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Environmental Innovation: A Controversial Doctrine

This chapter provides a critical analysis of the concept of environmental innovation. It therefore has two objectives. It aims, on the one hand, to present what can be designated as a doctrine, that is, elements of knowledge related to environmental innovation which, as demonstrated by part of the academic literature dedicated to this and a good number of deciding factors, now appear to be stabilized. This chapter intends, on the other hand, to question this doctrine by showing that, for all the points dealt with, many questions remain unanswered. This doctrine is based on three main elements – definition, typology and determining factors – which will be treated successively in this chapter in three sections.

In the first section, therefore, we will consider the definition of environmental innovation. The questions underlying this development will be to know whether it is possible to distinguish a generic innovation from an environmental innovation. We will thus return to the origins of this notion, its diffusion and the discussions around it within economic theory at the start of the 1970s up to the present. While the debate surrounding the first report of the Club of Rome (1972) partly relates to the perspectives created by technical progress – economists from the University of Sussex, involved in this controversy, play a crucial role in this theorization of environmental innovation – a settled definition would have to wait until the end of the 1990s and the start of the 2000s. However, questions remain with respect to what constitutes an environmental innovation. The judgment that can be made about this is effectively and necessarily *ex post*.

To extend this thought process, we will look at the typology of environmental innovations in the second section. As is the case with generic innovations, a distinction is usually made between environmental innovations as a function of the degree of change that they bring about. The first form of innovation is incremental and is mainly based on “end-of-pipe” technologies. The second form of innovation is known as “radical”, because “clean” technologies review what already exists by proposing a preventive approach. A third form of innovation is known as “systemic”, which is illustrated in the circular economy approach with its flow loops of energy and materials. We will add a fourth form of innovation, complementary to the three previous, based on the notion of eco-efficiency. Its problem is perhaps just another way to designate increases in productivity, susceptible to lose all environmental specificity.

A third and last section will focus on the drivers of environmental innovation. What is it that promotes or slows down the emergence of environmental innovations and their technological clusters? The successive phases of prosperity and economic crisis represent, in theory, an essential point in understanding the appearance of innovations, even those which are environmental, as much on a macro-economic level as within companies. However, in a context where practices in certain sectors should be more respectful of the environment, the dominant designs in place can no longer exclusively arise from an economic process. This is why the theory of transition management presents itself as equipping public policies and thus facilitating the transition process. In essence, doctrine (found among evolutionist economists as much as among ecological economists) today identifies a trio of consumer-driven incentives for the socio-technical regime in place and for public policies pertaining to innovation and the environment. Authors agree to acknowledge the specificity of environmental was innovation in the latter, which echoes the now-famous “Porter hypothesis” relating to the opportunities for competition that the environmental constraint would provide. Without removing all meaning from environmental policies, we can, however, note that in a situation characterized by what Godard [GOD 93] called a “controversial universe”; it is in fact the state of technology that is likely to determine what the environmental problem is. Such causality, such as the presence of rebound effects, disturbs the meaning of the concept of environmental innovation.

1.1. Progressive conceptualization of "environmental innovation": a journey back through 40 years of controversies

This section is dedicated to tracking the progressive conceptualization of the notion of environmental innovation. Taking this into account, we have tried to divide debates pertaining to understanding of this special reality that is environmental innovation into time periods, from the beginning of the 1970s up to the present. The decade of the 1970s is the one which highlights contemporary recognition of the environmental problem. From the outset, as evidenced by the controversy surrounding the first report of the Club of Rome (1972), the role of technology in the interaction between societies and the environment was central to the discussion (see section 1.1.1). The pessimism of some opposed the optimism of others, a division which persisted in the decade of the 1980s, notably by means of what is known today as "rebound effects". However, beyond macrosocial thinking, in which mythology resonates (see the recurrent invocation of Prometheus) and which also marked this era, innovation which is more respectful of the environment was also characterized by the approaches of engineers who wanted to be more pragmatic (see section 1.1.2). In the 1990s, which now subscribed to the sustainable development perspective, significant schools of thought (Neo-Schumpeterian, ecological economics, etc.) took hold of this problem of environmental innovation. This decade is also marked by the appearance of articles by Porter and van der Linde [POR 95a, POR 95b], which, according to the "Porter hypothesis", provided what still constitutes today one of the main elements of the doctrine relating to environmental innovation (see section 1.1.3). During the 2000s, theorization efforts continued and the need for a summary arose. Thus, a number of authors (Rennings, Kemp, Van den Bergh) sought to assemble all the work carried out in a single doctrine, one part of which is found in the very definition of environmental innovation itself. The 2010s bore witness to standardization of the concept of environmental innovation, evidenced by the indicators and databases amassed by large international public institutions and the creation of specialized academic journals (e.g. *Environmental Innovation and Societal Transitions*). However, at the same time questions and doubts remain from an academic point of view about the meaning and applicability of this notion (see section 1.1.4).

1.1.1. *Environmental concerns and innovations: the first proposals of economic theory during the 1970s*

1.1.1.1. *"Generic" innovation, creative destruction and the economic crisis*

The neoclassical school of thought has for a long time considered technological progress and innovation as elements which are exogenous to the economy and to growth [GUE 12, p. 421]. The function of neoclassical production is considered as a group of given optimal technical possibilities, within which the producer selects the best technical combinations as a function of the prices of inputs and outputs. The choice of these optimal technological possibilities depends above all on maximizing profit according to "perfect competition" conditions. Amendola and Gaffard [AME 88] justifiably criticized this approach which focuses on "the effects of the change on the relevant magnitudes of the economy (productivity, employment, etc.) from the comparison of the feature of its productive structure before and after the change" [AME 88, p. 1], and insists on the fact that "the point arrival of the process of change – that is, on the configuration of the productive capacity if the economy (of the firm) that results from the adoption of a given technological advance and is uniquely determined by the characteristics of the latter" [AME 88, p. 1]. We thus envisage technological progress as an automatic update of the optimal technological possibilities, but nothing had yet been said about the process of creation, selection and optimization of these techniques.

However, in his book *Industry and Trade*, Marshall [MAR 19] already upheld that technologies have endogenous characteristics and that technological change is conditioned by institutions and socio-economic contexts. It is no surprise that these characteristics were of particular interest to Schumpeter at the beginning of the 20th Century. He identifies an entrepreneur[1] as someone who combines technologies in such a way as to generate profit. This profit exists thanks to innovations; however, in order to obtain it, three stages are necessary. First, the entrepreneur develops an invention arising from the ingenuity and mobilization of skills. In order to advance beyond the prototype stage, it will only become an innovation if it is made available to consumers in a market. Once it has been made available via a trading process, the entrepreneur will benefit, or not, from diffusion of

1 For Schumpeter, an entrepreneur is not an inventor, but rather a person who succeeds in combining the expertise of others in order to bring his own ideas to fruition.

their innovation. In actual fact, Schumpeter [SCH 39, vol. 1, p. 84] proposed a very broad definition of innovation: “doing things differently” in the realm of economic life. According to Schumpeter, these three stages – invention, innovation and diffusion – have a direct influence on a technological change which can only be studied from a dynamic point of view. This dynamic is characterized by a process of “creative destruction” which “incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one” [SCH 42, pp. 121–122]. According to this viewpoint, we are no longer in the situation where an economic agent makes decisions depending on a set of equilibrium prices. On the contrary, Schumpeter believes that technological change results from grouping these innovations together and will influence the economic system in place.

He also indicated that new innovations appear in clusters [SCH 42]. These clusters consist of five types of innovation [SCH 34, p. 66]. An innovation can be an “introduction of a new good – that is, one with which consumers are not yet familiar – or of a new quality of a good”. It can be the “introduction of a new method of production that is one not yet tested by experience in the branch of manufacture concerned; which by no means needs to be founded upon a scientifically new discovery, and can also exist in a new way of handling a commodity commercially”. Innovation is also presented as “the carrying out of the new organization of any industry, like the creation of a monopoly position (e.g. through trustification) or the breaking up of a monopoly position”. An innovation can still be the “opening of a new market that is a market into which the particular branch of manufacture of the country in question has not previously entered, whether or not this market has existed before”. Finally, the last type of innovation: “The conquest of a new source of supply of raw materials or half-manufactured goods, again irrespective of whether this source already exists or whether it has first to be created”. These innovations, once combined, form an “innovation branch” and lead to both stochastic and systemic effects on technological change.

Technological change influences our society on several levels. On a global scale, the notion of a “socio-technical paradigm” appears, which, according to Dockès [DOC 90, pp. 39–40], is “a way of thinking about production in the wider sense [...], that is, the social, economic and technological organization of production shared by all entrepreneurs and ‘decision makers’ [...] and which tends to extend to the entire population in question”. This includes a variety of production systems and possibilities, meaning that several types of innovation clusters coexist, opposing each other, in order to respond to consumer requirements. These overall transformations depend on existing and emerging techno-economic paradigms. Reinforcing the concept of Nelson and Winter's [NEL 82] "general natural trajectory", Freeman and Perez [FRE 88] considered that "changes involved go beyond engineering trajectories for specific product or process technologies and affect the input cost structure, and conditions of production and distribution throughout the system" [FRE 88, p. 47]. Here, the emergence of innovations in the face of pressure from competition is conditioned by questions of technical feasibility, expertise and economic viability.

Dosi [DOS 88, p. 1127] explained at a simpler level that the technological paradigm, combining practices and schools of thought, or "patterns" in his words, guides innovators towards the resolution of problems in a complex world. Malerba and Orsenigo [MAL 96] added weight to this suggestion by highlighting the existence of entrepreneurial technological regimes in which new companies and existing companies are brought face to face. This encounter can be seen in two ways. First, new companies compare their new ideas to those of companies in the past. Then, the technological regime implemented by companies in the past imposes entrance barriers, in such a way as to force new arrivals to use existing innovations. In addition, these interactions between innovation clusters have the capacity to profoundly modify the development of economies and societies, even going as far as to cause crises.

1.1.1.2. *An overall vision of cycles of innovation and growth*

Schumpeter wanted to understand the impacts that these innovation clusters have on technological change in the long term [SCH 42]. He identified several phases within this economic movement. The first is a phase of prosperity, a growth phase, during which a great number of innovations are introduced. While this is going on, industry leaders throw themselves at new opportunities, thus modifying their strategies and their practices. Diffusion of these innovations reaches a state of maturity from the moment when these economic agents adopt it to the point of causing a reduction in prices. This is when a second phase comes into play, a recession phase, where some industry leaders are not capable of survival and adaptation under pressure from competition. The third phase, which follows, brings about a depression that halts the spirit of innovation. Entrepreneurs who survive are those who have adapted the most in opting for new methods, new learning processes and creativity: this is the precursory sign of a new era of prosperity.

These periods of time follow one after another, alternating between recession and prosperity, prosperity and recession, taking the shape of economic cycles and forming part of the long-term picture. Kondratieff's work also allowed Schumpeter to specifically study their nature and to also reveal long economic periods characterized by the emergence of particular technologies, periods ranging in length from 40 to 60 years. Thus, an entire economic story is being told, from the industrial revolution to the present day.

1.1.1.3. *Criticism of* The Limits to Growth*, or when future ecological concerns are resolved by machines*

The economic crisis of the 1970s and the first concerns about the environment was the time to go back to basics after several decades of a dominating economic theory in favor of infinite growth. This is what *The Limits to Growth* seeks to do, which was published by a team at the Massachusetts Institute of Technology (MIT) directed by Meadows [MEA 72]. The Club of Rome, which requested this study, makes an appeal for us to consider a scenario different to that of the pursuit of exponential growth in the long term. A certain type of pessimism is expressed with respect to technological progress that is also found, in the same era, in the work of the ecologists Ehrlich and Holdren [EHR 71]. They strongly advocate a formula rooted in the Malthusian culture: IPAT[2]. This equation gives an account of the interactions between mankind and its environment, and it bears witness to the fact that, whatever the way in which societies modify their use of technology, the population will in any case have an effect on the environment.

The controversy was ferocious. It came from, among other places, a group of researchers at the University of Sussex, who subsequently became reference figures in the transition to sustainable development, and who published the work *Thinking About the Future: Critique of "Limits to Growth"*, also entitled *Models of Doom: A Critique of The Limits To Growth* [COL 73], translated into French under the title *L'Anti-Malthus* [COL 74].

2 The environmental impact (I) would be the outcome of a union between the population (P), affluence (A) and technology (T).

While these authors express genuine respect for the work carried out by the Meadows team, the criticisms that follow are strong, particularly with respect to the role of technology in this report. The first criticism concerns the choice of hypotheses based on assumption and the "relative disregard for economics and sociology" [COL 73, p. 7]. The second criticism concerns the role played by growth, criticized so much in the Meadows report. According to the researchers at the University of Sussex, the "Growth versus No-Growth" [COL 73, p. 10] debate has become quite a sterile discussion, a kind of "Tweedledum/Tweedledee" question, in their own words (*ibid.*), which tends to ignore questions relating to what growth of production comprises, and to the distribution of the outcomes of growth. Far from condemning growth, the University of Sussex team believes that a certain type of growth is entirely compatible with the overabundance of environmental problems and could even resolve them. While the main critique concerns the non-neutrality of the theoretical model used [COL 73, p. 7], the authors highlight the presence of a pessimistic ideology in this first report [COL 73, p. 11]. The idea is that technological progress is under-estimated, and one of the major hypotheses put forward in the Meadows report is that its rate remains constant [COL 73, p. 10]. Julien, Freeman and Cooper highlight that "this implies the denial of the possibility of that continuous technical progress which is (probably correctly) taken for granted in the capital sector. Similarly in relation to pollution, the possibility of steady improvement in anti-pollution technology is excluded. Moreover, widespread and heavy capital investment in anti-pollution technologies in industry would in the model perversely lead to an increase in pollution and an acceleration of growth with constant IGOR. In the real world, it would lead to a reduction in pollution, and probably a slowdown of growth and a rise in the capital/output ratio" [COL 73, p. 72]. On the contrary, as emphasized by the team of researchers from the University of Sussex, all possible means should be implemented to accelerate and turn technological progress into a hope for the future[3]. These authors insist on "[...] the inclusion of technical progress in the MIT model

3 Pollution could decrease as production increases. In Chapter 12 of [COL 73], Sinclair maintains that, in general, England was a much dirtier place one or two centuries ago than it is today, despite current production levels being much higher. He also demonstrates that the introduction of anti-pollution legislation has produced real effects by reducing the apparent absolute levels of pollution while allowing greater production, and also that the capacity of society to impose social controls to reduce industrial emissions (including pollution) has improved, although perhaps in an unequal manner, since the 19th Century [COL 73, pp. 175–192].

in sectors from which it is omitted has the effect of indefinitely postponing the catastrophe which the model otherwise predict" [COL 73, p. 10, ss5]. Some solutions are even proposed by these authors, such as recycling and the reduction of waste [COL 73, p. 35]. This hope remains somewhat naïve[4], because acceleration of production can cause side effects, like the use of pesticides in agriculture which was initially intended to slow down the effects of the decreasing yields of the ground [COL 73, p. 84]. Moreover, if just one idea were to be noted, it would be the impossible separation between, on the one hand, the industrial world, consumption, technological progress and pollution, and on the other hand, recognition of a complex world [COL 73, pp. 84–85 & p. 89]. These authors then discuss and expand on assumptions in the Technical Report of the Meadows report. First, pollution arises not only from industry and agriculture, but also from consumer behavior. Second, "the amount of accumulated pollution is determined by the integration of the difference between past rates of pollution appearance and pollution absorption" [COL 73, p. 80], however, this evaluation is relatively arbitrary [COL 73, pp. 81–82]. Third, the time taken for pollution to be absorbed by an environment will depend on the land areas and on the environment concerned. This is why the authors point out that "In any area where firm information is scarce, an operational or predictive model is bound to be more than usually biased by subjective pre-conceptions. The present authors' views are that the way in which resources are at present being exploited could lead to disaster (although not necessarily on a world scale); that this is by no means a necessary outcome of the growth in the use of technology; and, in addition, that there is no possibility of adequately supporting the existing, let alone projected, population of the world without industrial development in countries which do not yet have it. Having said this, the pollution sub-system in World 3 appears to us to have the following strengths and weaknesses" [COL 73, p. 82]. Fourth, taking time into account in the assimilation of pollution: this perspective is still relatively complex since certain types of pollution can be more easily absorbed than others and their

4 For example, Marstrand and Sinclair [MAR 73, p. 83, §3] criticized the Meadows report concerning the nuclear sector by underlining that "In drawing other examples from an area mentioned in *Limit to Growth*, nuclear power production, it should just be noted that the work cited is entirely polemical and associated with such energy sources are extremely difficult to fit to the model assumed by Meadows. For example, the rupture of the containment shell of a nuclear reactor in the most disastrous case would have high, immediate and lethal impact at a local level followed by serious long-term effect." The lack of hindsight of the authors concerning the Fukushima nuclear disaster (2011) and the Chernobyl disaster (1986) must be noted.

dissemination on the earth's surface is unequal. Giving preference to technologies aimed at environmental conservation is, evidently, a complex subject which requires further clarification. This is why the work of Cole *et al.* presented two types of technology, one "ordinary" and the other "required for pollution control" [COL 73, p. 88], but, as the authors specify, "At any given level of technology, there are bound to be diminishing returns to abatement expenditures. The level of environment quality attained will depend upon the willingness and ability of society to pay for it, and on the state of abatement technology" [COL 73, p. 87]. Moreover, as explained by these same authors, the cost of implementation does not appear to be a problem in itself. They quote that "the costs during the first half of this decade [the 1970s] will have only a relatively modest effect on the ability of a nation to satisfy any other urgent needs of a society. The expected pollution cost is, in general, considerably lower than some other welfare-oriented expenditures" [COL 73, p. 87]. On the contrary, if these technologies can only emerge where the consent to pay exists, who will the winners and losers be? What about the role of public authorities in the management of conflicting relations which could escalate to the point of imposition of new forms of innovation?

1.1.1.4. *Environmental innovations and technologies pertaining to prometheus in the context of the oil crisis*

In the context of the "oil crisis" which broke out in 1973 and led to questions surroundings economic growth, Georgescu-Roegen, author of the major reference work *The Entropy Law and the Economic Process* [GEO 71], decided to enter into the controversy whipped up by the first report of the Club of Rome. He moved closer to Meadows and to his colleagues at the MIT [LEV 10], and proposed to help them answer criticisms directed at to their work by neoclassical economists such as Solow, Nordhaus and Beckerman [NOR 94]. A production system, according to Georgescu-Roegen, is above all a system of transformation of materials and energy which aims to generate economic value and "zest for life", as described by the philosopher Bergson. Now, he continues, standard economic theory leads us to believe that "engines, homes and even living organisms (if they could exist at all) would never wear out. […] In such an imaginary, purely mechanical world, there would be no true scarcity of energy and material" [GEO 75, p. 353]. This collaboration with the MIT team, as referenced in his article "Energy and Economic Myths" [GEO 75], only lasted for a certain time. His “bio-economic program”[5] was in fact, as explained by Levallois [LEV 10], perceived as “too radical” by the Meadows team. To his great dismay, Georgescu-Roegen considered that his former partners had quite simply “taken a direction that is almost identical to that of standard economists, who claim that with their models and their computers they can bring about the economic New Jerusalem” [LEV 10, p. 2276].

Developing his thoughts further, Georgescu-Roegen then concentrated on the path opened by researchers from the University of Sussex [COL 73]: in particular, conservation of the environment through the possibility of finding technological solutions. It is of some significance to know that Georgescu-Roegen considers his true spiritual master to be Schumpeter, whom he met in the United States in the 1930s – they even planned to write a book together. Georgescu-Roegen identified four broad categories of innovation. The first is an innovation of economy, focused on the efficient use of resources. It seeks to “[…] achieve a net economy of low entropy be it by a more complete combustion, by decreasing friction by deriving a more intensive light from gas or electricity, by substituting materials costing less in energy for others costing more, and so on” [GEO 75, p. 362]. This objective is based on “the discovery of new processes of use of low accessible entropy” (*ibid*.). The second innovation category involves substitution innovations, which radically modify the way in which a problem can be solved[6]. A third category represents product innovation. Finally, a fourth category is based on energy substitution.

What then of “technology clusters” – that other Schumpeterian concept? According to Georgescu-Roegen, the history of humankind and, in particular, the history of our social relations is marked by the appearance and

5 In the chapter “From Thermodynamics to Ecology and Ethics” in his book *The Entropy Law and the Economic Process* [GEO 71], Georgescu-Roegen advocates the requirement to develop a minimal bio-economic program “[...] which should not only take the destiny of our contemporaries into consideration, but also that of future generations. Economists have preached in favor of maximization of our own benefits for too long. It is high time that realize that the most rational path to take consists of minimizing regrets. Every weapon, just like every big car, means less food for those who are hungry today, and fewer tools for certain future generations of humans (however far-off they may be), similar to ours” [GEO 71].

6 To illustrate his words, the author takes the example of the transition from the catapult to the use of gunpowder, which had the same objectives, but was based on a completely different kind of technical solution.

adoption of what is denoted as "Promethean technologies". The first Promethean technology corresponds to the discovery of fire. This "Promethean gift", as highlighted by the author, has resulted in civilizations placing wood at the heart of their economic developments. Its overexploitation has brought about its loss – and led Georgescu-Roegen [GEO 84, p. 30] to refer to the "wood crisis" which affected the West in the 17th Century. This brought about the second Promethean technology, "Prometheus II", based on steam engines[7] that transform heat into mechanical energy, aided by the combustion of fossil fuels such as oil and coal. The oil crisis in the 1970s, according to Georgescu-Roegen, simply sounded the death knell for the exploitation of fossil fuels. Hence his question: "The problem now is whether a new Prometheus will solve the present crisis as Prometheus II solved that of the Wood Age" [GEO 84, p. 30]. The solution appears to come from the use of solar energy and "can only be a new age of wood, different even so from the past, because our technical expertise is more extensive today. It could not be otherwise given that all evolutionist process is irreversible" [GEO 79, p. 213]. While awaiting the arrival of this "Prometheus III", which would propel humanity towards a new era of prosperity, the author makes a recommendation to "minimize regrets" and calls on politicians to be prudent, in particular making efforts to play on the demand for goods and services, a perspective of limitation on requirements that is denoted today as "degrowth", and idea which goes against the grain of the perspective advocated by the team of researchers at the University of Sussex [COL 74].

For the next nearly 10 years, Georgescu-Roegen decided to dedicate the end of his life to the identification of "Prometheus III" and to its characterization. His article entitled "Feasible recipes versus viable technologies", published in 1984, thus makes the distinction between a "feasible technology" and a "viable technology" [GEO 84]. Tempering the optimism of the era with regard to technological progress, he believes that the technologies aimed at environmental conservation, the "feasible technologies", are not necessarily viable. According to him, "a technology is viable if and only if it can maintain the corresponding material structure and necessarily the human species" [GEO 84, p. 29]. A helpful example of the truth of viability is in a living organism or a biological

7 The instructions for the steam engine were invented by Heron of Alexandria [LAN 78, p. 28].

species. What does appear necessary to highlight is that each technology is supported by at least some fuel – by a small amount of resources taken from the environment – but that no technology can create its own fuel. On the contrary, a non-viable technology is a "[...] technology in which the only principal tool is a hammer that hammers the same type of hammers from freely found stones. The same hammer is used to crack some very hard nuts which are the only food of the population. If one hammer cannot last long enough to hammer another hammer *and* crack a specific amount of nuts to maintain the population, then that technology is not viable" [GEO 84, p. 29].

1.1.2. *Involvement in environmental technologies and green growth in the 1980s*

1.1.2.1. *Prometheus prostrated or unchained? Seeking new paths for growth*

Following the controversy created by *The Limits to Growth* and *Models of Doom: Critique of "The Limits to Growth"*, Georgescu-Roegen was not the only economist to invoke Prometheus. Several articles were published during the 1980s which showcased a Prometheus that is prostrate, as did Onuf [ONU 84] or, on the contrary, unchained, as according to Freeman [FRE 86]. Should we be optimistic or pessimistic with regard to the capacity of technology to harmonize relations between the economy and the environment? Freeman, the main author in Neo-Schumpeterian theory and member of the University of Sussex research team, reminded us that "MIT modelers and certain Marxists have made the error of confusing the limits of a particular paradigm and the limits of growth of the entire system. In the case of MIT, the limits were seen as an absolute hindrance to the continuation of economic growth" [FRE 86, p. 26]. According to this perspective, the end of capitalism is nigh, but history has often demonstrated the importance of "social adaptation [...] of the system". This adaptation is based on the way in which technologies will be perceived and their orientation chosen, and allows us a glimpse at the possibility of obtaining growth integrating qualitative criteria that will be found later under the name of green growth. This is why Freeman condemns Onuf's technological optimism who sets his hopes on information technologies, which seem to be a technological "control" technique [FRE 86, p. 34]. Although past errors must be avoided, Freeman emphasized the risks of a society based on "well-meaning fascism" [FRE 86, p. 35]. To refute this radical transition, the author indicates that "it is very rare for the reaction to be a rapid adoption of revolutionary techniques and the introduction of new products". On the contrary, he goes on, "economic sectors can protect each other and perpetuate with existing products and methods exploited to the maximum, and, even if there are now ones, they will still belong to the old paradigm" [FRE 86, p. 33].

1.1.2.2. *Technological optimism in the face of the rebound effect: Returning to the Khazzoom–Brookes theorem*

These bitter discussions were more heated when it became a question of studying the long-term effects of technologies that are more respectful of the environment. The fight against waste of energy and natural resources became the priority of the day to counter economic and oil crises [LOV 84]. However, the optimism of Lovins with regard to the positive effects of energy optimization was rapidly confronted by that of Khazzoom [KHA 80]. The latter demonstrates that, despite the implementation of waste prevention policies and adjustment and diffusion of more efficient technologies from an energy point of view, global energy consumption has not decreased, very much the contrary. Subsequently, Khazzoom concluded that the increase in efficiency of technologies "will result not in a reduction of demand, but rather in an increase in demand that will require a major price hike to arrest it" [KHA 87, p. 85]. This paradox, known as a "rebound effect", and directly attributed to the behavior of economic agents, was previously studied on a global scale by Jevons in his book *The Coal Question*: *An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines* [JEV 65]. In this book, Jevons takes the Malthusian theory of geometric progression and extends it to national coal consumption, leading him to predict that in the long term, once resources are exhausted, the British Empire, whose economic strength is founded in coal, would collapse.

Khazzoom stated that a technological goal must be observed from two points of view. The first is that of the technician, who improves the efficiency of technologies by offering as much, or more, satisfaction with the least possible resources. The other is the economic dimension and more particularly its price elasticity, which directly influences consumer behavior towards it. Supported by a mathematical model based on households in the United States, Khazzoom demonstrated that electric heating in housing, in spite of requiring two-thirds less energy, induces a much higher energy consumption, due to the price elasticity of electricity [KHA 86]. Then, he reinforced this point by reporting that "when my car's efficiency triples, the gasoline required to meet my old travel demand is a third of what it used to be, I can now also travel three miles for the price of one – which is equivalent to saying that the price of gasoline has dropped to a third of what it used to be. And, so long as my price elasticity of demand is not zero, the lower gasoline price, implicit in the higher car efficiency, will exert an upward pressure on the demand for travel" [KHA 87, p. 86]. In 1988, Lovins defended himself against this argument by proclaiming that the price elasticity of the requirement for a service is very difficult to evaluate and that this Jevons/Khazzoom paradox cannot be generalized. Although this controversy again reflects the tension between technological optimism and pessimism, a consequence of this is that technology influenced by the effects of the "law of markets" risks accentuating the environmental problem rather than avoiding it; and therefore risks integrating something into a new growth model that would cause it to fail. The theory of Jevons and Khazzoom therefore encourages us to consider technological movements with the greatest possible prudence.

1.1.2.3. *From recognition to introduction of the first forms of evaluation, and of environmentally friendly technologies*

The OECD has concerned itself with the idea of technologies with an environmental mandate since the beginning of the 1970s. By the 1980s, therefore, there were sufficient statistical data to understand this object and the movement which accompanied it. Despite the economic crisis, two large countries set out on this path: Germany and the United States. Germany was a pioneer in this matter since, in the space of four years from 1980 to 1984, its expenditure on more environmentally friendly technologies increased by nearly 200% [HAR 85, p. 2]. North American efforts were less robust, with the same expenditure increasing by about 50% between 1980 and 1990 [OVE 81, OVE 86, OVE 88]. Lanjouw and Mody [LAN 96] pointed out the reduction in this public expenditure implemented by the Reagan government. In Table 1.1, we note that expenditure on "end-of-pipe" technologies had the best deal in these "process changes", whereas expenditure on clean technologies took second place; this is a trend, according to these authors, which is repeated in other OECD countries within this same period [LAN 96, p. 556]. In other words, periods of budgetary restriction at that time had rather encouraged implementation of technological solutions leading to a low level of change.

Theme/years		1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Air	Millions of USD	2,106	1,990	1,569	859	888	1,030	1,144	n/a	1,143	1,313	1,796
	"End-of-pipe" (%)	84	86	85	84	80	70	64	n/a	73	–	71
	Process change (%)	16	14	15	16	20	30	36	n/a	27	–	29
Water	Millions of USD	1,146	933	839	684	760	811	812	n/a	967	1,317	1,859
	"End-of-pipe" (%)	87	87	86	88	83	88	82	n/a	83	–	78
	Process change (%)	13	13	14	12	17	12	18	n/a	17	–	22
Solid waste	Millions of USD	251	239	187	165	211	398	270	n/a	547	480	573
	Hazardous (%)	–	–	–	31	36	66	49	n/a	54	–	40
	Non-hazardous (%)	–	–	–	69	64	34	51	n/a	46	–	60
Total	Millions of USD	3,503	3,161	2,595	1,708	1,859	2,239	2,226	n/a	2,567	3,111	4,228
	Total percentage of investments in terms of environmentally friendly technologies	5.0	4.4	4.1	3.3	2.9	3.4	3.7	n/a	4.2	4.4	5.9

Table 1.1. *Expenditure on measures for the reduction of pollution in the manufacturing sector in the United States, according to reduction method, 1980–1994, in millions of USD (source: Lanjouw and Mody [LAN 96, p. 556][8])*

8 Data for the year 1987 are not available.

1.1.2.4. *From the implementation of technologies with an environmental mandate: a new challenge for process technicians*

The end of the 1980s is marked by the publication of the Brundtland report [WCE 87] and by the diffusion of the notion of sustainable development. Chapter 8 of the report, entitled “Producing more with less,” is truly programmatic and normative. It is a reference in the business world. As solid evidence, it inspired the concept of eco-efficiency put forward by the World Business Council for Sustainable Development a few years later [SCH 92]. But, while waiting for management specialists to take full hold of this objective, at the end of the 1980s clean and preventive technologies were still the skills specifically of technicians and engineers. Taking this into account, Overcash [OVE 88] suggested a classification of environmental impacts and solutions suitable for production systems, by identifying two concerns: reducing waste and eliminating use of hazardous materials. Two types of technologies can resolve these problems: those which bring about significant changes to the production system itself, and those which develop strategies for recycling and waste repurposing. These two approaches can modify the production system in four ways. First, the waste can be incinerated to produce energy. Second, thermal treatments allow what was not previously recyclable to be made so. Third, chemical, physical and biological treatments allow waste to be assimilated by the earth. Finally, composting presents itself as the last solution. While these four technical solutions are interesting, Overcash ponders the question of the impacts on the environment which arise from this modification of production systems.

At the same time, another viewpoint, presented this time by engineers, came to light with the publication of the article by Frosch and Gallopoulos, “Strategies for Manufacturing”, published in a special edition of the journal *Scientific American* called *Managing Planet Earth* [FRO 89]. These two engineers from General Motors proposed an industrial ecology which includes all strategies reducing the negative impacts of production on the environment, by taking inspiration in particular from nature. They observed that “[today’s] industrial operations do not form an ideal industrial ecosystem, and many subsystems and processes are less than perfect” [FRO 89, p. 146], and proposed the following: “[...] Remembering that people and their technologies are a pan of the natural world may make it possible to imitate the best-working biological ecosystems and construct artificial ones that can be sustained over the long term" [FRO 89, p. 152]. More precisely, these authors believed that technologies with an environmental mandate represent true opportunities for companies, combining competitiveness with environmental protection. Using proposed means which are similar to those described by Overcash, "[…] the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process" [FRO 89, p. 7]. These proposals and the viewpoint that they support would soon become a discipline, "a science of sustainability", as Diemer and Labrune [DIE 07] remind us, which, according to Erkman [ERK 98, p. 10], claims to be "[...] essentially analytical and descriptive, aim[ing] to understand the dynamic of flows and stocks of materials and energy related to human activities, from extraction and production of resources to their inevitable return, sooner or later, to biogeochemical processes". The foundations of industrial ecology were rounded off by contributions from Ayres and Weaver [AYR 98], more recently in the manual *A Handbook of Industrial Ecology* [AYR 01]. The latter insist on the need to dematerialize production and to recycle materials and energy, with the aim of increasing productivity by fighting against waste, a consequence of pollutants and devoid of all economic values.

1.1.3. *Diverse theoretical appropriations of the concept by economic sciences from the 1990s onwards*

1.1.3.1. *From clean technology to environmental innovation: Neo-Schumpeterian appropriation of the concept*

The conditions for appearance and diffusion of "clean" technologies caught the eye of evolutionist economic theory. Kemp and Soete [KEM 90, KEM 92] were the first authors from this school of thought to take an interest in the subject, in particular through their article, "Inside the 'green box': On the economics of technological change and the environment" [KEM 90]. Their analysis, which aims to give an account of the possibilities available to make clean technologies economically viable, is based on the standard principles of economy of innovation, to which the internalization of Pigovian externalities is added [PIG 21].

These authors reuse the typology of technologies with an environmental mandate proposed by specialists of production processes, using some adjustments to their definition. Initially, clean technologies were those which profoundly modified production processes. Currently, "cleaning technologies" are "end-of-pipe" technologies, whereas preventive technologies have become "process-integrated techniques"[9]. Both cases were now accepted, whereas during the 1980s, production process specialists showed a preference for preventive approaches. This conceptual evolution comes from the fact that, as noted by the authors, co-existence of these two approaches is possible. While "end-of-pipe" technologies can respond to environmental demands over the short term, integrated technologies generate impacts in the long term, and it is precisely this relationship between time and opportunities that is of interest to these authors. The aim is to contribute to production optimization and substitution of resources used in production processes and products. However, we note that Kemp and Soete do not talk about ultimate waste issues and the perspective of "zero pollution".

A few years later, Kemp and Arundel returned to this problem and this time proposed to measure environmental innovation [KEM 98, KEM 01]. According to them, "integrated" environmental innovations of products are cleaner and consume less energy. Cleaning or restorative technologies should also be included. Parallel to these innovations, there are environmental innovations of processes. They can be divided up into "end-of-pipe" technologies, control tools, and integrated production processes. A new form of innovation pertaining to organizations is added to this, although it is part of process innovations: this includes environmental audits, management of waste and wastewater treatment, and implementation of repurposing and recycling methods.

The book *New Technologies and Environmental Innovation* by Huber [HUB 04, p. 39] confirms the establishment of three large categories of environmental innovations during the 1990s. The first relates to the addition of technological measures and represents all "integrated" technologies, destined to be cleaner, and to contribute to maintenance and rehabilitation of production systems. The second category is the family of processes, including "end-of-pipe" processes, pollution control technologies, and waste and wastewater treatment. Waste repurposing and recycling also belongs to this category. Within the third category, a new change of perspective is at work, since this encompasses the organizational measures related to

9 The authors emphasize that clean technologies can be understood using a palliative approach – "end-of-pipe technologies"/"cleaning technologies" – and a preventive approach – "which environmental damage is prevented" – in their own words [KEM 92].

environmental management and standardization of innovations. Thus, we find among evolutionist economists a sort of conceptual "hard core", with some categorical variations, comprised of products, organizations, and processes, divided into "integrated" and "end-of-pipe" approaches.

1.1.3.2. *The first contributions by Georg, Røpke and Jørgensen in the integration of clean technologies and ecological economics*

Compared to standard economic analysis, the "ecological economics" school of thought at the start of the 1990s was characterized by a greater level of skepticism with respect to the possibilities offered by technology in terms of sustainable development. This is one of the characteristics of "strong sustainability" promoted by a large part of the ecological economics community, which opposes the model of "weak sustainability" put forward by standard economics [NEU 03]. In this context, Georg, Røpke and Jørgensen [GEO 92], authors in the field of ecological economics, advised us of the fact that all technologies, even those considered to be "clean", bring about impacts on the natural environment. This is why, in their view, preference should be given to a preventive approach: "It must, however, be noted that there is no such thing as a clean technology in any absolute sense. Even the clean technologies will give rise to some pollution. The concept of clean technology connotes a continuous development process, with the prime purpose of minimizing pollution associated with the production processes and products rather than just treating the pollutants" [GEO 92, p. 548]. To achieve this result, these authors adopt this conceptual "hard core" that we have just identified: "Clean technologies seek to prevent pollution by input-substitution, process changes (increasing input-efficiency), encouraging recycling, lengthening product durability and developing cleaner consumer products. Clean technologies can entail such things as 'better housekeeping techniques', which seek to optimize existing plant facilities from an environmental perspective, as well as more radical changes of production techniques, organization and products" [GEO 92, footnote 2]. Therefore, we do indeed find clean technologies within products, processes, and organizations, giving preference to the optimization of production and substitution of resources thanks to both preventive and palliative approaches, but it is no longer a question of solely "end-of-pipe" technologies.

1.1.3.3. *When respect for the environment becomes a source of competitive advantage and a source of inspiration for company strategy*

While environmental innovation appears to be a pertinent solution which takes into account concerns relating to sustainability, its adoption was still limited at the start of the 1990s. In particular, we note the skepticism expressed by Greeno and Robinson [GRE 92] in regards to management taking the environment variable into account. This remains above all an economic constraint and a subject of lesser interest for many companies. This is the reason why some authors wish to challenge this preconceived idea.

Alluding to the Rio de Janeiro Earth Summit and the active participation of Schmidheiny [SCH 92], Bhargava and Welford have dedicated a chapter, and even an entire book, to environmental management, whose objective is certainly to deal with the question of the environment but above all to include company strategy more generally in a sustainable development perspective [BHA 96, p. 18]. While their analysis of strategic behavior remains at least of interest, in particular we note the forms of environmental innovations discussed, since they are somewhat reminiscent of those presented in previous sections for the hard sciences. “Clean” technologies, effectiveness of resources and “green” consumption do indeed figure in their proposals, but so does analysis of the life cycle of products, extending from the “cradle-to-grave” [BHA 96, pp. 16–17]. This normativity creates a central theme for industrialists who would like to turn the constraint of environmental concerns into a source of competitivity.

It was not until the foundational publications of Porter and van der Linde that a true change in the situation occurred [POR 95a, POR 95b]. Although they do not clearly define what an environmental innovation is, since they only talk about it at the end of their article [POR 95b, p. 111], they are instead more interested in competitive opportunities and creation of new opportunities created by the environmental regulations. From the first page of their article entitled “Green and competitive: Ending the stalemate” [POR 95b], the authors demonstrated “logical underlying links between the environment, productivity of resources, innovation and competitivity”. “End-of-pipe” technologies and “secondary processes” are again proposed. However, as pointed out by the authors, “it changes nothing else”; this is why a preventive approach is advocated by the authors, which is based on the quality of products, recycling, repurposing by-products, waste, and energy via closed circuits with lower production costs [POR 95a, p. 102]. This again evokes borrowing from technicians with a view to optimizing production and replacing innovations which pose a real risk to the surroundings and to health. These authors do however make the effort to integrate them into the field of industrial economics and the economics of innovation. They point out that competitive opportunities proposed by environmental innovations appear to arise from a certain prioritization: the primary objective is to contribute to new opportunities by using new products developed by processes which are responsive to an organization, based on repurposing materials and energy, considered as new raw materials. In addition to the products, processes, organizations, and new raw materials, Porter and van der Linde insist on new market opportunities, which is a broadening of the concept of environmental innovation.

1.1.3.4. *A concept more and more widely diffused, but still fragile*

During the 1990s, the concept of environmental innovation was diffused more and more. Hemmelskamp [HEM 97], specialized in the relationship between innovations, the environment and public policies, emphasizing the behaviors and intentions of investors. The author considers that environmental innovation is based on the same principles as non-environmental innovations.

The definition given by Hemmelskamp of these environmental innovations is quite broad [HEM 97] since "product innovations are taken as meaning creation of new, hitherto unknown or fundamentally altered products (basic innovations) and improvements concerning product quality (incremental improvement innovations). Process innovations refer to a company's gradual shift to new or substantially improved production methods, that is, methods making it possible to produce a given quantity at a lower cost or a larger quantity at the same cost". On the basis of the general description of the term "innovation", environmental innovations can be defined as those which aim to reduce the negative environmental impacts caused by production methods (process innovations) and products (product innovations). To achieve this reduced impact, care must be taken that environmental innovations serve to "avoid or reduce emissions caused by the production, use or consumption and disposal of goods, reduce resource input, clean up environmental damage done in the past, identify and control pollution" [HEM 97, p. 2]. Once again it is a question of, on the one hand, preventive actions using the verb "avoid", which can be based on the concept of integrated technologies, and, on the other hand, palliative actions using the verb "reduce", which are based on "end-of-pipe" technologies. We encounter many product and process innovations, but environmental innovation comes from a pre-existing innovation which is slightly modified. In all cases, according to Hemmelskamp, "[...] the definition of 'innovations' is a very personal one and consequently it is difficult to come up with an exact delimitation in empirical studies" [HEM 97, p. 2]. Yet, since environmental innovations respond to a specific objective, fed by normative principles, leaving room for personal judgment runs the risk of being counterproductive in terms of public policies or collective movements.

This type of problem is found in the book *Driving the Eco-Innovation* by Fussler and James [FUS 97], with which the authors attempt to follow industrialists in their approaches to innovation by proposing radical changes and continuous improvement methods in the context of population growth and increasing need [FUS 97, p. 124]. The suggestions made here are not unlike Schumpeterian innovation. In terms of categorizing innovations, we come across process changes, the acquisition of new raw materials (recycling, biodegradability) [FUS 97, pp. 123, 270–275], a change in products and establishment of new organizational modes with a view to reusing of materials. The objective is the search for eco-efficiency [FUS 97, p. 129]. Despite all this, the authors do not provide a precise definition of environmental innovation. Nor does an entry pertaining to this concept feature in the index to their book. The authors prefer to call it "super-innovation". In the end, environmental innovation remains, once again, a relatively imprecise concept.

Klemmer, Lehr and Lobbe [KLE 99] believed that environmental innovation is essentially the same as standard innovation, the difference being that environmental conservation is an objective of the latter. It is, effectively, "a subset of innovation which leads to an improvement of the ecological quality. [...] It encompasses all innovation which serves to improve the environment, independent of any additional – economic – advantage”[10] [KLE 99, p. 13]. According to these authors, then, environmental innovation is nothing more than a sub type of “standard” innovation. Such diverse representations bear witness to the relative malleability of the concept, as in Schumpeter’s view, all innovation can be environmental.

Fueled by these multiple scientific contributions, Frondel *et al.* [FRO 07, p. 2] emphasized that the OECD will use two aspects to identify environmental innovation: first, an increase in “the production of a given amount of output (goods and services) with less input”; second, organizational innovations which are based on reorganization of “management systems and the overall production system and its methods, including new types of inventory management and quality control, and continuous quality improvement” [OEC 97, p. 23]. We come across this theme again in Fussler and James [FUS 97] where they explain the advantages of the ISO 14001 standard Eco-Management and Audit Scheme (EMAS) and life cycle analysis. In these two key elements, we find the goal of having various forms of environmental innovation, which would in fact contribute to increased wealth as a result of environmental constraints; but we also note that the issue of hazardous products is no longer present.

1.1.4. *Conceptual beginnings and an existential crisis in environmental innovations during the 2000s*

1.1.4.1. *Evolutionary economists contribute to the concept of environmental innovation: environmental performance*

After a period of beginnings and exploration of the concept of environmental innovation in the 1990s, the 2000s saw a new framing of the notion, and establishment of what has become a doctrine. In this capacity, the article published by Rennings [REN 00] in the journal *Ecological Economics* has become a standard reference. This author continues from the first

10 From the following definition in German: “Der Begriff der Umweltinnovationen ist damit final definiert; er umfaßt alle Innovationen, die der Verbesserung der Umwelt dienen, gleichgültig, ob diese Innovationen auch unter anderen – namentlich ökonomischen – Gesichtspunkten vorteilhaft wären”. [KLE 99, p. 13]

works published in this field by highlighting that environmental innovation allows us to “develop new ideas, behavior, products and processes, apply or introduce them and [...] contribute to a reduction of environmental burdens or to ecologically specified sustainability targets” [REN 00, p. 4]. Categorization of Schumpeterian innovations and the environmental dimension are also reflected in the objectives and behaviors evoked. However, in addition to reduction of waste, the originality of this work is to reintegrate a typology of the main environmental impacts: greenhouse gas emissions, depletion of the ozone layer, acidification and eutrophication of surroundings, the impacts of toxicity on ecosystems and mankind, the effects on biodiversity, the use of the earth itself and its resources. Categorizations which are both quantitative and qualitative can be obtained from this list by insisting on the practices of production optimization and substitution of resources.

To reduce these impacts, the author uses the typology of environmental innovations identified in the past. Rennings first examines integrated technologies, which are seen as a modular assembly. He considers these to originate from a preventive approach since, according to him, it is possible to substitute, in a first instance, less abundant or dangerous inputs; then, secondly, to optimize production (or replace the production process in favor of more optimal production) by re-using by-products and waste. Once the material has been transformed, outputs are directly sold or, when they are no longer of any use, directly reinserted into the production line which generated them. Integrated technologies are therefore systemic and aim for the implementation of closed circuits by means of modifications to existing innovations. Pollution and by-products are, in terms of environmental innovation, opportunities that need to be prioritized and located on a production site. Rennings then considers palliative technologies, or additive technologies, as he calls them. These focus on recycling, which takes place outside the production site: the spatial location matters little, as the priority is the products. Moreover, according to the author, recycled products can very feasibly be re-inserted into other production/transformation processes. In addition, waste no longer presents a problem, but rather an opportunity. In Rennings’ work, “end-of-pipe” and “integrated” technologies are combined and co-exist to contribute to implementation of a circular economy, whereas Overcash [OVE 88] emphasized that clean technologies are based either on recycling or on the change in processes.

The work of evolutionary economists, for their part, is getting closer and closer to the proposals made in the field of ecological economics. Through following empirical studies, Kemp and his colleagues made the observation that environmental innovation "consists of new or modified processes, techniques, systems and products to avoid or reduce environmental harms. They can concern either technical or organizational innovation. The latter include changes in the organizational structure, routines and practices of a company" [KEM 98, p. 5]. Here, we do indeed come across the categories and innovation clusters that Schumpeter presented and which resemble line by line the proposals made by ecological economics.

Nuij [NUI 01] added services to these clusters. According to him, environmental innovations "aims to develop new products and services that are not based on redesign or incremental changes to existing products but rather on providing the consumer with the function they require in the most eco-efficient way" [NUI 01, p. 1]. It is then preferable, according to this author, to propose new functions for products and services and thus to show, implicitly, that the radical view of environmental innovation allows a greater yield in the use of resources.

Evolution and widening of the view of environmental innovation is also seen in the work by Oltra and Saint Jean. They first say that environmental innovation includes "combinations of expertise, knowledge, equipment and organizations required to reach certain environmental targets, to conform to certain regulations and to produce new technological artifacts" [OLT 01]. Over time, they move closer to the suggestions made by Kemp and Arundel [KEM 98], by highlighting that these innovations are "[...] 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" [OLT 07, p. 7]. A few years later, the authors selected a general definition by considering that "broadly speaking, environmental innovations can be defined as innovations involving new or modified processes, practices, systems and products which benefit the environment and thus contribute to environmental sustainability" [OLT 09, p. 567]. In the end, we cannot help but make the observation that the principles of environmental innovation appear to dissolve.

Kemp and Pearson proposed to gather together all of these elements and emphasize the notion of "environmental performance". Rather than returning to the impacts, "[...] we decided to base the definition of eco-innovation on *environmental performance* instead of on environmental aim because it is not the aim that is of interest but whether there are positive environmental effects related to its use" [KEM 08]. This environmental performance can be obtained by means of analyses of product life cycles, as members of the ecological economics domain also say, like van den Bergh *et al.* [VAN 11]. Kemp and Pearson, propose the following definition of environmental innovation: "[...] the production, assimilation or exploitation of a product, production process, service or management or business method 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" [KEM 08, p. 7]. This perspective effectively shows how ecological economics and evolutionary economics have moved closer together.

Huber [HUB 04, p. 4] supports this idea. According to him, technology/environmental innovations (TEIs[11]) serve to "[...] help to reduce the quantities of resources and sinks used, be they measured as specific environmental intensity per unit of output, or as average consumption per capita, or even in absolute volumes. [...] Rather than doing less of something, TEIs are designed to do it cleaner and better by implementing new structures rather than trying to increase eco-productivity of a suboptimal structure which has long been in place. TEIs are about using new and different technologies rather than using old technologies differently. TEIs can be characterized as being upstream rather than downstream, i.e. upstream in the manufacturing chain or product chain respectively, as well as upstream in the life cycle of a technology" [HUB 04, p. 37]. In other words, the combination of a radically different behavior with a preventive approach allows environmental innovation to use a productivity intensification approach in the use of resources, integrating quality and a "metabolic" approach: this is environmental performance.

11 The author denotes *technology/environmental innovation*.

1.1.4.2. *From theoretical questioning of the existence of environmental innovation…*

Finally, after working for nearly 20 years on the question of environmental innovations, Kemp [KEM 10] admitted his doubt about the existence of technologies that are favorable to “sustainable” development[12]. His approach is original compared to the proposals studied until then, because he gives more serious consideration to the expression “relevant alternatives”, against which he compares environmental innovations: “Eco-innovations are innovations with environmental benefit compared to relevant alternatives. Similarly, sustainability innovations may be defined as innovations which have both environmental and social (societal) benefits” [KEM 10, p. 7]. He combines these reflections from the course of his work with the “standard” definition of innovation proposed by OECD [OEC 05], with the aim of identifying a number of categorizations which take the form of products and services, processes, organizations, “covering innovations”[13] and innovation systems. Once these categories have been laid out, Kemp returns to the subject of Pigovian externalities, which, as mentioned earlier, he had worked on at the beginning of the 1990s. For this, he uses standard economic theory with the hypothesis that environmental innovation is the outcome of a situation which alters the *status quo*. Its viability would emerge from a situation which is, at best, “Pareto-superior”, between the private costs of pollutants for economic agents and the social cost, as shown in Figure 1.1. In spite of this, the author alerts the reader about the great difficulty that there is in identifying what a “sustainable technology” is, since all technologies have an impact on the environment – which he illustrates by comparing several examples ranging from motor vehicles to renewable energies. Thus, evaluation of the private cost and the social cost which make environmental innovation viable is very subjective, complex and difficult to identify *ex ante*. This systemic dimension demonstrates the great difficulty in identifying environmental innovations in the face of economic and environmental concerns. This encourages prudence in relation to lessons that can be learnted from databases constructed and indices calculated by large public institutions, such as the OECD and the European Union.

12 He uses the expression *sustainable technologies*.

13 Innovations associated with the development of actions carried out in terms of environmental actions.

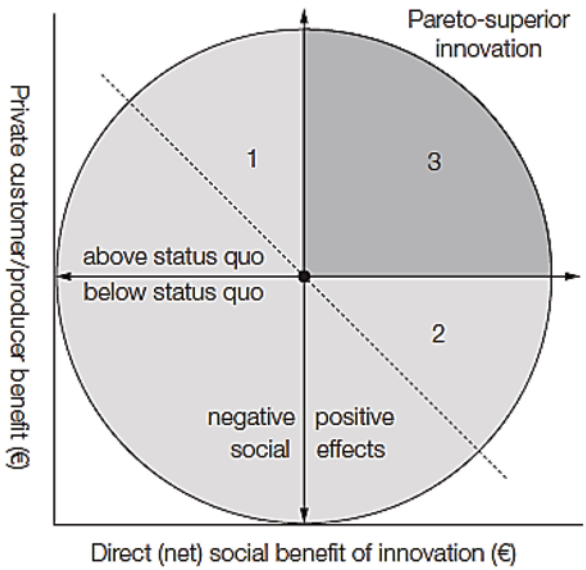

Figure 1.1. *Quadrants of the private and social benefits of innovation compared to the status quo (source: [KEM 10, p. 7])*

1.1.4.3. *… To institutional recognition*

Because the definition of environmental innovation was still unstable, the OECD tried, at the end of the 2000s, to summarize all proposals made by Kemp and Rennings. By considering that environmental innovation is like generic innovation, but with "[...] two further significant, distinguishing characteristics: [First], it is innovation that reflects the concept's explicit emphasis on a reduction of environmental impact, whether such an effect is intended or not. [Second], it is not limited to innovation in products, processes, marketing methods and organizational methods, but also includes innovation in social and institutional structures (Rennings 2000). Eco-innovation and its environmental benefits go beyond the conventional organizational boundaries of the innovator to enter the broader societal context through changes in social norms, cultural values and institutional structures" [OEC 09, p. 13].

Here, we take note of the systemic nature of innovation, an induced radical change [OEC 09, p. 6], and also several stages to obtain it. It would appear that “end-of-pipe” technologies constitute a first stage, and then they are replaced by clean technologies. These contribute to eco-efficiency, which is based on an analysis of the life cycle in order to contribute to circular economy reasoning that is promoted by industrial ecology [OEC 09, p. 10]. The concept of environmental innovation appears, in consequence, to be clearly identified and stabilized.

Moreover, in the following year, the OECD published a book dedicated to environmental innovation: *Eco-Innovation in Industry: Enabling Green Growth* [OEC 10]. As this title suggests, such innovation in industry would benefit conservation of the environment and act as a driver of green growth. As in the 1980s, eco-innovation is defined as “the production, assimilation or exploitation of a novelty in products, production processes, services or in management and business methods, which aims, throughout its life cycle, to prevent or substantially reduce environmental risk, pollution and other negative impacts of resource use (including energy)” [OEC 10, p. 38]. Environmental innovation, as defined by the OECD, starts with the principles of standard innovation and adds the preventive and palliative approaches supported by life cycle analyses. Meanwhile, in the same period the European Commission set up an environmental innovation task force whose main mission is to develop indicators that would measure and track efforts made by member countries in this field. These include the inputs necessary for innovation, the outputs they generate, the mobilization of companies, economic and social consequences, and finally, efficient use of resources. These are, essentially, performance indicators of environmental innovation which, on the one hand, outline all activities[14] related to them in a country since 2010, and, on the other hand, allow comparison of the results to be made, using scoreboards[15], between countries within the European Union (see Figure 1.2).

14 Countries file an annual report on environmental innovation and the circular economy. The report summarizes the performance indicators of environmental innovation, the barriers and drivers , and also the role of public policies during the reporting year.

15 Scoreboards are available at the web address: https://ec.europa.eu/environment/ecoap/scoreboard_en.

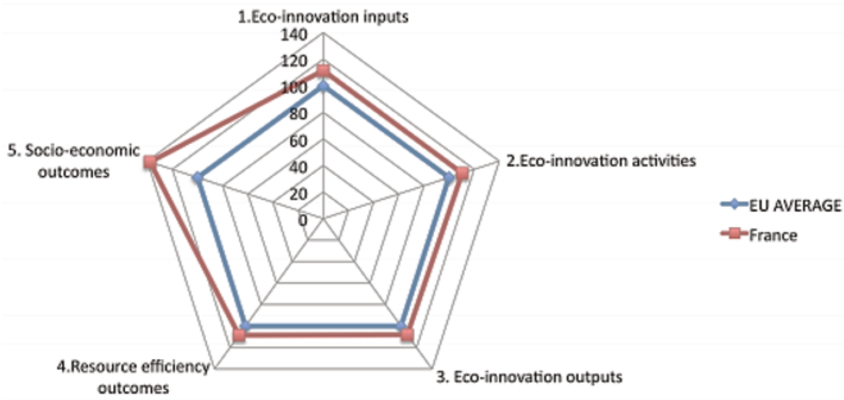

Figure 1.2. *Example of a composite index of environmental innovation for France in 2015 (source: [MAL 16, p. 15])*

Between 2010 and 2015, it is clear that a certain pattern or hierarchy was maintained (see Table 1.2). At the top are the Scandinavian countries, Germany, and Ireland, contrasted with Eastern European countries, new members of the European Union, and Greece. France is located in the middle of the classification, significantly below the bar of 100, which attests to an average level of effort. However, it is best to be very careful with this type of index, which incorporates a lot of information. Effectively, as we have been able to see by means of the definitions that we have studied, the notion of environmental innovation encompasses very different technical and economic realities.

Finally, since 2011, the doctrine of environmental innovation, which has run its course, has been reinforced and it even stretches to the rank of *sustainable innovation* as demonstrated by the themes dedicated to it during the Conference of Parties (COP) (see Box 1.1). This increase in influence is also found in a specially dedicated scientific journal, Environmental Innovation and Societal Transitions, edited by researchers with backgrounds in evolutionary economics, ecological economics management, and industrial ecology. We will now explore the ideas of some major contributors: van den Bergh, Truffer and Kallis[16]. In their articles, they propose to define environmental innovation as "recovery, repair, renovation, re-manufacturing and recycling" [VAN 11]. However, these authors emphasize that the search for optimization and efficiency can be very difficult, because products "dissipate during use (like solvents or detergents)" and "cannot be reused", an idea that was also expressed in the work of Georgescu-Roegen [GEO 79]. "Products that are very difficult to deconstruct cannot be repaired, renovated or remanufactured. [...] [Thus] these 'end-of-life' stakes must be taken into consideration right from the start [...] during the design process" [VAN 11]. Here, preventive approaches can certainly be used for a circular economy and to substantially modify an existing product.

	Country	2010	2015	Rank in 2010	Rank in 2015
The 6 first	Denmark	155	167	2	1
	Finland	156	140	1	2
	Ireland	101	134	9	3
	Germany	139	129	3	4
	Sweden	128	124	5	5
The 6 last	Greece	55	72	23	22
	Slovakia	48	72	26	22
	Malta	66	64	18	24
	Cyprus	64	60	19	25
	Poland	54	59	24	26
	Bulgaria	58	49	21	27

Table 1.2. *Ranking of countries making the greatest and least effort in terms of environmental innovations (source: [EUR 18a], from the Eco-Innovation Index, code: t2020_rt200)*

16 These authors contributed to the first edition of the English-language journal *Environmental Innovation and Societal Transitions* published in 2011, of which van den Bergh is Editor-in-Chief.

Since 2009, discussion spaces and conferences dedicated to "sustainable" innovations (Sustainable Innovation Forums) have been organized on the sidelines of the Conference of Parties (COP). These forums encourage industrialists, interested parties (NGOs, for example), and public authorities to invest, to propose solutions, and to actively participate in a transition towards sustainable development through the lens of green growth.

Looking back at the events organized over the course of the last eight occurrences, between 2009 and 2017, the main themes have been dedicated to economic incentives, technical solutions and new practices. There are the essentials, such as the incentive power of the price of carbon, the market of pollution rights, and solutions coming from the world of finance. The most recent ponders the question of new forms of public–private partnerships, especially when public authorities are expected to create new business opportunities for companies.

These forums also present the innovative potential of certain key sectors, such as energy (e.g. renewable energies), transports (e.g. electric vehicles), forestry, and agriculture. Thus, we test managerial practices including management of resources, management of waste, energy efficiency and the use of water and soils. Other themes sometimes surface, like conservation of biodiversity, and also relations between population growth and food requirements in developing countries.

Finally, more recently, since COP 21 in Paris, new topics have emerged, such as energy storage and the circular economy and its business model – indeed, a session was entirely dedicated to this for the first time at COP 23 in 2017 – and also topics focused on breakthrough innovations. These are symbols of high hopes for technology, or even a hope for something that has yet to happen.

Box 1.1. *Sustainable Innovation Forums and COP, a new hope orientated towards innovation and technological change*

1.2. Critical analysis of the typology of environmental innovations

Environmental innovations, as we have seen, are not only defined in a general manner, but they are also divided up according to those which have a greater or lesser influence on the socio-technical regime. Here, we will look at the different degrees of change possible for non-environmental, or standard, innovations (see section 1.2.1). This first step will lead more easily to an understanding of the specifics of the typology of environmental innovations. Thus, first we will look at a degree of technological change which happens in environmental innovations known as "incrementals", which are fed by "end-of-pipe" technologies that result in palliative actions regarding the environment (see section 1.2.2). However, as the saying goes, prevention is better than cure. This is the role attributed to environmental innovations known as "radicals", which rely on "clean" technologies in order to respond in a preventive way to environmental concerns (see section 1.2.3). A third category is made up of systemic environmental innovations (see section 1.2.4). In particular, they take on the form of a circular economy, in which we seek to create circular flows of energy and materials. This can be divided into site logistics, with "industrial symbioses", or the workflow towards a product, according to an approach known as "cradle-to-cradle". In addition to these three classic forms of environmental innovation, there is a fourth transverse one that we come across in the three previous forms, namely "eco-efficiency" (see section 1.2.5). As we have previously noted, this notion refers directly to the title of Chapter 8 of the Brundtland report: "Producing more with less" [WCE 87].

1.2.1. *Degrees of change of environmental innovation*

1.2.1.1. *Classic typology of innovations*

Economists have identified several degrees of change since they first took an interest in technological change. The first represents the "improvement in the arts already practiced" [POL 08, p. 34]. In other words, a small degree of change is possible through adding to an existing innovation. This is what is called an incremental innovation, according to evolutionary economic theory [DOS 82]. The second degree of change represents an entirely new approach: a "new art". Innovation can then have a more radical impact determined by the depth to which it modifies the evolution of production processes, practices, organizations and even the way in which structures and strategies are established [FRE 90]. These degrees of change have featured in the work of evolutionists since the 1980s. This type of breakthrough does not necessarily mean "revolution", since a sector proposing a radical innovation can have an incremental effect in other sectors. Thus we add a third category that unites systemic innovations with Schumpeterian innovation clusters resulting in complex and stochastic effects on economic development (see Table 1.3).

Innovations	**Principle**	**Degrees of change**
Incremental	Addition of a special feature	Low
Radical	Breakthrough	High
Systemic	Combination of radical/incremental innovations	Systemic

Table 1.3. *Typology of the degrees of change*

1.2.1.2. *Towards similar degrees of change for environmental innovations*

Are these degrees of change similar for environmental innovations? In the face of environmental concerns, it is common to hear that we must "radically" change our way of life and the way we act. Before reaching that stage, it is clear that, since it is environmental, eco-innovation must integrate a dual objective: the first answers economic concerns and is viable in the short term, and the second integrates the conservation of the environment in the long term. We therefore ask which degree of change of innovations should be given preference, since it can be entirely possible for incremental environmental innovations to be better than the radical ones in the long term, without it being possible to be certain of this *ex ante* (see Table 1.4).

Innovations	**Short term – means**	**Long term – objectives**	**Consequences**
Standard	Economic means	Objectives versus economic uncertainties	Incremental innovation can prevail over radical innovation
Environmental		Objectives versus environmental and economic uncertainties	Incremental innovation can prevail over radical innovation

Table 1.4. *Innovations confronted with uncertainties*

Since the 1970s, the researchers who are interested in environmental innovation have conserved a typology similar to standard innovation with this distinction between incremental, radical and systemic changes. In the next section, we will see that "end-of-pipe" technologies are presented, in our view, as incremental and palliative environmental innovations, modifying the production system to a marginal extent. Then, we will look at "clean", preventive technologies, which are presented as radical environmental innovations. We will finish off with systemic environmental innovations, aiming to assemble a group of innovations and to structure them in such a way as to promote the rise of industrial ecosystems based on a path towards a circular economy, either in a territory or for a product, and whose final objective is to connect the technosphere, our industrial society, to the biosphere.

1.2.2. *"End-of-pipe" technologies: a limited palliative approach to conservation of the environment?*

1.2.2.1. *Principles of "end-of-pipe" technologies*

When pollution and environmental pollutants are observed or when environmental legislation becomes more restrictive, the first possible response, according to academic literature, is to find a "quick fix" by adapting and changing existing economic models and technological systems [CRA 90]. A few examples can be seen in Box 1.2. They are defined as "investment in equipment and plant for pollution control, and special anti-pollution accessories (mainly end-of-pipe equipment)[17]". It appears to be more economical and efficient to opt for this strategy of rapid adaptation of production conditions rather than seeking to totally substitute the existing production process and risk losing a well-established economic income. The additive nature of "end-of-pipe" technologies does not profoundly modify the behavior of users; this is why we can qualify this approach strategy as incremental, which can reduce environmental impacts in the short term.

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17 These technologies with an environmental mandate are recognized by European institutions, as pointed out by the regulation (CE) no. 295/2008 of the European Parliament and the Council of 11th March 2008 relating to structural statistics on companies (reworking). Details are available here: http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008R0295&from=EN

"End-of-pipe" technologies based on incremental solutions remain relatively dated and temporarily act to conserve the environment [ERK 98]. Sometimes, they are also the only alternative while awaiting other more radical solutions [DEB 16]. Here, we will cite a few examples.

The energy sector resorts to this type of technology to limit the environmental impact of coal power stations, which emit huge amounts of carbon dioxide (CO_2) and sulfur dioxide (SO_2). To reduce emissions, two "end-of-pipe" technologies exist. The first is to place filters at the chimney exits, which ensures sulfur emissions are captured, thus limiting acid rain. This was, moreover, a subject of much debate during the Stockholm Conference in 1982, for example [OEC 12, pp. 64–65]. The second, for its part, is based on capture and storage of carbon (CCS). Here, pollution is stored definitively at a site that is not used by mankind. After the capture stage, the CO_2 is transported and stored in a geological reservoir, which is buried deep underground [IPC 13]. This has no intrinsic value, except in the case of EOR (*Enhanced Oil Recovery*), a process which uses buried CO_2 to improve the yield of oil wells. Other than this, the value of a CCS investment depends on the value of the unreleased CO_2, via the market for negotiable permits in Europe. The scope of this technology appears to be limited, since the carbon footprint of CCS varies significantly depending on the activity sector and the local characteristics, which makes generalization complicated [LAU 15].

The motor vehicle industry has also been one of the main sectors affected in terms of polluting emissions with internal combustion engines since the 1990s. Installation of catalytic converters, considered to be an "end-of-pipe" solution, is only a temporary response to this problem, because they have no limiting effect on the use of vehicles in the long term and on greenhouse gas emissions [REI 96].

In the chemical industry, biorefineries can resort to it to avoid causing harm to the local population in terms of noise, dust and odor emissions. These temporary solutions are in place, as it so happens, to respond to a form of social acceptability, also known as "end-of-pipe", of biorefineries in place [GOB 16].

Box 1.2. *A few examples of "end-of-pipe" technologies*

1.2.2.2. *The limitations of "end-of-pipe" technologies*

This type of incremental environmental innovation has its limitations. First, taxes and regulations for the environment, which influence technological trajectories, can increase the costs of operation and use. The costs arise from the level of pollution that must be reduced, whereas this depends on the level of production. The more the production increases, the more pollutants and costs also increase, and the company faces decreasing yields leading to an increase in expenses and a reduction in income. To avoid these constraints, companies can make the decision to relocate or to move their dangerous production activities to countries where environmental concerns are taken less seriously. In summary, these "end-of-pipe" technologies can be a means of reducing pollutants in the short term, but in the long term, they are a hindrance to production and to obtaining new sources of income. The European Commission confirms that the costs of implementation of these technologies do not appear to encourage innovators to act for the environmental cause. "[...] End-of-pipe solutions do not usually result in efficiency or productivity gains, therefore representing a pure cost to the firms. Cleaner technology, on the other hand, improves process efficiency. Furthermore, cleaner technology usually reduces polluting emissions to all media instead of shunting them from one to the other" [EUR 03, p. 2]. In contrast to what has been suggested in the literature since the beginning of the 1980s, these technologies are continually growing.

Effectively, according to estimates made by Eurostat, countries which appear to be the most committed to this cause are the leading countries of the European Union. They are, for example, Germany, France, Italy, Poland, Spain and the United Kingdom. More generally, expenditure related to investments in "end-of-pipe" technologies have increased in Europe by 174% between 2001 and 2014, rising from 3 to 7 billion euros, and their acceleration did not cease until 2008, then slowed down during the financial crisis. Since 2013, the progression seems to be increasing (see Figure 1.3).

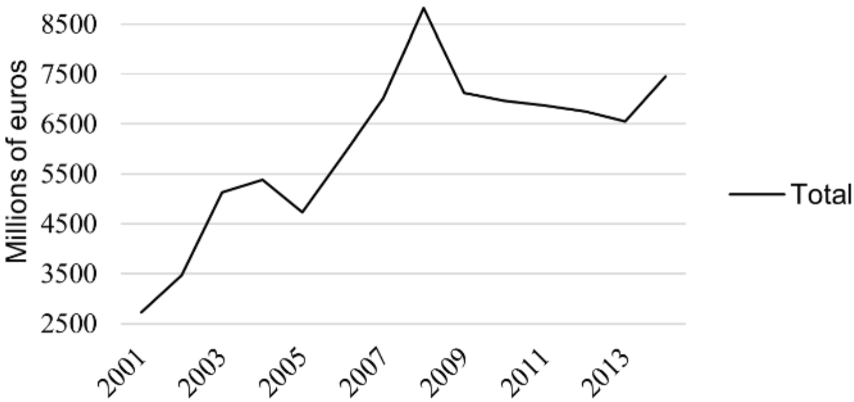

Figure 1.3. *Total investment in "end-of-pipe" technologies in the European Union (source: [EUR 18d], references sbs_env_dom_r2 and sbs_env_2b_02)*

1.2.3. *Clean technologies, a preventive, radical and modular approach*

1.2.3.1. *The principles of clean or "integrated" technologies*

As we have seen in the previous section, integrated technologies based on a preventive approach were the solution that was initially given preference in the literature. The European Commission defines them as "technologies that extract and use natural resources as efficiently as possible in all stages of their lives; that generate products with reduced or no potentially harmful components; that minimize releases to air, water, and soil during fabrication and use of the product; and that produce durable products which can be recovered or recycled as far as possible; output is achieved with as little energy input as is possible" [EUR 03, p. 2]. The particularity of these integrated technologies is that they are established in such a way as to avoid polluting where possible. The solution is based not only on avoiding hazards, but also on optimization of the use of energy and material flows. Quite evidently, this preventive approach must "attack pollution problems more effectively and in a more profitable way; the operator should take these points into consideration" [CON 96]. Since then, integrated technologies have been sought to profoundly and radically revise the manner of production, while remaining economically and ecologically viable.

"Integrated" technologies rely on more radical solutions within socio-technical regimes [DEB 16]. With the theme of parallelism in mind, we look back at the activity sectors that we have just presented in the previous box.

The energy sector evolves and develops technologies which provide "de-carboned" energies. This is the case for renewable energies which rely on hydraulic, ocean and wind resources. Although they provide the user with the same electrical energy, their implementation requires practices, expertise and strategies in terms of territorial development, for example, to be modified.

The motor vehicle sector also proposes solutions by producing electric, hybrid and hydrogen-powered vehicles. Here, the displacement method scarcely has an effect on users, with the exception of surrounding ancillary infrastructures (charging, management and maintenance of lithium cells and fuel cells, for example).

The chemical industry has taken the direction of the paradigm of "green chemistry" based on 12 founding principles [ANA 00], then towards that of "doubly green chemistry", turning biomass, which includes agricultural resources, into the basis of a new chemistry [NIE 10]. The processes which accompanied it have contributed to production of "clean" products, such as solvent-free paints [STE 16, p. 220].

Box 1.3. *A few examples of "integrated" technologies*

1.2.3.2. *Slowing of "integrated" technologies, left far behind "end-of-pipe" technologies*

The literature pleads in favor of integrated technologies which promote a collection of preventive actions. Unfortunately, data from the European Union seems to show an overall reduction in investment in this direction in recent years: the increased effort between 2001 and 2008, as shown in Figure 1.4, slackened off completely from that year onwards, undoubtedly due to the occurrence of the economic crisis. "Integrated" technologies have always been surpassed by "end-of-pipe" technologies, and their respective expenditure reached approximately 3.5 billion euros compared to 7 billion for the latter – in other words twice the amount[18]. “Integrated” technology therefore remains quite simply in the background. Could this situation be explained by the existing limits on deployment of these integrated technologies on production sites?

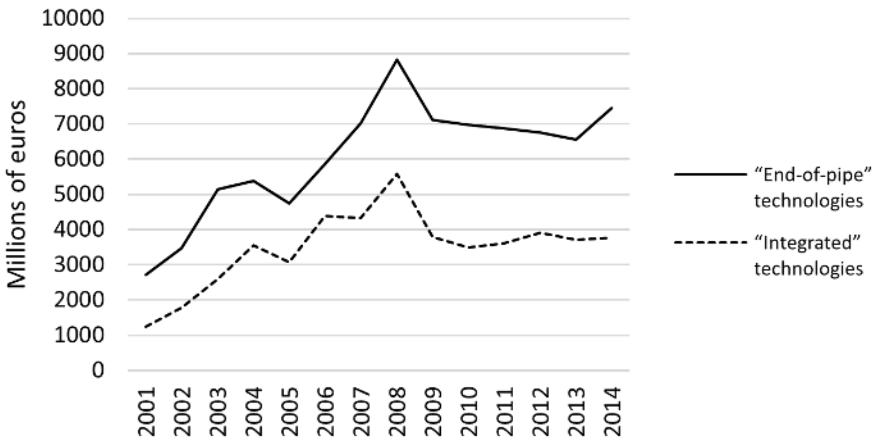

Figure 1.4. *Comparison of the total investments between “end-of-pipe” and “integrated” technologies within the European Union (source: [EUR 18d], references sbs_env_dom_r2 and sbs_env_2b_02[19])*

1.2.3.3. *Limits to “integrated” technologies*

Thoroughly revising a production system means questioning the basis on which innovative companies are founded, compared to the competition. These radical changes bring about significant costs in terms of implementation, training and modification of expertise. Taking into account all the stages of production and acting in response to this requires, in fact, solid economic and technical means. From this point of view, faced

18 Eurostat includes some sectorial activity in its statistics. Mining activities, factories, gas, electricity and water suppliers are found here. In addition, the information provided is relatively heterogeneous depending on the country. Therefore, we will remain prudent concerning interpretation of this figure. Furthermore, analysis of the main components could have led to the identification of groups of countries which would give information about which ones would be the most likely contenders for integrated technologies. However, due to a lack of precise data, this is impossible for us to do.

19 Please see note 18 above.

with the competition and a difficult context, companies wishing to commit to this type of initiative thus risk increased risks of failure in the short term. Moreover, their capacities for adaptation respond to the established sectorial dynamics [PAV 84]. Still more than the "end-of-pipe" technologies, "integrated" technologies, due to their radical nature, are faced with questions of economic feasibility and a high level of uncertainty.

1.2.4. *The circular economy: Another form of systemic environmental innovation*

1.2.4.1. *Seeking circular flow loops through industrial ecology*

Publications by the chemist von Liebig laid down the first milestones of studies looking at the interactions between industrial and agricultural activities [VON 45]. These publications were not devoid of influence on the reflections of Marx, who adopted the idea of social metabolism [VIV 05, p. 72], even if Podolinski, by proposing to integrate energy analysis into the analysis of productive forces, found it very difficult to make himself heard by the latter [PAS 10]. However, through the Odum brothers' ecosystem sciences[20], Duvigneaud's study of "urb systems" [DUV 74], and works published by Fischer-Kowalski [FIS 88][21], there has been a development, a century later, in analysis of the metabolism of our society. This has systematized the perspective opened up by eco-energy analysis and mass balances, which became widespread in the 1970s and 1980s. Then, at the end of the 1980s, industrial ecology, as we have previously mentioned, came to light at the right time to give new life to the study of the "industrial metabolism" and "industrial ecosystems". This viewpoint, which reflects the thoughts of Marshall, is also rooted in the industrial experiments carried out in the United States by Ford and in Russia by Lenin (see Box 1.4 for more information).

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20 We can also cite the work of Commoner [COM 71] and his "four laws of ecology". First, all living entities are interconnected in the biosphere. Second, the transfer of energy and material is such that there is no waste in nature and that the Earth remains the only place where they could be stored. Third, human activity is capable of contributing to the evolution of nature, but any modification disturbs the ecosystem. Finally, all material and energy exchanges have a cost.

21 Fischer-Kowalski was elected president of the International Society for *Ecological Economics* in 2011. She works in collaboration with researchers from various disciplinary fields, like industrial ecology and the theory of *transition management*, close to evolutionary economics, that we see in the following sections of this book [FIS 09].

In an era when transport infrastructures were limited, Alfred Marshall highlighted the interest of industrial districts with respect to resources and technologies available on a territory [MAR 90, Chapter 10]. Marshall even mentioned an "industrial atmosphere" and believed that "when an industry has thus chosen a location, there is a good chance it will stay there for a long time, so large are the advantages, for those also in the same industry, presented by being located close to each other" [MAR 90]. This close connection, and therefore this sharing of interests, demonstrates that implementation of a pilot industry can be an incentive to collaborate with those close by. This collaboration results from the opportunities for reduction in production costs which allow productivity to be intensified. According to Marshall, income opportunities arising from collaboration and exchanges mean that "[...] auxiliary industries are born from the surroundings, supplying the main industry with tools and raw materials, organizing its circulation and allowing material savings to be made in many cases" [MAR 90]. Around a decade later, Henry Ford established an "industrial symbiosis" at Red River, not far from Detroit. There, he completed inventories and sought solutions to increase the efficiency of raw materials and of production. Just like supporters of industrial ecology, he will see its production as a collection of energy and material flows, while seeking to reduce production costs as far as possible: "Even a microscopic saving, as one Ford publication put it, 'assumes impressive proportions when multiplied by a million or two'" [MCC 06]. This classification of end-of-life products and by-products occurs in four families. First, the by-products are materials which can be reintegrated into the production process or be sold to companies capable of exploiting them. Second, certain waste is directly recovered and is immediately useable – salvaged – which requires a process of collection and sorting. For example, at the time, damaged drills were reconditioned and melted down again, so as to give them a second life in another industrial department. Third, Ford was obsessed by energy optimization. Fourth, at the end of their life cycle, products designed/produced on site and distributed to consumers are considered to be economic opportunities which can become agricultural fertilizers and industrial alcohols for the town of Dearborn located not far from the production site [MCC 06, p. 61]. To give an example, disused vehicles were bought by Ford to be deconstructed and thus ensure the autonomy of the production system. This industrial site which advocated self-sufficiency is faced with malfunctions because, as noted by McCarthy [MCC 06, p. 75; also see p. 81], "the real problem in waste utilization is more economic than technical. Many wastes do not occur in sufficient quantity at any one spot to make their use possible, or the cost of collection and storage defeats the project". In addition, despite the highly advanced dimension of this "industrial ecosystem", it would appear that its self-sufficiency was slowed down by the quest for more and more intense productivity.

This concern of production rationalization is also found in the USSR with Lenin, a dedicated reader of Taylor. In 1916, he evoked the need to "the grouping in a single enterprise of different sectors of industry, which represents either consecutive steps in the processing of raw materials (e.g. the smelting of iron ore into pig iron, the conversion of pig iron into steel, and the further manufacture of different products from steel), or cooperation between industrial sectors (e.g. the utilization of waste materials or by-products and the production of packing materials)" [SAT 06]. On the basis of this interest in inter-organizational collaborations and "[u]nder socialism the urgent problems of environmental protection do arise in the course of scientific and technological progress" [SAT 06]. During the 1950s and 1960s, the leaders of the Soviet Union wished to intensify productive forces by "creating a closed-cycle, no-waste production process", to end up with combined production systems, considered to be "the driving force of progress" [SAT 06].

Box 1.4. *Industrial symbiosis and its examples in history*

1.2.4.2. *The different integration levels of circular flows*

Allenby and Cooper [ALL 94] modeled "industrial ecosystems" according to their degree of openness to environmental issues (see Figure 1.5). They distinguish between three ideal types. The type I ecosystem is based on the assumption that material and energy sources to be drawn on and the possibilities of throwing waste away in the environment are unlimited. In this scenario, exploitation *ad vitam æternam* of natural resources is sufficient, without worrying about the waste that will accumulate as a consequence of that.

If we go back to the case of "end-of-pipe" technologies, we note that they could be included in this course of action, since the exploitation of resources continues to grow until the production system reaches an economic threshold which prevents it from further reducing the pollution that it generates. The type II ecosystem corresponds to partially cyclic loops of energy and material flows which lead to partial repurposing, and synergies which induce partial self-sufficiency of the entities in the system. To overcome this, those who uphold industrial ecology propose to refer to a type III ecosystem, entirely self-contained from a material point of view, which only requires an energy source – in the same way as a spaceship[22] [ERK 98, p. 36, AYR 04, KOR 05].

22 Buclet [BUC 11, pp. 191–208] considered that the type III ecosystem is a utopia, and those who uphold industrial ecology agree.

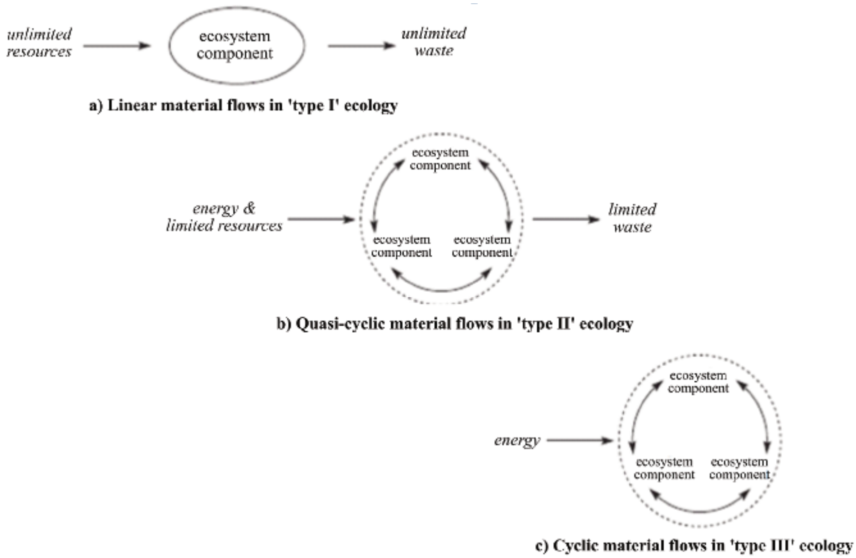


Figure 1.5. *Typology of industrial ecosystems (source: Lifset and Graedel [LIF 02, p. 5])*

1.2.4.3. *Circular flows, a systemic dimension to environmental innovations*

This view of a type III ecosystem is seen in economic literature. If we look closely at the suggestions made by Hohmeyer and Koschel [HOH 95], reused by Rennings [REN 00], we observe that underlying the notion of "environmental technology" are found both "integrated" and "additive" approaches, which, although initially in opposition, have become complementary, even essential, to create circular flows of energy and materials (see Figure 1.6). The "integrated" form uses the principles of the preventive approach and the modularity of the production system: inputs and outputs which are linked to each other through recycling and feedback measures. In parallel with this, there are "additive" technologies, which are there to deal with emissions and pollutants caused by production and consumption. These can no longer be considered as simple "end-of-pipe" technologies, since they feed integrated technologies thanks to a secondary recycling measure. Then, as highlighted by Antoine and Cornil [ANT 02], "end-of-pipe" technologies are after all also "integrated" into an existing production process; "investment in the environment corresponds to the additional cost resulting from integration of equipment. Since this type of anti-pollution equipment is not identifiable as being the separate element from the production process, the cost of this should be estimated by comparing it, for example, with similar existing installations (or parts of installations) which do not comply with legislation regarding the environment" [ANT 02, p. 172]. Implementing industrial ecosystems and creating circular flows of materials and energy has made these two types of technology, which were initially opposed to each other, complementary.

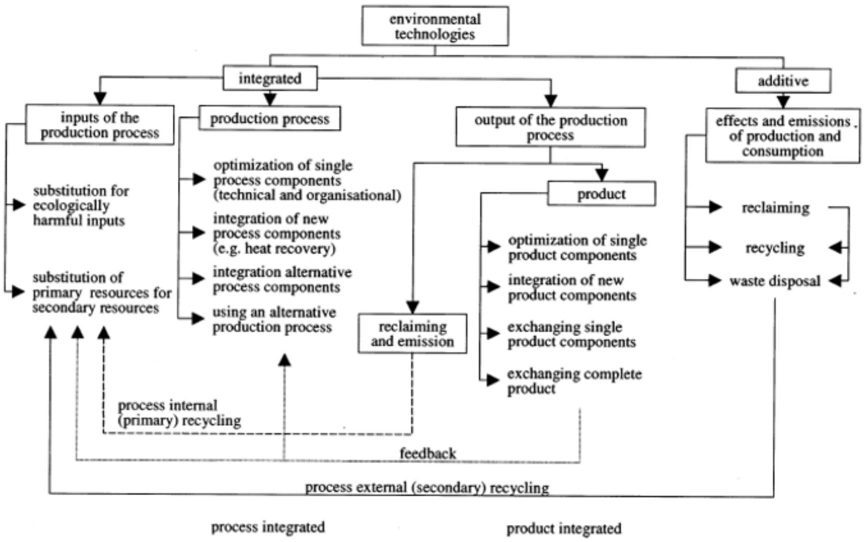


Figure 1.6. *Environmental technologies and circular flows (source: Hohmeyer and Koschel [HOH 95]; Rennings [REN 00, p. 323])*

1.2.4.4. *From circular flows to the circular economy: systemic environmental innovation to service green growth*

In recent years, industrial symbioses have become more and more highly valued case studies. While it was possible to see this during the 2000s [GIB 07, SAK 11], reports carried out by the company Sofies and the Swiss Federal Office for the Environment have recently been able to draw up a complete global inventory. The main objectives of these symbioses are successively, according to Massard and his colleagues [MAS 13, MAS 14], waste management, energy efficiency, water management, and management of material flows, which confirm our previous statements with regard to what environmental innovation would constitute.

Up to 2014, 301 industrial symbioses had been identified around the world. Of these, 67% are on the European continent, with Germany, Switzerland, France and Italy as the main host countries, and the best known being incontestably the one located in Kalundborg in Denmark. Among these symbioses, 78% were operational, most of them being destined for industrial uses, they were sometimes mixed, shared across industrial sites and towns, and they were rarely dedicated to urban areas exclusively (see Table 1.5).

	Identified industrial symbioses			Particularity of industrial symbioses for which details are given		
	Identified	**No details**	**Details provided**	**Industrial**	**Mixed**	**Urban**
Europe	202	87	115	92	19	4
Rest of the world	99	47	52	40	9	3
Total	301	134	167	132	28	7

Table 1.5. *Industrial symbioses around the world (source: Massard [MAS 13])*

The Orée (2013–2016) project, for its part, gives us more information about the case of France. The final report of this is part of an exponential increase in projects based on circular flows at a local scale (see Figure 1.7): they have multiplied by eight between 2000 and 2010, even doubling after this until 2016, thus reaching the bar of 76 projects, compared to 2 in 1989[23]. These figures demonstrate an intense and constant diffusion in the French economic, social and territorial landscape. While these initiatives initially belonged to the industrial sphere, it is now observed that it is a way in which politicians and civil society can participate: the starting point took place undoubtedly during the 2007 Grenelle Environment Project. Moreover, these initiatives have since then become institutionalized in the same way as the French Circular Economy Institute set up in 2013 [GAL 16], or even the National Centre for Independent Information on Waste which was renamed

23 Large regions which have taken part to the greatest degree in this dynamic are respectively Aquitaine-Limousin-Poitou-Charentes (21%), Auvergne-Rhône-Alpes (14.5%), the Grand Est (12%) and Île-de-France (10.5%). On the contrary, cases in the large Center region do not figure in this report. We also specify that we have grouped former regions within the new administrative regions.

Zero Waste France[24] in June 2014. They also took on a legal dimension when they appeared in article 70 of the *Journal officiel* relating to energy transition for green growth, which was released on 17th August 2015[25]. In addition, it is one of the main themes tackled by the public think tank *France Stratégie* in terms of CSR[26]. *In fine*, the desire to turn environmental concerns into an inexhaustible source of alternatives to generate "green" growth is becoming self-evident.

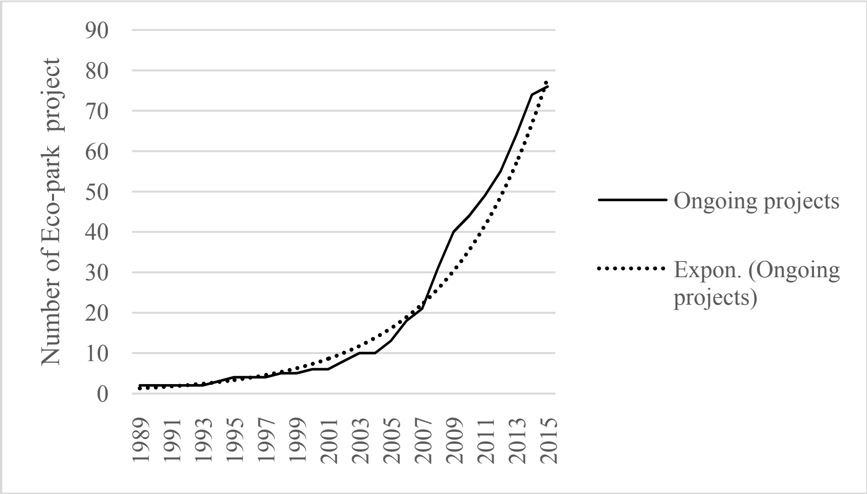


Figure 1.7. *Many industrial ecosystem installations operate in France (according to the Orée report, Lavoisy [LAV 16], compiled by the current author)*

1.2.4.5. *From site-based reasoning to product-based reasoning*

Industrial symbioses are the dominant forms of the circular economy on a global scale [GAL 16]. However, today there is another form of environmental innovation partially related to these circular economy and industrial ecology approaches, which is instead reasoned on the basis of products and their end-of-life management. Nicolas Buclet effectively believed that "[...] the industrial process is less and less based on the raw materials available, and on their characteristics. Thanks to progress made in

24 The Zero Waste France organization aims to provide advice to civil, private and public society, while also sounding the alarm.

25 According to the French law no. 2015–992.

26 To create, for example, new jobs.

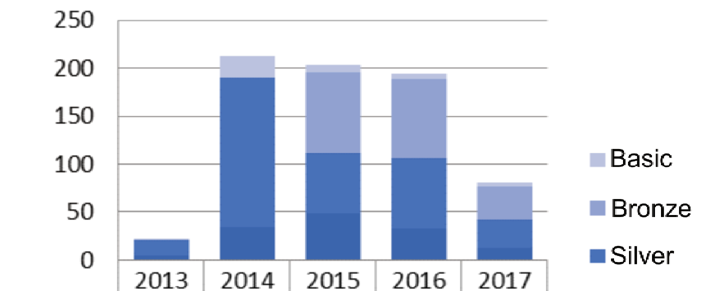
chemistry, and in the flexibility of petroleum resources, raw materials are transformed as a function of the processes. This is at least a fundamental trend which is being drawn up. It is no longer a case of processes which are constructed to adapt to the available resources [...]. It follows that the resources are chosen, extracted where they are available and depending on the flexibilities with regard to the process rather than the opposite" [BUC 11, p. 199]. In other words, the current processes are capable of transforming materials from all sources and origins. Would there then be another perspective of a circular economy focusing only on the product, no matter where it is located?

Looking back at the three forms of ecosystem modeled by Allenby and Cooper [ALL 94], Braungart and McDonough [BRA 02] decided to apply them to a "product" approach. A type I ecosystem demonstrates that a company cannot take into account the fate of its products once they have left the production site. The reasoning behind this point of view is limitless production, named "cradle-to-gate", since product monitoring stops at the "gate" of the production site. The second point of view, based on a type II ecosystem, is an approach known as "cradle-to-grave", which takes into account the product end-of-life and takes greater interest in environmental impacts. Finally, a third view, constructed from the type III ecosystem model, is associated with a reasoning known as "cradle-to-cradle", in which producers take into account the manufacture, end-of-life and, in the case of recycling, the capacity for products to rise again from their ashes [BRA 02]. This last possibility is becoming a practice which is highly valued by industrialists who, rather than focusing on the design of industrial parks, can, with the help of accreditation and of the "cradle-to-cradle" label[27], individually envisage establishing measures to create circular material and energy flows. Five levels of demand are proposed – named "Platinum", "Gold", "Silver", "Bronze" and "Basic" – the first of which denotes a high degree of technical change, whereas the last denotes a low degree. Since 2013, these notation methods have been reviewed several times[28]. At the time, we had noted no less than 350 products benefitting from this certification, but

27 In 2014, a new product certification costs €2,000, an annual renewal certification costs €500, examination of an intermediate evaluation costs €500 and correction of the certificate costs €80.

28 A version 2.1.1 and a version 3.0 exist, then recently a version 3.1 exists. The main themes broached are the health impacts, the re-use of materials, the use of renewable resources, management of water and social responsibility. The two changes are replacement of the "social equity" theme by the latter, and elimination of carbon management.

the relative youth of this measure prevented us from drawing any kind of conclusions about its popularity. Today, approximately 500 products are registered and the five years which followed saw an exponential increase in accreditations between 2013 and 2014, before reducing by three points two years later (see Figure 1.8). Let us note all the same that the "Silver" certifications, which correspond to an average degree of technical change, are the most represented today since they account for approximately 50% of accreditations and, inversely, only 18% of them reach at least the "Gold" or "Platinum" level. Therefore, we can deduce from this that the "cradle-to-cradle" strategy is not a major source of radical change.



	2013	2014	2015	2016	2017
Basic	1	23	9	5	4
Bronze	0	0	83	83	35
Silver	16	156	64	74	30
Gold	5	34	48	31	12
Plat.	0	0	0	1	0

Figure 1.8. *Evolution of products certified as cradle-to-cradle and those in the process of being certified, between 2013 and 2017, as a function of their degree of change (compiled by the current author using data from http://www.c2ccertified.org, consulted in 2013 and 2017, Debref [DEB 14])*

1.2.5. *The quest for eco-efficiency, an objective based on a productivist approach*

According to Huppes and Ishikawa [HUP 05], "The most modest position in eco-efficiency is that, setting aside the question of optimality, we do know that achieving environmental improvements for a lower price is to be preferred over more expensive options". From their point of view, echoing the title of Chapter 8 of the Brundtland report, Braungart and McDonough [BRA 02, p. 51 and p. 53] emphasized the great importance of "producing more with less", in the same way as the company 3M which achieved savings of 750 million dollars between the 1980s and the 1990s, or the company Dupont which reduced dangerous emissions from its products by 70%. In fact, and quite rightly, Knight and Jenkins [KNI 09, p. 28] remind us that these founders of the *cradle-to-cradle* approach believe that "eco-efficiency only works to make the old system a little less destructive [...] much remains to be done and industry needs to go further". In other words, since the 2000s, eco-efficiency has been seen as a solution which would lessen the ecological impact of the production system, and environmental innovations must subscribe to this view to modify the socio-technical regime in place.

The book *The Jevons Paradox and the Myth of Resource Efficiency* by Polimeni, Mayumi, Giampietro and Blake [POL 08] is partially dedicated to the application of eco-efficiency. These authors highlight that this notion was already present in the first works by Petty in the 17th Century, who set himself the task of studying productivity of exploitation of agricultural activity to feed the population. In this book, he compares energy efficiency with the productive forces which allow goods supplying flour mills to be transported by water and by land. Malthus also expressed this idea, with the view that "The Earth has been sometimes compared to a vast machine, presented by nature to man for the production of food and raw materials; but, to make the resemblance more just, as far as they admit of comparison, we should consider the soil as a present to man of a great number of machines, all susceptible of continued improvement by the application of capital to them, but yet of very different original qualities and powers.[...]" [POL 08, p. 18] Say added that "the knowledge of the civilized man, compared with that of the savage or barbarian, gives him the power of constructing a much greater number of instruments out of the same materials" [POL 08, p. 19]. Smith also used ratios about the quantity of work required in order to gain knowledge of the productivity of soils and mines. These examples show that eco-efficiency has, on the one hand, a technological character and, on the other hand, this type of ratio allows nature and industrial activity to be related with an economic dimension [POL 08, p. 21].

Box 1.5. *Eco-efficiency, a subject broached over the course of the last few centuries by economic theory*

Let us first pause to look at the terminology: we have *eco-effectiveness*[29] as opposed to the term *eco-efficiency* [POL 08, p. 13]. These authors aim to cater to environmental concerns while providing an opportunity to create value. Eco-efficiency is calculated using a ratio which has input as the denominator and output as the numerator, which allows material intensity of production and productivity of raw materials to be evaluated. This ratio can be used according to two objectives: on the one hand, to maximize the level of production by dividing two material variables (e.g. to calculate the energy required to produce 1 kg of merchandize); and, on the other hand, to increase the added value as a function of the quantity of resources in order to increase the economies of scale [OEC 12a, OEC 12b]. Intensity and "efficiency" can therefore go hand in hand for environmental questions. In this respect, "material flow accounts" have only recently become established as a Eurostat indicator to account for the efforts made within countries that are members of the European Union and by large sectors of industry. A report by the OECD [OEC 12b, p. 3], entitled "Resource Productivity in the G8 and the OECD *A Report in the Framework of the Kobe 3R Action Plan*", reinforces this route by stipulating that the eco-efficiency increases the competitiveness of companies while responding to the problem of sustainable development. This appears to be confirmed by European statistics, which have recorded a 36.47% increase in the productivity of raw materials since the year 2000 in the European Union. The use of material flows has, on the contrary, only fallen significantly by 12.5% for the same time period, despite, by way of indication, a strong negative correlation [EUR 18e, EUR 18f] (see Figure 1.9). This result means that greater efforts were being made and that the reduction in the use of raw materials has led to an increase in wealth creation. However, can we further reinforce this intensification?

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29 The authors specify the subtlety, sometimes ambiguous, which surrounds the terms "efficiency" and "effectiveness": "Throughout the following examination of our authors' definitions of efficiency, it is axiomatic that efficiency denotes *a ratio*. The numerator is output and the denominator is (energy) input. 'Efficacy', 'effectiveness' or, more ambiguously, 'power' denote in contrast the causation of a given amount of output regardless of cost or input. Ontologically, the thing that is more or less efficient is the input. [...] The ubiquitous classical concept of 'productive power' thus implies, like the Latin-based term efficiency, both a 'making' and an 'out of something'. The inverse of *efficiency* is intensity, as in the 'material intensity of production' common in today's environmental efficiency discussion" [POL 08, p. 15].

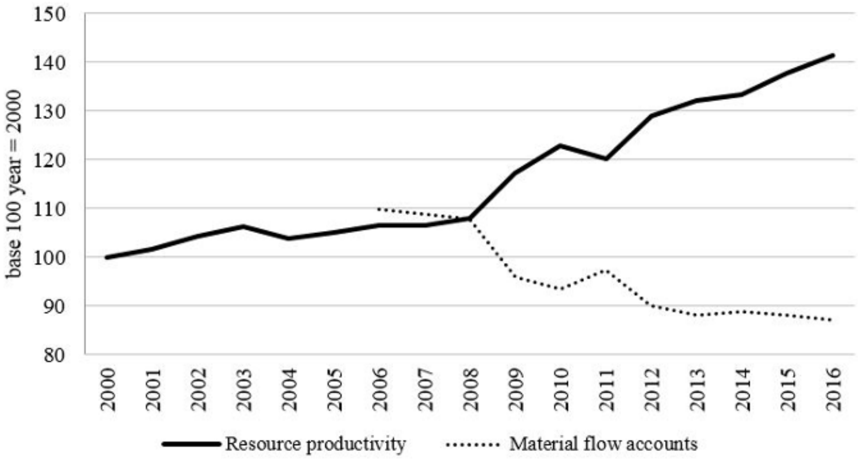

Figure 1.9. *Index of the productivity of raw materials and accounting of material flows in the European Union, for the 28-member states between 2000 and 2016, base 100 year = 2000 (source: Eurostat [EUR 18e, EUR 18f], references: tsdpc100 and env_ac_mfa; correlation coefficient – 0.90)*[30]

Today, strategies which give priority to eco-efficiency are no longer limited to a single production system that can be treated as independent of other economic activities. The ratios have recently been put into hierarchical order then linked to the different production systems during the material and energy cycle. Here, it is a question of extracting, to a maximum degree, all the potential of eco-efficiency by applying strategies of use, known as *cascading use*, which aim to reinject materials into activities with high added value in different production processes to then end up with energy recovery and even obtaining co-products. This is a concept which is often found in industry sectors that use biomass, like forestry, the paper industry and biomaterials [KEE 13, ESS 14, CIC 15]. Except that, while optimization of the transformation of energy and materials drives down production costs, at the same time as reducing waste of resources during the production process, the increase in eco-efficiency remains influenced by the substitution of available technologies, methods and raw materials. Thus, for example, Polimeni *et al.* noted that the eco-efficiency of making cuts in materials increased "when cutting tools change from steel to ceramics to carbide (diamonds), these raise cutting efficiency but are not more efficient uses of a

30 New arrivals in the European Union between 2000 and 2012 are included in the Eurostat statistics.

given material" [POL 08]. This applies equally to dangerous substances used, which should be replaced in order to increase productivity. In other words, the intensification of production arising from eco-efficiency is achieved either by substituting inputs or technologies, or by maintaining the existing as long as possible.

Here we look at the results of our PhD work on the European sector of hard-wearing floor coverings (e.g. PVC and linoleum flooring) [DEB 14, pp. 238–240]. In this, we demonstrated that innovations based on eco-efficiency were only there for the purposes of intensification of production; moreover, they extended their scope of action over several decades, passing from a site-based approach to a circular economy which extends across Europe.

The beginning of the 1990s was a time when there was a true lack of interest in strategies aiming to counter industrial waste and by-products. Producers had the possibility of transforming the environmental constraint into a competitive advantage by means of optimization of production processes. Projects began by the deployment of innovations which recovered plastic offcuts, easily recyclable, by reinjecting them directly into the production process on site. Others were even more specialized in terms of energy savings, either by improving cooling circuits, or by constructing new buildings, or by investing in new, less energy-consuming machines. Finally, certain companies took action by repurposing waste coming from biomass (e.g. sawdust) in the form of steam: this course of action therefore guarantees energy independence of a sort.

Since the 2000s, the high volatility of the price of oil and social concerns relating to plastics (e.g. PVC, phthalates) have led industrialists to reinforce this first form of eco-efficiency. To do this, producers rallied around the EPFLOOR project – 700 million euros per year on average between 2002 and 2017 and self-financed – in order to contain all end-of-life hard-wearing floor coverings across Europe. Other solutions are added to this. On the one hand, professional French fitters, for example, were trained to sort end-of-life products into allocated bins at the fitting site. On the other hand, products have also been adapted to supply a "ready-for-use" repurposable resource immediately on completion of their life-cycle, with the objective of making the circuit more fluid (adhesive-free, click-lock installation, for example). The result leaves no room for doubt. Since the 2000s, producers of hard-wearing floor coverings have multiplied the amount of post-consumer products by eight between 2001 and 2016 (i.e. 500 to around 4000 tonnes per year).

Box 1.6. *Expansion of eco-efficiency and intensive production: the case of hard-wearing floor coverings*

This section confirms the idea that the typology of environmental innovations currently gives priority to incremental solutions. If this concerns isolated innovation, this situation is also found in the case of systemic environmental innovations based on a circular economy approach. While, during the 1970s, intensification of production was easily condemned, it must be noted that eco-efficiency, the fourth type of environmental innovation that we have distinguished, is considered today to be a solution giving preference to conservation of the environment. This raises the question of the drivers which cause this low degree of change and this relative stability; this will be the subject of the third and last section of this chapter.

1.3. Drivers of environmental innovation in the face of institutional tensions

Analysis of the drivers of environmental innovation is first and foremost part of a Neo-Schumpeterian view. We will see, then, that the impacts of technical change vary considerably depending on the existing dominant design. The Dutch school of transition management is particularly interested in this notion, which proposes to steer technical change with sustainable development in mind (see section 1.3.1).

Second, we will look at works which model the drivers of environmental innovation by means of a complex game of incentives emanating from markets, from the technical regime in place and public policies, and we will demonstrate, for example, the importance of the "Porter hypothesis" which gives a critical incentive role to environmental regulations in the innovation dynamic (see section 1.3.2).

Third, we will consider the approach in terms of the "controversial universe" and environmental conventions proposed by Godard [GOD 93] (see section 1.3.3), and then we will finish this section by returning to the literature dedicated to rebound effects which questions the existence of environmental innovations (see section 1.3.4).

1.3.1. *Modifying the dominant design, thanks to transition management theory*

1.3.1.1. *The theory of dominant design in sectorial dynamics*

Abernathy and Utterback [UTT 75, UTT 78] believed that understanding sectorial dynamics is essential, because this is where there is a predominance of innovations which influence the socio-technical regimes in place. This domination process takes hold in three phases. The birth phase is characterized by the occurrence of a rupture arising from original technological and productive combinations. This rupture is felt by the other actors in the sector, which must adapt. Starting from this, these same companies then find themselves in a situation of economic uncertainty that has to be overcome in time by accumulating experience and skills as well as by observing the actions of other competitors.

This phenomenon, better known under the name of dominant design, will then structure itself and stabilize. Proposing homogeneous innovations is not necessarily economically viable. This is why competition will lead to differentiation strategies and price reductions to the point where only minor modifications are made to standards in innovation.

The second phase will conserve the dominant design, but innovations reach a threshold of maturity and diffusion such that the only solution, for industrialists who still want to get out while the going is good, is to propose lower prices by optimizing production processes. The dominant design movement fades out in the third phase. This comes from the fact that expertise is no longer evolving to give priority to creativity, but to incrementality. From that point on, the market saturates and intensifies the uncertainty of industrialists: the dominant design is then in crisis. Domination of a form of innovation can influence the entire sector, impose itself as standard, and be maintained over time as optimization of processes allows. This is all the more important when it is necessary to involve environmental innovation in the sectors where the dominant design is particularly stable but highly contested.

1.3.1.2. *Transition management: a multi-level perspective to direct the views of future technical changes?*

Modifying the dominant design to help environmental innovations to become established poses the question of the way in which the transition operates to reach a "sustainable" socio-technical regime. The Dutch school of transition management is presented today as the prevailing school of thought. Since the beginning of the 1980s, Ackerman [ACK 82] defined transition as an organizational change which allows us to go from one social state to another. Taking up this proposal, authors such as Grin *et al.* [GRI 10] added the role of irreversibility to it through reorganization of the developing socio-technical regime, whereas Kemp [KEM 94] underlined the role of prices and markets. While this analysis of transition remains general, de Vries and de Riele [DEV 06] insisted on the fact that this transition is above all a meeting between different models of development which can present themselves as possible alternatives to change the prevailing mode of development. However, this change dynamic is influenced by the evolution of social norms and unforeseeable events [VAN 05, p. 168].

To explain the viability of environmental innovation and its characteristics within such complexity, Geels [GEE 04, GEE 05, GEE 10, GEE 11] demonstrated true originality when he proposed to adopt a multi-level approach to explain the technical change [GEE 07]. The author takes two questions into account in advance in order to steer the transition and, *a fortiori*, the dominant design. The first is taking into account social challenges and the need to substitute an innovation with another. In our case, taking environmental concerns into account will serve as a guide. The second is to determine how to combine the innovations in such a way as to generate novelty as a function of the identified social demands, to modify the innovation already in existence while managing cohabitation between the existing and the new. According to Geels, this dynamic process is understood in three stages. First, technological niches are there to conserve and reinforce the longevity of environmental innovation in the face of dominant design. Sufficiently strong, the latter are introduced into the socio-technical regime in place, to the point of modifying the socio-economic landscape (see Figure 1.10).

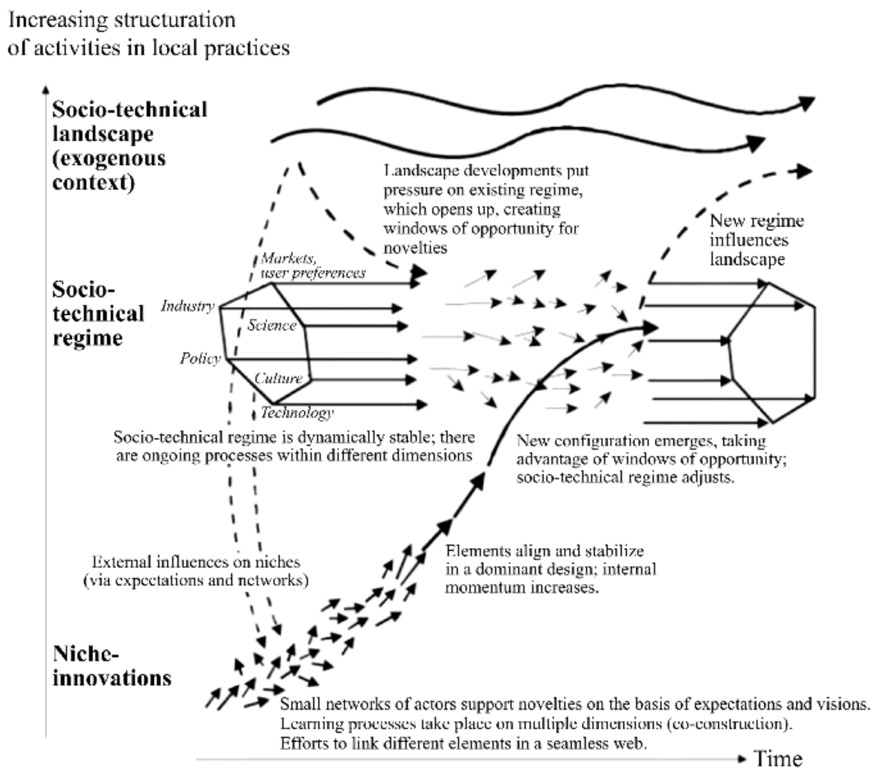

Figure 1.10. *The approach in terms of a multi-level perspective (source: Geels and Schot [GEE 07, p. 401])*

The "S"-curve shown in this diagram, as well as the many arrows that it contains, encourage reading of the innovation dynamic to pass from technological niches to the socio-technical regime, to the point of modifying the socio-technical landscape. In fact, this model can be interpreted in three different ways. First, if we consider that the evolution of environmental innovations occurs stochastically and systemically, then the effects of the diffusion of innovations on the socio-technical regime in place are only seen *ex post*. In other words, it will only be possible to validate the objectives *a posteriori*. This approach would appear logical, insofar as it is impossible to anticipate its economic and environmental impacts *ex ante*. Second, certain technological niches can exist and develop without fixed objectives and will, by chance, have an influence on the socio-technical regime in place. Once again, the positive impacts will be seen *ex post*. Finally, we have the third interpretation, where the objectives have been fixed right from the start in order to correctly modify the dominant design. In this scenario, this model is understood from an overall point of view based on hindsight, insofar as the actors of the niches and the regime in place represent a vision of the future: they anticipate and are coordinated. This situation, better known by the name of *backcasting*, shows that actors steer environmental innovations thanks to their collective beliefs, their "view of the world", to the point of modifying the system in place. Evolutionist economists at the University of Sussex rightly criticize the Dutch school on this last point, since they believe that substitution of one technological system by another is above all influenced by institutions, regulations and standards [BER 03]. Smith and Stirling [SMI 08, p. 9] insisted, moreover, on the existence of "modulation of steered objectives". Scoones *et al.* [SCO 07] reinforced this hypothesis by demonstrating the existence of communities which structure and steer the dominant design.

1.3.2. *Moving towards a specificity of technological trajectories of environmental innovations?*

1.3.2.1. *Technological trajectories of "standard" innovations and analysis ex post of the effects*

When observing the technological trajectories of standard innovations, Pavitt [PAV 84] noted, using a database of approximately 2000 major innovations in the United Kingdom, the existence of patterns [PAV 84, p. 354]. These patterns establish profiles of activity by sector and are in constant interaction [PAV 84, p. 364]. The author identifies the sectors influenced by the dominance of suppliers, by specialized suppliers, by companies founded on a mass production approach, and by those founded on science. Dosi [DOS 82, DOS 88, DOS 93] delved deeper into these results by underlining three forces of influence. The trajectory of the innovations depends on consumer demand: known as the "demand pull". Since each technology combines with the others, a second strength lies in existing technologies: known as the "technology push". A third strength comes from knowledge banks and all scientific discoveries: known as the "science push", which opens new perspectives with an innovative approach. These three strengths, with largely unexpected effects, create a system that makes technological trajectories evolve. What, then, is the situation regarding environmental innovation?

Do we come across the set of strengths identified by Dosi? As even Nijkamp *et al.* [NIJ 01] admitted, "the process of adopting environmental innovations is generally less transparent than that for normal innovations". The authors do however agree to say that, while they share certain drivers, technological trajectories associated with environmental innovations are also influenced by other factors.

1.3.2.2. *Normative demands based on an* ex ante *approach*

At the beginning of the 1990s, Becher *et al.* [BEC 90] highlighted that environmental pressures are there to influence standard innovations (see Figure 1.11). These drivers come specifically from consumer and investor concerns, which are gathered under the expression "ecology pull". The intervention of public powers is added to this by means of the implementation of regulations and taxes, and the imposition of new production standards. We can also cite the participation of consumers and investors – the interested parties – and pressure from the media. This "ecology push" approach, to pick up on the expression used by the authors, therefore shows to what point pressures external to the market play a central role in the emergence of environmental innovations. Still in reference to Figure 1.11, we can see that these strengths make the economic system converge towards recycling, or towards a circular economy, the systemic form of environmental innovation that we have identified previously.

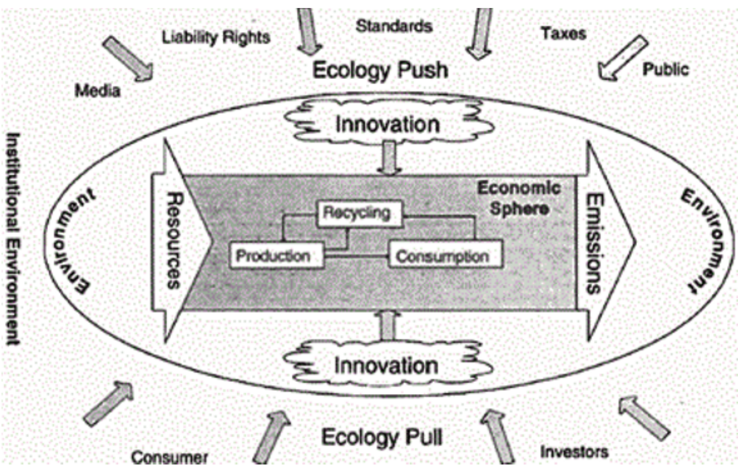

Figure 1.11. *Drivers of environmental innovations according to Becher et al. [BEC 90]*

Other authors pondered the factors which give preference to environmental innovations at the beginning of the 1990s [CRA 90]. Kemp and Soete [KEM 92] indicated three major drivers. The first involves technological opportunities which turn environmental innovations into innovations which have to adapt to environmental concerns within sectors. These adaptations are structured around technologies which already exist, or technologies which substitute others. The influence of the "technology push" is in evidence here. The second determinant depends on the demand requirements in terms of the environment, which influence industrial practices: this is the "demand pull". Finally, a third factor remains in the appropriation conditions of these technologies, which depend on two elements: cost and public support, in terms of patents and standards for example.

This importance attached to public standards was again highlighted during the 2000s, as much for supporters of the ecological economy as for evolutionary economists. Looking back at the technological trajectories of Dosi, Rennings [REN 00, p. 8] added the influence of the technology push by integrating normative variables into it such as eco-efficiency, the quality of resources and energy. Regulations, the "regulatory push", are taken into account via the enactment of environmental laws, technical standards and fiscality which arise from the prerogatives of public authorities. The impulses of the market by means of the expression of the consumer demand, the demand pull, are also considered decisive. As shown in Figure 1.12, these three strengths are present in the work of evolutionist economists Oltra and Saint Jean [OLT 07, p. 8] which leads us to believe that with regard to drivers, the analysis of environmental innovations has today become stabilized.

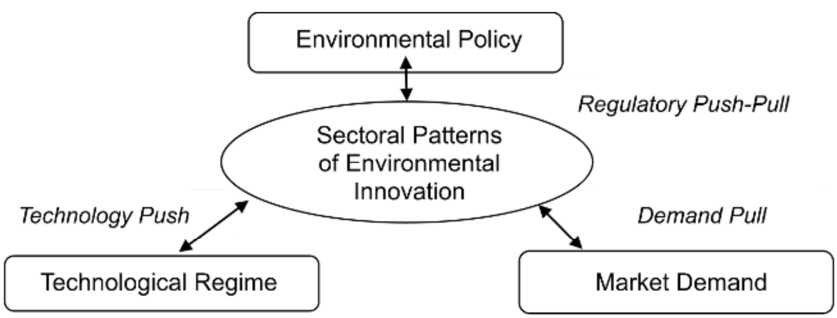

Figure 1.12. *Technological trajectories of environmental innovation (source: Oltra and Saint Jean [OLT 07, p. 8])*

1.3.2.3. *From environmental constraints…*

Ambec *et al*. [AMB 13] have for several years given reminders of the interest taken by economic theory in the role of environmental pressures, in particular those which are regulatory, about the innovative behavior of companies. It is true, let us remind ourselves, that environmental innovation is based on a double dimension, the short term and the long term, which obliges the manager to thoroughly review their judgment and their choices. Profit remains a legitimate objective, but the costs of production are not the only elements which must be taken into account. It is also necessary to take into account the uncertainty, the aversion of the entrepreneur to risks, their limited rationality, and their customs [AMB 13]. This situation undoubtedly leads to a reduction, in the field of possibilities, which can thus threaten the very existence of environmental innovation. This is why, during the 1990s, Porter and van der Linde [POR 95a, POR 95b] set out on an original path, stipulating that the environment would be an opportunity for competitivity, rather than a constraint.

1.3.2.4. *… to the necessary intervention of public authorities*

This reversal of perspective, signs of which were found in the 1980s [ASH 93, ASH 94], came clearly to the forefront when the prevailing economic theory observed that the market strengths were not sufficient to include the environmental constraint in the movement for technological change. Only through intervention by public authorities, notably through their standards and regulations, would it be possible to link environmental constraints and competitivity [AMB 13]. These authors highlight the role of environmental regulations and taxes which encourage companies to become leaders by allowing them to benefit from new incomes as monopolies. This situation, known as the first mover advantage, cannot prevail if regulations are felt to be too oppressive, because companies will move away to other areas and territories, less demanding from an environmental point of view, thus simply causing the displacement of pollution. Another concern relating to the asymmetry of information is added to this. Effectively, it could be that consumers concerned about the environment do not have all the required information to evaluate the responsible measures taken by companies. This is why public authorities have this role of putting labels and accreditations in place [AKE 70, AMB 07]. Another failure, significant in our opinion, pertains to practices in the field of research and development. Ambec *et al.* [AMB 13] pointed out that, if public authorities did not intervene, then no company would have an incentive to initially take the risk of integrating environmental concerns into their strategy.

1.3.2.5. *Environment and competitivity: a look back at the Porter hypothesis*

In the face of these failures, Porter and van der Linde [POR 95a, POR 95b] decided to persuade companies and decision makers, who are skeptical regarding the effectiveness of environmental regulations. The environment, these authors explain, is not a constraint, but rather an opportunity to be competitive, which can be used to our benefit in adapting a "win–win" approach. To achieve this, they develop five themes. First, regulations guide companies regarding priority resources and possible technological improvements. Second, they gather the information required for industrialists to be able to make decisions. Third, they reduce the uncertainty when investment is made in environmental conservation. Fourth, they provide the necessary pressure to encourage companies to innovate and progress. As a fifth point, regulation means the transition can be managed, by surveying which companies do not want to invest in favor of environmental innovations. Despite this set of arguments, as pointed out by Ambec *et al.* [AMB 13] and Palmer, Oates and Portney [PAL 95], one question remains: in what way are public authorities best placed to say what the most beneficial move for companies would be, while the former are not necessarily up-to-date with the particularities of the latter?

1.3.2.6. *The various levels of the Porter hypothesis*

Academic literature has further explained the words of Porter and van der Linde, since the positive effects of environmental regulations on competitivity are not automatic [AMB 13]. Three degrees of influence have been identified [JAF 97]. The first is a "weak" influence, insofar as environmental regulation can, certainly, motivate innovation in favor of the environment, but nothing tells us if it will be favorable or not to the company. In the opposite case, a second "strong" influence of regulations reduces the costs of production and ensures the competitivity of companies. Finally, situated half-way between the two, a third, "narrow", influence is more pragmatic, with a flexible environmental regulation which is adapted to the characteristics of the companies. Using this approach, let us try to understand how this normative pressure is going to be set up.

1.3.3. *Creation of technical conventions promoting conservation of the environment*

1.3.3.1. *Institutions and presence of path dependences*

Regulations and the learning process which lead to technological change are based on past experiences and a "known precedent" [BAT 01, p. 133]. Here, history counts, and the evolution of innovations is based on phenomena which go beyond the frame and the purely merchant movement. Dominique Foray highlights the existence of "historical accidents", a theory that he supports by taking the example of nuclear energy after the Second World War. He observed that this technological paradigm is "[…] accidental from the point of view of the dynamic process […]. It is not accidental, however, from the point of view of the historical context, with which the decision made is obviously consistent" [FOR 91, p. 308]. At the time, nothing could have foreseen the criticism on an environmental level, nor its importance for the French economy. This is why the author draws our attention to the unpredictable, irreversible (locked-in), potentially ineffective, and also (in our view) environmental character of standard innovations.

David took a special interest in this phenomenon for the case of innovations, in general, by studying the case of the typewriter keyboard [DAV 85]. He compared the performance of the QWERTY keyboard and that of the Dvorak Simplified Keyboard (DSK), perfected in 1932 by Dvorak and Dealey, and quickly realized that by using the second solution, writing could be done faster and more intuitively than with the first. However, today, the QWERTY has prevailed, despite its inferior performance. Over time, Arthur explains to us, the innovation selection process goes on and becomes stronger, because of the multiplication of interactions, the generation of scale economy, technological complementarity, and the principles of irreversibility generated by learning and habits are all capable of making sub-optimal technology a standard [DAV 85, p. 334]. It can also be a "bottleneck" since it will be difficult for new technologies not to refer to the dominant technology. In addition, this "path dependence" indicates to us to what point the technological convention does not necessarily go hand in hand with the intrinsic effectiveness of an innovation, whether environmental or not.

1.3.3.2. *Moving towards several forms of path dependence?*

Margolis and Liebowitz [LIE 95] complemented the hypotheses made by David [DAV 85] and Arthur [ART 89]. According to them, it would not seem to be a case of one path dependence, but three, each being of a different kind. The first degree of path dependence does not lead to negative effects on the evolution of technologies, because cost is the factor that is going to steer a sub-optimal dominant path. The second degree comes from technological choices which, in the eyes of the innovator, seem *ex ante* to be optimal and suitable; however, they will notice *ex post* inferior performances to those initially seen: path dependence will also be based here on a transfer of errors. The third degree of dependence originates from the starting conditions during the decision-making process. At the beginning, the innovator makes an error of judgment and, when he realizes this, manages to correct it. In this case, the transfer of error can be repaired. Certainly, but at what price?

The authors take the example of two technologies, VHS tapes and Betamax, which have the same televisual features. They show, in a first hypothesis, that the choice between these two technologies is not well defined, since they both have strong advantages. As the process is carried out, the authors identify the second degree of path dependence. Effectively, over time, it would seem that Betamax technology has a much higher performance than VHS from a technical point of view. However, it has not succeeded in becoming prevalent. Designers only noticed this irreversible error later; irreversible because it would be too onerous to take a step backwards. Moreover, rather than being incapable of improving one's own technology, which is initially quite onerous, the authors explain that the innovator can choose between sacrificing opportunities in the long term in favor of lower risk [LIE 95, p. 132]. Now, in the face of these path dependencies, it is entirely possible to see environmental innovations fail to emerge or remain with unexploited capacities.

1.3.3.3. *The process of innovation, dependent on multi-actor relationships*

These phenomena are also governed, according to Witt [WIT 97], by the presence of critical masses. These come from the fact that all innovations are interrelated and that grouping them together can impose restrictions on the emergence of new forms of innovation. Here, a simple cost/benefit relation is not sufficient to explain the decision-making, since the innovator will anticipate and try to imitate other actors in order for their future innovation to be able to follow the others in becoming economically viable. Consequently, the choice is based on subjective criteria resulting from the behavior of other innovators: this group and the effect of "self-organization" force us to look at the influence of the regulations and practices in technical change [FOR 91b, p. 585].

Torre [TOR 93] started with the statement that all innovations generate positive externalities, even with patents or other legal protections. These externalities are knowledge and expertise which are a source of interactions between producers, consumers and innovations already in existence. Sometimes, in the interests of innovation, industrialists (although in competition with other) cooperate by establishing joint ventures, that is, projects in common which aim to share patents, for example. Beyond these official projects, these same industrialists also have the informal means for better innovation, such as sharing "rival knowledge" [VON 89]. This rival knowledge is important, insofar as it allows each participant to combine their technologies and to leave technological bottlenecks behind. It is therefore not surprising, here, to see Torre introduce the notion of "production relations", which can cause resistance when it becomes necessary to steer the dominant design. This resistance is based on two strategies. The first is that of wanting to "protect established market positions from attacks carried out by [...] newcomers or from threats made by potential newcomers, with the aim of constructing technical barriers at the entrance. [The companies] also have an interest in collaborating to discourage new domestic competitors from entering the market from other branches. In fact, rapid technological changes lead to market re-structuring which allows a step to be taken from one industry to another depending on the diffusion of socio-technical paradigms" [TOR 93, p. 91].

The second strategy is based on the idea that competitors can become partners clustered around innovations in order to exclude cooperation of other industrialists: informal relationships therefore allow the competition to be influenced by means of common design rules. Torre explains this phenomenon through the influence of phenomena which are "sociocultural, such as common language, education, ideology, family relations, shared interests and friendships", which lead to a "consensus" and cooperative arrangements which structure the innovation process in the long term. The objective of this cooperation, according to the author, is to "contribute to slowing down decreasing technological yields" [TOR 93, p. 99]. This choice is explained either because of the strong uncertainty faced by industrialists, or because of the need for technical complementarity and interconnection. If standard innovations are influenced by this collective and non-trade dynamic, is the same true for environmental innovations?

1.3.3.4. *Environment, controversial universes and institutional reorganization*

In many cases, environmental concerns reinforce the collaborations between economic agents. Starting in 1987, industry sectors that are highly affected by environmental concerns, such as the chemical industry, have developed collective projects with the help of heavy measures, such as patents and specialist commissions, in order to collectively modify the processes and products that have been incriminated [LEV 87, pp. 794–797]. The question is asked in particular in the case of "controversial universes", which was studied by Godard and Salles [GOD 91] and Godard [GOD 93].

These environmental problems have been initiated with scientific knowledge which are both sufficient to recognize that these are problems, and therefore the need to make public opinion and decision makers aware of them, but insufficient for exact knowledge of the ins and outs to be known, hence the controversy. Since it did not come rapidly to a close, this scientific controversy soon spills over into the public sphere, where it encounters the presence of other interested parties: industrialists, politicians, media and so on, who are going to try to influence the discussion, some with an interest in ending the controversy but others, on the contrary, with an interest in keeping it open.

In this case, as Godard and Salles [GOD 91] pointed out, actors – including industry leaders – must be in agreement about what the environmental problem is. Yet, it does happen for this controversy to be partially resolved by technical solutions that certain actors have available to them, around which "technical conventions" are then set up [GOD 91, p. 241][31]. It is not rare to encounter, on this occasion, a situation known as "inversed risk" [ROQ 88, p. 46], which is characterized by the fact that companies not acting as a result of the environmental risk initially detected,

31 "In fact, this is a set of conventions and social structures (a formally well-constructed language, objectives, and means represented as clearly separate, abstract equivalences established between objects and between phenomena) which allow an arguable collective decision to be produced, instead of this being just the place for opposing opinions from different actors to be laid out […]" [GOD 91, p. 241].

but instead motivated to respond to this environmental problem by the industrial or commercial risk presented by the possibility of correction by the authorities (by means of regulations, a tax system, etc.).

The most illustrative example of this movement "in reverse" – where available technologies or improvements that can be made to them are the defining elements of the environmental problem, and not the opposite – remains the widespread use of catalytic converters by the European motor vehicle industry in the 1990s to respond to the problem of acid rain, recognized around 10 years earlier. As Godard and Salles [GOD 91] indeed demonstrated, the consensus reached beforehand between industrial actors and German politicians about a certain "environmental convention" – which included the causes of the problem, the designation of those responsible and the technical solutions which can be applied to them – would then allow this convention to be adopted by all European Union member states. The thorn in the side of the story – but also the great lesson to be learned in terms of industrial strategy and environmental policy – is that it is no sure thing that the installation of catalytic converters has really answered the initial environment problem. This calls into question whether what we denote as "environmental innovation" is well-founded. The same occurs with the notion of "rebound effect".

Today, the effects of the 1992 Rio Earth Summit are still echoing in the memory of the industrialists affected by environmental and social concerns. The legitimacy of the chemical sector was one of the first to be called into question: this is the case of producers and transformers of polyvinyl chloride (PVC) in the 1990s. This raw material coming from oil was criticized by associations and public authorities due to its chlorine-based composition: a health danger for consumers.

Our PhD work has demonstrated that producers of PVC have succeeded in turning the situation around by working together, thanks to collective practices based on voluntary commitment and sectorial self-regulation. They put in place an environmental innovation of large scope based on the circular economy (recycling, for example) which has paradoxically allowed us to maintain the disputed dominant design [DEB 14, pp. 209–212].

Everything began in the chemical industry during the 1990s when North American chemical industrialists launched the "Responsible Care" project to establish a technological roadmap. A few years later, around 60 countries supporting it gathered around the focus of a global charter, christened the "Responsible Care®

Global Charter", which proposes nine courses of action intended to give preference to "institutionalization of good environmental practices" [BER 05, p. 5; see Table A.1]. These regulations are clearly displayed in the project "Suschem France Roadmap 2010" supported by the Union of Chemical Industrialists (Union of Chemical Industries for France (UIC), DGCIS[32], 2011).

The plastic sector followed this movement, starting in 1995, by establishing two charters which invite PVC producers and plastic resin producers to take environmental and health impacts into account in their innovation strategies [VIN 01]. Since May 2000, PVC industrialists decided to follow a roadmap entitled "Vinyl Plus 2010"[33]. This collective project invited them to commit voluntarily to an approach supported by the project named "The Natural Step" which advocates recycling and environmental protection. Here, recycling is a solution to stabilize activities and conserve the existence of their key molecule.

It is therefore not a coincidence to see a gathering of European producers of hard wearing floor coverings, which use PVC, under the name of European PVC Flooring Manufacturers, subsequently known as the European Resilient Flooring Manufacturers' Institute, a sectorial homogeneity which was also seen in France with the appearance of the group SolPVCpro, destined to "highlight the shared values of all the brands" [SOL 14]. Except that, who would have thought, 3 years later, the powers that be among the French competition would prove the existence of a "lino cartel" among the leaders, where, for example, non-competition agreements about environmental communication adopted within the SFEC (relevant French trade union) were found (French Competition Authorities, 2017, p. 52)? The ratio of power between this sector and the public authorities is also encountered in work by Schwartz [SCH 09]. Moreover, the author highlights that Tarkett, a leading, established company, put pressure on public policies in such a way as to "influence the legislation and the authorities by introducing plastic PVC flooring with incorporated recycled materials. [The company] sought to ensure acceptance of a PVC product inspired by the recycling concept through the use of persuasion in a demanding environment. Certain Federal states even canceled their bans on PVC, because the difficulty lay in finding substitutes offering the same quality as PVC products, and also due to lobbying from the German plastics industry".

Box 1.7. *Systemic environmental innovation, a means of collective resistance in controversial sectors?*

32 Senior management group for competitiveness, industry and services in France.

33 The main financers of the project are the European Council of Vinyl Manufacturers, the European Stabilizer Producers Association, and the European Council for Plasticizers and Intermediates.

1.3.4. *The rebound effect, the forgotten impacts and macrosystemic crises*

1.3.4.1. *Efficiency of raw materials and its rebound effects: the incapacity to evaluate the environmental impact* ex post

As we have already demonstrated, "end-of-pipe", "clean" and "systemic" technologies all aim for eco-efficiency, which, let us remind ourselves, is presented as a solution for savings to be made in terms of raw materials and to counter waste, while limiting the environmental risks. However, the complex dynamic of socio-economic systems can have surprises and paradoxes in store. Effectively, on the one hand, energy and materials savings give us the sensation of conserving natural resources. On the other hand, the reduction in resulting prices or the increases in efficiency obtained can stimulate the requirement for new technologies and increase their degree of use. The savings made by the least amount of initial consumption of resources encourage the actors to further consume these same resources, which lead to acceleration of their rarefaction process in the long term.

Saunders [SAU 00], Alcott [ALC 05], Herring and Roy [HER 07], who all operate within the field of ecological economics, highlighted that interest in this problem of "rebound effects", after it had re-appeared in the 1970s, again increased during the 2000s. Alcott [ALC 05] and Polimeni *et al.* [POL 08] thus offered a rich and captivating study, which is complementary to the work of Khazzoom [KHA 80], Greening *et al.* [GRE 00], Binswanger [BIN 01] and Sorrell and Dimitropoulos [SOR 08]. What are the drivers of this phenomenon? By seeking to respond to this question, Sorrell and Dimitropoulos [SOR 08, p. 637] presented two families of rebound effects. The first is a direct effect that results from the avidity of the consumer to obtain even stronger feelings of well-being with goods or services bought for less, which is played out by means of the effects of revenue and substitution. The second involves indirect effects which encourage the consumer to benefit from savings that he has made with less energy-consuming technology. The authors remain prudent with respect to these effects, because they are difficult to measure empirically, but this raises an important point when it becomes necessary to identify environmental innovations [SCH 00]. These phenomena arise from the energy substitution occurring within production factors.

Polimeni *et al.* [POL 08] took the analysis further by identifying six causes of rebound effects, whose first half would be direct and whose second half indirect (see Table 1.6). Concerning the direct effects, the first cause is a consequence of reduced production costs which would allow consumers, with a restricted budget, to consume more products thanks to lower sales prices. These latter have the possibility of consuming more resources for the same price, which can be associated in micro-economy with a substitution effect and a revenue effect. This economic condition is moreover essential to make environmental innovations viable. Second, the authors point out that lower costs allow access to technologies for a population who did not have the means for it up until that point. This is the case for environmental innovations which aim to modify our mode of development. Paradoxically, due to the fact that a larger number of users want to enjoy the benefits of this intensity of productivity, the pressure on resources is going to increase. The third effect comes from the fact that eco-efficiency in a sector offers income opportunities. Competition between different branches of activity which are seeking to survive then causes a price war by proposing products which consume less energy and which are more beneficial to the consumer.

Impacts	Principles
Direct	More efficient technologies, but an increase in their use
	Growth of the population and its revenues
	Movement and substitution of branches
Indirect	Substitution by machines of work done by hand, with the same quantity of necessary energy
	Demand elasticity equal to 0
	Reduction in the price of raw materials

Table 1.6. *The six rebound effects which limit the scope of eco-efficiency (adapted from Polimeni et al. [POL 08])*

Let us now consider the indirect causes of rebound effects, which are more difficult to understand. The fourth type of effect concerns the substitution by machines of work previously done by hand, capable of providing the same quantity of energy and strength of work for the same quantity of inputs. This means that the economic agent frees up time either to produce more, or to consume more, since leisure time increases incessantly. This is what Jean Fourastié observed when looking at the working time from the Middle Ages up to the present in his book *Les 40 000 Heures* (*The 40,000 Hours*) [FOU 66]. The fifth type of rebound effect can be explained by non-elastic demand, meaning that the reduction in prices of certain products has no effect on the behavior of consumers who are, for their part, more and more numerous. Finally, the sixth form of rebound effect comes from the effects of the reduction in price of raw materials which affects the process of energy substitution. The discovery of new resources arising from the dominant energy/materials paradigm[34] reinforces its position until no more are discovered. This situation can have a greater impact on the resources crisis, because the time required for innovations to emerge which allow a change to be made from one "carboned" socio-technical regime to a different one which is not, will be all the more reduced.

1.3.4.2. *Moving towards a dynamic approach to the rebound effect*

Greening *et al.* [GRE 00] carried out a literature review which studies the size of the rebound effect within households, companies, and the macro-economy. We should note the extreme prudence of these authors with regard to this effect, because the data are rare and cannot account for the complexity of the interactions. These authors believe that a statistical analysis of individual preferences is not sufficient to give an account of the situation. The most advantageous research perspective, according to them, would be to bring together all consumptions and investments. The change in preference of individuals intervenes when technologies change, then move on to transform institutions and production systems. On the contrary, the link between the evolution of preferences and these rebound effects remains to be proven, because, according to these authors, "there is no all-inclusive theory for predicting those effects, which could result in more or less energy consumption" [GRE 00, p. 391]. Greening *et al.* will choose consumers, companies and the worldwide level of production to demonstrate that rebound effects have diverse origins. For the first, the size of the rebound effects is evaluated as a function of the use of air conditioning, heating, transport and domestic electrical appliances. The authors note great variations ranging from 0% to 50%. For companies, the increase in production would have increased the size of the effect by 20% in the short term; the very wide variety (too much so) of results in the long term prevents any hasty conclusion from being

34 For example, the discovery of new oil resources influences its own exchange rates and costs, and can therefore delay the desire to adopt alternative resources.

drawn. Finally, with respect to the macro-economy, it would indeed appear that an increased standard of living and the consumption of "luxury" goods are the main causes of such effects [GRE 00, p. 399].

1.3.4.3. *Towards an acknowledgment of the risks of rebound effects by public authorities?*

While consumption behaviors can accelerate the risks of the rebound effect, do the public authorities not end up having a role to play before the system gets definitively carried away? Recent publications by Font Vivanco, Kemp and van der Voet [FON 16] agree with this by proposing tools according to different types of scenarios (see Table 1.7). They first identify three major strategies based on the dynamics of consumption: consuming more efficiently, consuming less, or consuming differently. They are determined by the political ideas, consumption behavior, innovation policies, public policies on the subject of environmental protection, and the *business models* in place. Let us note that these drivers are not so different from those that we have just presented in the preceding sections, but the authors have the merit of using them in specific places using tools to attenuate this paradox.

This question also holds an interest directly at the highest degree for certain political institutions: this is the case for the United Kingdom Energy Research Centre. The report, entitled "The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency", directed by Sorrell [SOR 07] picks up on Khazzoom's assumption and confirms the existence of rebound effects. Sorrell, a member of the University of Sussex, poses a new challenge to his colleagues who have criticized the Meadows report because, while environmental innovation can change the course of history, this will not necessarily be in the expected direction. The European Union also takes an interest in it, as illustrated in the report "Addressing the Rebound Effect" by Maxwell *et al.* [MAX 11]. Although this is based again on the famous IPAT equation, the authors have the merit of giving concrete examples[35] and insisting on the psychological dimension. For example, it could be that consumers, concerned about

35 For example, the risks of rebound effects in the use of cars, household appliances, heating, lighting (in the United States and developing countries), road transport, the effects of traffic of mobile phone data, and even the effects of dematerialization of paper in offices.

environmental conservation, steer their consumer behavior in the name of citizen responsibility. Yet, this enthusiasm can also generate new forms of acceleration which are sources of rebound effects.

Type of political path	**Attenuation strategies of the rebound effect**		
	Increased eco-efficiency – "consuming more efficiently"	**Change in consumption – "consuming differently"**	**Reducing the extent of consumption – "consuming less"**
Political ideas	– Recognition in political ideas – Wider definitions and toolbox – *Benchmarking* tools		
Sustainable behavior and consumption		– Consumption – *Benchmarking* – Identity marking – Standardization	– Autonomous frugal consumption
Innovation	– Targeted environmental innovation		
Economic policy dedicated to the environment	– Energy/carbon tax – Bonus-malus principles – Principles of limitations and business		
New *business models*	– Bonuses and subsidies – Service production systems		

Table 1.7. *Political trajectories to reduce the rebound effect according to the type of instrument and the general strategy (source: Font Vivanco et al. [FON 16, p. 118])*

Despite all these questions and fears, the calculated results do not bring good news. The Eurostat center for European statistics observes in fact that "resource productivity within the EU increased between 2000 and 2007, but decoupling between material consumption and the GDP has only been relative" [EUR 11][36,37]. In addition, contrary to the dematerialization scenarios that some advocate[38], nothing, for the moment, confirms that intensification of eco-efficiency is the solution to reducing the use of resources (see Figure 1.13).

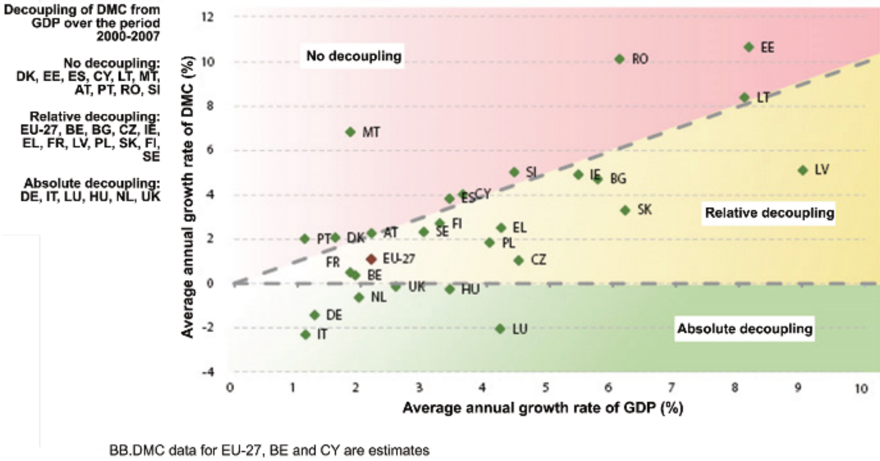

Figure 1.13. *Consumption of domestic products and GDP per country (annual average growth rate 2000–2007) (source: Eurostat – references: tsdpc230 and nama_gdp_k)*

36 Eurostat has changed certain phrases featuring in our study. This phrase has replaced the following: "Despite an increasing trend in resource productivity (measured by the GDP divided by the domestic material consumption) in the EU between 2000 and 2007, the use of resources has not ceased to increase".

37 The reader will have access to the latest Eurostat reports at the web address: http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Statistics_Explained

38 Dematerializing the economy is presented as a solution to slow down the use of resources and therefore, in fact, slow down the probable arrival of a rebound effect. The solution envisaged is to deconstruct objects and to turn their functionalities into a source of value. At first glance, this disconnection between materials and functionality appears to be a pertinent solution. For example, using IT to avoid using paper would allow resources to be saved. However, the effectiveness of such a tool remains difficult to prove, because the implementation of this dematerialization requires new technical means (and therefore new energy consumptions of energy and materials) [HER 07]. This perspective would therefore only move the problem elsewhere. Moreover, according to Binswanger [BIN 01, p. 131], seeking to accelerate the transfer requires a lot of energy and would only dynamically accentuate the rebound effects.

1.4. Conclusion

While its role was initially underestimated, or even disputed during the 1970s and 1980s, the hope for technological progress and the emergence of sustainable development have allowed environmental innovation to be considered as an unavoidable solution to conservation of the environment and, a fortiori, to profound modification in our society (section 1.1). Environmental innovation has taken precedence to the point of becoming a doctrine fueled by publications from various schools of thought and disciplines.

However, after having studied its typology (section 1.2), the path to follow is multiple, insofar as the incremental, radical or systemic change has an influence, or not, over the socio-technical regime in place. As evidence, although the radical change which is based on preventive actions and avoidance of pollution was welcomed with open arms initially, it must be noted that the incremental and palliative approaches are the ones that have increased continously since 2007. This coexistence is accompanied by more complex systemic environmental innovations, comprising innovation swarms which are structured around the circular economy, circular energy and material flows, directly inspired by natural ecosystems. These ecosystems applied to the technosphere take the form of industrial symbioses which are far from being original, inspired by another era, at the same time guaranteeing reinforcement of activities and further intensification of production to companies which are concerned about their image. Finally, we add the "cradle-to-cradle" approach, which commits companies to think along preventive lines and, in an even more advanced way, about what their products are going to become when they reach the end of their life, by creating circular flows between the technosphere and the biosphere; but as of yet very little exploration has been carried out in this direction.

The development of our societies is governed by economic cycles with phases of prosperity and crisis, by processes of adaptation and resistance to change (section 1.3). In light of the economic context of these last few years, crises are a good time to observe the capacity for adaptation of companies, especially when the environmental crisis is added to this. Innovative companies can find new opportunities in this, can diversify their portfolio of activities, and can construct entrance barriers to oppose newcomers, but, beyond the time dimension, environmental innovation can only appear if, and only if, it is compatible with other technologies and innovations. This system is constantly trying to find stability and, when diffusion of a new type of innovation is required, the main question is to know how it could modify the dominant design, to turn the situation around in the face of certain predominant methods which have become inappropriate from an environmental point of view. In recent years, researchers have set themselves the task of directing and modifying the complex dynamics of technical change at work by relying on transition management. Constitution of roadmaps represents a path to transition, but it cannot exist without a consensus agreeing, anticipating and foreseeing what the best solution would be. From then on, if the economic context is a determinant of environmental innovation, the collective behavior plays, just as great a role in steering technological trajectories. These trajectories of environmental innovations depend on demand, technologies and institutional pressures such as regulations and standards. These institutional pressures represent an additional cost for the company, but they offer opportunities for competition, on the condition, of course, that they can be adapted according to the particularities of the innovation system in place. This adaptation therefore motivates the question of the constitution of environmental standards which must integrate both environmental and economic demands.

Decision-making is structured around previous, past technologies, which can, at the same time, slow down the emergence of environmental innovations which influence the socio-technical regime in place. Constraints are of an institutional order, insofar as suboptimal technologies, performing less well than others, can succeed in taking precedence and adding themselves to other technologies for which an about-turn is impossible. This situation is reinforced when innovators follow collective behavior in order to make their innovations more reliable. Many environmental problems are characterized by controversial universes, which often see environmental conventions emerge with a strong technological dimension. At this time, sectors initially opposed for their activities are presented as guardians of environmental protection. Yet, nothing says that environmental innovations will not themselves also cause environmental problems due to the existence of rebound effects. In this scenario, multiple interactions and retroactions between innovation and the environment in the short and the long term make the task of identifying them difficult. Although today we observe that environmental innovation is considered as a hope for change in our society towards sustainable development, even the most optimistic are obliged to recognize that nothing has yet become stabilized.