air pollution, energy use, water pollution, noise, waste generation and soil contamination. Given the number of environmental criteria, the global environmental impact of an innovation is very difficult to assess. Generally speaking, the use of an environmental innovation may or may not lead to an absolute reduction in environmental harm. In particular, it depends on rebound effects, the classical example being cost-saving innovations that have a rebound effect through increased expenditure. So environmental innovations cannot be defined in terms of absolute environmental impact, but in reference to alternative technologies[3].

These considerations lead to the following definition of an environmental innovation:

"The production, assimilation or exploitation of a product, production process, service or management or business methods that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives" (MEI Report, 2008)[4].

With such a definition, environmental innovations correspond to a very heterogeneous set of innovations, since every process or product that is more resource efficient and/or less polluting is an environmental innovation. Moreover, the degree of novelty is considered at its minimum level, which is at the firm level. Consequently, this definition embraces all the

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ecosystems… (including) cleaner technologies, products and services which reduce environmental risk and minimize pollution and resource use." (OECD, Eurostat, 1999).

[3] This criterion is the one used in the European Environmental Technologies Action Plan (ETAP) (http://ec.europa.eu/environment/etap/index_en.htm).

[4] In MEI Report (2008) this definition is given for an "eco-innovation" which is synonymous with environmental innovation.

innovations which enable a firm to decrease, progressively or drastically, its negative environmental impacts through new products, processes, services or methods.

Like innovation in general, environmental innovations may be classified into three types: product innovations (for example, solvent-free paints), process innovations and organisational innovations (for example, environmental management systems). What is specific to environmental innovations is the distinction, within process innovations, between end-of-pipe technologies and cleaner production technologies (or "integrated technologies"). In the first case, the solution to the pollution problem consists in treating the pollution by the way of several technical apparatus which take effect at the end of the production process ("additive" technology). In that case, the production process is not modified and polluting emissions are treated at the very end of the process. Basic examples are filters, dust removal techniques or desulphurization equipment. As to cleaner production technologies, they result from environmental innovations which imply a reduction of the pollution *at source* thanks to an integrated change in the production process, for example through input substitution or the use of an alternative production process. Cleaner production technologies are frequently more advantageous than end-of-pipe technologies for both environmental and economic reasons, particularly in a long run perspective. Part of the literature on environmental innovations focuses on the choice between end-of-pipe and cleaner production technologies, showing that environmental regulations tend to encourage the use of end-of-pipe technologies, which are still dominant in many OECD countries, and that a shift to cleaner production technologies would be environmentally and economically beneficial (Frondel and al., 2007).

2.2 Determinants and specificities of environmental innovations

Traditionally, the empirical literature on the determinants of environmental innovations focuses on the role of regulation. Since the 1990s, several empirical studies try to identify other determinants at the demand or supply side. These research works are very heterogeneous in terms of methodologies and results, since one of the main difficulties is to find adequate data and indicators on environmental innovations[5]. Table 1 in appendix summarizes the findings of the main references on the determinants of environmental innovations. Even if there are still some controversies on the effective impact of environmental regulation on innovation and on the most efficient policy instruments in terms of incentives, many references emphasize a positive correlation between environmental

[5] For a survey on the measuring of environmental innovations, see for example Arundel and al. (2007).

innovation and regulation. These results tend to bring empirical support to the so-called Porter hypothesis according to which "…properly designed environmental standards can trigger innovation that may partially or more than offset the costs of complying with them" (Porter and Van der Linde, 1995). Some recent empirical studies put the emphasis on policy stringency, and more precisely on the perception of stringency by regulated firms (cf. OECD survey in Frondel and al., 2007), as a key determinant of the innovative response of firms. Many authors argue that regulatory design is a key factor that may influence firms' innovative response, in particular when considering its stringency, flexibility and limiting uncertainty. Ashford and al. (1985) argue that, while stringency is the most important factor for eliciting an innovative response, flexibility towards the means of compliance, variation in the requirements imposed on different sectors and compliance time periods contribute to stimulate alternative technologies. Thus the effects of regulation depend on the type of regulatory instruments and on the way it is implemented.

In spite of the incentive role of regulation, environmental innovations cannot be considered to be a systematic response to regulation. Other factors linked to market conditions and to the technological capabilities of firms determine the technological response of regulated firms (cf. table 1). Several empirical studies stress that cost savings and productivity improvements are determining factors of environmental innovations, particularly for process environmental innovations and clean technologies. As emphasized by Frondel and al. (2007), innovation in clean technology tends to be driven both by cost savings, in terms of energy and material savings, and by regulation. Other empirical studies, in particular Mazzanti and Zoboli (2006), Rehfeld and al. (2007) and Wagner (2007), show that organizational innovations tend to be strongly correlated to environmental product and process innovations. The implementation level of environmental management systems seems to have a positive impact on environmental innovations. Finally, very few empirical studies consider the role of "traditional" supply side determinants of innovations, like R&D activities, supply chain pressures or networking activities. Scott (2003) presents an econometrical analysis of environmental R&D based on an original survey on the industrial R&D response of US manufacturing firms to the regulation of the emission of hazardous air pollutants. The author shows that on average 24 % of the industrial R&D performed by firms is related to improving the environmental performance of their products or processes, with a highest share linked to cleaner products. In summary, it appears that the supply side determinants of environmental innovation are very similar to the determinants of innovation in general.

As to demand side determinants, it is generally assumed that market forces alone would provide insufficient innovation incentives and that consumers' willingness to pay for environmental improvements tends be too low (Rennings, 2000). Nevertheless, several empirical studies try to identify and to evaluate the incentive effects linked to environmental pressure coming from consumers. According to Florida (1996), Popp and al. (2007) and Horbach (2008), customer demands and public pressure are essential driver of environmental innovations. But even if the ecological concerns of consumers and the expected increase in future demand for environmental products are assumed to trigger environmental innovations, it remains very difficult to evaluate how do consumers really valorise and take into account the environmental characteristics of products. In comparison with non-environmental innovations, demand pull effects are strongly provoked or supported by environmental policies, such as regulations or taxes, that seek to affect the intrinsic and external (through incentive schemes) motivations of consumers. But as emphasized by Taylor and al. (2006), demand pull instruments shape more the adoption and the diffusion of environmental technologies, than the innovative activity itself.

This overview of the literature shows that environmental innovations are driven, as innovation in general, by a set of determinants which respective influence is difficult to evaluate (cf. table 1). In spite of the controversies, we can argue that the main specificity of environmental innovations, besides their positive impact upon environment, is linked to the determining role of regulation. This specificity is related to what is called the “double externality” problem. Environmental innovations produce two types of positive externalities: usual knowledge externalities in the research and innovation phases, and externalities in the adoption and diffusion phases due to the positive impact upon environment. In other words, the beneficial environmental impact of environmental innovations makes their diffusion always socially desirable. This creates a twofold obstacle, or market failure, for firms to invest in environmental innovation since the private return on R&D in environmental technology is less than its social return. As a consequence, the double externality problem tends to cause a lack of private incentives leading firms to under-invest in environmental R&D and innovation. This double source of market failure justifies the needs of policy instruments and the existence of what Rennings (2000) calls the "regulatory push-pull" effect.

Regulation and policy determinants	Implementation of environmental policy instruments: economic and regulatory instruments Existence and anticipation of environmental regulations Regulatory design: stringency, flexibility, time frame
Supply side determinants	Cost savings, productivity improvements Organizational innovations: environmental management systems, extended producer responsibility R&D activities Industrial relationships, supply chain pressure, networking activities
Demand side determinants	Environmental consciousness and consumers' preferences for environmentally friendly products Expected increase in market share or penetration of new market segments

Table 1 Determinants of environmental innovation

The existence of this "regulatory push-pull" effect should not lead to consider environmental innovations as systematically induced by regulation, and so to under-estimate the role of supply and demand-side determinants. As shown in the literature, the environmental objective is generally not the direct and only purpose of environmental innovations, but comes in addition to other objectives. In that sense, an environmental innovation should not be considered as a completely different and specific innovation, but as the result of a search for technological compromises between various determinants and objectives. As emphasized by Florida (1996), the relationship between industrial and environmental performances can take the form of a trade-off, but the simultaneous achievement of both objectives is also possible. The capacity of firms to develop and to adopt environmental innovations depends on their ability to combine productive efficiency and product quality with environmental objectives[6] (Oltra and Saint Jean, 2005a, 2005b). As a consequence, we argue that the analysis of environmental innovations should focus more on the complex interactions between their various determinants and on the relationships between competitiveness and environmental performances of firms.

3 Towards a sectoral and dynamic approach of environmental innovations

Even if the recent empirical literature emphasizes that environmental innovations are driven by a set of various determinants, it is striking to observe that this literature does not make any room for sectoral determinants. It is implicitly assumed that the effects of regulation, and of

[6] This capacity to combine multiple objectives is the necessary condition to achieve "innovation offsets" in the sense of Porter and Van der Linde (1995).

the other supply and demand side determinants, can be generalized to all the industrial sectors. However one of the most important contributions of the evolutionary analysis of innovation is to show that there are significant inter-industry differences in the properties of innovative processes and in the nature of the knowledge bases and learning processes that underlie these processes.

3.1 The evolutionary literature on technological regimes

The literature on technological regimes provides a useful framework for an empirical analysis of the microeconomic dynamics of innovation. The concept of technological regime, initially developed by Nelson and Winter (1982), corresponds to a description of the technological environment in which industrial firms operate. It identifies the properties of learning processes, sources of knowledge and nature of knowledge bases that are associated with the innovation processes of firms active in distinct sets of production activities (Dosi, 1982). In the Schumpeterian tradition, two types of technological regime are generally distinguished[7]: the *"entrepreneurial regime"*, which is characterized by an innovative base continuously enlarging through the entry of new innovators and the erosion of the competitive and technological advantages of the established firms in the industry, and the *"routinised regime"* based on the dominance of a few established firms which are continuously innovative through the accumulation over time of technological capabilities. This distinction primarily concerns the relative role of innovative entrants and established firms in the innovation process. Malerba and Orsenigo (1996, 1997) show that these Schumpeterian patterns of innovation are linked to the characteristics of technological regimes. They define a technological regime as the combination of four factors: knowledge base, technological opportunities, appropriability conditions and cumulativeness of innovation. Using patent data, they show that "routinised regimes" are characterized by high appropriability and cumulativeness conditions, which allow innovators to accumulate technological knowledge and to build up innovative advantages over potential entrants. On the contrary, "entrepreneurial regimes" tend to be characterized by low appropriablity and cumulativeness conditions, which enable new innovative firms to enter the industry and lead to a turbulent market structure. These results suggest that "technological imperatives" play a major role in determining the patterns of innovative activities.

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[7] This distinction has been introduced by Winter (1984).

In comparison to Malerba and Orsenigo (1996, 1997), Marsili (2002) puts more emphasis on the role of technological barriers to entry and intra-sectoral technological diversity. Technological barriers to entry in an industry define the competitive advantage that any established firm can gain as outcome of innovation with respect to its potential competitors from outside the industry. The main sources of entry barriers that can be identified in relation to the properties of learning processes and the nature of the knowledge base are the specificity of knowledge to industrial applications (Winter, 1987), the existence of advantages related to production scales, the cumulative nature of learning and the requirements of in-house technical competencies and complementary assets in innovation processes (Teece, 1986). As to technological diversity, it reflects the number of possible 'technological trajectories' along which the normal process of technological learning takes place and the idiosyncratic ability of any firm to exploit a selected trajectory (Marsili, 2001). A technological regime constrains the set of trajectories that a firm may explore (Dosi, 1982), as well as the range of available strategies, competencies and forms of organization of innovation processes in a firm (Malerba and Orsenigo, 1993).

Marsili (2001, 2002) develops a new typology of technological regimes and emphasizes three main conclusions on innovative entry:

- The complexity of the knowledge base, which is produced internally and externally to a firm, and the diversity of technological trajectories coexisting within a regime influence the overall level of technological entry barriers in a sector, and therefore the dynamic pattern of industrial competition.
- Increasing technological opportunity conditions are not necessarily associated with an advantage of new firms, but may enhance innovative advantage of established firms. The extent to which technology creates opportunities for new entrants depends on the nature of the underlying knowledge base.
- Innovative entry may be favoured in an industry in which the prevailing technological regime entails a variety of possible search trajectories and innovative behaviours. A similar argument is made by Sutton (1998) who shows that the co-existence of diverse technological trajectories, associated with differentiated products in an industry, increases the profitability of potential innovative entry and thus reduces market concentration.

In summary, the evolutionary literature on technological regimes provides a range of theoretical and empirical models addressing the interplay between the properties of technological regimes, the sectoral patterns of innovation and the evolution of market structure. The contribution of this literature to the analysis of environmental innovations is twofold:

- It highlights the relevance of sectoral approaches of innovation and the importance of taking into account the industry specific context.
- It identifies the main properties of technological environment which may impact innovative activities of firms, thus providing a set of factors which have to be taken into account when analysing environmental innovations and the effects of policy instruments.

3.2. Technological regimes, environmental innovations and industrial dynamics

Research works on environmental innovations are rarely conducted at a sectoral level and the question of the relevant level of analysis is not discussed. Horbach (2008) emphasizes that there are significant sectoral differences in terms of propensity to realize innovations with environmental effects. He argues that firms belonging to sectors with high average sales of new products are more likely to innovate be it environmental or other innovations. Within the same line of inquiry, Mazzanti and Zoboli (2006) show that sector effects on innovation prevail over size effects on both input and output sides of the innovation process. They identify environmentally critical sectors like chemicals, ceramic and paper, which are more involved in innovative dynamics than others. They also emphasize that the types of environmental innovation (emission reduction, waste management, energy related…) differ according to sectors. These results illustrate that sectors' involvement in environmental innovations is linked to their propensity to innovate in general, but also to their relationship with environment (type of productive activities, level and nature of polluting emissions, regulatory framework…). A better understanding of these sectoral specificities could help to identify the factors affecting environmental innovations and so to go deeper in the analysis of the innovative effects of policy instruments.

- The role of technological regimes

The literature on technological regimes can be used to investigate how the properties of the research and learning environment affect the sectoral patterns of environmental innovations. It provides a framework that might be useful to study sectoral patterns of environmental innovation and to grasp inter sectoral differences. Following the literature on technological regimes, we argue that five "technological determinants" should be taken into account in the analysis of sectoral patterns of environmental innovation:

- **Technological opportunities linked to environment**: Like all innovations, environmental innovations are basically determined by the technological opportunities linked to environment, and more specifically linked to regulation. In several industrial sectors, environmental regulation opens new directions of research, for example in order to substitute polluting inputs, to find new materials and to develop new cleaner production processes, thus creating new technological opportunities for firms. Accordingly the sectoral patterns of environmental innovation, and particularly the type and the sources of innovation, are strongly determined by these opportunity conditions, i.e. the level and the nature of the technological opportunities linked to environment.
- **Knowledge bases**: The evolutionary literature on technological regimes and innovation emphasizes that the properties of the knowledge base, in particular the specific and complex character of knowledge, but also the sources (external / internal) of knowledge, strongly shape the innovative dynamics and the technological trajectories followed by firms. Consequently, the analysis of environmental innovations should take into account the properties of the knowledge bases underlying the technological opportunities linked to environment. In particular, we should consider to what extent the environmental objectives linked to regulation do call into question the existing knowledge base of firms. Does the compliance with regulation imply a technological breakthrough and the development of new knowledge bases? And if yes, what type of knowledge (specific/generic, applied/fundamental, complex/simple…) should be developed? A focus on the properties of the knowledge bases underlying environmental innovations can certainly be enlightening on the patterns of innovation and on the impediments to environmental innovation.
- **Appropriability conditions**: The appropriability of innovation defines the competitive advantage that an innovator can acquire with respect to its competitors. The question of the modes and the levels of appropriation of environmental innovations should be explored further. Are environmental innovations patented? If yes, what is the impact of patents on innovative patterns and on the diffusion of environmental technologies?
- **Cumulativeness of innovation**: In his econometrical study, Horbach (2008) emphasizes that the accumulation of technological capabilities is an important determinant of environmental innovations. Cumulativeness of research and innovative activities tends to create path-dependency and "innovation breeds innovation" effects. These effects strongly determine the sources of environmental innovation, in particular in the sectors

corresponding to 'routinised technological regimes' which innovation dynamics is driven by large established firms.

- **Technological barriers to entry**: As emphasized by Marsili (2001), technological barriers to entry strongly influence the industrial dynamics of sectors. In the field of environmental innovations, the question of the sources of innovation, in terms of established *versus* new firms, is rarely investigated. Do environmental technologies create opportunities for new firms? It is certainly the case in eco-industries in which new market segments may develop with small specialized firms. But in some traditional industrial sectors, environmental innovations are mainly developed by large established firms or their suppliers which certainly have an impact upon the type of environmental innovations and the technological trajectories followed by firms.

-*'Environmental regimes'*

In order to apprehend sectoral patterns of environmental innovation, one should also take into account the environmental characteristics of industries. Environmental innovations depend on environmental constraints and regulations, and more generally on the relationships of the considered industry with environment. Even if all industries have to cope with the same global environmental challenges, particularly climate change, they are subject to specific constraints and regulations according to their productive activities and their energy and pollution intensity. Several indicators can be used to characterize the 'environmental context or regime' of an industry. The traditional indicators, notably used to distinguish between dirty and clean industries (Mani and Wheeler, 1998), are emission intensity[8] (in air, water, waste and soil pollution), energy intensity (in general and per type of energy sources) and pollution abatement expenditure. These indicators enable to evaluate the polluting character of an industry as well as the level of investment to protect the environment. Obviously the 'environmental regime' of an industry is also characterized by the policy context, i.e. the type of instruments, the number and the stringency of regulations the industry is subject to.

Globally the 'environmental regime' of a sector may be described by the combination of these four factors which jointly frame the technological opportunities and the environmental innovation strategy of firms. According to the properties of the 'environmental regime', industrial firms may have more or less regulatory incentives and profit opportunities linked to environmental innovations. Basically what we call the 'environmental regime' captures the

[8] i.e. level of polluting emissions per unit of output.

level and the sources of environmental pressure in a given industry. Finally, the basic idea is that 'technological and environmental regimes' jointly mould sectoral patterns of environmental innovation. Nevertheless, this does not imply that all the firms of a given industrial sector systematically follow the same research trajectory and innovative strategy. The concepts of technological and environmental regimes are not incompatible with intrasectoral diversity. According to their accumulated knowledge and competencies and to their perception of opportunities, firms may follow different technological trajectories within the same industry. But the characterization of environmental and technological regimes enables to identify common properties of environmental innovation processes within sectors and to interpret asymmetries across sectors. Moreover it provides a framework to explore in a more comprehensive and dynamic way how technological imperatives combine with environmental factors.

Technological regimes	Environmental regimes	Patterns of environmental innovation
Technological opportunities related to environment	Pollution intensity	Innovation intensity
Knowledge bases	Energy intensity	Type of innovation (product/process, end of pipe /clean technology)
Appropriability conditions	Environmental policy context	Sources of innovation (new entrants/established firms, suppliers, public laboratories)
Cumulativeness of innovation	Pollution abatement expenditure	
Technological barriers to entry		
⇒ *characteristics of the technological environment of the considered industry*	⇒ *relationships of the considered industry with environment (level and sources of environmental pressures)*	⇒ *properties of the sectoral patterns of environmental innovation*

Table 2: A sectoral approach of environmental innovations: main concepts and variables

4. Technological competition and demand-side dynamics

In this section, a review of the recent literature on evolutionary modelling of technological competition and demand side dynamics is presented in order to emphasize the main results that can be applied to environmental innovations.

4.1 The literature on technological disruption and succession

One of the most influential expression of the role of demand in technology competition has been Christensen (1997) examination of *disruptive technologies*. Disruptive technologies are new technologies that introduce a different performance package from mainstream technologies and are inferior to mainstream technologies along the dimensions of performance that are the most important to mainstream consumers. Technology disruption occurs when, despite its inferior performance on focal attributes, the new technology displaces the mainstream technology from the mainstream market (Adner, 2002). Christensen introduces the idea of 'performance oversupply' to explain that mainstream consumers adopt the disruptive technology in spite of the superiority of the incumbent technology. The principles of performance oversupply states that once consumers' requirements for a specific functional attribute are met, evaluation shifts to place greater emphasis on attributes that were initially considered secondary. Adner (2002) develops further this demand-based view by formally modelling the role of the demand environment in shaping competitive dynamics. The author shows that the essential aspect of technology disruption is consumers' decreasing marginal utility from performance improvements beyond their requirements, which translates into a decreasing willingness to pay for improvements. This argument complements the notion of performance oversupply, by suggesting that technology disruption is likely to occur when consumers are willing to accept a worse price/performance ratio because the absolute price of the new option is sufficiently low. So the price at which the new technology or product is offered becomes critical to a disruptive outcome. Adner (2002) also shows that the structure of consumers' preferences shapes the competitive dynamics and in particular the degree of preference asymmetry among market segments which determines firms' differential incentives to compete for new segments.

The various contributions on technology competition depart one with each other regarding their respective assumptions on the characteristics of the competing technologies. Do the competing technologies offer exactly the same characteristics in the sense of Lancaster (1971)? And so do they compete on the same market segment? Is the new technology inferior or superior to the old one? These elements strongly determine the outcome of the competitive dynamics. Windrum and Birchenhall (2005) use the distinction between two cases of displacement of an established technology by a new one: technological substitution and technological succession. In the latter case, the new technology offers one or more new service characteristics[9] that were previously unavailable using the old technology. The authors identify a set of potential conditions for a technological succession to occur. Using a simulation model, they show that successions are more likely to occur when the gain in direct utility of consumers from the new technology is high. The results emphasize that the initial

[9] For a presentation of the concepts of technical and service characteristics of technology and product, see for example Frenken and al. (1999).

quality differential between the new and the old technology designs is an important determinant of successions. Windrum and Birchenhall also identify a strong "sailing ship effect" in the sense that the entrance of new firms competing with a new technology stimulates old technology firms to innovate in order to improve the quality of their products[10]. Consequently, the probability of a succession depends on the relative rates at which new and old technology firms successfully innovate.

4.2 Technological competition and environmental technology diffusion

In many cases, the adoption and the diffusion of environmental technologies[11] can be viewed as a typical case of technological competition between an established technology, or a dominant design, and an alternative (or a set of alternative) environmental technology(ies). The findings of the literature on technological competition can be used to draw some lessons on the most favourable demand conditions for the adoption and diffusion of environmental technology.

As emphasized by Adner (2002) and by Windrum and Birchenhall (2005), the price and the utility associated to the new technology (or product) are critical to determine the outcome of the competitive dynamics. These arguments are particularly relevant in the case of environmental technology for which the price-performance ratio is often critical. We can consider an environmental technology to be a new technology introducing new or improved service and technical characteristics (or attributes) in terms of environmental performances. But the competitiveness of the technology is not merely determined by its environmental performances, but by the whole performance package characterizing it. As shown in the literature, the outcome of the competitive dynamics depends on the global performances (environmental and non-environmental) of the new technology and, more particularly, on the performance criteria or 'focal attributes' that are the most important to what Christensen (1997) calls "mainstream consumers": the more efficient the new environmental technology on the mainstream characteristics, the more likely its diffusion. Consequently, the crucial element of the competitive dynamics is the correspondence between the global performance

[10] Significant improvements are often induced in technologies under competitive threat from the new technology, so that the diffusion curve is shaped by the evolving pattern of competitive advantage between rival technologies – a phenomenon which is called "sailing ship effect" (Graham, 1956).

[11] Here the term 'environmental technology' encompasses process and product innovations. For a definition, see § 2.1.

of the new environmental technology and the distribution of consumers' preferences on the whole set of product characteristics (or attributes). Within this perspective, the question of tradeoffs and synergies between the various characteristics or performance criteria of environmental technologies (or products) appears as a central element of the competitive dynamics.

Very often, environmental performances are improved at the expense of other product characteristics. In that case, there is a tradeoff between the environmental performances and the quality or the functional attributes of products. Here the literature on technology competition can be of interest to identify the conditions which may be conducive to a technology disruption or succession. As emphasized by Windrum and Birchenhall (2005), the initial quality differential between both competing technologies (or products) and the direct utility of consumers linked to the new technology are important determinants of successions. The literature on technology disruption highlights that a shift in consumers' preferences is necessary for the diffusion of the disruptive technology to occur. Such a shift in preferences implies that consumers place greater emphasis on environmental attributes that were initially not considered or as secondary ('performance oversupply'). In summary, it means that when a new environmental technology exhibits inferior performances along the attributes that are the most important to mainstream consumers, a change in preferences is a necessary condition for the diffusion of the considered technology. This argument may help to understand why the diffusion of certain environmental technologies (or policies promoting them) fail or succeed.

In this respect, the role of environmental preferences of consumers, and of what some authors call "green consumers"[12], is essential. But even if the ecological concerns of consumers and the expected increase in future demand for environmental products is assumed to trigger environmental product innovations, a formal analysis of the structure of preferences and of purchase criteria is still lacking. A critical issue remains how do consumers valorise and take into account the environmental characteristics of products. Here a particularly relevant preference is the preference to consume in an environmentally friendly manner. Frey (1999) characterizes this consumption behaviour as intrinsically motivated behaviour as oppose to externally motivated behaviour. But the evolution of consumers' preferences also raises the question of the perception and the assessment of the environmental characteristics of products. Consumers have to cope with the typical problem of experience goods since they cannot know *ex ante* the environmental characteristics of goods. To be able to valorise the

[12] See for example Gladwin (1993), Drumwright (1994) and Conolly and al. (2006).

environmental characteristics of products and so to set up some environmental preferences, consumers need some information and specific knowledge on the environmental properties of goods. It is the reason why policy instruments such as information provision and eco-labels are necessary to inform consumers efficiently and to stimulate the diffusion of environmental products[13]. More generally, the understanding of the social dynamics underlying preference change can bring important contributions on the demand-side dynamics of environmental technologies[14].

Finally, the literature on technological competition also insists on the determining role of the relative price of each competing technology. A technology disruption can occur only if the absolute price of the new technology is sufficiently low to compensate its worse price-performance ratio (Adner, 2002). Very often this condition is not fulfilled since many environmental technologies are characterized by a price premium. In that case, the willingness to pay of consumers become critical and the price associated to the environmental technology may impede its diffusion. In these conditions, the diffusion of the technology may be restricted to small niche markets characterized by what Malerba and al. (2007) call "experimental users". To avoid the diffusion of environmental technology being doomed to isolated experiments remains one of the main challenges that need to be addressed by public policy supporting technological transitions.

5. Technological transitions

Technological transitions have become a central focus of environmental policy aiming at radical changes to improve the sustainability of major technological systems. A technological transition is generally understood as the substitution of a large complex technological system by a new "more sustainable" system. For example, the transition to the internal combustion engine car system to a future fuel-cell car system or, more globally, to a new sustainable transport system. Technological transitions are characterized by the systemic nature of the changes involved, the large number of heterogeneous agents and institutions, as well as by the large scale of change and the long term horizon. In the multi-level perspective developed by Geels (2002), transitions are considered as the result of the interactions between three levels:

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[13] For an evolutionary modelling of the effects of eco-labels, see for example Bleda and Valente (2008).

[14] See for example Janssen and Jager (2002).

the sociotechnical regime, technological niches and the sosiotechnical landscapes[15]. In this section, we focus on the contributions of evolutionary theory to the analysis of technological transitions at micro and meso-economic levels. The objective is to discuss how the evolutionary literature on innovation can contribute to the analysis of the processes of innovation, selection and competition which underlie technological transitions towards more sustainable systems.

In an evolutionary framework, technological transitions can be viewed either as a change in technological paradigms or as a change in dominant designs. Both concepts, which have close connections[16], might relevant to emphasize the necessary conditions and the difficulties to "un-lock" technological systems.

- *Technological transitions in terms of paradigmatic changes*

The concept of technological paradigm developed by Dosi (1982) has been highly influential in the field of economics of technological change. A technological paradigm is defined by Dosi (1982) as a 'model' and 'pattern' of solution of selected technological problems based on selected principles derived from natural sciences and on selected material technologies. For example, diverse paradigms, with their distinct knowledge bases and trajectories of advance, tend to be associated with distinct energy sources and mode of generation of heat, electricity and motion. Thus the generation of electricity through fossil fuel and through nuclear fusion are associated with two distinct technological paradigms. Similarly in transportation, the internal combustion engine is the current dominant paradigm of automobile design and production. Many scholars emphasize that it is hard to see how on the grounds of current technological paradigms, one could reach zero net emissions of carbon dioxide or a decrease in emissions sufficient to reverse the current greenhouse effect (Dosi and Grazzi, 2006). A technological transition towards new sustainable energy and transportation systems are likely to come only with the development of new technological paradigms. In his seminal work, Dosi (1982) emphasizes that some discontinuities in technological innovation are necessary to the emergence of a new paradigm and that market selection is not the primary determinant of paradigmatic changes. Market prices and other forms of 'inducement' are

[15] Within this framework, the socio-technical landscape is an extended version of the concept of technological regime.

[16] For a discussion on the link between scientific paradigms and dominant designs, see for example Murmann and Frenken (2006).

indeed able to tune up or to slow down the rates of technological change, but this happens within the relatively narrow boundaries set by the nature of the incumbent paradigm (Dosi and Grazzi, 2006). As emphasized by Dosi (1982), the emergence of a new paradigm stems from the interplay between scientific advances, economic factors, institutional variables and unsolved difficulties on established technological paths. Within this framework, a technological transition involves a 'technological paradigm shift' during which society abandons certain patterns of solutions to certain problems and develop new patterns of solutions derived from scientific research and supported by a change in "selection devices" (economic, institutional and social factors). One major difficulty is linked to what Dosi (1982) calls the *negative heuristic* embodied in a technological paradigm, which focuses research efforts and innovative activities in rather precise directions, while ignoring other directions and possibilities[17].

- The literature on dominant designs

In the evolutionary literature, the establishment of a technological system is often conceptualized with the concept of dominant design. Dominant design models begin when invention and innovation create several technological variants designed to meet some expected consumer demand (Abernathy and Utterback, 1978). A period of uncertainty, called the 'era of ferment', ensues as variants compete for performance improvements and market share. The era of competition ends when one of the variants captures a critical mass of the market and becomes the *de facto* standard (Anderson and Tushman, 1990). For Henderson and Clark (1990), a dominant design is characterized both by a set of core design concepts embodied in components that correspond to the major functions performed by the product and by a product architecture that defines the ways in which these components are integrated. With such a definition, a dominant design is defined by its core components, i.e. the components of the technological system that control the other 'peripheral' components. Again the establishment of the internal combustion engine as the source of automobile propulsion is an example of a lock-in of an industry on a dominant design. Scholars of dominant designs have appealed to a variety of underlying causal logics to explain how and why a particular design emerges as the dominant one. Five types of arguments can be emphasized:

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[17] Metcalfe (1995, page 35) has put this well: "A technological paradigm is a device for dealing with the tyranny of combinatorial explosion…Rather than being random, technological development is guided in such a way as to reduce the rate of mutational error."

- According to Abernathy and Utterback (1978) and Utterback and Suarez (1993), a dominant design becomes dominant because it represents the best technological compromise among the different functional characteristics of the technology.
- A second explanation for the emergence of a dominant design is linked to economies of scale and network externalities which create dynamic increasing returns (Klepper, 1997; David, 1985; Arthur, 1989; Frenken and al., 1999).
- Empirical studies have also showed that the lock-in of a dominant design results in an industry shake out where producers of alternative designs are forced out of business, which is conducive to industry concentration (Abernathy and Utterback, 1978).
- Empirical studies also emphasize that, following such a shake out, the surviving oligopolistic firms shift their focus from product to process innovations.
- According to Dosi (1982), a dominant design thus defines a so-called natural trajectory of expected improvements by widening the scope of application through innovation in peripheral components and deepening the quality of the dominant design by improving the core components.

Technological transitions necessarily involve changes in dominant designs. As already argued, what is needed is to find new technological compromises among the various functional and environmental characteristics of technologies. The difficulties result from the fact that the transition towards sustainable technological systems calls into question the core components of systems and requires radical innovations (radical in terms of their impact upon both knowledge bases and environmental performances) on these core components. It is all the more difficult that established firms tend to innovate mainly on the dominant design, in order to improve either their production process or the quality of products, but with the same core component technology. In terms of environmental innovations, it is mainly conducive to end of pipe technology and to environmental innovations on the dominant design ('sailing ship effect', cf. §4.1). These arguments also imply that incumbent firms are rarely the source of innovations that leads to the obsolescence of existing dominant designs (Henderson and Clark, 1990; Bower and Christensen, 1995). As a consequence, it is entrepreneurial entrants, operating outside the considered industry or exogenous to the dominant design, which may bring about the technological discontinuities necessary to a change in dominant designs.

To summarize, this literature stresses that, in complex technological artefacts or systems, the process of technological development is a local, cumulative and path dependent search process that is, to a large extent, insensitive to changes in factor prices of component technologies. The gradualism of technological development is primarily due to interdependencies among the component parts of complex technological systems. Computational experiments have showed that the probability of success of an innovation in a complex system with high interdependency is inversely related to the number of parts or dimensions that are changed simultaneously (Murmann and Frenken, 2006). It explains why transitions are mainly gradual processes through which new technology diffuses niche by niche (Levinthal, 1998).

- *Unlocking technological systems*

The question of how to overcome lock-in has been little explored. But some implications can be drawn from the evolutionary literature on innovation and path dependency. This literature shows that to overcome lock-in, it is necessary that some extraordinary events or shocks occur. Cowan and Hulten (1996) explore the problem of escaping the lock-in of internal combustion automobiles and argue that it requires the occurrence of six "extraordinary events": crisis in the existing technology, regulation, technological breakthrough producing a cost breakthrough, changes in taste, niche markets and scientific results. To a certain extent, we can argue that, in several technological fields, the energetic constraints, the regulatory context, as well as the evolution of scientific research, might be conducive to the achievement of some of the conditions or shocks for a transition to occur. But, as emphasized by Unruh (2002), technological transitions imply both market and technological breakthrough. Thus finding market space where the new technology can develop is an important challenge. As discussed in section 4, it is typically the role of *market niches* provided by a group of users willing to pay a significant premium for some superior characteristics of products ("experimental users" in the sense of Malerba and al. (2007)). The creation of a market niche for radically new technologies with a low environmental impact should be considered as a learning environment, not just for suppliers and users of these technologies, but also for public authorities who want to achieve a smooth transition towards a more sustainable system (Kemp, 1994). The general conclusion arising from the literature on market niches holds that niches are indeed important for technological transitions to take place, as the new technology can be developed within the niche before being introduced in the mass market. It supports government policy aimed at creating niches by subsidies or regulation, an approach also known as strategic niche management (Schot and al., 1994; Kemp and al., 1998; Schot and Geels, 2007).

But to trigger a technological transition, it is necessary that the new technology diffuses outside the niche or to other market niches. With an elementary evolutionary model of technological substitution with network externalities, Bruckner and al. (1996) show that a critical mass of adopters is necessary for a switch to the new technology system and that this critical mass depends on the fitness differential between the new and the old technology. As discussed in the previous section, such a transition also depends on the evolution of market demand conditions, and more precisely on the evolution of consumers' preferences. The growing awareness of the environmental effects of some products and its translation into environmental preferences of consumers are necessary conditions for a technological transition to occur (cf. section 4).

Lastly, the evolutionary literature on technological transition also emphasizes the critical role of technological diversity. *Diversity*, or variety, is a key concept within evolutionary economics[18]. The literature on technological diversity concerns more the problem of avoiding premature lock-in on suboptimal technology than the one of unlocking existing lock-in. Nevertheless both problems are closely interrelated and many authors emphasize that, rather than accelerating the adoption of a specific technology, policy can also aim at the preservation of technological diversity to gain more information about the exact properties and costs of all alternatives (Kemp and al., 1998; Carillo-Hermosilla, 2006; Van den Bergh and al., 2007). In other words, the deliberate pursuit of a diversity of technological options and innovative strategies provides a means to forestall lock-in under increasing returns. These arguments highlights the problem of the trade-off between efficiency and diversity, and consequently the difficult question of the optimal level of diversity (Van den Bergh and al., 2007), as well as the strategic value of timing and the role of 'windows of opportunity' for policy intervention (David, 1987; Sartorius and Zundel, 2006).

6. Conclusion

As emphasized in the literature, one of the main specificity of environmental innovations is the double externality problem which results from two types of positive externalities: usual knowledge and research externalities, and externalities due to the positive impact upon environment. The evolutionary literature on innovation provides a theoretical framework dedicated to the analysis of technological change and industrial dynamics. The purpose of this paper is to show that such a framework may bring relevant contributions to the analysis of the

[18] For a survey, see Van den Bergh and al. (2007) and Stirling (1998).

micro and meso dynamics of environmental innovations. We argue that the evolutionary literature on innovation, and more particularly on technological regimes, provides a relevant framework in order to analyse the various determinants of environmental innovations and the double externality problem in an industrial dynamics context, which enables to study how market dynamics and technological competition influence environmental technological trajectories of firms.

The concept of technological regimes can be used to investigate how the properties of the research and learning environment shape the sectoral patterns of environmental innovations. We argue that a thorough analysis of what we call "technological and environmental regimes" can contribute to explore the sectoral determinants of environmental innovations and so to explain inter sectoral differences. Such an approach may bring relevant policy implications on the effects of policy instruments on innovation according to technological regimes.

But environmental innovations are, like innovation in general, also shaped by demand side determinants. The evolutionary literature on technological disruption and succession sheds light on the role of demand characteristics in technology competition. This literature puts emphasis on the microdynamics of technological competition and on the determining role of the preferences of consumers and of the relative prices of the competing technologies. By stressing the demand characteristics that are necessary to the diffusion of a new disruptive technology, evolutionary models on technological competition may bring relevant policy insights on the adoption and the diffusion of environmental innovations, and more precisely on the role of niche markets.

Finally we also discuss the potential contributions of the evolutionary literature on the topic of technological transition. In an evolutionary framework, technological transitions may be viewed either as a change in technological paradigms or as a change in dominant designs. Within this perspective, technological transitions are analysed at a meso-economic level and the focus is on learning processes and path dependency phenomena which enables to identify the different sources of lock-in. The main policy implications concern the role of technological and behavioural diversity, as a necessary condition to technological transition, as well as the gradualism of transitions which implies to pay more attention to technological hybridizing and to transition or pathway technologies.

Appendix

Table 1 Overview of empirical studies on the determinants of environmental innovations

References	Data	Main determinants	Main results
Green and al. (1994)	Survey of UK firms	Existence and anticipation of environmental regulation Expanding market share (green products) Cost savings	The top three determining factors are: - for product innovations: the existence and the anticipation of regulation and the prospect of expanding market share - for process innovations: the existence and the anticipation of regulation, and cost savings through better use of materials/energy. There is a significant correlation between the influence of regulation and of commercial factors.
Florida (1996)	Survey of US manufacturing firms	Innovation in advanced manufacturing systems; environmental regulation, corporate citizenship and other factors associated with industrial performances	Validation of the hypothesis according to which the adoption of environmentally conscious manufacturing is related to the adoption of advanced manufacturing systems. While environmental regulation and corporate citizenship remain key elements of corporate environmental strategy, a series of factors associated with industrial performance are also important, notably customer demands and productivity improvement.
Lanjouw and Mody (1996)	Environmental patents	Regulation	Positive correlation between pollution abatement expenditure (linked to domestic regulation) and number of patents (one to two year lag). Environmental innovation in a country also responds to regulations in other countries.
Jaffe and Palmer (1997)	Industry-level panel data: R&D expenditure and patent applications	Regulatory stringency measured by compliance costs	No significant correlation between regulatory compliance costs and patenting activity. Significant positive relationship between regulatory compliance costs and R&D expenditure by the regulated industry.
Brunnermeier and Cohen (2003)	US environmental patents	Regulatory stringency measured by pollution abatment and control expenditure.	Positive correlation between pollution abatement costs and environmental innovations (environmental patents). International competition stimulates environmental innovation.
De Vries and Withagen (2005)	European patents on sulphur dioxide abatement technologies	Policy stringency with regard to SO2	Validation of the weak version of the Porter hypothesis: strict environmental policy with regard to SO2 induces new abatement technologies.
Mazzanti and Zoboli (2006)	Surveys on a sample of Italian manufacturing firms	Policy effect (evaluated by environmental costs), eco-auditing schemes, firms' size, sector effects, industrial relations intensity and environmental R&D.	The main drivers of environmental innovation are: firms involvement in group and networking activities, 'innovative oriented' industrial relations, environmental policy related costs, R&D and voluntary environmental schemes.

Frondel and al. (2007)	OECD survey (2003)	Policy stringency (perception), regulatory measures, cost savings	A significant positive correlation between policy stringency, technology standards and regulatory compliance with the introduction of end-of-pipe technologies, but not with clean technologies. Innovations in clean technology tend to be more market driven and so motivated by cost savings. The variable R&D is only significant for clean technology.
Popp, Hafner and Johnstone (2007)	Patent data on two chlorine free bleaching technologies used by the pulp and paper industry (process environmental innovation)	Policy versus public (consumer) pressure	Regulation is not the only driver of innovation and diffusion of these technologies. The development of alternative bleaching technologies increased before the implementation of new regulations of chlorine use, suggesting that public pressure was the primary driver of the first waive of innovation.
Rehfeld and al. (2007)	Firm level dataset of the German manufacturing sector	Environmental organisational measures, environmental policy	The certification of environmental management systems has a significantly positive effect on environmental product innovations. Environmental policy seems to be a driver for product innovations, albeit the positive effect is rather small. Technology push (R&D) and market pull also have a positive effect on environmental product innovations.
Scott (2003)	Survey on environmental R&D expenditure of US manufacturing firms	Regulation of the emissions of hazardous air pollutants Size of firms and competitive pressure	R&D related to cleaner products appears as dominant (comparatively to clean process R&D). The extent of firms' emission problems (linked to regulation) and the presence of competitive pressure are associated with greater R&D expenditure. Large firms do more environmental R&D.
Wagner (2007)	Survey and patent data of German manufacturing firms	Environmental management systems	The implementation level of environmental management systems has a positive effect on environmental process innovations.
Horbach (2008)	Two panel databases on German firms	R&D, demand pull effect, environmental regulation, environmental management tools.	Improvement of the technological capabilities by R&D is very important for environmental innovation. The hypothesis that "innovation breeds innovation" is validated (cumulativeness). An increase in the expected future demand triggers environmental innovations. Environmental regulation and environmental management tools are highly relevant determining factors.

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