Industry & Innovation
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713424563

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Online publication date: 18 April 2011

To cite this Article Kemp, René and Oltra, Vanessa(2011) 'Research Insights and Challenges on Eco-Innovation Dynamics', Industry & Innovation, 18: 3, 249 — 253
To link to this Article: DOI: 10.1080/13662716.2011.562399
URL: http://dx.doi.org/10.1080/13662716.2011.562399

Industry and Innovation,
Vol. 18, No. 3, 249–253, April 2011

Introduction

Research Insights and Challenges on Eco-Innovation Dynamics

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Increasingly the term environmental technology is superseded by the broader concept of eco-innovation in recognition of the shifting attention to changes in product characteristics, product chains and processes. Issues of resource efficiency, the closing of material loops and alternative systems of consumption and provision are discussed under the new label of eco-innovation. Eco-innovation is also the stated aim of national and EU policy. It is part of the sustainable development strategy and the economic growth strategy of the European Commission because of the policy assumption of offering a "double win". In 2008, the Executive Agency for Competitiveness and Innovation (EACI) of the European Commission launched a programme dedicated to eco-innovation with the aim of supporting innovative products, services and technologies that can make better use of our natural resources and reduce Europe's ecological footprint.

Whereas environmental technology and environmental services come from the environmental goods and services sector, eco-innovation is produced in all sectors. Eco-innovations are innovations whose environmental impact on a life cycle basis is lower than those of relevant alternatives and many innovations qualify as such. The innovation may be an adaptation of an existing product or technology process, a product or process new to the world, something organizational, distributional or presentational, and a mix of old and new elements. Like normal (non-eco) innovations, eco-innovations may be technological, organizational, intangible or systemic, and, like any innovation, they require knowledge, attention, capabilities, resources and coordination for their development and adoption.

Since the 1990s, an extensive theoretical and empirical literature has been developed on the effects of environmental policy instruments upon innovation and competitiveness, as well as on the different types of environmental innovations and eco-technologies developed by firms. Initially this question has been tackled in the field of environmental economics with a focus on the debate on economic vs. regulatory instruments. Within this literature the

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1366-2716 Print/1469-8390 Online/11/030249–5 © 2011 Taylor & Francis
DOI: 10.1080/13662716.2011.562399

eco-innovative activities are not analysed per se, but considered to be quite systematically induced by regulation and market-based instruments. In the 1990s, people from the field of innovation studies started to study eco-innovation as a specific type of innovation (e.g. Green *et al.*, 1994; Lanjouw and Mody, 1996; Kemp, 1997; Rennings, 2000). In the past 10 years, many studies have been undertaken into the determinants and dynamics of eco-innovation based on different types of data (patents, innovation surveys, case studies) and methodologies. As a result, our understanding of the characteristics, shaping factors and effects of eco-innovation has been improved (see, e.g., Rennings and Zwick, 2002; Frondel *et al.*, 2007; Horbach, 2008).[1]

The main motivation of this special issue is to collect together empirical insights on eco-innovation dynamics which bring new insights on the micro- and meso-dynamics of eco-innovation, more particularly on firms' performances and competences linked to eco-innovation, and on the role of market dynamics and policy instruments dedicated to specific eco-innovations. These topics should enable us to go further in the understanding of the specificities of eco-innovations, which is a crucial question in eco-innovation research. The main specificity emphasized by the literature (Rennings, 2000; Horbach, 2008) is the role of policy and regulation, that is, "regulatory push–pull effect" in Rennings (2000). Policy is crucial for giving environmental benefits a value in the marketplace through the use of regulations, taxes and tradable emission rights. No other actor than the government can do this on a large scale and systematically. Eco-innovation is also supported by innovation policy, industrial policy and sectoral policies.

A second difference with normal innovation is that suppliers and especially users must understand environmental issues in a way that is meaningful for them (consumers must be able to make a link with climate change when learning about low-carbon products). Eco-innovation depends on values, the attribution of meaning and on environmental knowledge. In the absence of special regulations and incentives, a sense of responsibility is needed for dealing with the conflict between individual rationality and collective rationality.

Like any innovator, an eco-innovator must deal with trade-offs. The trade-offs depend on the state of technology and contextual factors such as prices and infrastructure. These trade-offs are conducive to various technological compromises which shape the technological trajectories of firms (Oltra and Saint Jean, 2005a, b). This is particularly true for product innovations whose diffusion depends on user benefits. The extent to which eco-innovations combine environmental performances with product quality and with the conventional service characteristics of products determines their diffusion. The same holds true for cleaner production methods: processes and methods that combine resource efficiency benefits with environmental benefits can diffuse more quickly and widely because of these double benefits.

After this short introductory discussion, we now turn to the five papers of this special issue. The first one by Klaus Rennings and Christian Rammer revisits an old theme in environmental economics, which is whether environmental regulations through innovation promote economic growth or hamper it. Using data from the German innovation survey, Rennings and Rammer investigate the effects of regulation-driven eco-innovation on

[1] An overview of econometric results can be found in Jaffe *et al.* (2003) and Vollebergh (2007) and an overview of case study findings can be found in Del Rio Gonzalez (2009).

innovation success and firm performance. By using an econometric model, the authors investigate whether firms with innovations that have been initiated by environmental regulations are able to achieve a similar innovation success compared to other innovators. The estimation results show that there is no general negative impact of this type of innovation on the innovation success of firms. Using econometric techniques, the study examined whether the companies which introduced environmental regulation-induced innovation have a greater or lower innovation success, measured as the sales from market novelties in the case of product innovations and achieved cost reduction in the case of process innovations.[2] The study finds that the effects differ per sector. Process innovators in the field of sustainability mobility are found to have lower profit margins, whereas the introduction of product innovations in the field of resource efficiency is associated with higher profitability. On average, environmental innovations do not perform worse compared to other innovations, which leads the authors to the conclusion that "Porter is right when saying that environmental innovations do not harm the competitiveness of firms in general" (p. 275 of this issue) (Porter, 1991; Porter and van der Linde, 1995).

The next two papers use the framework of technological innovation systems (TIS). The paper by Ulrich Dewald and Bernhard Truffer examines the market dynamics for a specific eco-innovation, the photovoltaic (PV) panel. They offer an in-depth analysis of the different market segments: centralized PV power systems, small-scale homeowner systems, large-scale roof-mounted systems and civic corporate solar systems. What is special about their analysis is that the authors examine how the different market segments contribute to the broader TIS for PV in terms of the functions of knowledge generation, legitimacy, access to resources and the contribution to overall market progress. They also provide a structural analysis of the actors, networks and institutions of each market segment, as well as process analysis of market segments with special attention to interdependencies. The paper makes an original contribution to the literature on technology innovation systems through a fine-graded market analysis with attention to actors and market segment relations.

The paper by Sally Gee and Andrew McMeekin investigates the biofuel innovation trajectories of the USA and Brazil in a historical perspective. The paper brings out the unfolding nature of those trajectories and how these reflected different concerns which gave rise to different problem–solution sequences. By comparing both trajectories and the role of public policies and national programmes in each country, the authors show that innovation trajectories are problem-based but that the functional problems that innovation systems are mobilized to solve are interwoven with social, economic and political factors which are manifestly different in different nations. This paper is in the old tradition of innovation studies looking at the multitude of factors that shape innovation trajectories. In their paper the economic innovation perspective which is more functionalist is merged with a social constructivist perspective of innovation.

The last two papers adopt a more microeconomic perspective focusing on firms' eco-innovative strategy and on technological lock-in. Paolo Zeppini and Jeroen C. J. M. van den Bergh present a model of sequential decisions about technological investments, in which firms can invest in dirty and clean technologies. Their analysis makes a contribution to the

[2] The innovation success is for all innovations of the eco-innovating company (a common problem with innovation surveys is that the effects of innovation apply to all product or process innovations).

literature on path dependence and lock-in (Arthur, 1989; Cowan and Hultén, 1996) by examining how recombinant innovation (such as the hybrid electric car) can help to escape lock-in to a technology. In the model, a "dirty" and a "clean" technology compete in the market. Recombination of these technologies is possible, giving rise to a technology with favourable environmental (clean) and economic (viable) characteristics. Escaping lock-in depends on the strength of the recombinant effect. The authors show that, if the initial advantage of the dirty technology is too big, the system converges to a complete dominance of this technology, due to network externalities. A different picture arises when recombinant innovation is strong. The effects of environmental policy are also studied. The implementation of environmental policy can unlock the system from the dirty technology. This will happen if the negative externality from pollution weighs more in agents' decisions than the advantage of the initial network externalities of the dirty technology. This paper fits within the tradition of formal modelling which so far is weakly developed in the field of eco-innovation.

Avrath Chadha's paper presents an original contribution on firms' competences and dynamic capabilities for developing radical eco-innovations. The paper is based on a case study on biopolymer technology, a radical innovation relatively to oil-based plastics. Based on firms' interviews, the author studies the organizational structures as well as the competences applied by the sample of firms developing successfully biopolymer technology. This case study provides interesting insights on the dynamic capabilities developed by firms in order to overcome technological lock-in. The author identifies five competences enabling firms to overcome technological lock-in and to go beyond their traditional technology and knowledge base. These competences are inter-firm alliances (mostly R&D consortia with suppliers and/or customers), independent project houses, technology monitoring, cross-functional integration and bootleg research (i.e. research in which some motivated employees, sometimes secretly, organize a part of the corporate innovation process). This paper takes a management and qualitative empirical approach to the issue of escaping lock-in, which complements the formal analysis of Zeppini and van den Bergh.

To conclude, the five papers are quite different, covering different topics and using different research approaches. They don't cover the whole area of eco-innovation research and there are some gaps in eco-innovation research where more work is needed. One such gap is the linking of economic models with physical models, where there are some methodological challenges in integrating eco-innovation into economic-physical models. A second gap is tracing the chain from science through to environmental impact, green jobs and governance (Berkhout, forthcoming). A third topic on which more work should be done is eco-innovation in developing countries and newly industrialized countries. The field of eco-innovation studies is dominated be contributions from especially the USA and Europe. As the studies of this special issue show, eco-innovation is context-specific which is why we need research from those countries, by researchers from those countries who understand the broader context and societal processes in which eco-innovation is embedded.

Acknowledgements

This research has been supported by the European Network of Excellence DIME ("Dynamics of Institutions and Markets in Europe", European Commission FP6, Contract No. 513396, CIT3).

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