Lock-in and path dependence: an evolutionary approach to eco-innovations

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REGULAR ARTICLE

Lock-in and path dependence: an evolutionary approach to eco-innovations

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Abstract The article presents an overview of the evolutionary approach to eco-innovations with particular emphasis on the role of lock-in and path dependence. In doing so, it focuses on the processes of radical change and the transition of technological systems that require the co-evolution of technology, firms, institutions and the society as a whole. Starting from clarifying the different notions of eco-innovations used in the literature, the article discusses the issues of lock-in and path dependence, by investigating the technological, organizational, institutional and social processes that strengthen as well as weaken path dependence. To this aim, it draws upon the evolutionary literature and discusses the relevance of path dependence and lock-in processes to understand the development of eco-innovations.

Keywords Eco-innovation · Evolutionary approach · Technological change

JEL Codes B52 · O3 · O13 · Q13

1 Introduction

As opposed to their neoclassical counterparts, evolutionary economists have attributed a central role to innovation in the process of economic growth. In this respect, the role of eco-innovations is crucial as they can enable sustainable economic growth. As put forward by Rennings (2000) and by van den Bergh (2007), the evolutionary approach to innovation and technical change can deepen our understanding of the dynamics of

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eco-innovations, and permit formulating fine tuned and effective policy tools. One of the reasons behind this is the central role attributed to path dependent processes and lock-in within evolutionary theories in explaining technical change as well as the co-evolution of technological, social and institutional systems. In this paper, a review of the literature on eco-innovations has been carried out from an evolutionary economics perspective. In particular, the focus of the paper is on two concepts that have an important role in the way evolutionary economics has approached technical change, namely path dependence and lock-in.

These concepts are used to explain why and how certain technologies may dominate markets, despite potential inefficiencies. While, in the case of standard innovations (i.e. non eco-innovations), such inefficiencies are often taken in the standard innovation literature as inabilities to meet consumer needs, in the case of eco-innovations inefficiencies are important from an environmental, social, and institutional perspective, concerning the achievement of long run sustainable growth patterns. In this sense, understanding the specific social, institutional, and technological processes that strengthen path dependence is very important in designing sound policies towards sustainable growth. In the eco-innovations realm, path dependence is especially critical, since many of the existing dominant technological trajectories have been shown to have detrimental enviromental effects, preventing sustainable economic growth. This is why it is important to unravel the different mechanisms that can strengthen possibilities of lock-in, as well as those forces that can help lock-out. In the paper, we present empirical evidence from a range of industries, about these two forces that shape technological trajectories.

In addition to underlining the theoretical understanding of the evolutionary framework applied to eco-innovation, this paper has both policy and managerial implications. On the one hand, the article highlights how, in different sectors, the diffusion/ development of eco-innovations can be improved. On the other hand, it has managerial implications, as it suggests to companies how to overcome the lock-in effect. The article is organized as follows. Section 2 details the notion of eco-innovation and highlights the difference between eco-innovations and standard innovations. Section 3 summarizes how path dependence and lock-in are undertaken in evolutionary economics, with emphasis on social, institutional, organizational and technological realms. Section 4 presents empirical evidence concerning the factors that strengthen lock-in and facilitate lock-out in a range of industries, by drawing upon the empirical literature. Conclusion and discussion follow.

2 The notion of eco-innovation in evolutionary thinking

In this section, we provide an overview of the definitions of eco-innovation used by the evolutionary economics community, for which the topic of eco-innovation is not new. Early contributions include Freeman (1992), who underlined the key role of eco-innovations in the emergence of an environment-friendlier “sixth techno-economic paradigm”. Kemp and Soete (1992) and Freeman (1994) explored the dynamics of the greening of technological progress from an evolutionary perspective, and argued at the time that current technological trajectories had reached their environmental limits and needed to be replaced by environment-friendly ones. O’Connor (1993) also stressed these limits and the interdependence and coevolution of human societies and natural ecosystems. Two decades later, environment-friendly trajectories still have problems emerging because actors and institutions are locked-in to the old technological regime. In their evolutionary perspective on environmental change, Kemp et al. (1998) describe how technical change is locked in to dominant technological regimes and suggest ways to escape from them, such as strategic niche management. Ayres (1991: 255) argued that this lock-in of whole technological systems was due to economies of scale and influence over the political system. Other studies brought forward ways to escape from such lock-in, such as Clarke and Roome (1995), who highlighted the role of networks in fostering incremental and radical environmental changes, and Sarkis (1995), who underlined the role of "environmentally conscious manufacturing". Den Hond and Groenewegen (1996) stressed the role of environmental management in triggering environmental change in companies, and Lanjouw and Mody (1996) used patent analyses to study the diffusion of environmental innovations between 1970 and 1990. They highlight the influence of environmental regulation on technological change in companies, which will later be confirmed by other studies (Kemp 1997). Finally, Verheul and Vergragt (1995) explored the potential of bottom-up experiments to unlock greener technological change in the cases of refrigerators, wastewater treatment, and wind energy in three European countries.

Many studies have followed; they will be discussed in Section 4. When studying eco-innovations, the existing literature uses different terms, such as ecological innovation, eco-innovation, green innovation, or environmental innovation. This suggests that the argument of Chen (2001), according to which 'greening' is not a well-defined concept, might still be valid today.[1] As Kemp (2010) puts it: "The analytical basis of eco-innovation is under construction, there is no commonly agreed definition". In order to understand better what eco-innovation entails, we present below its differences and points in common with other types of "standard" innovations.

2.1 Differences between eco-innovations and standard innovations

Eco-innovations have to meet, intentionally or not, specific environmental or social goals. This is not the case with standard innovations, which may eventually cause detrimental effects to human beings and natural ecosystems. As a consequence of this specific environmental performance requirement, eco-innovations can hardly be detected ex ante, except if they follow strict guidelines, norms, labels or standards. Rennings et al. (2013: 333) make it explicit that eco-innovations do not need to be aimed at environmental improvement: "*Environmental innovations consist of new or modified processes, techniques, practices, systems and products to avoid or to reduce environmental harms. Environmental innovations may be developed with or without the explicit aim of reducing environmental harm.*" For Taylor et al. (2005: 698), this environmental performance achievement of eco-innovations takes the form of safeguarding public goods, which are not necessarily protected by standard innovations: "'*Environmental technology' refers to everything from 'end-of-pipe' pollution control technologies to alternative energy technologies that share the characteristic of helping to maintain the 'public good' of a clean environment.*" Kemp and Oltra (2011:

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[1] See Table 1 in appendix, which shows examples of the definitions used by evolutionary scholars.

249) explain that eco-innovations are "innovations whose environmental impact on a life cycle basis is lower than those of relevant alternatives". Similarly, Clarke and Roome (1995: 192) describe 'green' technology as the one "*perceived to be the least damaging to physical, biological and cultural systems*". Along the same line, Oltra and Saint Jean (2009: 267) define environmental innovations "*as innovations that consist of new or modified processes, practices, systems and products which benefit the environment and so contribute to environmental sustainability*". This sustainability objective, broader than the mere environmental one, corresponds to a more institutional definition of eco-innovations, such as the one adopted by EU's environmental technology action plan: *"Eco-innovation is any form of innovation resulting in or aiming at significant and demonstrable progress towards the goal of sustainable development, through reducing impacts on the environment, enhancing resilience to environmental pressures, or achieving a more efficient and responsible use of natural resources"* (European Commission 2011).

A second key difference between eco-innovations and standard innovations is that the former can be apprehended from a life cycle perspective, as in Kemp and Oltra (2011). This enables them to assign specific objectives to eco-innovations in relation to life cycle phases that can have direct environmental effects, as the end-of-life. For example, according to Janssen and Jager (2002), eco-innovations can characterize products that are returned to the producer to be refurbished or remanufactured in order to extend their lifetime and improve their reparability. Brouillat (2009) also sees 'green products' as easily recyclable and with a long lifetime, but underlines the fact that firms tend to invest more to improve recyclability than to expand the lifetime of products. Sharma and Henriques (2005) use the term 'eco-efficiency' to characterize an environmental objective seeking to reduce waste and energy and material use at the source, and 'eco-design' for changes in products or processes that are made more durable or easier to disassemble and reuse, taking the whole life cycle into account and discontinuing the use of harmful chemicals.

2.2 Commonalities between eco-innovations and standard innovations

Eco-innovations and standard innovations have several features in common. Kemp and Oltra (2011: 249) state that, similarly to non eco-innovations, eco-innovations can be intangible or systemic, and require similar resources such as knowledge, capabilities, coordination and attention to be developed and adopted. The development of eco-innovations might also be intentional or unintentional, and they might concern production equipment, methods and procedures, product designs, product delivery mechanisms, new or modified processes, practices, systems and products (Shrivastava 1995: 185). Therefore, eco-innovations can also result from organizational changes: as much as eco-innovations can increase the durability of products, they can also transform organizational processes such as the management of recycling schemes. This is, for example, the case of "Environmental Management Systems", which aim to reduce waste and organizational risks and to comply with legislation while fulfilling customer's expectations (Zutshi and Sohal 2004). Another example is 'Environmentally Conscious Manufacturing' (ECM), which is an organizational innovation aiming to reduce pollution at the source and involving "*the planning, development and implementation of manufacturing processes and technology that minimize or eliminate* *hazardous waste, reduce scrap, are operationally safer, and can design products that are recyclable, or can be remanufactured or reused*" (Sarkis 1995: 80). Even if the objective is clearly environmental, authors such as Goldstein (2002: 497) suggest that such organizational changes should encompass the objective of capturing market demand, which the author calls "Strategic Environmental Management". Finally, although some authors such as Chen (2001) envisage eco-innovations as 'green products', just like other types of innovations, the latter are not restricted to the firm level but can be extended to larger systems. For example, organizational eco-innovations can apply to meso-economic systems, such as industrial parks in order to close the loop of material flows (Lambert and Boons 2002; Ayres 1991; Desrochers 2002; Gibbs et al. 2005).

The dynamics of eco-innovations differ from the ones of non environmental innovations (Rennings 2000; Kemp and Oltra 2011; De Marchi 2012). First, there is a well-known issue of double externality: eco-innovations produce positive spillovers in both innovation and diffusion stages. In the presence of (positive) externalities, firms have reduced incentives to develop innovations, which might result in underinvestment in eco-technologies given that their benefits are not valued by the market. As a consequence, the role of regulations and policy interventions in the case of eco-innovations is prominent to ensure that R&D activities are carried out by firms, by providing a market value to environmental benefits. Second, the development of eco-innovations depends upon the degree of environmental knowledge and sensibility towards green issues on producers' and consumers' sides. Third, firms (and consumers) committed to eco-innovation must face trade-offs regarding the relationship between environmental performance and cost/price/quality factors (Oltra and Saint Jean 2009).

3 An evolutionary perspective on eco-innovations: lock-in and path dependence

The concept of lock-in was originally developed by Arthur (1989), who discussed the outcome of competition among technologies in the presence of increasing returns to adoption. In particular, small historical accidents can provide a given technology an initial advantage over competitors that can create path dependence – because of switching costs – and therefore lead to the locking out of alternative solutions. With increasing returns to adoption, one path becomes dominant due to self-reinforcing processes and absorbing states, and this causes the economy to lock itself in to an outcome which is not necessarily superior to alternative ones, not easily altered and not predictable in advance (Arthur 1989; Cowan and Gunby 1996). The presence of increasing returns creates a bandwagon effect by increasing the profitability of the innovation as the number of adopters increases (Abrahamson and Rosenkopf 1997). The most famous variants of increasing returns on adoption are network externalities (Farrell and Saloner 1985; Katz and Shapiro 1985, 1986, 1994), which occur when the value of adopting a technology increases with the number of other users that join the network. The presence of network externalities very often leads to the emergence of lock-in and to the creation of de facto standards, because of technical interrelatedness (complementarity/modularity) among hardware and software components, system scale economies and quasi irreversibility of the investments because of high switching costs (David 1985).

The extent to which lock-in and path dependence generate costs and inefficiency to the economy has been more carefully discussed by Liebovitz and Margolis (1995), who distinguish among three forms of path dependence. The first-degree path dependence is a situation whereby the influence of some initial events on the final outcome does not create any inefficiency in the economy. The second-degree path dependence is characterized by the scarcity of information in the initial phases of decisional process, which leads to regrettable outcomes that are not remediable. Finally, the third-degree path dependence refers to situations in which an inefficient outcome could have been avoided because of the existing better alternatives. Witt (1997) also suggests that the (detrimental) effects of lock-in need to be considered in light of the existing conditions – e.g. effective availability of better alternatives. In particular, the original model of Arthur (1989) relies on the assumption that technological lock-in amounts to foregoing wealth increases.

Even if the original notion of lock-in was tightly connected to competition among technologies, it is possible to apply this notion also to companies. In organization theory, lock-in has been often referred to as structural inertia and imprinting (Hannan and Freeman 1989). The idea is that companies are endowed with a set of routines and competences (Nelson and Winter 1982) that define and bound their behavior and strategies. The existence of these routines limits the adaptive intelligence of organizations, making it possible for them to search, to explore and to learn only at a 'local' level (Nelson and Winter 1982; Levitt and March 1988). Individual agents use routines to economize on cognitive resources and to make up for their bounded rationality (Becker et al. 2005; Sinclair-Desgagné and Soubeyran 2000; Davies and Brady 2000). At the level of organizations, routines represent "successful solutions to particular problems" (Dosi et al. 1992: 191–192) and can be considered as firms' 'organisational memory' (Nelson and Winter 1982). They contribute to the persistence of firms, and depending on their characteristics, routines can be a source of lock-in or unlocking (Gossart 2005). Firms' competences and routines are developed over time along a specific technological trajectory, so that, as much as they represent a competitive advantage, they are also a constraining force (Dosi 1982). Therefore, when facing radical technical change and disruptive innovations, firms may find themselves struggling to compete and survive in the market, as they need to adapt their original technical and non-technical (complementary) capabilities to the new context (Tushman and Anderson 1986; Henderson and Clark 1990; Christensen 1997; Tripsas and Gavetti 2000). Existing incumbents in a market can fail in the presence of a disruptive and/or competence destroying technology, as firms' capabilities – processes and values – also define its disabilities, i.e. they make it hard or impossible for a company to successfully face disruptive changes (Christensen 1997). In other words, core competences might turn into core rigidities (Leonard-Barton 1992). Along a similar line of research, Henderson and Clark (1990) argue that, when a new technology changes the architectural knowledge of the firm, i.e. the knowledge about the way in which the components of a technical system interact, established firms struggle to reconfigure their capabilities and to maintain market leadership.

Besides the technological and organizational sides of lock-in, we do find inertia and resistance towards innovations also in consumers. This inertia might be related to the technological lock-in, but may also derive from individuals' characteristics, attitudes and behaviors (Rogers 1995). Potential adopters of an innovation may find that the costs of learning outweigh its performance benefits. Thus, the extent to which an innovation is perceived is relatively difficult to understand, and use is also a major determinant of adoption (Rogers 1995; Davis 1989). Furthermore, the literature has also emphasized that consumers place a great importance upon the compatibility of an innovation, both in terms of technical features and, more relevantly, in terms of existing socio-cultural values, past experiences and individual needs (Rogers 1995).

Finally, lock-in at the consumer level may occur because their decision towards the adoption of innovations might be influenced by the social context, which can be understood in terms of fads, fashions, and, more in particular, interpersonal influence and network effects (Katz and Shapiro 1985; Abrahamson 1991; Bikhchandani et al. 1992; Roehrich 2004; Clark and Goldsmith 2006). When people are facing the emergence of new products, the diffusion process may have already started, so that some other people may have already adopted the product, and this can strongly influence potential adopters' decisions. Regarding this issue, the literature on diffusion has largely focused on the role of information and other external factors in determining the process of adoption and diffusion of new technologies.

When discussing the emergence and diffusion of innovations, an important issue is the role of institutions and policies in fostering or hindering the process of change. This idea is connected to the national systems of innovation approach (Lundvall 1992; Nelson 1993), which investigates the components and relations at the national level that interact in the production, diffusion and use of new and economically useful knowledge. The analysis of innovation processes cannot be limited to the study of the specific organization of knowledge production, but needs to analyze the central framework conditions for the innovation process (Lundvall 1992; OECD 2000). Therefore, the national systems of innovation approach highlights the importance of investigating the formation and transformation of institutions, with specific reference to codification and standardization processes. As much as organizations can be locked-in and experience inertia, so can institutions. This substantially affects their role in the innovation process through the provision of research and education and through the development of ad hoc interventions. Authors have argued that most of the factors determining increasing returns (and lock-in) for technologies can similarly be found in institutions (North 1990; Foxon 2002) – in particular, high fixed costs, learning effects, coordination effects and adaptive expectations. Following Pierson (2000), one reason for which institutions are subjected to increasing returns is that political actors can use their power to modify rules to their advantage. Based on Nelson (2005) and Nelson and Sampat (2001), Foxon (2011: 2261) adds that institutions can lead to lock-in through self-reinforcement, because "economic benefits of new technologies are only fully realised when institutions (…) evolve and adapt to these new technologies".

4 Empirical evidence on lock-in and eco-innovations

In the case of eco-innovations, lock-in is a persistent characteristic of the innovation landscape, with varying degrees of strength and potential of lock-out. In this section, we explore the role of path dependent processes in the social, technological and institutional realms for a variety of technologies, so as to unravel factors that contribute to lock-in, and to highlight those factors that can facilitate lock-out.

4.1 What causes lock-in? Evidence from eco-innovations

The empirical evidence on eco-innovations clearly shows that most countries, sectors and firms are locked-in in pollution-intensive technologies. Kemp and Oltra (2011) explain that when the initial advantage of an old and pollution-intensive technology is too strong, it will dominate the whole system. Very often, the continuous improvements in these technologies further strengthen their market. For example, Oltra and Saint Jean (2009) show that the trajectory of the internal combustion engine was environmentally improved by efficiency inventions such as direct fuel injection, particle filters, and new combustion concepts. The internal combustion engine is a strong and persistent dominant design, and most engine innovations are still focused on incremental changes within this design, supported on the consumer side by a demand for incremental changes.

The case of power plants constitutes more evidence of how gradual improvements may strengthen a technology. The technological trajectory of power plant technologies is dominated by a global increase in coal-fired power plants, no radical innovation having succeeded in the past 30 years in this technological area (Rennings et al. 2013). The only changes that occurred in the trajectory of power plant technologies took place at the level of technological components, such as scrubbing technologies used to remove sulphur and nitrogen oxides. The successful implementation of these technological changes is due to the fact that they did not necessitate fundamental changes in existing plants, and thus did not negatively impact plants' performance. As a consequence, the energy efficiency of German power plants has been gradually improved by combining established gas and steam cycles. Old technologies could catch up with new ones that were locked in technological niches, further reinforcing the barriers to paradigm shifts (ibid.). According to Costantini and Mazzanti (2012), one reason for the successful diffusion of incremental innovations is related to the sunk costs associated with new infrastructure and capital required for more radical technological changes. Sources of lock-in might also emerge on the consumers' side, as they may prefer products with relatively low environmental performance because they do not believe in the new products, or are unaware of their green peculiarities (Rehfeld et al. 2007; Chen 2001).

In the case of the automobile industry, Dijk et al. (2011) argue that these developments have led to the emergence of two main trajectories: the improvement of vehicles powered by internal combustion engines running on diesel or gasoline; and the (slow) diffusion of electricity-powered vehicles. The authors explain this slow diffusion by the fact that new capabilities (that are difficult to acquire) are required to develop electric propulsion engines, and that consumers are not yet attracted by them. The main successful alternative within the emerging electric propulsion technological trajectory has been the hybrid car, which requires heavy infrastructure investments such as plug-in and charge systems or the combination with agrofuels (Lee et al. 2006). In France, since 40 % of automotive patent applications were linked to environmental objectives, Oltra and Saint Jean (2009: 579) argue that fuel cell vehicles might be the most promising option for breaking out of lock-in in the automobile industry. However, Bento (2010) emphasizes that the absence of infrastructure is the main justification used by companies to delay investment in the sectors of personal transportation, industrial gas, fuel cell manufacturing, electricity and gas.

4.1.1 Cost-related factors

Cost-related factors are cited in the literature to be a significant strengthening factor of an existing technological trajectory in a variety of sectors. Ayres (1991: 255) argues that the lock-in of whole technological systems was “partly due to economies of scale”. For example, Oltra and Saint Jean (2009) stress that increasing returns to scale keep costs down, and that an existing technology such as the internal combustion engine limits high sunk costs related with the development of a new fuel infrastructure. These transition costs associated with the adoption and diffusion of eco-innovations are particularly important in the energy sector, where there are high sunk costs in power plants and high investment costs in refuelling infrastructures. In the agricultural sector, increasing returns to adoption enabled the environmentally inferior technology of chemical pest control to dominate integrated pest management (Cowan and Gunby 1996).

The costs related to the adoption of a cleaner technology result in the persistence of an old technological regime, in which the existing knowledge, competences, infrastructure, and capital lead to entrenchment in a pollution-intensive trajectory. Besides, since the financial capital market is biased towards short term profitability, given that incumbent suppliers of energy are users of capital-intensive assets, the promotion of large-scale investments in new energy technologies is counterproductive for them (Walsh 2012).

The importance of the financial commitment required to eco-innovate is often mentioned as a barrier to implement environmental programs (Noci and Verganti 1999), but it is particularly the case for SMEs (del Brío and Junquera 2002; Zutshi and Sohal 2004). Besides, the high sunk and investments costs associated with eco-innovations tend to be irreversible, which is a strong disadvantage when prices are volatile (Cortazar et al. 1998). Also, many environmental problems are related to negative externalities for which there are no economic incentives to create environment-friendly products and processes. According to Horbach (2008), this is another counterincentive for firms to ecoinnovate since their higher costs might not be compensated. Therefore, public support is especially important for eco-innovations given the high upfront costs of implementation (Cantono and Silverberg 2009). Windrum et al. (2009) also stress that government intervention is required in the form of environmental policies to reach desirable sustainability outcomes.

Finally, if high costs are a barrier to the adoption of eco-innovations for firms, they are also a source of lock-in on the consumer side. Indeed, a higher (initial) price of eco-innovations is cited by companies as one of the main obstacles for market penetration. As mentioned earlier, customers may prefer products with low environmental performance because of their lower prices, or simply because they do not trust the new product or are unaware of its green specifications (Rehfeld et al. 2007; Chen 2001).

4.1.2 The role of technology: technological niches and complexity

The literature on eco-innovations reveals that most technologies within a new trajectory exist before their wide implementation within protective spaces called “technological niches”. While the creation of technological and market niches is an important driver of change, the literature reveals that niches can also contribute to the strengthening of an existing trajectory in various ways.

The fact that the success of technological niches is highly uncertain deters firms from adopting the technologies nested in those niches (Shrivastava 1995). This risk aversion is strengthened by a lack of know-how and environmental information, and by the difficulty to control the displacement of pollution from one privileged phase of the life cycle to another. The perceived radical nature of eco-innovations can further reinforce that risk and the uncertainties associated with it (Hansen et al. 2002). For example, eco-innovations such as the ones relying on integrated gasification combined cycles or on pressurized pulverised coal combustion hardly made it out of pilot plants or technology niches such as the refining industry. The regime in place could not reduce the market uncertainties deterring investment in new technologies, and the existing pollution-intensive technological paradigm remained dominant (Rennings et al. 2013). As a consequence, when environmental policies seek to support the development of radical eco-innovations, firms can engage in lobbying activities to delay the required environmental R&D investments (Gerard and Lave 2005). According to Chadha (2011: 336), because radical eco-innovations are subjected to a higher degree of uncertainty, they require "competencies which differ from those used to manage incremental eco-innovations". Furthermore, if too many niches emerge, they can act as "parasites". For example, the overlap between biogas and ethanol increased the resources available for biogas, which captured funding directed to ethanol (Sandén and Hillman 2011: 411).

In the case of power plants, it was the lack of radical alternatives which further strengthened the existing pollution-intensive trajectory. Radical alternative eco-innovations were too weak to enter and change the dominant trajectory, and this very weakness enabled the further strengthening of the more polluting technological regime. In the case of personal vehicles, although a range of alternative niches are available such as zero emission vehicles; none of them has yet resulted in a system-level transition, notably because of a lack of market outlets. Also, as in the case of crystalline solar panels, a strategy aiming to un-lock a technological system by supporting a specific eco-innovation might also lock the system in a suboptimal trajectory (Faber and Frenken 2009), from both economic and environmental points of view. Another explanation for niche failure is caused by the heterogeneity of actors at the level of an innovation system: the latter having different preferences, they cause firms to inefficiently split their resources between traditional and sustainable innovative activities (Alkemade et al. 2009). But intrinsic niche problems can also strengthen the existing system by failing to change it. For example, Faber and Frenken (2009) argue that fuel cell technology seems to have remained a technological niche confined to small scale projects. According to Oltra and Saint Jean (2009), this is notably due to the incompatibility between the new and existing infrastructures, to high eco-innovation costs, and last but not least, to the difficulty of producing, storing, and distributing hydrogen.

In the case of eco-innovations, very often lock-in derives from the existence of a complex knowledge base and interdependences and complementarities between different parts of technological systems. These factors can impede the adoption of eco-innovations and strengthen existing pollution-intensive trajectories. For example, Oltra and Saint Jean (2009) mention that the complexity of the product and of the related knowledge base of internal combustion engines was one of the factors that strengthened their market. The complexity of the knowledge base, and the increased interdependence between its various components, can result in a self-reinforcing mechanism by which different actors accumulate experience and learning, further strengthening the prevailing trajectory.

Strong self-reinforcing processes within a technological trajectory, and tightly integrated components at the systems level, can also diminish possibilities of complementarities with a new technology, creating what Noailly (2008) defines as the “chicken-and-egg problem”. For example, car manufacturers claim that it is difficult for them to use fuel cell engines as long as there are no hydrogen filling stations; on the other hand, infrastructure can only be provided if there is enough demand for fuel cell vehicles. After developing in a protected and stimulating niche environment, a technological trajectory can only be changed if the niche lines up with the dominant regime and its ongoing processes (Schot and Geels 2008). At the moment, the trajectory of electric vehicles is stalled by technological hurdles such as the high price and low autonomy of batteries (Schot and Geels 2007). The case of personal vehicles shows that the locking out of the dominant trajectory was not related to the lack of niches, but rather by the extent to which these radical alternatives could line up to the dominant regime, especially as far as the existing infrastructure was concerned.

4.1.3 The role of stakeholders: organizations, policy makers and society

Other important sources of lock-in and self-reinforcing processes relate to coordination effects at the level of organizations, policy makers and society. Firm-level environmental strategies impact the whole organization, which causes difficulties in coordinating environmental actions across firms’ departments (Noci and Verganti 1999). Organizational inertia is an important mechanism that can cause lock-in. In this case, firms’ stable routines and standard procedures act as a barrier to eco-innovating (Shrivastava 1995). Indeed, if, as Gossart (2008) argues, organizational routines are key mechanisms used by firms to improve their environmental performance, they can also contribute to lock-in. Besides, the context in which routines are implemented will also influence their capacity to contribute to lock-in or unlocking, since “the routine might be declared effective in some specific contexts, but perhaps not in others” (ibid.). For example, the design rules of incandescent light bulbs that impose a low limit on their expected lifetime conflict with the new market context favoring more environment-friendly products that last longer such as LEDs. According to Sarkis (1995), this could be changed with the diffusion of “environmentally conscious manufacturing”, which is a sound business practice; Santolaria et al. (2011) have shown the link between eco-design practices and overall innovation performance.

At the policy level, coordination between different policy contexts can also cause lock-ins. For example, environmental policies might conflict with innovation policies because their objectives are not lined up. In the case of Finland, Kivimaa and Mickwitz (2006) argue that environmental policy should be integrated to meet the present needs for the energy and material efficiency of new technologies, because if they do not line up with firms’ capabilities and resources, they might be overlooked. Institutions can both trigger lock-in and enable lock-out from unsustainable trajectories. As Foxon (2011: 2261) puts it: “Institutions both constrain behaviour, by defining socially acceptable ways of acting, and enable behaviour, by providing agreed-on social contexts for acting, which do not need to be continuously negotiated.” Similar to technologies, we have previously mentioned that institutions benefited from path dependent increasing returns to adoption. For example, in the case of carbon-based electricity generation systems, institutional factors have created favorable conditions for large-scale centralized electricity generation. In this case, the "desire to satisfy increasing electricity demand" and a "regulatory framework based on increasing competition and reducing unit prices to the consumer" contributed to lock-in.

Regulation can also strengthen an existing, and possibly inefficient trajectory, by promoting incremental improvements within this trajectory. In fact, regulation is not always beneficial for the environmental trajectory of an eco-innovation, as demonstrated by the solar photovoltaic case, for which early policy stimulation has led to a technological regime lacking diversity. This suggests that regulation might force inventive activity along a certain pathway away from others that might be more environment-friendly (Taylor et al. 2005). In the case of the Swiss bioenergy sector, Wirth and Markard (2011) show that if energy policies stimulated investments in wood-to-energy technologies, electricity feed-in schemes may have triggered a lock-in to environmentally suboptimal technologies focused on power generation, as opposed to alternative approaches based on gas generation.

Finally, social actors can have different representations about the issues at stake: "For example, an environmentalist may see a wind turbine as a clean and renewable form of energy generation, whereas as a 'country guardian' may see it is as an intrusive and unreliable blot on the landscape" (Foxon 2011: 2261). These actors can also disagree about the "shared meanings about the way in which a technology is used, e.g. primarily for business, recreational or social purposes" (p. 2262). The author also underlines the notion that lock-in can appear not only when there are problems within key coevolving systems (ecosystems, technologies, institutions, business strategies, user practices), but also when there is a poor articulation between them. These can help generate alternative framings of the new problem to be solved, as well as new eco-innovation strategies (Foster et al. 2012). Maréchal (2010) shows that, in the case of energy consumption patterns, habits could be a source of lock-in, but that they can be overcome by the joint use of feedbacks and commitment strategies that disturb people's context.

4.2 How to un-lock?

4.2.1 Technological niches and diversity

To overcome a situation of lock-in, some authors analyze the role of policies to unlock socio-technical systems (Faber and Frenken 2009; Rennings et al. 2013; Zeppini and van den Bergh 2011); others study the potential of specific alternative technologies alongside the dominant one to transform the dominant technological regime (Janssen and Jager 2002). In both cases, the role of technological niches is mentioned as a key instrument to escape from a dominant pollution-intensive paradigm. As shown in the case of solar cells, radical niches can contribute to change the dominant energy technology trajectory, sometimes with the support of gradual improvements brought about in other niche areas. For example, van den Heuvel and van den Bergh (2009) highlight the role of niche applications such as calculators and space travel in improving solar cell efficiency. Consequently, the technological trajectory of solar cells moved from a technological niche to a market niche. In the case of electric vehicles, Cowan and Hulten (1996) also suggest in the case of electric vehicles that "regulation could create enough niche markets so that some self-reinforcing processes would become possible". Defined as a "protective space for path-breaking innovations" (Smith and Raven 2012), a niche helps articulate new ways of using technologies, generate lessons about eco-innovation feasibility, develop and improve alternative technologies, and group different actors whose common point is to support the changes conveyed by these eco-innovations (Kemp et al. 1998). In other words, a technological niche creates a space in which a new technology is protected from the harsh selection environment while it strengthens itself, through learning processes, for example. Niches also give time to social and physical environments to adapt to the alternative technology (Freeman 1992; Verheul and Vergragt 1995; Schot and Geels 2008).

In the case of volatile organic compounds used in paints and glues, at the end of the 1990s, supportive legislation helped more environmentally friendly paint companies to increase their sales significantly, even if they had been put on the market since the 1960s (Geldermann et al. 2007; Oltra and Saint Jean 2005). This success was backed by the evolution of consumers' perceptions, as they eventually acknowledged the environmental benefits deriving from the adoption of these eco-innovations (Kammerer 2009). In the case of solar photovoltaic electricity in the UK, demonstration programs contributed to strengthen advocacy coalitions that lobby in favor of the development of this alternative technology. In addition to providing R&D funding, these programs enrolled a variety of professionals such as architects and planners. These actors generated new narratives about the potential of photovoltaics, "opening up an interpretative flexibility towards PV that linked it to salient discourses about environment, jobs and greening the economy" (Smith et al. 2014: 121). In the case of bio-refinery production in Italy, Lopolito et al. (2011) underline the importance of networking with powerful actors in the emergence of the niche, in which knowledge creation and sharing were key eco-innovation barriers. In the case of SMEs, Klewitz and Hansen (2013) argue that the interaction with external stakeholders could improve eco-innovative capacity.

Niches enable eco-innovations to grow in a protected environment so as to develop and compete in the main market (Caniëls and Romijn 2008). After developing in the protected and stimulating niche environment, the technological trajectory can only be changed if the niche lines up with the dominant regime and its ongoing processes (Schot and Geels 2008). For example, the case of personal vehicles shows that locking out of the current trajectory was not related with the lack of niches, but rather with the extent to which these radical alternatives could line up with the dominant regime, especially as far as the existing infrastructure was concerned. An invention can emerge and diffuse in a market through different processes such as natural selection, breakthrough innovations, market niche development, and technological niche development (Schot and Geels 2007). In the case of alternative fuel vehicles, Kwon (2012) suggests that a specific policy directed to niches such as "strategic niche management" could strengthen the impacts of financial incentives. Actors' environmental awareness also play a key role in the success of a new and cleaner technology (Verheul and Vergragt 1995). Islas (1997) suggests that production niches could help locking out thanks to increasing returns to adoption. For example, the gas turbine emerged from its niche "when certain very specific electricity company projects encouraged hybridization between the steam turbine and the gas turbine". Only then could gas turbines function as auxiliary devices of steam turbines and such a combined cycle enable the operation of high load factors.

As Foxon and Pearson (2008) argue, "Promoting a diversity of technology and institutional options" can help overcome the lock-in of unsustainable technologies and supporting institutions. A strategy that aims to un-lock the system might also lock-in the new eco-innovation that is not optimal (Faber and Frenken 2009). This situation can be illustrated with the case of crystalline solar panels. To avoid such lock-ins, van den Heuvel and van den Bergh (2009) argue that technological diversity should be ensured in order to make available the most efficient eco-innovations throughout all the phases of the product lifecycle. For example, according to Sandén and Hillman (2011: 411): "The introduction of cars that can run on alternative fuels was made possible not only by the relative success of ethanol and methane in the bus niche, but also by the parallel development of electric vehicle demonstrations". Indeed, Swedish cities had created test organizations that paved the way for alternative vehicles. Costantini and Crespi (2013) also argue that, in the case of the biofuel sector, preserving niche diversity is paramount to avoid directing technological change to specific paths that might cause lock-in. Such diversity is particularly beneficial to radical eco-innovations that substantially contribute to reduce ecological impacts. According to Carrillo-Hermosilla et al. (2010), diversity of both product and process eco-innovations (from incremental and drop-in innovations to systemic changes) characterize eco-innovations and can play a major role in sustainable transitions; and thus eco-innovations developing and diffusing on different timescales are needed. According to Triguero et al. (2013), for process eco-innovations in European SMEs, cost-savings are the only significant driver.

In the case of the energy sector, Jacobsson and Bergek (2004) stress the importance of supporting variety in innovation for a transition to self-sustaining systems. Knot et al. (2001) add that knowledge related to the environment and sustainability evolves with technological change, so it is better to ensure flexibility in technological development than to focus on a specific sustainable technology. Similarly, Sartorius (2006) stresses that an evolutionary definition of sustainability should encompass the capability to adapt to different trajectories.

Following Wirth and Markard (2011), an alternative trajectory for power plants might be biomass-based facilities. In this case, variety is enabled by the nature of technology itself. Bioenergy technologies transform organic matter into usable energy by consuming various types of inputs such as wood or manure. This explains the great variety of technologies deployed in the sector, such as biomass combustion, biomass digestion, co-firing, or biomass gasification (Hekkert and Negro 2009).

According to Chadha (2011), in the case of biopolymer technology, centralized established decision processes are the main causes of lock-in. To overcome them, escape routes were found by promoting network diversity (firm alliances, R&D consortia, partnerships, standard-setting organizations, …). This enabled firms collectively to reduce costs and risk, while at the same time enhance technological predictability. Diversity in the sources of knowledge contributed to lock-out, for example, by supporting bootleg research (motivated employees organize part of the innovation process), technology monitoring that encourages search outside the usual box, and involvement in the firm's road mapping. Knowledge diversity was also achieved by cross-functional integration, for example, by involving staff from marketing and manufacturing departments and from external organizations, such as raw material producers, polymer product associations, or governmental bodies. The setting up of independent project houses also supported knowledge diversity by fostering the systematic interaction between market research teams and potential customers, which also helped shortening time-to-market (ibid.).

4.2.2 Firm-level strategic changes and lead users

Besides the creation of technological niches, the stimulation of technological diversity, regulation, firm-level strategic changes and the presence of leading users can trigger the initiation of a self-reinforcing demand for the adoption of eco-innovations.

For firms, it is important to distinguish between two processes concerned with eco-innovations. The first is related with the adoption of an environment-friendly practice, technology, or system in an organization (e.g. an environmental management system). The second is concerned with the competences of the firm to eco-innovate. As reviewed in previous sections, lock-in may occur when the existing knowledge base favors innovations in an existing technology, and acts as a barrier to disruptive innovations. These two processes are not independent from each other, and their interdependence can trigger a self-reinforcing mechanism. In the case of the adoption of environmental management systems, they can have an impact on eco-innovations and vice versa. For example, Rehfeld et al. (2007) find a significant positive impact of environmental management systems on environmental product innovations, while Wagner (2008) finds a positive impact on process innovations. Den Hond and Groenewegen (1996) also underline the role of environmental management in triggering environmental change in companies. However, whether an environmental management system leads to eco-innovation remains ambiguous. This is because firms applying such systems are usually already environmentally active and capable (Ziegler and Seijas Nogareda 2009). But it is important to note that proactive environmental strategies can lead to the development of valuable organizational capabilities (Sharma and Vredenburg 1998), since the knowledge capital of a company grows from investing in environmental R&D (Horbach 2008). Successful firms are the ones that can change their capabilities, organizational routines, and knowledge to address environmental issues (Ziegler and Seijas Nogareda 2009). In the case of SMEs, Hansen et al. (2002) suggest that the eco-innovative capabilities of a firm consist in its competencies, network relations and strategic orientation. Only if firms consider the long-term benefits that are intangible and hard to copy (long-term learning, reputation, legitimacy) will they be motivated to make such changes without direct economic stimulation (Sharma and Henriques 2005; Ziegler and Seijas Nogareda 2009).

Change in consumer preferences is another factor that can trigger eco-innovative changes. Using evolutionary concepts, Windrum et al. (2009) show how the trajectory of personal transportation technologies was disrupted by ecological concerns. Indeed, environmental concerns triggered the emergence of heterogeneous consumer preferences, which in turn led to the development of cleaner product designs within the dominant technological paradigm, soon replaced by a more environmentally benign one.

According to Dijk et al. (2011), in relation to consumer products, there are different social feedback loops: 1) interactive learning between suppliers and users, 2) endogenous tastes among consumers, and 3) social learning (attribution of meaning). The authors also stress that early adopters play a crucial role in attributing meaning to the product. Environmentally aware and intrinsically motivated consumers can drive eco-innovation by contributing to the emergence of a niche market. Understanding the underlying social dynamics such as peer pressure, imitation and status is therefore crucial to understanding the success or failure of consumer product eco-innovations (Faber and Frenken 2009), as shown in the next example. In the case of solar thermal systems in Germany, Woersdorfer and Kaus (2011) underline the importance of peer groups in adopting and diffusing the emerging technology, and when examining the impact of "protective spaces" on transition management, Smith and Raven (2012) stress the key role played by niche actors.

Sharma and Henriques (2005) analyze a case study of the Canadian forestry sector. They show that stakeholder pressure has been crucial to the improvement of environmental performance. Major customers of this industry were pressured by social and ecological stakeholders to act sustainably, which led to the rise of recirculation practices. Withholding pressures such as environmental protests at company operations from social and ecological stakeholders led to eco-design practices. However, other markets witnessed the emergence of a growing segment of 'green' consumers who spontaneously preferred eco-friendly products (Sarkis 1995; Shrivastava 1995). Even more so, some self-organizing citizen groups, NGOs and entrepreneurs can support the creation and implementation of environmentally sustainable alternatives (Verheul and Vergragt 1995).

In the case of solar cells, van den Heuvel and van den Bergh (2009) stress the role of niche applications such as calculators and space travel in improving their efficiency. Consequently, the technological trajectory moved from a technological niche to a market niche, while R&D by vested companies and universities continued. Besides, a technology has a higher chance of further developing if it links up with existing sectors, as in the case of co-firing (coal sector) or through biomass input (agricultural sector). Indeed, firms only seem to adopt cleaner technologies when there are product offsets, such as higher productivity or better performance. The adoption of a cleaner technology that could trigger a change in the dominant paradigm seems to rely on the ability of a firm to address the (lack of) compatibility between the new technology and the old one, and on its capacity to respond to users' needs (Oltra and Saint Jean 2009).

By increasing pressure on firms concerning corporate social responsibility, consumers, employees, governments and other shareholders can contribute to regime shifts (Chen 2001; Paton and Siegel 2005). However, Kesidou and Demirel (2012) find that demand side factors do not determine the level and intensity of eco-innovations; rather, they influence firms' decisions to undertake eco-innovations.

Following Malerba (2005), developing a market for environmentally safe products is a reaction to public concern over pollution that receives greater attention from governments compared to longer term initiatives. The engagement of key stakeholders in the innovation process also enables a greater market acceptance of eco-innovations (Carrillo-Hermosilla et al. 2010). And Lanjouw and Mody (1996) show that the increasing interest in environmental protection actually led to eco-innovations in pollution control technologies.

4.2.3 Regulation

The 'regulatory push' factor (Brem and Voigt 2009) is particularly relevant when discussing eco-innovations, since governments can shape the value of eco-innovations in the market place on a large scale and in a systematic manner (Kemp and Oltra 2011). According to Nameroff et al. (2004), legislative and other regulatory pressures are the main external forces leading to the adoption of eco-innovations. For van den Heuvel and van den Bergh (2009), this regulatory push is often the first opportunity for firms to start along an eco-innovation path by complying with regulatory standards. For example, in the cases of Brazil and the USA, Gee and McMeekin (2011) showed that government support was key to trigger investment in biofuels. According to Nameroff et al. (2004), in the US, large revisions of environmental law during the 1980s and 1990s were followed by a rapid growth in green chemistry patenting. In the US electricity market, Carley (2011) argues that state-level participation in energy policy initiated policy momentum at the state level. For Egyedi and Spirco (2011), standards can catalyze infrastructure transitions provided that they meet key stakeholder interests and if standard specifications are simple and performance-oriented.

Brunnermeier and Cohen (2003) show that environmental innovation seems to respond to increases in pollution abatement expenditures, although increased enforcement activities do not seem to provide additional incentive to innovate. In relation to SO_2 pollution abatement technologies, Taylor et al. (2005) find that public R&D for technology push was less effective than governmental demand creation through the construction of niche markets from legislation and regulation. In the case of the hydrogen energy sector in Korea, Choi et al. (2011) show that the creation of government-driven knowledge networks facilitated risk sharing and solidified the knowledge base in an emerging sector. Clarke and Roome (1995) also highlight the role of networks in fostering incremental and radical environmental changes. Van der Vooren et al. (2012) show that government intervention contributed to the change in automobile consumption patterns towards greener ones, but that R&D support was most useful in the presence of diverse technological performance options. The authors emphasize that infrastructure for electric vehicles should receive substantial support, and policy-makers should be able to evaluate all available options.

When supporting eco-innovations, environmental policies tend to focus on incremental process changes, which seldom trigger radical product or process changes (Kemp 2007). For example, in the US, the increasing use of personal cars led to reconsider the environmental friendliness of personal vehicles, and in 1978 a regulation was introduced to combat emissions from transport. Lee et al. (2006) explain that this change in the technological regime triggered the development of two technological solutions: the first one was the catalyst, an end-of-pipe solution, and the second was the compound vortex controlled combustion engine (CVCC), which by enabling controlled fuel injection was the most fuel-efficient technology; its manufacturers could capitalize on this eco-innovation to develop other energy-saving vehicles, supported by new climate change-driven regulations (Los and Verspagen 2009).

Kemp and Pontoglio (2011) also argue that "there is more evidence of regulations stimulating radical innovation than of market-based instruments doing so", but that it depends on the situation in which they are applied. Successful eco-innovation policies have to adapt to the needs of specific actors. For example, Hansen et al. (2002) point out the need to develop specific policy support to help SMEs develop eco-innovations. As a consequence, Sharma and Vredenburg (1998) suggest that public policy makers "raise the environmental bar" predictably and timely, while leaving the details of how to meet the requirements to firms' innovativeness and technical possibilities. They argue that this would favor pro-active companies, and bring other firms within the industry to an environmentally acceptable level.

The capacity to anticipate coming regulations is another factor of success of environmental regulatory push, as in the case of SO_2 remediation technologies analyzed by Taylor et al. (2005). If such a success depends on firms' anticipatory capacity, policy makers should also reduce uncertainty in the development of new regulations, since, according to Veugelers (2012), more than present ones, it is future regulations that have an impact on current eco-innovations. In the case of the solvent-free technological trajectory, Geldermann et al. (2007) suggest that this alternative technology could persist because producers could anticipate regulatory stability and invest in it. To succeed, environmental policies also need to be complemented by innovation policies "aimed at equipping innovation systems with adequate scientific and technological knowledge in order to respond creatively to changes in external constraints" (Costantini and Crespi 2013). Since Vona and Patriarca (2011) note that increased income inequality could reduce incentives to adopt eco-innovations, environmental policies should be coupled with social policies.

Finally, government regulation is effective not only in terms of its potential to change firm behavior but also consumer behavior. Horbach (2008) and Wagner and Llerena (2011) underline the crucial role of market demand to direct eco-innovations, and the complementary role of regulation for their diffusion. High costs are a barrier to the adoption on the consumer side, since a higher (initial) price of eco-innovations is cited by companies as one of the main obstacles to market penetration. Consequently, public policy is necessary to increase the value of eco-innovation in order to materialize environmental benefits that are not valued by the market (Technopolis 2008; Kemp and Oltra 2011). Because of a strong relationship with social appraisal and regulatory support, the diffusion of eco-innovations differs from the one of non environmental technologies (Dijk et al. 2011). The evidence suggests a strong role of public support to raise environmental awareness so that customers increase their willingness to pay for eco-innovations.

In the case of personal vehicles, for example, the social dimension of an invention proved to be important, since a positive environmental connotation could influence demand. In the case of wind mills, public cooperation supported the maturing of the niche market for wind power. Processes used by chemical industries are energy-intensive and petroleum-based. In addition, they use hazardous materials and generate waste harmful to humans and the environment. Most rules and regulations affecting the sector were adopted following accidents such as the ones that took place in Seveso in 1976 or in Bhopal in 1984. These regulations were part of a socio-technical landscape which in the 1970s and 1980s had triggered investments in end-of-pipe cleanup technologies (Nameroff et al. 2004). European governments have also contributed to shaping a regime favorable to the diffusion of solar renewable energy, for example, by means of households' subsidies. However, this seems to have resulted in a trajectory dominated by silicone-based solar panels that crowded out more efficient solutions such as more complex and expensive thin film panels (ibid.). According to Farla et al. (2010), further diffusion of hybrid vehicles would benefit from changes in the regime, including stimulating tax schemes. The fact that environmental concerns are rising might be an element supporting the diffusion of hybrid cars, which in turn may open up the market for other electric propulsion vehicles (Dijk et al. 2011). Coad et al. (2009) suggest that governments and NGOs can influence the dominant regime by using the heterogeneity of consumer preferences to increase their interest for electric propulsion vehicles, either with information provision policies or by means of financial incentive schemes.

5 Conclusion

In this paper, a review of the literature on eco-innovations in the area of evolutionary economics has been carried out, with particular emphasis on path dependence and lock-in processes. These two concepts, which are central in explaining technical change in evolutionary economics, play a special role when it comes to eco-innovations. In particular, most of the technological trajectories, as a result of path dependent processes in social, institutional and technological realms, are often pollution-intensive. We have unravelled the factors that contribute to lock these trajectories in pollution-intensive technologies, as well as the ones that help break away from pollution-intensive paths. This is key to the support of policies and strategies capable of decoupling wellbeing and pollution trends. In this conclusion, before highlighting promising avenues of research, we combine the results of the literature about lock-in and lock-out factors in order to point out which, in our opinion, are the most important findings that can help maximize the contribution of eco-innovations to sustainable development.

A first group of factors are common between standard innovations and eco-innovations, and thus might be addressed by standard innovation strategies and policies. The literature pointed to three main sources of lock-in leading to pollution-intensive path dependencies (costs, technologies, and stakeholders). It also suggested that the interdependences between these three forces are complex, and may often result in a self-reinforcing loop that can further strengthen an existing technology. Regarding cost-related factors, they are presented in the literature as a significant barrier to eco-innovate for both organizations and consumers, and case studies suggest that they can best be dealt with by government regulation. In particular, in many sectors, the effectiveness of public policies to shape the market value of eco-innovations has been demonstrated. As far as technological constraints are concerned, the complexity of the knowledge base of an existing trajectory can set in motion increasing returns. This means that different knowledge components that make up a technological system can have their own development path that further strenghtens the trajectory. As a result, it is seen of crucial importance to support the development of technological niches that are protected from the effects of those increasing returns. Empirical evidence also suggests that the promotion of variety in eco-innovations is key to limiting the risk of technological entrenchment. In evolutionary theories, the existence of diversity is one of the pathways to stimulate innovation, permitting a broader set of alternative recombination paths (Weitzman, 1998). In the context of eco-innovations, diversity is critical not only to increase alternative recombination paths, and hence to promote innovation, but also to increase the flexibility of technological systems so that they can adapt to trajectories they might face throughout their life cycle. Finally, our survey highlights the importance of having a very good knowledge about stakeholder behavior, which implies consulting them regarding their representations about the issues at stake, and to have a very good understanding of the mechanisms they use to address them. For example, organization-level routines and established regulatory systems can slow down the adoption of environmental technologies.

A second group of findings relates to the fact that the extent to which each factor contributes to lock-in, and the interactions between these factors, depend very much on the specific trajectory considered. In other words, empirical studies point out that eco-innovations do not follow one single trajectory and are very much context-specific, especially because they aim at solving a specific environmental problem, which is not the case with standard innovations. This implies that each eco-innovation may require a specific abatement strategy and trajectory, which might explain the importance in our survey of research on eco-innovation incentives and of case studies. Therefore, qualitative approaches are extremely important to uncover unlocking mechanisms that might be overlooked by aggregated approaches such as econometric or modelling studies (Kemp and Pontoglio 2011).

The third important finding that can be highlighted from the literature concerns the essential role of regulatory instruments to foster eco-innovations. Because of the peculiar nature of eco-innovations, regulations can act as double-edged swords: they can either support the transition to eco-friendly technologies or inhibit them. Empirical findings suggest that regulations deterring eco-innovation tend to be the ones which are not designed and implemented in harmony with other policy objectives such as employment or competitiveness. They also emphasize the notion that social awareness plays a prominent role in supporting eco-innovation-friendly regulations, because environmentally sensitive citizens put pressure on governments and firms to pass these regulations, such as the ones supporting technological niches.

Finally, the fourth finding that can be brought to the fore is the role of the dominant hydrocarbon energy sources in our current socioeconomic system. This dependence is not specific to eco-innovations, but since, as opposed to standard innovations, they aim at reducing negative environmental impacts, the high pollution intensity of fossil fuels affects them more. Indeed, life cycle assessments stress that environmental impacts are very sensitive to the constitution of the energy mix (Hischier and Reichart 2003). Therefore, the dependence from hydrocarbon energy sources prevents eco-innovations from diffusing and achieving their environmental goals. This dependence is of a systemic nature, since fossil fuels have fuelled all innovations since the beginning of the industrial revolution. As long as radical eco-innovations the life cycle of which is entirely based on low impact renewable energies emerge, fossil fuels will remain major obstacles to the success of eco-innovations. In this case, it is not only the technological trajectories that are locked-in, but also the dominant paradigm revolving around the (still relatively) cheap availability of hydrocarbon energy sources.

This review of the literature of the evolutionary approach to eco-innovations has enabled us to decipher some key mechanisms that could either block or enhance the diffusion of eco-innovations. This strand of research has provided insightful results, which allow us to suggest promising lines of research. At first, this paper highlights the need in future work for more research to unravel the interaction effects between the three lock-in factors (costs, technologies, and stakeholders), both theoretically as well as empirically through long-run historical case studies. Second, more research is needed regarding the design rules that would permit the emergence of eco-innovations. For example, so far these rules have been dominated by a cradle-to-grave model. But, for example, in order to minimize the negative end-of-life impacts of eco-innovations, a cradle-to-cradle approach is needed. What would be the impacts of this new design model on the dynamics of eco-innovations, for example, in terms of production routines? Besides, relying on renewable energy sources will also impact the design of eco-innovations, to accommodate the specificities of these energy sources. For example, eco-innovation design rules should accommodate the fact that renewable energy output can hardly be stored and is not stable, since it fluctuates with natural environmental conditions. Also, in order to ensure that eco-innovations do meet their environmental goals, design rules should require systematic life cycle assessments. Given the high costs of these evaluations, financial and knowledge supports should be granted to SMEs to carry them out.

Appendix

Table 1 Definitions of eco-innovation

Subject	Definition	Source
Innovations		
Eco-innovation	"*Innovations whose environmental impact on a life cycle basis is lower than those of relevant alternatives and many innovations qualify as such.*"	Kemp and Oltra 2011: 249
Environmental innovations	"*In a broad sense, environmental innovations can be defined as innovations that consist of new or modified processes, practices, systems and products which benefit the environment and so contribute to environmental sustainability.*"	Oltra and Saint Jean 2009: 267
Environmental innovations	*"Consist of new or modified processes, techniques, practices, systems and products to avoid or to reduce environmental harms. Environmental innovations may be developed with or without the explicit aim of reducing environmental harm. They may also be motivated by the usual business goals such as profitability or enhancing product quality.* […] *environmental innovations are technological, economic, institutional and/or social changes which result in an improvement in environmental quality."*	Rennings et al. 2013: 3–4
Environmental innovations	"*Environmental innovations have been defined as* "*. . . measures of relevant actors (firms, . . ., private households), which: (i) develop new ideas, behaviour, products and processes, apply or introduce them, and; (ii) contribute to a reduction of environmental burdens or to ecologically specified sustainability targets."*	Rennings 2000: 322
Eco-innovations	*"Eco-innovation means the creation of novel and competitively priced goods, processes, systems, services, and procedures that can satisfy human needs and bring quality of life to all people with a life-cycle-wide minimal use of natural resources (material including energy carriers, and surface*	Technopolis 2008: i

Table 1 (continued)

Subject	Definition	Source
	area) per unit output, and a minimal release of toxic substances."	
Technologies		
Environmental technology	"'*Environmental technology' is a range of products and processes that either control pollutant emissions or alter the production process, thereby preventing emissions altogether* […] *'Environmental technology' refers to everything from 'end-of-pipe' pollution control technologies to alternative energy technologies that share the characteristic of helping to maintain the 'public good' of a clean environment*"	Taylor et al. 2005: 698
Green technology	*"'Green' technology is used to describe technology which is currently perceived to be least damaging to physical, biological and cultural systems. Moreover, it describes technology where environmental concerns are built into the development, design and operation of the product or process."*	Clarke and Roome 1995: 192
Environmental technologies	"*Environmental technologies* [are] *production equipment, methods and procedures, product designs, and product delivery mechanisms that conserve energy and natural resources, minimize environmental load of human activities, and protect the natural environment.*"	Shrivastava 1995: 185
Clean technology	*"All techniques, processes and products that prevent or diminish environmental damage at the source, and/or minimise the use of raw materials, natural resources, and energy"*	Kemp et al. in Oltra & Saint Jean 2005: 191
Eco-efficiency	"*Eco-efficiency (Hart, 1995 and 1997) or conservation approaches (Gladwin et al.* 1995) *involve the changing of processes and products to reduce wastes at source, reducing the use of energy and materials, water conservation, and greater fuel efficiency"*	Sharma and Henriques 2005: 163
Eco-design	"*Fundamental design changes in their products and processes by reducing or eliminating packaging, making products more durable and easy to disassemble and reuse, examining the life cycle environmental impacts of their products, services and operations, and eliminating harmful and toxic chemicals. This includes analyzing the materials and energy used in the production, transportation and consumption of products/services as well in their disposal, and the impact of operations on ecosystems.*"	Sharma and Henriques 2005: 165
Green products		
Green products	"[…] *green products, which are products with low environmental impacts.*" "*Green products are defined as products with an alternative design such that less physical resources are required during its life cycle. Products are*	Janssen and Jager 2002: 283, 288–289

Table 1 (continued)

Subject	Definition	Source
	implemented as a chain of actions. The non-green type of product is sold to the consumers, and will not return back to the producer. The green product is leased to the […] *consumers.* […] *Old products are taken back by the producer, which refurbish products for the production of new products.*"	
Green products	"*'green' products,* i.e. *those which are easily recyclable and which have a long lifetime*"	Brouillat 2009: 471
Green products	*...prevent pollution from the beginning through product design and innovation.*"	Chen 2001: 251
R&D activity		
Environmental R&D	Having the purpose to increase the "*gross environmental performance of the production process.*"	Oltra and Saint Jean 2005: 197
Green chemistry R&D	*Is an environmental, health and safety strategy (EHS) that emphasizes pollution prevention; it is the invention, design, and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances.*	Anastas and Warner in Nameroff et al. 2004: 960
Organization		
Adding broader SD elements	"*product stewardship, protection of habitats, operation within a region's environmental carrying capacity, protection of the interests of future generations, as well as the equitable balancing of the interests of all segments of society*"	Sharma and Henriques 2005: 160
ECM – Environmentally Conscious Manufacturing	"*ECM involves the planning, development and implementation of manufacturing technologies and processes that minimise or eliminate hazardous waste, reduce scrap, are operationally safe and can design products that are recyclable or can be remanufactured or reused"*	Sarkis 1995: 80
SEM – Strategic Environmental Management	"[SEM provides] *routes to competitiveness based on redesign of products themselves.* […] *Product redesign has been aimed at reducing materials- and energy-intensity and pollution, across production, use, and post-usage disposal.* […] *It may also entail efforts to capture market demand.* […] *This kind of strategic positioning is what distinguishes SEM from earlier, more limited pollution prevention practices. In its most developed form, SEM links individual products and processes to a vision of systemic sustainability, which requires that the sum total of all individual activities not create environmental burdens exceeding the earth's carrying capacity"*	Goldstein 2002: 497
EMS – Environmental Management Systems	*Organise the implementation of environmentally improved processes, which are related to waste reduction, a decrease in organisational risks and complying with legislation.*	Zutshi and Sohal 2004

Table 1 (continued)

Subject	Definition	Source
Industrial Ecology		
IE- Industrial Ecology	"*Industrial ecology is thus an attempt to combine both product competitiveness and environmental improvement by shifting from a linear to a materials cycle approach.*" "[…] *ways to connect waste-producing processes, plants or industries into an operating web that minimizes the total amount of industrial material that goes to disposal sinks or is lost in intermediate processes. The focus changes from merely minimizing waste from a particular process or facility (*i.e. *pollution prevention) to minimizing waste produced by the larger system as a whole.*"	Gibbs et al. 2005: 172-173
IE - Classic industrial parks	"*An industrial system of planned materials and energy exchanges that seeks to minimise energy and raw materials use, minimise waste, and build sustainable economic, ecological and social relationships.*"	Lambert and Boons 2002: 472
IE – Mixed business parks	"*a community of businesses that collaborate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community.*"	Lambert and Boons 2002: 471

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