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Incrementalism of environmental innovations versus paradigmatic change: a comparative study of the automotive and chemical industries

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Gradualisme des innovations environnementales *versus* changements paradigmatiques: Une analyse comparative des industries de l'automobile et de la chimie

Résumé

L'objet de cet article est de présenter une analyse comparative des trajectoires d'innovations environnementales de l'industrie automobile et de l'industrie chimique. Le cas de l'automobile, et plus particulièrement des innovations environnementales dans le domaines des véhicules à faibles émissions, nous permet de mettre en évidence le caractère persistant du paradigme dominant du moteur à combustion interne, ainsi que les effets de verrouillage technologique qui tendent à favoriser une trajectoire d'innovations incrémentales. Nous montrons que cette tendance au gradualisme est liée à la multiplicité des objectifs environnementaux et à la difficulté à combiner de tels objectifs avec les autres caractéristiques des véhicules. Le cas de la chimie verte nous permet de nous intéresser aux conditions d'émergence d'un nouveau paradigme technologique. Nous mettons en exergue le rôle prépondérant de la recherche scientifique dans le régime technologique de la chimie, les partenariats public-privé qui en découlent, la sévérité de la réglementation, en particulier les interdictions de produits, ainsi que la forte pression publique liée à l'image de l'industrie chimique. Ce cas permet également de montrer que la définition de principes communs, définis par les industriels et les experts scientifiques, et alliant les objectifs environnementaux et économiques, est une condition nécessaire à l'émergence d'innovations radicales et au développement d'un nouveau paradigme technologique.

Mots-clés : Innovations environnementales ; régime technologique ; paradigme technologique ; réglementation environnementale ; automobile ; chimie verte

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Abstract

The purpose of this article is to analyse and to characterize sectoral patterns of environmental innovation, with a focus on the question of incrementalism and paradigmatic changes. The presentation of the case study of the automotive industry emphasizes a tendency towards incrementalism linked to the persistence of a strong dominant design, i.e. the internal combustion engine, which is continuously improved and creates lock-in effects. We argue that this tendency is mainly due to the difficulty to combine environmental objectives with non-environmental criteria, particularly the price of vehicles and their primary functionalities. The comparison with the chemical industry enables us to concentrate on the question of paradigmatic changes by focusing on green chemistry which opens radically new directions of research. We emphasize that the science-based character of the chemical industry, in particular the role of public-private partnerships in research, as well as the stringency of regulation with product bans, and the public pressure create favourable conditions to a transition towards a new green paradigm. It also shows that the definition of common selected principles by a community of scientific researchers and experts, which combine environmental and economic objectives, is a necessary condition to the development of radical environmental innovations and paradigmatic changes.

Key words: Environmental innovations; technological regime; technological paradigm; environmental regulation; automotive industry; green chemistry

JEL : Q55; O31; L62; L65

Introduction

Hybrid vehicles, fuel cell vehicles, catalytic converters, solvent free paintings, polyester regeneration technology, green synthetic catalysts, today environmental innovations are at the very core of the innovative strategy of industrial firms. As a matter of fact, they are not only seen as an imperative way of complying with regulation, but also as a source of competitiveness and a way of improving the public image of firms. But in spite of this increasing interest for environmental innovations, the concept remains vague with unclear outlines. There is a consensus on the broad definition according to which 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. In spite of this consensus, environmental innovations take very different forms and exert different impacts upon environment, so that there is an increasing competition between various technological options and it remains difficult to identify the best solutions in a long term perspective.

Industrial sectors exhibit different patterns of environmental innovations in terms of rate of innovation, intensity of environmental investments and types of innovation (end of pipe equipments, clean technology, incremental or radical innovations). The purpose of this article is to analyse and to characterize these sectoral patterns, with a focus on the questions of incrementalism and paradigmatic changes. Indeed even if it is now acknowledged that massive reductions in the levels of net emissions are likely to come only with the development of new technological "green paradigms" for the generation of heat, electricity and motion, many industrial sectors tend to follow incremental trajectories and to be locked in the dominant technological paradigm.

This article is organized as follows. The first section presents our framework for the analysis of the sectoral patterns of environmental innovation. This framework is structured around three elements which are technological regime, market demand and environmental policy. The sectoral patterns of environmental innovation result from the interplay between technology push effects, demand pull and regulatory push-pull effects. Sections 2 and 3 are dedicated to our comparative study of the automotive and the chemical industries. The choice of these two sectors is motivated by their dynamism in the field of environmental innovations and by the determining role of regulation, but also by the existence of significant differences between them in terms of environmental innovative strategy. As a matter of fact the automotive industry tends to follow an incremental trajectory strongly anchored within the dominant paradigm, which is the internal combustion engine, while the chemical industry exhibits signals of a progressive shift towards the new "green chemistry" paradigm. The regulatory context, as well as demand conditions and the properties of technological regime, are considered as the main determinants of these two sectoral patterns of environmental innovation.

I. A sectoral analysis of environmental innovations: framework of analysis

A good knowledge of the specific characteristics of sectoral systems of innovation is necessary to understand the patterns of environmental innovation. The evolutionary literature on innovation clearly shows that industrial sectors exhibit different patterns of innovation. The works on technological regimes [1, 2, 3, 4] and on sectoral systems of innovation and production [5] provide a framework for analysing the determinants and the characteristics of industrial dynamics and innovation at a sectoral level. Since environmental innovations share common features with innovation in general, we propose to apply such a sectoral framework for analysing the patterns of environmental innovation of industrial firms, while taking into account their specificities and in particular the role of regulation. We first present the core elements of our framework, which are technological regimes, environmental policy and market demand (§ I.1), in order to explain how the dynamic interplay between them shape the sectoral patterns of environmental innovation (§ I.2).

I.1 Technological regimes, environmental policy and market demand

- Technological regimes

Evolutionary works on sectoral systems of innovation are usually based on the concept of technological regime. This concept initially developed by Nelson and Winter [6] provides a description of the technological environment in which firms operate. According to Dosi [7], a technological regime is defined by the properties of learning processes, the nature of the knowledge base and the sources of knowledge used by firms in their innovative processes. In [1, 2] the authors define a technological regime as the combination of four factors which are knowledge bases, technological opportunities, appropriability conditions and cumulativeness of innovation. These four factors shape the innovative patterns of firms and so the properties of the industrial dynamics. By extending the previous taxonomic exercises [1, 8] and by focusing more on the role of innovative entry, Marsili [4] proposes a new typology of regimes which distinguishes five industrial technological regimes: science based, fundamental processes, complex systems, product engineering and continuous processes. Each regime corresponds to a specific combination of technological opportunities, technological entry barriers, sources of knowledge and types of innovation. Such taxonomy of technological regimes provides an analytical framework that summarises the empirical evidence on the microeconomic dynamics of innovation.

If these concepts enable us to understand the main features of the dynamics of innovation in general, they can certainly be of great relevance for the analysis of environmental innovations. The main peculiarity of environmental innovation is that they produce positive spillovers in both the innovation and the diffusion phases [9]. This specificity is linked to the component of public good that characterizes environmental goods. Positive spillovers in the diffusion phase are due to the smaller external costs compared to competing goods on the market [9]. This peculiarity, which is called the "double externality problem", tends to reduce the incentive for firms to develop environmental innovation. Therefore the double externality induces a second peculiarity which is the importance of regulation as a key determinant for environmental innovation. The main difference with innovation in general is that the incentives for firms to develop or to adopt environmental innovation mainly come from the regulatory pressure. It is the reason why the regulatory context, and environmental policy in general, must be at the core of our analysis since it strongly determines the rate and the directions of environmental innovations.

- Environmental policy

Many works have been carried out on the effects of environmental policy instruments on innovation. These effects depend on the type of instruments (regulatory or economic instruments) and on the specific context in which they are applied. According to Jaffe and al.

[10], economic instruments (taxes and tradeable permits) tend to be more cost effective than regulation and provide ongoing incentives for firms to adopt new technology[1]. Empirical works also show that environmental policy instruments rarely lead to radical innovation, but rather support incremental innovation and technological diffusion [11, 12]. According to [11], only product bans and regulation on producer responsibility may lead to radical innovations. The time frame and the stringency of regulation are considered to be the most important factors influencing environmental innovation [13]. For example, short time frames for compliance often force firms to adopt the least innovative, but less risky, technologies. On the contrary, significant process innovations occurred in response to stringent regulations that gave firms in the regulated industry enough time to develop comprehensive strategies. Ashford and al. [14] show that regulatory flexibility towards the means of compliance, variation in the requirements imposed on different sectors and compliance time periods are aspects of performances standards that contribute to the development of superior technological responses. In summary, it seems that there is no single best instrument to foster environmental innovation and that the most common response of firms to environmental policy is incremental innovation and technological diffusion.

So economic instruments and environmental regulation are not sufficient to induce innovation and other policy instruments are needed, such as voluntary agreements, public procurement, information, knowledge-sharing measures (eco-labels, environmental management systems) and integrated product policy[2] (producer responsibility, life cycle analyses, guidelines for eco-design). This set of instruments defines what we call an *environmental policy mix* which purpose is to promote more sustainable systems of production and consumption. This policy mix determines the incentives to innovate and the directions of research by defining some environmental priorities and some objectives in terms of emissions, quality of inputs or products, but also by shaping market conditions and interactions among actors. Public procurement and information policy can have a strong impact on the market by creating niche markets for environmental technologies and by changing the preferences of consumers, in particular by giving them access to relevant information on the environmental characteristics of products.

- *Market demand*

Like for innovation in general, demand pull effects are important to spur environmental innovations and to foster their diffusion. In recent years, there are consistent reports which indicate that market opportunities play an increasing role in promoting environmental responsiveness of industry. The major market driving forces come from the environmental concerns of consumers which tend to include some environmental criteria in their choice characteristics, for example concerning the toxicity of products, their reliability, longevity and recyclability. This increasing environmental concern of consumers is triggered by the diffusion of information on the environmental life cycle performances of products and on the environmental impacts of toxic substances and polluting emissions. Progressively environmental criteria appear in the preferences and requirements of consumers, thus creating a demand for greener products and services. Such a demand determines market opportunities

[1] In theoretical models, the superiority of economic instruments is generally derived under the assumption that environmental innovations are developed by the polluting firms and not sold to other firms and that there are no information problems.
[2] Integrated Product Policy (IPP) is an approach based on a mix of instruments aiming at reducing the life cycle environmental impacts of products from the mining of raw materials to production, distribution, use and waste management [15].

for environmental product innovations. But in spite of a trend towards more environmental concerns of users, market failures are still dominant in the field of environmental innovations. That is the reason why demand for greener products needs to be reinforced through information and education policy.

In the field of environmental product innovations, market failures are also often linked to incompatibility effects between the different characteristics or functions of products. The environmental criteria should not substitute to the other characteristics of products, but should be combined with them in a way of not calling into question the fundamental functionalities of products. This statement is not a trivial one because of the big amount of features that usually characterizes a technology or a product. As a consequence, greener products are rarely perfect substitutes to conventional ones because some functionalities, or characteristics, of the products have been altered by the "greening" of the technology. That is the reason why the diffusion of a majority of environmental product innovations is restricted to niche markets, which tends to weaken demand pull effects. Market opportunities for environmental product innovations strongly depend on the ability of innovators to find an efficient technological compromise over the environmental and non-environmental characteristics of products.

Moreover the competitiveness of green products is also dependent on the price elasticity of demand. Demand pull effects are not only linked to the ecological concerns of users but also, and above all, on their willingness to pay. The valuation of the environmental characteristics of products by consumers is a crucial determinant of market pull effects since environmental performances are often associated to an increase in the price of products linked to the costs of technology. So the price elasticity of demand can be a barrier to the diffusion of environmental product innovations.

Finally demand pull effects do not only result from the demand of final consumers, but also from the demand of industrial clients and institutional users. According to industrial sectors and technological regimes, industrial clients can strongly influence the innovative strategy of their suppliers. In some sectors, like in automobile or electronics, supply chain pressure, which is mainly linked to regulation, represents an increasingly significant driver for environmental innovations. As to institutional users, they are constituted of public service firms and local municipalities which can represent an important niche market in order to experiment new technology and to support the diffusion of environmental innovations. In that case demand pull effects stem from public procurement policies and the purpose is to create a learning environment in which environmental technologies can develop and be protected against selective pressure.

I.2 Sectoral patterns of environmental innovation

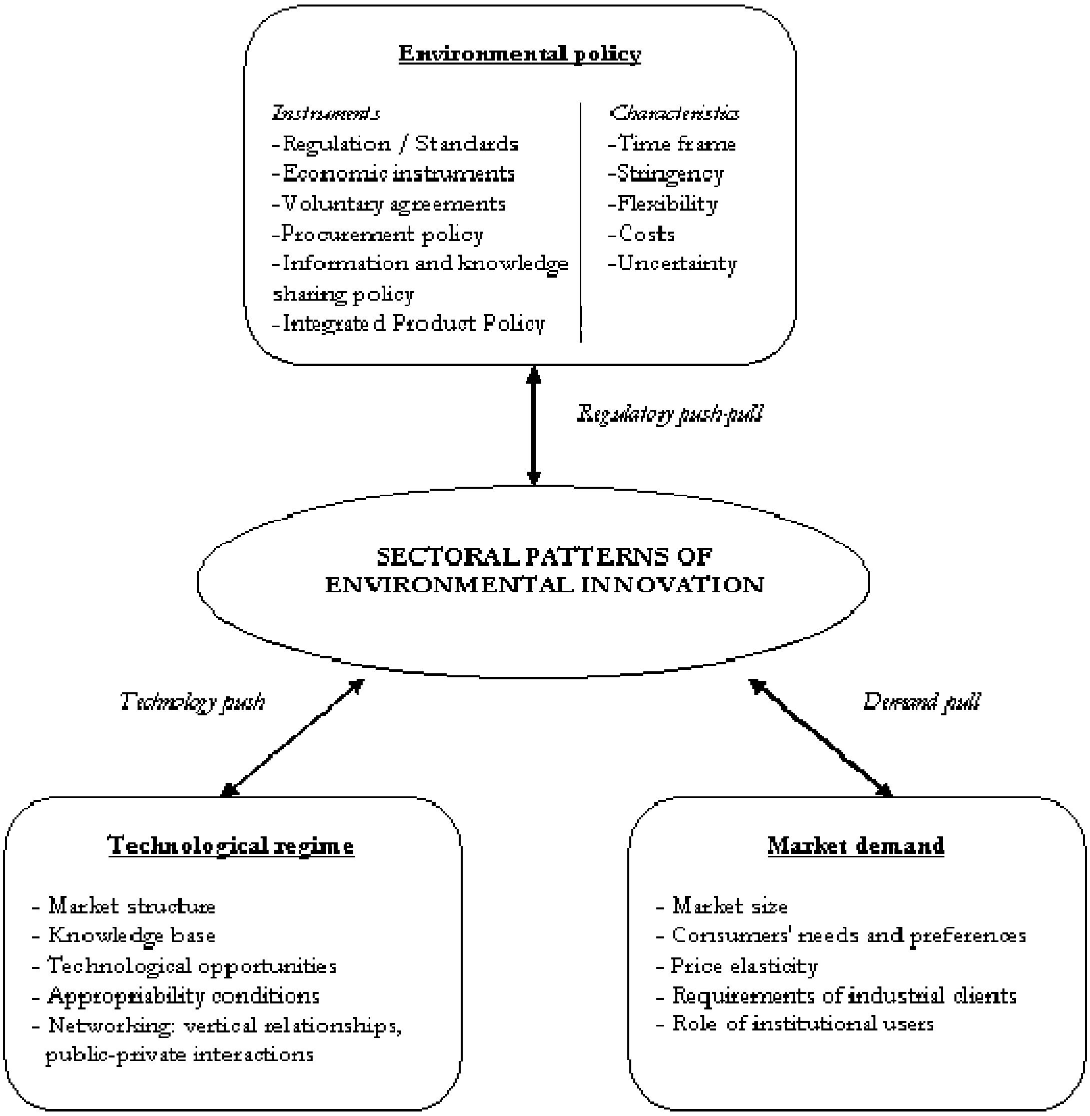
Sectoral patterns of environmental innovation result from the interplay between technology push effects, demand pull and regulatory push-pull effects, as depicted in figure 1.

Environmental innovations can concern products, processes and organizations, and can take very different forms according to their environmental impacts. The basic distinction is between end of pipe technology (or compliance technology) and clean technology. In the first case, the technological solution consists in controlling and treating pollution by the way of several technical apparatus which take effect at the end of the production process (additive technology), while clean technology implies an integrated change in the production process and a reduction of pollution at source. Clean technologies are considered to be the best option in terms of long run environmental impacts since they imply changes in practices and processes and so a reduction of pollution at source. The term clean technologies is often used in the sense of clean processes since the case of clean products, more often called green (or greener) products, is generally studied separately because of its specific link to the market[3].

Environmental innovations can also be characterized by their degree of novelty, that is with respect to how radical they are. The distinction between radical and incremental innovations is important because of the disruptive effects that may be generated by radical changes. Radical innovations are usually the result of deliberate R&D activities and require new knowledge and practices which may call into question the prevailing technology [16]. They could not arise from the incremental improvement of existing products and processes, since they require new knowledge and skills. It is for example the case of the electric and hybrid vehicles in transport. Incremental innovations are concerned with improvements in the existing array of products, processes and organizations. Usually they are closely linked to the development of market demand and the experience of users. As for innovation in general, incremental innovations are the most frequent type of environmental innovations.

[3] We can observe that in the economics of innovation, product and process innovations are generally studied separately because they exhibit different characteristics and determinants.

Figure 1: Framework for the analysis of sectoral patterns of environmental innovation



Thus the innovative patterns developed by firms may differ significantly, going from incremental changes, to diffusion of end of pipe technology or to radically new clean technologies. For each type of innovation, the directions of research, the scientific principles to be used and the needs to be satisfied are defined by the prevailing technological paradigm[4] [7]. The establishment of a dominant technological paradigm is a way of reducing uncertainty by defining the directions of research and some specific rules for the acquisition and the diffusion of knowledge. For example, the internal combustion engine is at the core of the dominant paradigm of the car industry, as well as petrochemical is the one of the chemical

[4] The concept of technological paradigm is defined as "a model and a pattern of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies" [7].

industry. The question of paradigmatic change is of prime importance for environmental concerns since a real increase in environmental performances, in particular in greenhouse gases effects and in energy consumption, can only be reached if technological trajectories move to new "green paradigms[5]", such as photovoltaic energy, green chemistry or hydrogen propulsion for transportation. Such paradigmatic changes are very difficult to achieve since they imply clusters of radical innovations and structural changes, the development of new knowledge bases and practices, and so a strong uncertainty concerning the directions of research and the most promising paths.

This question of paradigmatic changes *versus* incremental innovations is a crucial point in our analysis of the sectoral patterns of environmental innovation. These sectoral patterns can be characterized by the types of environmental innovations (radical/incremental, end of pipe/clean technology), but also by the sources of innovation (producers, suppliers, public institutions), the type of research carried out by firms (individual or cooperative) and the rate of diffusion of innovations. All these features are strongly dependent on the technological regime, the environmental policy and the demand conditions. That is what we are going to illustrate with the automotive and chemical industries.

Our framework also takes into account feedback effects between the sectoral patterns of environmental innovation and the three core elements of the framework. The technological trajectories driven by environmental innovations can modify the features of technological regime because of their impacts upon knowledge bases, opportunities and appropriability. In the same way, environmental innovations also have an impact upon environmental policy instruments. For example, the standards settled by regulation depend on the best available technologies, while seeking to provide incentives to innovate and to develop new environmental technologies. This coevolution between environmental policy and innovation raises the question of the necessary compromise between static and dynamic efficiency objectives of environmental policy. The characteristics of policy instruments in terms of stringency, flexibility and time frame are essential elements of this search for a compromise. Finally as to the role of demand, it is also dependent on the type of environmental innovations: demand pull effects tend to be stronger for product innovations than for process ones. In the field of process innovations, since end of pipe technologies can be transferred to one industry to another, they exhibit a higher market potential than clean technologies which are more specific. For that reason, market pull effects play an important role in the development of end of pipe technology and eco-industry.

II The case of the automotive industry: the power of incrementalism

In order to study the patterns of environmental innovation in the automotive industry, we first discuss the features of the technological regime, the demand conditions and the regulatory context (§ II.1). Finally we study the patterns of innovation developed by firms in the field of low emission vehicles (LEVs) (§ II.2).

[5] This term is already used in [16] and [17].

II.1 Technological regime, demand conditions and regulatory context

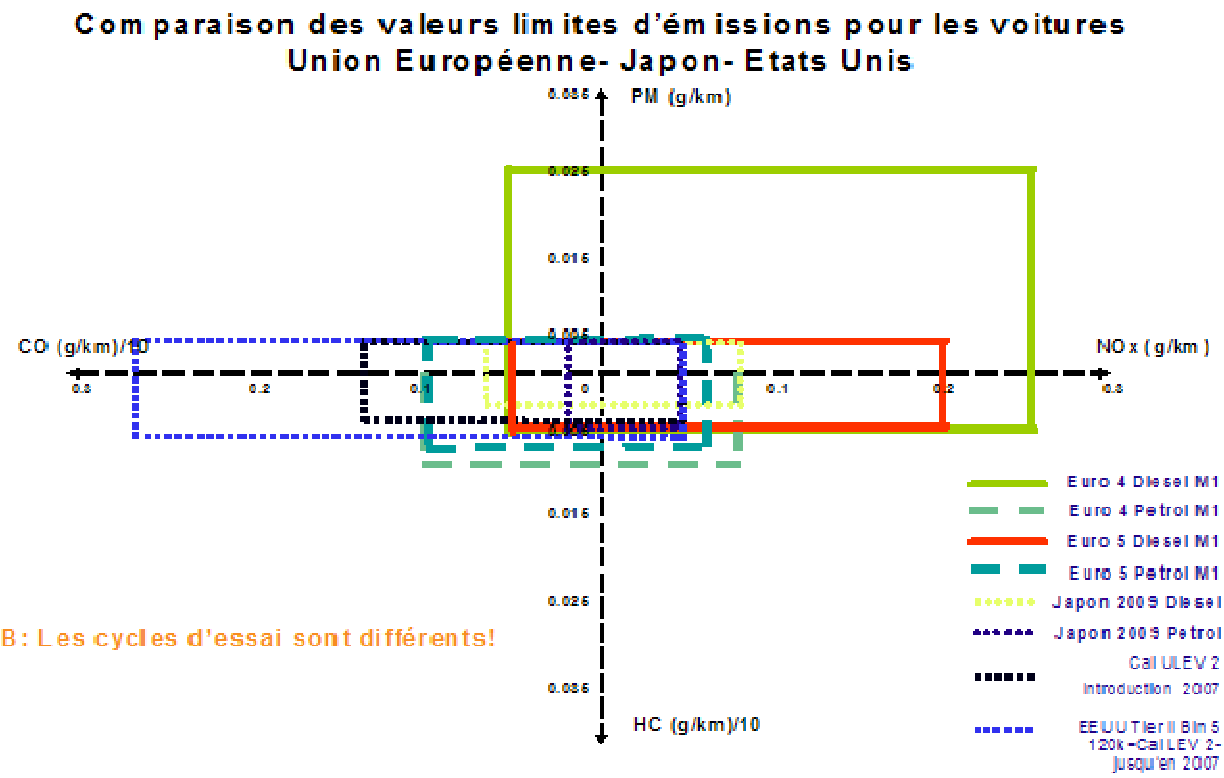
Motor vehicles manufacturing is a capital intensive industry with high levels of investment in fixed capital, plant and equipment, which creates high economies of scale and contributes to barriers to entry. According to [4], the automotive industry corresponds to a "complex system regime", that is a technological regime producing a complex system product which requires firms to manage and to coordinate a broad array of different sources of knowledge, internal and external to the firms, and to integrate different scientific disciplines and technologies. Such features reflect the complexity of products and production processes, and result in knowledge bases mainly characterized by complexity and specificity.

In terms of innovation, even if the automotive industry is not considered to be a high-tech industry, it is a major driver of new technologies and exhibits high investment rates in R&D. According to the Community Innovation Survey (CIS4 survey), over the period [2002-2004], 52.2% of the firms of the automotive industry have innovated in products or processes, which is one of the highest score of the survey. This CIS4 survey also shows that the automotive sector is characterized by an intensive continuous investment in internal R&D (on average 2.6% of the turnover), an intensive use of patents to protect innovation, a frequent collaboration with suppliers for innovative activities and an increase in the rate of innovation in particular in process innovations. But the combination of mass production with the complexity of system products tend to increase the risks of failure related to radical innovations, which can explain that processes and products are developed mainly incrementally. Indeed processes and products are improved continuously, but the development of new disruptive technologies is more critical. We will see that this tendency towards incrementalism is all the more strong for environmental innovations.

As to demand conditions, they are mainly characterized by the stagnation of market demand in developed countries since the 1990s, the development of emerging markets, the strong dependency of sales on brand and marketing innovations, a high price elasticity of demand and an increase in the lifetime of products which implies a low rate of fleet renewal [18, 19]. In terms of demand pull effects, these characteristics do not create incentives for radical environmental innovations, particularly because of the high price elasticity of demand which represents a strong constraint relatively to the cost of environmental technologies. Moreover the low rate of fleet renewal tends to slow down the diffusion of innovation.

Finally regulatory push-pull effects are particularly strong since the automotive industry is one of the most regulated sectors in Europe. The United States, especially California, have been precursory in the regulation of tailpipe emissions from cars. Progressively the stringency of emission standards increased and several pollutants are regulated: CO2, NOx (nitrogen oxide), SO2 (sulphur dioxide), HC (hydrocarbons) and diesel particles (PM for particles matter). Japan, which has to cope with the same problems of urban air pollution as California, follows the same stringent regulatory strategy, also motivated by their exportations to the US. During the 1990s the European Commission sets up the "Auto-Oil programme I an II" which defines new standards for vehicle emissions. More recently, EURO 4 standards have been introduced (in 2006 for all new registered vehicles) with a decrease of exhaust emissions levels, in comparison with EURO 3, by 30% for NOx, CO and HC and by 80% for diesel particles. Nevertheless if we compare the regulatory context in Europe, US and Japan, we see significant differences among countries in terms of targeted emissions and stringency. Figure 2 shows the emission limit values of PM, CO, NOx and HC defined by the most recent regulations in Europe (EURO 4 and EURO 5 (planned for 2009)), in United States (LEV2 and ULEV2)[6] and in Japan (target values for 2009). This figure clearly shows that Europe is characterized by less stringent standards, particularly for PM and NOx emissions of diesel cars. In the meantime the European standards are the most stringent for CO emissions which have been for a long time the priority with fuel consumption. Given the large share of diesel cars in Europe[7] and the leading role of European car manufacturers in the production of diesel vehicles, we can argue that these features are mainly motivated by market and strategic reasons. This comparison emphasizes the differentiated strategies of regulation among countries which strongly influence the patterns of environmental innovation since they define the directions of progress.

Figure 2: Comparison between emission limit values of vehicles in Europe, Japan and United States (source: [20])



Generally speaking we can say that, under the pressure of regulation, the technological trajectory of the automobile industry is directed towards the search for new less polluting technologies in terms of CO, NOx, PM and HC emissions. But the existence of various targeted pollutants calls for a trade-off between the reductions of these pollutants[8]. This argument is used by the European Automobile Manufacturers Association (ACEA) against

[6] Low Emission Vehicles standards are introduced in 2004 and Ultra Low Emission Vehicles standards in 2007.
[7] Half of all new vehicles in the EU are diesel, with the share of diesel reaching more than two thirds in several national markets. This is in sharp contrast to the US and Japanese markets where diesel exists only as a fraction of the market.
[8] The main trade-off is between emission reduction and fuel consumption and hence CO2 emissions. For example, the laws of thermodynamics explain the negative correlation between NOx levels and fuel consumption: a higher combustion temperature will lead to higher fuel efficiency, but also to higher NOx emissions.

the new EURO 5 standards which strongly lower NOx and PM emissions for diesel cars. ACEA members argue that such a proposition will have undesired consequences on fuel consumption, and so on CO2 emissions, and will affect the competitiveness of European car manufacturers. This trade-off argument is all the more relevant that the car industry is also subject to many other regulations concerning end of life vehicles, durability and weight of vehicles, fluorinated gases used in cars' air conditioning systems and access to vehicle repair information. This dense and diversified regulatory context defines the framework of the innovative activities of car manufacturers and the main directions of research (with some potential contradictions). It also tends to increase the number of criteria, in the Lancasterian sense, on which vehicles must be competitive with priorities varying through time and across countries.

II.2 Gradualism of environmental innovations in LEVs

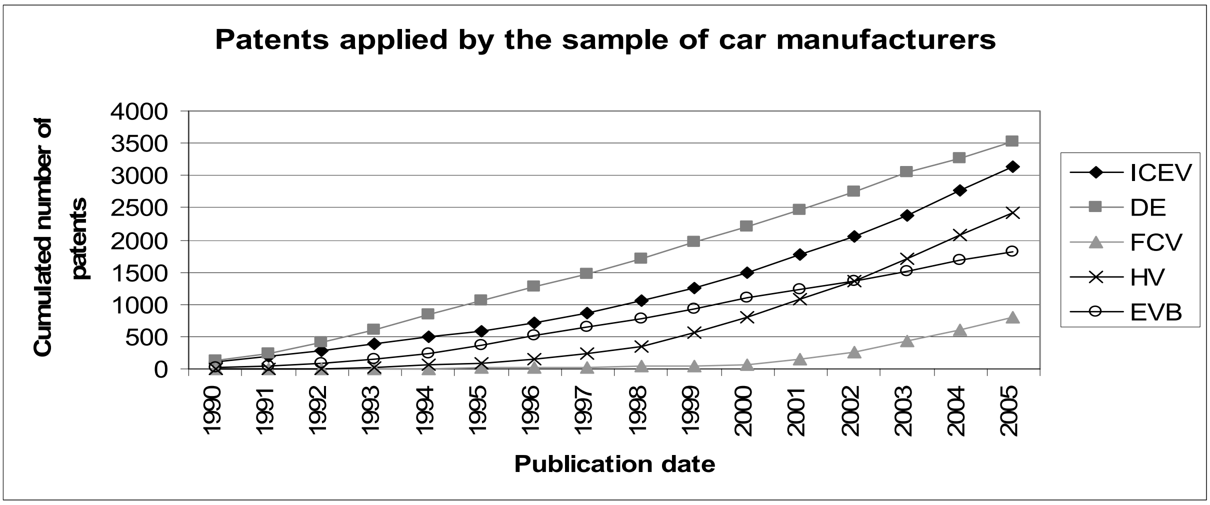
Many economic works emphasize that the stringent regulatory context of the automotive industry has been a source of technological opportunities and innovations [18, 21, 22]. As a matter of fact, regulations on tailpipe emissions have created new technological opportunities in the field of motor vehicles and engines, which lead to an intense activity of environmental innovation. As a consequence between 1995 and 2008, European car manufacturers have introduced more than 50 new technologies into their vehicles, particularly new CO2 efficient technologies[9]. The main areas of research in the automotive industry include conventional powertrain, alternative powertrains (such as hybrid and fuel cell vehicles), new materials, aerodynamics, energy efficiency of car components and driver information devices. These various research fields are linked to the diversity of environmental objectives. In order to cope with these objectives car manufacturers have developed a lot of environmental innovations which have led to a tremendous decrease in fuel consumption, noise and tailpipe emissions, but also to an increase in the complexity and the weight of vehicles. The challenge of car manufacturers is to find a technological compromise that enables them to find a tradeoff between these various, and sometimes opposite, environmental objectives. Moreover the environmental criteria must be combined with the conventional ones concerning the primary functions of vehicles that are range of use, price, comfort and power.

To find an efficient technological compromise between tailpipe emissions, fuel consumption, energy efficiency, power and range of use of vehicles is the real challenge of research and innovative activities in the field of low emission vehicles (LEVs). Innovative activities in LEVs follow two types of technological trajectory: the continuous improvements of internal combustion engine vehicles (ICEVs), which constitute the persistent dominant design of the car industry, and the development of alternative engine technologies, such as electric vehicles (EVs), hybrid vehicles (HVs) and fuel cell vehicles (FCVs). If we want to study the innovative strategies of car manufacturers in that field, we can use patent data as an indicator of innovation and of the technological positioning of firms[10]. In [23], we study the evolution of the patents portfolios of a sample of eleven car manufacturers[11] over the period [1990-2005] by counting the number of cumulated patents for each engine technology. Figure 3 shows that the dominant design, which is considered as a very mature technology, is still continuously under improvements, and in particular diesel engine vehicles (DE). Thanks to the innovative activities of car manufacturers, but also of their component suppliers, a steady rate of technological

[9] For a list of these CO2 efficient technologies, see the ACEA website: http://www.acea.be
[10] For a complete presentation of the methodology see [23].
[11] The sample is composed of the following car manufacturers: Toyota, Honda, Renault, Ford, Nissan, Mitsubishi, Hyundai, General Motors, PSA, Daimler Chrysler and Volkswagen.

progress continues to make the ICE vehicle gradually better and cleaner. These innovative activities support the dominant design which is far from being played out, since patents show that it still represents the core of the innovations of the automotive industry. This feature strengthens the argument according to which the car industry demonstrates a strong preference for incremental technological change. According to most car manufacturers, particularly the European ones, adopting clusters of incremental innovations meets environmental performance requirements in the most cost effective manner. Indeed to improve gradually the environmental performances of the dominant design is a way of complying with regulation while going on exploiting the increasing returns linked to the adoption of the ICE technology.

Figure 3: Evolution of the cumulated number of patents (source: [23])



Concerning the search for alternative engine technologies, we can observe a shift in research focus from EVs to both hybrid and fuel cell vehicles. From 1990 to 1996, the EV was considered to be a serious alternative to ICEV. Because of the constraints on the batteries and on the range of use of EVs, there was a change in perspective and the FCV progressively appeared as the most promising technology. As a consequence since 2000, there is a significant increase in research and development activities of car manufacturers in the field of fuel cells[12]. Even if a majority of stakeholders present FCVs as the future new technological paradigm for transportation, there remains a lot of uncertainties concerning the production and the storage of hydrogen, the indirect emissions and the costs of the necessary infrastructures[13]. That is the reason why more recently, HVs have progressively developed and plays now a dominant role in the innovative strategy of car manufacturers. Figure 3 stresses that the accumulation of patents in HVs by car manufacturers has tremendously raised and is superior to the cumulated number of patents in EVs since 2002. When we look at patents as an indicator of the technological trajectories followed by firms, HVs clearly appeared as the preferred technological option of car manufacturers. This feature is mainly linked to the transitory character of this technology that enables to exploit technological complementarities between the dominant design (ICEV) and the electric engine. We can argue that it is another signal of a step by step trajectory still strongly dependent on the dominant design.

[12] This trend is also characterized by strong differences among car manufacturers which exhibit different choices of technological specialisation [23].
[13] For a complete evaluation and comparison of the LEVs technologies see [24].

Technological complementarities play an increasing role in this competition among LEV technologies since there exist spillovers between technologies. For example, the improvements of EVs have benefited to HVs, as well as the innovations on HVs benefited to FCVs. Moreover we also observe that research activities on fuel cells result in the development of the use of fuel cells for the feeding of electronic and electric devices of ICEVs. As a matter of fact, there is an increasing overlapping of technologies which enables car manufacturers to exploit technological complementarities between alternatives. This overlapping of technologies is a way of building a gradual path towards radically new engine technologies. As a result the technological competition among LEVs is characterised by a persistent diversity of options, no signs of premature lock-in and increasing complementarities between technologies which mainly benefit to HVs [23,25].

III The transition towards a new green paradigm: the case of “green chemistry”

The chemical industry shares common features with the automotive industry, but distinctive characteristics also exist and play a major role in environmental innovations (§ III.1). Empirical evidence, such as observed with patent data, show the progressive shift of chemicals from the petrochemicals paradigm to the green chemistry one (§ III.2).

III.1 Technological regime and regulatory context

Like the automotive industry, chemicals are characterised by a relatively high degree of concentration in comparison to the total manufacturing industry and by the continuity of large multinational firms through R&D, scale and scope and the emergence of vertical division of labour [5]. Likewise, internal R&D plays a significant role in chemicals as well as patent protection. Data from the CIS4 survey show that 75.2% of the chemicals, rubber and plastics firms belong to a group and that 43.6% of the chemical firms have innovated in products or processes between 2002 and 2004, which represents 85.1% of their turnover. The survey also shows that 82% of the innovative chemical firms have carried out internal R&D over the period 2002-2004 and that 43.6% of the chemical firms have applied patents over the same period.

However distinctive features from the automotive industry can be outlined that will enlighten a change in the directions of research in the chemical industry. First, the chemical industry is basically a science-based industry which benefits from the quite important and direct contribution of scientific advances in academic research. Second, it is also a very heterogeneous sector with different product segments: base chemicals, specialty and fine chemicals, consumer chemicals and pharmaceuticals. Concerning the applications of chemical products, it is worth noting that only 30% of the chemicals are dedicated to final consumption, but the majority of chemicals is delivered to and applied by other industries (manufacturing, service and administration, agriculture and construction). In terms of demand, it implies that industrial clients represent an essential share of the market. Another implication of the segmentation of the market structure is that the size of companies varies considerably. SMEs are often suppliers and customers of the larger companies and they play an important role in the chemical industry network, providing a certain degree of flexibility. In particular, the fine and specialty chemicals sector is made up of several thousands of small and medium-sized companies as well as a number of larger players. In terms of innovation, it implies that R&D and innovative activities can be seen as benefiting from huge economic drivers, leveraged by a fairly small number of firms, with diverse opportunities in small-scale initiatives [26].

Third, the chemical industry relies on public-private partnerships to conduct its innovative activities and to develop networking partnerships. Many works emphasise that internal R&D in chemicals is increasingly complemented by external links and knowledge, and that innovation requires the interaction between R&D capabilities and external sources of scientific and technological knowledge [27-29]. Such complementarities have led to the emergence of three types of networks in the chemicals: interfirms, university-industry and users-producers in specialty segments [5]. CIS4 data show that 44.9% of the chemical firms have collaborated with various actors in the innovative activities over the period 2002-2004.

A last but not least distinctive feature relates to the stringency of environmental regulation implemented in the chemical industry. Indeed, the type of regulation adopted in this sector takes the form of product bans that impede the use of harmful chemical inputs in the production process itself, and thus force the producers of chemical substances to seek for alternative substances and correlatively to change the traditional production practices, as well as the competences and the knowledge base. For example, the progressive phase-out of the major ozone depleters, such as chlorofluorocarbons (CFCs) and halons, corresponded to a product ban for the CFCs producers which had to search for substitutes. In this case Howes and al. [30] show how a stricter and more ambitious legislation could give an individual company (here Du Pont, one of the main CFC producers) within a sector an edge over competitors. They observe that Du Pont’s actions in response to the tighter regulation have paved the way for enhanced profits and also pre-empted further and possibly more severe controls by the regulators. Du Pont's research and patents for CFC replacements enable the firm to act first and to get a first-mover advantage. Such an example illustrates the ability of a stringent regulation to influence environmental innovations and to open new directions of research able to involve clusters of radical innovations of processes and products [13].

The fact that environmental regulation takes the form of product bans and prohibition in the chemical industry is linked to the very history of chemical activities and the suspicious image it reflects for the general public. Indeed chemical industry is energy-intensive, chemical products are largely created using non-renewable, petroleum-based resources as feedstocks and it is responsible for producing, using and transporting many harmful substances. As a matter of fact tighter regulations have often been implemented forcing the chemical industry to adapt consecutively to major industrial accidents (e.g. Bhopal, Three Mile Island, Seveso, AZF etc.) or to discoveries on the harmful effects of chemical substances (e.g. CFCs, VOCs). In spite of the existence of powerful lobbies, the question of the impacts of chemical substances upon public health is given more and more media coverage which creates an increasing public concern. Public health questions tend to have a significant influence upon consumer choices which reinforces demand pull effects. Moreover it represents a source of pressure forcing the chemical industry to adopt voluntary actions such as the Responsible Care Programme[14] or eco-management and audit schemes (EMAS). Such voluntary actions are part of the industry’s response in order to create a more secure set of relationships with the general public and with public institutions. All in all, consumers’

[14] Responsible Care started in 1985 in Canada and has spread to many industrialised countries (US and Europe). Such a programme embodies a public commitment to continuous improvement of health, environmental and safety performance, and to responding to public concerns about chemical products.

demand and government regulation in the form of product bans represent two forces able to push the chemical industry towards radical transformations.

Recently, an evolution in the regulation has put the emphasis on the prevention of pollution instead of remediation. In 1990, the Pollution Prevention Act in the US explicitly encouraged elimination of hazards at the source, thus giving birth to a new approach known as "green chemistry[15]" that challenges the way chemists are designing, producing and using chemical substances so far. In Europe, the REACH regulation[16] dedicated to the Registration, Evaluation and Authorisation of Chemicals is likely to reinforce the incentives to innovate in green chemistry. Indeed the REACH Regulation gives greater responsibility to industry to manage the risks from chemicals and to provide safety information on the substances, but also calls for the progressive substitution of the most dangerous chemicals when suitable alternatives have been identified. So in contrast to the automotive industry, we can observe a growing movement of the chemical industry towards radically new solutions which are based on a common frame such as illustrated by the twelve principles of green chemistry.

III.2 Patterns of environmental innovations and the moving towards "green chemistry"

In the same way as in the automotive industry, the major innovators in chemicals have shown great continuity in their innovativeness due to economies of scale and scope, cumulativeness and path dependency. Since much of the chemical industry is capital-intensive and based on economies of scale, large companies are typically slow to convert to new technologies. Private funding is mainly directed to incremental advance of existing approaches, such that the public portion of R&D funding is crucial to promote large-scale and radical technological shifts [31]. So important irreversibility effects remain that prevent the large shift of chemical firms towards green chemistry. Nevertheless the intensity of research and innovation in green chemistry is significantly increasing since the 1990s.

Green chemistry consists in an approach which aims at eliminating intrinsic hazard itself, rather than focusing on reducing risk by minimizing exposure. The development of green chemistry is intimately related to broad emerging trends in policy, regulations, industry initiatives, science developments, consumers' needs and societal concerns. It can be seen as a new style of thought that seeks to accommodate stake-holder interests in the model of 'doing science' [31]. In scientific terms, it has been posed as a scientific challenge in chemical process research, more precisely in alternative feedstocks, alternative solvents and alternative synthetic pathways. In that sense, it opens new directions of research and puts the grounds of a new technological paradigm in the sense of Dosi [7]. This new "green chemistry" paradigm is articulated in the twelve principles presented in table 1 in appendix. These principles offer a new model and a new pattern of solution of selected technological problems that explicitly integrate an environmental dimension in a preventive way. Moreover they combine environmental objectives with economic ones, in terms of costs and efficiency. For example, prevention of waste (principle 1) is also a way of decreasing costs and so increasing profit margin, while principle 2 seeks to increase the yields of reactions, and energy efficiency

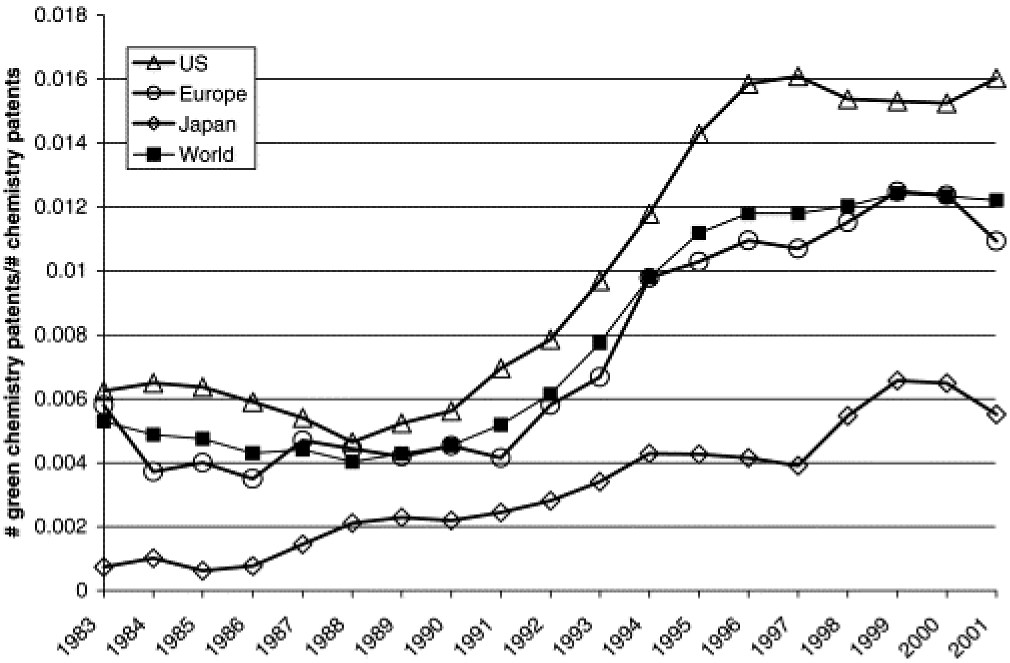
[15] For an overview of the more significant initiatives and instruments for the development of the green chemistry in US, see [27].

[16] It has been formally adopted on 18 December 2006 by the Council of Environment Ministers following the vote in second reading of the European Parliament on 13 December 2006. REACH has entered into force on 1 June 2007.

(principle 5) can reduce energy expenditures which represent about 9% of chemical product value. That is the reason why an increasing number of corporations are adopting green chemistry principles as an "environmental message" improving their image, but also as a way of strengthening their business and profits. This ability to combine environmental performances with economic objectives and competitiveness certainly explains why green chemistry is seen, in contrast to many previous initiatives, as a cooperative approach between industrial firms, government, experts and public laboratories. In the US, it is noteworthy that the 12 principles have been embraced by professional societies of chemistry and are flown as a banner on websites worldwide [31]. A significant movement on the front lines of research and education, but also in incentives and research programs of the Environmental Protection Agency, the National Science Foundation and the Department of Energy, and in the daily operations of company laboratories, is taking place illustrating the acknowledgement of the common selected principles by a community of scientific researchers and experts. In Europe, the adoption of the REACH regulation follows the same trend trying to put the basis of a radical shift in the knowledge base of the chemical industry.

Regarding innovations in green chemistry, Nameroff and al. [32] try to quantify the extent of adoption of green chemistry by using US patent data. Figure 4 shows the evolution of the number of green chemistry patents over the number of total chemistry patents (that is the sum of patents granted in the chemicals technology, polymer, plastic and rubber classifications). The ratio is calculated on the basis of a 3-year running average and shown for US, Europe and Japan. They show an increasing trend in the number of granted patents over the time period [1983-2001] even if different rates according to different time periods can be observed. The data also show that the chemical sector displays the highest number of green chemistry patents over 26 sectors (40,9% of the total number of green chemistry patents), exceeding the number of patents by the next sector by a factor of 3.6.

Figure 4: International comparison of patent activity in green chemistry (source: [32])



These results corroborate other indicators based on bibliometric data, searching on the phrase “Green Chemistry” in Scifinder Scholar, which stress that the number of scientific publications explicitly invoking the term “Green Chemistry” have grown exponentially over the past decade to a few thousand and increasing at a rate of several hundred per year [31]. According to the authors, the emergence of literature driven by the 12 Principles is to a large extent creating the knowledge base and tools to transform the craft of chemistry. Looking at the concentration of green chemistry patenting by sector, patent data also show that green chemistry activity appears to be particularly concentrated in universities and government agencies [32].

This set of results points to the following patterns of environmental innovations in the chemical industry, especially regarding what can be observed in the automotive industry. First, the continuous and generalised increase in patent activity in green chemistry illustrates the moving towards a new green paradigm which grounds on a common frame such as illustrated by the twelve principles. Second, universities and government agencies are a major source of innovation in this emerging area of green chemistry research. As underlined by Nameroff and al. [32], public research by universities and government sectors is decisive in fostering these radically new technologies. Third, in spite of strong irreversibility effects related to the dominant petrochemical paradigm, the main established firms have a substantial economic interest in green chemistry to ameliorate downstream costs given the social costs of coping with technological hazards and pollution involved by their activity. Thus by avoiding the generation of pollution in the first place, firms can reduce the cost of regulation, materials use and waste disposal and significantly reduce the risks associated with manufacture and use of chemical processes and products. Finally this case shows that a stringent regulation applied to a science-based technological regime, which is characterized by relatively strong industry-university collaborations, is able to pave the way for a paradigmatic change.

Conclusion

This paper provides an analysis of environmental innovations based on a sectoral approach. Our main argument is that environmental innovative activities of firms can take different forms which are determined by the features of the technological regime, the instruments of environmental policy and the conditions of demand. We focus on the cases of the automotive and chemicals industries, with particular emphasis on the question of radical innovations and paradigmatic changes.

The case of the automotive industry is mostly characterized by a persistent dominant design which is continuously improved through incremental innovations. In spite of the existence of various competing technologies for LEVs, lock-in effects on the internal combustion engine vehicle are very strong and firms try to exploit complementarities between alternative engine technologies in order to build a gradual path towards radically new engine technologies. This tendency towards incrementalism is also due to the difficulty to combine environmental objectives with non-environmental criteria, particularly the price of vehicles, their power, security, comfort and range of use which are the most important criteria for consumer choices. Moreover the flexibility of regulation, the coordination failures between policy instruments, as well as the lack of a consensus on the most promising technological option, tend to sustain such an incremental path of development.

The comparison with the chemical industry enables us to concentrate on the question of paradigmatic changes by focusing on green chemistry. The development of green chemistry is related to broad emerging trends in policy, regulations, industry initiatives, scientific research, consumers' needs and societal concerns. It opens new directions of research that seek to accommodate stake-holder interests and that put the grounds of a new technological paradigm. We emphasize that the science-based character of the chemical industry, in particular the role of public-private partnerships in research, as well as the stringency of regulation with product bans, and the public pressure linked to consumers' concerns and to the suspicious image of the chemical industry, create favourable conditions to a transition towards a new green paradigm. It also shows that the definition of common selected principles by a community of scientific researchers and experts, which combine environmental and economic objectives, is a necessary condition to the development of radical environmental innovations and paradigmatic changes.

Appendix: Table 1: The twelve principles of Green Chemistry

1) Prevent waste: it is better to prevent waste than to treat or clean up waste after it is formed.
2) Atom economy: synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product
3) Less hazardous synthesis: wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or ,o toxicity to human health and the environment
4) Safer chemicals: chemical products should be designed to preserve efficacy of function while reducing toxicity
5) Safer solvents and auxiliaries: the use of auxiliaries substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used
6) Energy efficiency: energy requirements should be recognised for their environmental and economic impacts and should be minimised. Synthetic methods should be conducted at ambient temperature and pressure
7) Renewable feedstocks: a raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable
8) Reduce derivatives: unnecessary derivatisation (blocking group, protection/deprotection, and temporary modification of physical/chemical processes) should be avoided whenever possible
9) Catalysis: catalytic reagents (as selective as possible) are superior to stoichiometric reagents
10) Design for degradation: chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products
11) Real-time analysis for pollution prevention: analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances
12) Inherently safer chemistry for accident prevention: substances and the form of a substance used in a chemical process should be chosen so as to minimise the potential for chemical accidents, including releases, explosions, and fires.
Cf. the US Environmental Protection Agency website: http:/www.epa.gov/greenchemistry/

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