Applying systems thinking and practice for promoting sustainable innovation for climate change mitigation

Timothy J. Foxon
4CMR - Cambridge Centre for Climate Change Mitigation Research,
Dept. of Land Economy,
University of Cambridge,
22 Trumpington St.,
Cambridge CB2 1QA, U.K.
E-mail: tjf12@cam.ac.uk

Paper for Heinrich Boell Foundation Montreal Follow-up Meeting, Berlin, 27 September 2006

Abstract

The challenge of addressing climate change in the context of moving society towards the environmental, economic and social goals of sustainability requires radical innovation of cleaner technologies and processes which meet individual and social needs at acceptable costs with significantly reduced environmental impacts. This paper describes recent work by the author and colleagues examining policy processes for promoting innovation for sustainability, and develops the argument that systems thinking and practice are needed to transform these processes.

In a report for policy-makers (Foxon *et al*., 2005a) arising from research under the ESRC Sustainable Technologies Programme, we set out five *guiding principles* to inform strategic thinking about the policy goals, processes, measures and instruments appropriate for a Sustainable Innovation (SI) policy regime.

This paper describes these guiding principles and examines the first and second in more detail. In particular, it argues for the concept of ‘systems failure’ as a rationale for public policy interventions, rather than the narrower economic concept of ‘market failure’.

1. Introduction

The challenge of addressing climate change in the context of moving society towards the environmental, economic and social goals of sustainability requires radical innovation of cleaner technologies and processes which meet individual and social needs at acceptable costs with significantly reduced environmental impacts. The work of a number of researchers, with prominent contributions from academics at SPRU over the last 40 years, has developed a systems theoretic understanding of innovation processes. Work in political sciences has similarly developed a view of governance as an interactive process shaped by institutional settings. However, these understandings have largely failed to inform policy processes for promoting innovation for sustainability. This paper describes recent work by the author and colleagues examining policy processes for promoting sustainable innovation (SI) (Foxon, 2003, 2006a,b; Foxon et al., 2005a,b; 2006a.b; Foxon and Kemp, 2006), and develops the argument that systems thinking and practice are needed to transform these processes.

The systems approach sees innovation as an iterative matching of technical possibilities to market opportunities, through both market and non-market interactions, feedbacks and learning processes, rather than as a one-way, linear flow from R&D to new products (Freeman and Soete, 1997). It also emphasises the importance of the institutional framework of social rules, conventions and organisations in determining the rate and direction of technological innovation. Policy measures form a key part of this framework. Thus, innovation is seen as a dynamic, cumulative, systemic and uncertain process, giving rise to path dependency and the potential for lock-in of technological and institutional systems (Grubler, 1998; Grubler et al., 2002; Foxon, 2003). Similarly, policy making is seen not as a top-down, linear process but as an interactive process of governance involving various forms of partnerships, collaboration, competition and negotiation, shaped by the institutional settings in which they occur (Rhodes, 1997; John, 1998; Kingdon, 1995; Foxon, 2006b). Individual policy domains, such as economic policy, innovation policy and environmental policy, are seen as having their own communities with specific preferences, ideologies and backgrounds, leading to distinct imperatives and rationales for action. In this view, in order to understand how substantive policy outcomes arise, and to enhance them, it is necessary to examine the policy processes from which they arise. Our research on sustainable innovation policy sought to begin to synthesise the implications of these theoretical insights for practical policy making in this important area.

This work was undertaken as part of the Sustainable Technologies Progamme, a research programme supported by the UK Economic and Social Research Council (ESRC). The project developed five guiding principles for SI policy processes, drawing on: two case studies on low carbon energy innovation in the UK, and EC policy-making processes relating to alternative energy sources for vehicles; the analysis of other policy-making frameworks, including the Dutch transition approach; and a series of workshops with policy-makers and other stakeholders. A report expounding these guiding principles was presented to policy-makers and other stakeholders at the UK Department of Trade and Industry in April 2005.

2. Co-evolution of technology and policy regimes

The systems and process-oriented view of both innovation and governance leads us to examine the co-evolution of technology and policy regimes relating to the innovation and diffusion of more sustainable technologies and supporting institutions. This leads us to argue that improved guiding principles are needed for the design of a sustainable innovation policy regime.

2.1. Bringing together environmental and innovation regimes

Until recently, innovation issues and environmental sustainability issues were usually addressed through separate policy regimes, based on distinct analyses of problems, types of policy instrument and rationales for policy intervention. Recently, however, researchers have increasingly tried to bring these regimes closer, e.g. the papers in (Hemmelskamp *et al*., 2000; Grubler *et al*., 2003; Edenhofer *et al*., 2006) and our own research, which set out the case for direct policy support for innovation to achieve environmental ends (Anderson *et al*., 2001; Gross and Foxon, 2003)[1]. It has also been increasingly recognised that there is a need to "translate the rather academic insights obtained thus far into practical results useful for policy makers" (den Hertog *et al*., 2003).

The traditional economic argument for policy measures relating to environmental or sustainable innovation has been based on correcting for two principal 'market failures':

(a) Firstly, because knowledge can easily be copied once it has been created, innovators cannot appropriate the full benefits of their investment in the creation of that knowledge, i.e. social returns to innovation exceed private returns, which means that private firms do not have sufficient incentives to undertake innovation to socially efficient levels (Arrow, 1962). This provides an underlying rationale for public support for research and development (R&D).

(b) Secondly, the existence of negative 'externalities', e.g., unpriced environmental impacts (Pigou, 1932). This provides the rationale for economic instruments (such as taxes or emissions trading schemes) and other instruments (such as emission or technology standards) to 'internalise' those externalities.

Measures to correct these market failures have largely been applied and assessed in separate regimes, with *innovation policy* dealing with the first failure, and *environmental policy* the second. However, both theoretical and empirical arguments suggest that these separate regimes are unlikely to be able to address adequately the challenge of promoting a transition to more sustainable systems of production and consumption - i.e. systems in which resource use and waste production remain within appropriate environmental limits and socially acceptable levels of economic prosperity and social justice are achieved.

---

[1] The case is based on four interrelated arguments: *the problem of time lags; risks and uncertainties of costs and benefits*; *the value of creating options*; and the *positive externalities of innovation*, and potential policy measures include market development policies and financial incentives, as well as support for R&D (Anderson *et al*., 2001; Gross and Foxon, 2003).

The theoretical arguments start from the recognition that technological development exhibits *path dependence* (David, 1985), i.e. the influence of systemic factors, expectations and small events implies that how (and whether) a technology develops also depends on the historical path of its development. Arthur (1989, 1994) argued that the increasing returns to adoption (including economies of scale, learning effects, adaptive expectations and network or co-ordination effects) can result in technological *lock-in*, where the dominance of incumbent technologies effectively creates barriers to the adoption of new technologies. Furthermore, institutions that support technological systems, from ways of thinking to regulatory regimes, exhibit similar types of increasing returns, due to high set-up costs, learning effects, adaptive expectations and co-ordination effects (North, 1990; Pierson, 2000). The interaction, or co-evolution, between technological and supporting institutional systems can reinforce the lock-in of techno-institutional systems. It is argued that many current techno-institutional systems are both unsustainable and locked-in, for example, the so-called *carbon lock-in* of current fossil fuelled energy systems (Unruh, 2000; Foxon, 2006b). Hence, there are serious policy challenges of how to promote a transition to more sustainable systems.

However, current environmental innovation policy regimes are largely based on a discredited 'linear' model of innovation, which assumes that greater levels of support for R&D of new cleaner technologies will automatically result in more of them reaching the market (Mytelka and Smith, 2002). As discussed in Section 2.2, modern innovation theory presents a much richer picture of innovation as a systemic, dynamic, non-linear process, involving significant uncertainties. We argue that these features tend to be inadequately represented, both in current models of innovation and diffusion processes, and in the design and implementation of policy measures to promote the innovation and diffusion of cleaner and more sustainable technologies.

Current policy-making processes face particular difficulty in addressing sustainability issues for at least three reasons: first, long-term social and environmental problems tend to receive relatively low priority in the face of more immediate policy pressures; second, the inter-related nature of these problems and radical uncertainties in future costs and benefits creates additional levels of complexity which are not easy to address within current processes; and third, the goals and trajectories required to ensure sustainability are inevitably contested.

2.2. Innovation systems approaches

An *innovation system* may be defined as "the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge" (Lundvall, 1992). The systemic nature of technological innovation is articulated by several related approaches (see the recent reviews in Kemp, 1997; Rip and Kemp, 1998; Foxon, 2003). These approaches emphasise that innovation is a dynamic process, arising out of interplay between different actors, and involving both knowledge flows and market interactions. Moreover, because of the multiple feedbacks and types of learning involved, these approaches do not draw a rigid boundary between the innovation of a new technology and its diffusion. This enables a more subtle and realistic picture to be drawn of the drivers and barriers to technological innovation and diffusion, although the approach has not (yet) yielded a model in mathematical form to match or replace the epidemic and rational choice models of diffusion. Nevertheless, we argue that innovation systems approaches, and empirical analyses based on them, can be used to provide policy guidance at a strategic level.

These systems approaches thus see innovation and diffusion as a *systemic*, *dynamic and non-linear* process, in which technological and institutional factors interact in a context of inherent *uncertainties*. The dynamics of technological and institutional change unfold at many different levels, and on different time scales. Individual technologies change relatively rapidly, whilst technological systems tend to change relatively slowly. Innovation is non-linear, as systems typically show increasing returns to adoption, so that small changes in initial conditions can result in radically different outcomes. Innovation processes are uncertain because neither future technological and market opportunities nor policy and regulatory regimes can be accurately predicted.

Systems approaches recognise that any actor - individual, firm or government – has limited ability to gather and process information for decision making – so-called 'bounded rationality' (Simon, 1955, 1959; Foxon, 2006c). Because the future is uncertain and firms lack perfect knowledge, what they know and how they learn becomes central to understanding the innovation process. Much innovation consists of making new combinations of existing knowledge, as a result of various forms of learning: *learning-by-doing* (Arrow, 1962b); *learning-by-using* (Rosenberg, 1982); and *learning-by-interacting* (Lundvall, 1992). Furthermore, the uncertain nature of innovation implies that firms' and investors' *expectations* of future markets, technologies and policies are a crucial influence on their decisions about which technologies to invest in and develop (Rosenberg, 1982; Mackenzie, 1992). Expectations are often implicitly or explicitly shared between different firms in the same industry, giving rise to trajectories of technological development which can come to resemble self-fulfilling prophecies[2].

Finally, innovation systems approaches emphasise the importance of institutional factors in influencing the rate and direction of innovation. These range from habits of thought and action to policy and regulatory frameworks (North, 1990; Hodgson, 1988).

The early work in this area focussed on national innovation systems, particularly undertaking comparative studies of how the innovation performance of different countries reflects their different institutional arrangements, including: systems of university research and training and industrial R&D; financial institutions; management skills; public infrastructure; and national monetary, fiscal and trade policies (Lundvall, 1992; Nelson, 1993).

More recent work has sought to apply innovation systems analysis to countries' efforts to promote innovation for environmental or sustainability goals. Jacobsson and Johnson (2000) developed and applied an analytical framework for analysing the diffusion of renewable energy technologies from an innovation systems perspective.

[2] The most well-known example is 'Moore's law', that the number of components on state-of-the-art microchips, and so the computing power, will double every 12-18 months. This widely known 'law', formulated by Gordon Moore in 1964, has held remarkably well from the first transistor in 1959 to present day chips, and may well have guided the efforts of innovators in the semiconductor industry. See: http://www.intel.com/research/silicon/mooreslaw.htm

They argue that an innovation system serves five functions (Johnson and Jacobsson, 2001; Jacobsson and Bergek, 2004):

- To *create and diffuse 'new' knowledge*;
- To *guide the direction of the search process* among users and suppliers of technology, i.e. to influence the direction in which actors deploy their resources;
- To *supply resources*, including capital, competencies and other resources;
- To *create positive external economies* through the exchange of information, knowledge and visions;
- To *facilitate the formation of markets*

They identify a number of mechanisms that may induce or block the development of effective functions for particular technology systems. Inducement mechanisms include: government policy (e.g. R&D funding, investment subsidies, tax incentives); ease of firm entry; and feedback from market formation. Blocking mechanisms include: uncertainty; lack of political support; poor connectivity of networks; opposing behaviour of established firms: and disincentives created by other government policies. Based on analysis of how these inducement and blocking mechanisms interacted in practice, Bergek and Jacobsson (2003) identify four factors that contribute to the relative success of the German wind turbine industry: (1) creation of variety in an early phase; (2) establishment of the social legitimacy of wind energy; (3) the employment of advanced market creation policies in a later phase; and (4) the use of industrial policy to favour the domestic industry.

Other recent work that has sought to incorporate sustainability considerations in innovation systems analysis includes the work of Malerba (2004) on sectoral systems of innovation, which emphasises the importance of sectoral specificities, and edited volume by Weber and Hemmelskamp (2005) analysing the environmental/ sustainability orientations of innovation systems.

2.3. Reconciling innovation policy and environmental/sustainability policy

We argue that the richer picture of innovation processes provided by innovation systems theory should provide a useful basis for reconciling innovation policy and environmental/sustainability policy to overcome the difficulties highlighted in Section 2.1. Influential recent reports in Europe and the U.S. by the Blueprint Network (Rennings *et al*., 2003) and the Pew Center (Alic *et al*., 2003) have presented similar arguments for the development of a sustainable innovation policy regime to address long-term environmental problems, such as climate change, by stimulating the innovation and diffusion of cleaner technologies, such as renewable energy and other low carbon technologies.

A clear analysis of the broad agenda of governance issues that governments face in further developing innovation policy and reconciling it with other policy objectives is given in a recent OECD report (OECD, 2005). This report argues for a 'third-generation' innovation policy which would take seriously the innovation systems approach, building on earlier OECD work developing the analysis of national innovation systems and the policy implications of this approach (OECD, 1999, 2002). It stresses the importance of *balancing imperatives*, recognising that policy for sustainable development may have different or even opposing objectives and imperatives to the fundamental economic growth imperative which usually underlies innovation policy. It argues for a reconciliation of innovation and sustainability policy through the promotion of a model of growth that limits negative environmental and social pressures. It also stresses the need for institutional changes to incorporate systems thinking, particularly through improving policy evaluation and learning processes.

2.4. Towards a sustainable innovation policy regime

These recent analytical and policy-relevant developments have begun to outline the challenge that policy-makers face in trying to reconcile innovation and sustainability policy objectives. We argue, though, that there is a need to develop greater guidance for policy-makers that will inform the development of sustainable innovation policy. In the course of our research, we have developed such guidance, based on our theoretical and empirical analysis and experience, as well as extensive stakeholder consultation. The guidance was presented at the UK Department of Trade and Industry in April, 2005 (Foxon *et al*., 2005a) and is intended for use by policy-makers and other stakeholders involved in sustainable innovation policy processes, including industry and NGO representatives, and consultants who provide policy advice. It is not intended to supplant current processes, but rather to aid policy-makers and stakeholders in developing and adapting policy objectives and processes so that they will be more effective in promoting sustainable innovation.

The guidance draws on our work on theoretical understanding of innovation systems (see Foxon, 2003), empirical analysis of recent policy developments through two case studies of UK and EC policy making, and insights from practical policy experience. The latter includes both work contributing to the UK Renewables Innovation Review and direct involvement in producing draft legislation to generate a mix of instruments to advance sustainable innovation in the transport sector, in the area of battery technologies. The case studies, which are described in a monograph presenting the project findings (Foxon *et al*., 2005b), show that policy processes are still often too short-term, dominated by current interests with relatively short-term goals and are not sufficiently flexible to promote long-term environmental aims in the face of changing circumstances.

Our proposed SI policy process guidance offers five key guiding principles that could form the basis for a ***Sustainable Innovation (SI) policy*** regime (Foxon *et al*., 2005a):

(1) Stimulate the development of a *sustainable innovation policy regime* that brings together appropriate strands of current innovation and environmental policy and regulatory regimes;
(2) Apply *systems thinking and practice*, engaging with the complexity and systemic interactions of innovation systems and policy-making processes;
(3) Advance the *procedural and institutional basis* for the delivery of sustainable innovation policy;
(4) Develop an *integrated mix of policy processes, measures and instruments* that cohere to promote sustainable innovation;
(5) Incorporate *policy learning* as an integral part of sustainable innovation policy process.

Such a regime would bring together relevant parts of current innovation and environmental policy regimes, in order to promote sustainable innovation.

3. Applying systems thinking to promote a transition to sustainability

We now turn to the second of our guiding principles for SI policy processes: *applying systems thinking, engaging with the complexity and systemic interactions of innovation systems and policy-making processes, to promote a transition to sustainability*.

As proposed in the Dutch transition approach framework (Kemp and Rotmans, 2005), for the promotion of sustainable innovation, a long-term strategic framework needs to be complemented by practical moves to create space for alternative technologies and institutions to grow and to supplant locked-in technological systems. Such approaches can be informed by theoretical and empirical understanding of the processes by which these kinds of radical innovations occur.

The three-level hierarchy proposed by Rip and Kemp (1998): *technological niches, socio-technical regimes* and *landscapes* provides a useful theoretical framework. In this hierarchy, each level has a greater degree of stability and resistance to change than the level below it, because of the interactions and linkages between the elements that form that configuration. Studies of past innovations (e.g. Utterback, 1994; Christensen, 1997) suggest that a new technology will typically first commercialise in niche markets, where the particular technology's advantages are strongest. These markets allow the technology to benefit from learning effects so that costs reduce and the technology's performance can improve. If this occurs sufficiently, the new technology may then become competitive with the existing technology in the wider market. Shifts to new technological regimes, and ultimately *transitions* to new socio-technological landscapes, then occur through the cumulation of niches, which gradually swell and coalesce to form a new regime (Geels, 2002). Other factors identified as key to successful innovation include the development of a skills base, and the creation of knowledge networks in the new technological system.

As described above, the increasing returns that accrue to successful technologies can lead to the 'lock-in' of mature technological and institutional systems, such as carbon-based energy systems. In most market areas, lock-in will eventually be overcome when a new technological alternative provides a bundle of attributes that is more attractive to growing numbers of customers. As Christensen (1997) describes, for a '*disruptive*' technology, this new package of attributes typically first appeals to customers in niche markets, which are ignored by existing market leaders who are focusing on their mainstream customers and markets[3]. The niche markets allow the disruptive technology the space for cost-reducing and performance-enhancing learning, and for demonstration of the value of the new package of attributes. If this occurs successfully, then the market for the disruptive technology can grow and eventually displace the existing technology. As the initial customers are outside the mainstream markets, disruptive technologies are typically first produced by entrepreneurial 'outsider' individuals and firms, rather than the current 'insider' market leaders.

[3] Among the examples quoted are the various generations of both mini and micro computers and of disk drive technologies.

For the innovation of more sustainable technologies, a key attribute of the new technology will be its improved environmental performance. However, this characteristic is frequently under-valued by existing markets. This will be necessarily the case when environmental externalities have not been internalised, but, as described above, even when policy measures have begun to be implemented, they will typically not fully internalise these externalities, because of the restraining influence of actors who are dominant within existing systems (Pierson, 2000; Unruh, 2000; Foxon, 2006b). Hence, there is a strong case for targeted policy measures to support niche markets for sustainable technologies, so that they can reap both environmental and economic benefits (Kemp et al., 1998). They are likely to be most effective when based on encouraging technologies that meet environmental and other performance standards, rather than on 'picking' particular technologies. To *overcome lock-in* of unsustainable technologies and supporting institutions, and in view of the uncertainties involved, it would be appropriate for SI policy to seek to promote a diversity of technology and institutional options.

We argue that a key aspect of the implementation of systems thinking implies the need for developing and applying the concept of '*systems failures*' as a rationale for public policy intervention.

3.1. Addressing 'systems failures'

The identification of conditions for policy intervention to promote sustainable innovation in this way has been considered within the innovation systems approach. Analysis of how innovation systems actually function, at national, regional and sectoral levels, including comparative studies with other countries (OECD, 1999, 2002), could reveal problems that are occurring in current systems and help to identify opportunities for public policy interventions. Intuitively, it is sensible that policymakers should examine best practice in other countries, and in regional and international policymaking bodies. Such an approach can allow for progressive policy "leap frogging" where jurisdictions learn from one another and accelerate improved policy interventions.

This approach would apply the concept of 'systems failure' as a rationale for policy interventions (Edquist, 1994, 2001; Smith, 2000). It advocates undertaking concrete empirical and comparative analyses of innovation systems to identify systems failures that can be rectified. It identifies two conditions for public intervention in a market economy:

(a) a *problem* must exist, i.e. a situation in which market mechanisms and firms fail to achieve objectives that have been socially-defined, through a public policy process; and

(b) the state and its agencies must also have the *ability* to solve or mitigate the problem effectively (i.e. the issue of potential government and bureaucratic failure must be addressed).[4]

In many cases, this concept of systems failure leads to similar or identical policy prescriptions to the economic concept of market failure, e.g. the use of policy

[4] It is recognised that the appropriate role of government and the ability of public agencies to address such problems will continue to be matters of intense political debate.

instruments to internalise negative environmental externalities. The crucial difference, however, is that it does not presume that public policy interventions can recreate ideal market solutions, which are assumed to have maximal economic efficiency. In some cases, this will have practical policy consequences, where other policy measures, e.g. to overcome institutional barriers to change, may be required to complement or substitute for instruments like environmental taxes or emission trading schemes.

Smith (2000) identifies four areas of systemic failure, which could provide a rationale for policy intervention:

(1). Failures in infrastructure provision and investment:

Both physical infrastructures, such as for energy and communications, and science-technology infrastructures, such as universities, technical institutes and regulatory agencies, are important parts of innovation systems. However, because of their large scale, indivisibilities and very long time horizons of operation, they are unlikely to be sufficiently provided by private investors, and so there is a case for public support for infrastructure provision.

(2). 'Transition failures':

Because existing firms, especially small firms, are necessarily quite limited in their technological capabilities and horizons, they are likely to experience great difficulties in responding to technological changes. These changes may be due to developments outside firms' area of expertise, changes in technological opportunities or patterns of demand which push the market into new areas of technology, or major shifts in technological regimes or paradigms. Public policies may be used to help firms to cope with such changes.

(3). Lock-in failures:

Path dependence, leading to 'lock-in' of existing technologies, arises because of system or network externalities, combined with the fact that technologies are closely linked to their social and economic environment. Hence, new technologies must compete not only with components of an existing technology, but with the overall system in which it is embedded. Similarly, industries and socio-economic systems can get 'locked-in' to a particular technological paradigm. This requires public policies to generate incentives for new technologies or technological systems, and to overcome barriers created by the prevalence of incumbent technology or system.

(4). Institutional failures:

The set of public and private institutions, regulatory systems and the policy system creates a framework of opportunities and barriers to innovation by firms. Hence, the performance of these institutions and systems in regard to innovation should be monitored and assessed, and if they are judged to be creating unnecessary barriers, this would provide a rationale for policy changes or interventions.

It is now widely recognised that markets are based on sets of legal and institutional rules, such as those guaranteeing private property and contractual arrangements (North, 1990; Hodgson, 1988; Williamson, 1985). These rules are often designed to provide incentives for socially-desirable types of behaviour which go beyond promoting pure economic efficiency. The task facing policy-makers is to design the rules so that they do not lead to excessive costs on private firms and individuals, or create unnecessary levels of bureaucratic intervention. The systems failure approach is designed to help policy-makers identify cases where changes to rule-systems could lead to more effective achievement of social objectives without excessive costs or unnecessary bureaucracy. This approach is particularly relevant to the analysis of dynamic socio-economic systems, such as those involving radical innovation, where it is difficult or impossible to identify equilibria in which optimal market solutions would pertain. In such cases, systems failures may be identified through empirical analyses of the effectiveness of current systems and comparative analyses of the effectiveness of systems operating under different legal and institutional rules.

This argument is supported by the findings of our case study of UK renewables innovation policy (ICEPT/E4tech, 2003; Foxon *et al*., 2005c; Foxon and Pearson, 2006b). Firstly, in order to create incentives for low carbon energy innovation, whilst pursuing other energy policy objectives including the development of competitive energy markets and the protection of poorer consumers, a complex and largely disjoint mix of instruments has been developed in the UK. The thinking behind the development of these instruments seems to have been dominated by a 'linear' view of innovation, allied to the view that market mechanisms generally provide the most effective incentives. As a result, unanticipated consequences have arisen, partly as a result of interactions between instruments, while the promotion of non-market aspects of the development of innovation systems, such as knowledge transfer and skills development, has largely been neglected. This has resulted in 'systems failures', such as those identified in current UK renewables innovation systems, relating to moving early stage technologies along the innovation chain (a) from demonstration to pre-commercialisation, e.g. for wave and tidal technologies, and (b) from pre-commercial and supported commercial, e.g. for offshore wind (ICEPT/E4tech, 2003; Foxon *et al*., 2005c).

Smith (1992) and Metcalfe (2002) also stress that policy making should take an adaptive approach, and look for design and formulation of institutional arrangements that promote business experiments and generate a greater connectedness between organisations generating knowledge, e.g. universities, and those applying such knowledge, e.g. firms. As aspects of technological and institutional systems co-evolve, this suggests that a continuous learning approach to improving policy processes and measures may be needed to cope with dynamic technological and institutional change (Foxon, 2004).

This approach seems particularly relevant for the social and environmental challenges of sustainability. Public policy actors have a key role in creating the right incentive structures to address these challenges and facilitating the involvement of stakeholders in developing and implementing such structures. However, a systems approach should not be perceived as having an "anti-market" bias (OECD, 2002) and market mechanisms still play a key role in promoting innovation, along with non-market interactions, such as knowledge networking.

4. Conclusions

This paper has argued for the application of systems thinking and practice to the promotion of innovation for sustainability. Systems thinking has been used as a framework for understanding both innovation processes and policy processes, but these ideas have had relatively little influence on policy-making in this area. We hope that the guiding principles discussed briefly in this paper, and in more detail in the report for policy-makers, will contribute to the application of systems thinking in promoting sustainable innovation.

Acknowledgements

The author acknowledges the support of the UK Economic and Social Research Council (ESRC)'s Sustainable Technologies Programme for this research. He would also like to thank Peter Pearson, Zen Makuch and Macarena Mata, who contributed to development of many of the ideas presented in this paper, and the stakeholders who attended our project workshops for their valuable contribution.

References

Alic, J, Mowery, D and Rubin, E, *U.S. Technology and Innovation Policies: Lessons for Climate Change*, Pew Center on Global Climate Change, November 2003

Anderson, D, Clark, C, Foxon, T J, Gross, R & Jacobs, M, *Innovation and the Environment: Challenges and Policy Options for the UK*, Final report from Workshops for ESRC Global Environmental Change Programme, Imperial College, January 2001, http://www.iccept.ic.ac.uk/pdfs/Innovation%20report.pdf

Arrow, K (1962a), 'Economic welfare and the allocation of resources for invention', in *The Rate and Direction of Inventive Activity* (ed. R. Nelson), 609-625, Princeton University Press

Arrow, K (1962b), 'The economic implications of learning by doing', *Review of Economic Studies* 1962, 29, 155-173

Arthur, W B, 'Competing technologies, increasing returns, and lock-in by historical events', *The Economic Journal* 1989, 99, 116-131

Arthur, W B, *Increasing Returns and Path Dependence in the Economy*, University of Michigan Press, 1994

Bergek, A and Jacobsson, S, 'The emergence of a growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries', in: Metcalfe, J S & Cantner, U (eds.), *Transformation and Development: Schumpeterian Perspectives*, Physica/Springer, Heidelberg, 2003

Christensen, C, *The Innovator's Dilemma: When new technologies cause great firms to fail*, Harvard Business School Press, 1997

David, P, 'Clio and the economics of QWERTY', *American Economic Review* 1985, 75, 332-337

Edquist, C (1994), 'Technology policy: The interaction between governments and markets', in *Technology Policy: Towards an Integration of Social and Ecological Concerns*, Aichholzer, G and Schienstock, G (eds.), Walter de Gruyter, Berlin, 1994

Edquist, C (2001), 'Innovation policy – a systemic approach', in *The Globalizing Learning Economy*, Archibugi, D and Lundvall, B-A (eds.), Oxford University Press

Edenhofer, O, Carraro, C, Kohler, J and Grubb, M (eds.) (2006), 'Endogenous Technological Change and the Economics of Atmospheric Stabilisation', *Energy Journal Special Issue*

Foxon, T J (2003), Inducing innovation for a low-carbon future: drivers, barriers and policies, The Carbon Trust, London, also available at http://www.thecarbontrust.co.uk/Publications/CT-2003-07.pdf

Foxon, T J (2004), 'Innovation systems as the setting for the co-evolution of technologies and institutions', Paper presented at *'Organisations, Innovation and Complexity: New Perspectives on the Knowledge Economy'* Conference, University of Manchester, 9th-10th September 2004

Foxon, T J (2006a), ‘The rationale for policy interventions from an innovation systems perspective’, Chapter for *Governing for Sustainability: Environment, Society and Technological Change*, Murphy, J (ed.), ESRC Sustainable Technologies Programme - Governance of Sustainable Technologies Network, Earthscan, London (to appear, 2006)

Foxon, T J (2006b), ‘Technological lock-in and the role of innovation’, Chapter in *Handbook of Sustainable Development*, G. Atkinson, S. Dietz and E. Neumayer (eds.), Edward Elgar, Cheltenham (to appear, 2006)

Foxon, T J (2006c), ‘Bounded rationality and hierarchical complexity: Two paths from Simon to ecological and evolutionary economics’, *Ecological Complexity* special issue on *Complexity and ecological economics* (to appear, 2006)

Foxon, T J, Pearson, P, Makuch, Z and Mata, M (2005a), ‘Transforming policy processes to promote sustainable innovation: some guiding principles’, Report for policy-makers from STP project, ESRC Sustainable Technologies Programme, ISBN 1 903144 02 7, March 2005 http://www.sustainabletechnologies.ac.uk/PDF/project%20reports/SI_policy_guidance_final_version.pdf

Foxon, T J, Pearson, P, Makuch, Z and Mata, M (2005b), Policy Drivers and Barriers for Sustainable Innovation, ICEPT Monograph 2005/1, ESRC Sustainable Technologies Programme, September 2005, available at http://www.sustainabletechnologies.ac.uk/PDF/106_Monograph.pdf

Foxon, T J, Gross, R, Chase, A, Howes, J, Arnall, A and Anderson, D (2005c), ‘UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures’, *Energy Policy* Vol 33, No.16, pp 2123-2137

Foxon, T J and Kemp, R (2005), ‘Innovation impacts of environmental policies’, in *International Handbook on Environment and Technology Management*, D. Marinova (ed.)

Foxon, T J and Pearson, P (2006a), ‘Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime’, *Journal of Cleaner Production* special issue on *‘Modelling, case studies and policy on cleaner technologies diffusion’*, (to appear, 2006)

Foxon, T J, and Pearson, P (2006b) ' Towards Improved Policy Processes for Promoting Innovation in Renewable Electricity Technologies in the UK, *Energy Policy* (to appear, 2006)

Freeman, C and Soete, L (1997), *The Economics of Industrial Innovation* (Third Edition), Pinter, London

Geels, F, ‘Technological transitions as evolutionary reconfiguration processes: a multi-level persepective and a case-study’, *Research Policy* 2002, 31, 1257-1274

Gross, R and Foxon, T J, ‘Policy support for innovation to secure improvements in resource efficiency’, *International Journal of Environmental Technology and Management*, 2003, Vol.3, No. 2, pp. 118-130

Grubler, A (1998), Technology and Global Change, Cambridge University Press

Grubler, A, Nakicenovic, N and Nordhaus, W (2002), Technological Change and the Environment, RFF Press, Resources for the Future, Washington DC and IIASA, Laxenburg, Austria

Hemmelskamp, J, Rennings, K and Leone, F (eds.), *Innovation-oriented Environmental Regulation: Theoretical Approaches and Empirical Analysis*, ZEW Economic Studies 10, Physica-Verlag, Heidelberg, 2000

Hertog, P den, Oskam, E, Smith, K and Segers, J, *Innovation Research and Innovation Policy: Usual suspects, hidden treasures, unmet wants and black boxes*, Position Paper, Ministry of Economic Affairs, The Hague, Netherlands, 2003

Hodgson, G, *Economics and Institutions*, Polity Press, Cambridge, 1988

ICEPT & E4Tech (2003), *The UK innovation systems for new and renewable energy technologies*, Report for UK DTI, June 2003, http://www.dti.gov.uk/energy/renewables/policy/icepttheukinnovation.pdf

Jacobsson, S and Bergek, A, 'Transforming the energy sector: the evolution of technology systems in renewable energy technology', *Industrial and Corporate Change* 2004, Vol. 13, No. 5, pp. 815-849

Jacobsson, S and Johnson, A, 'The diffusion of renewable energy technology: an analytical framework and key issues for research', *Energy Policy* 2000, 28, 625-640

John, P (1998), *Analysing Public Policy*, Continuum, London

Johnson, A and Jacobsson, S, 'Inducement and blocking mechanisms in the development of a new industry: the case of renewable energy technology in Sweden', in Coombs, R, Green, K, Richards, A & Walsh, V (eds.), *Technology and the Market: Demand, Users and Innovation*, Edward Elgar, Cheltenham, 2001

Kemp, R, *Environmental Policy and Technical Change*, Edward Elgar, Cheltenham, 1997

Kemp, R. and Rotmans, J., 'The Management of the Co-Evolution of Technical, Environmental and Social Systems', forthcoming in Matthias Weber and Jens Hemmelskamp (eds.) *Towards Environmental Innovation Systems*, Springer Verlag

Kemp, R., J. Schot and R. Hoogma, "Regime Shifts to Sustainability through Processes of Niche Formation. The Approach of Strategic Niche Management", *Technology Analysis and Strategic Management* 1998, 10(2), 175-195

Kingdon, J, *Agendas, Alternatives and Public Policies*, HarperCollins College Publishers, 1995

Lundvall, B-A (ed.) (1992), *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*, Pinter Publishers, London

MacKenzie, D, 'Economic and sociological explanations of technological change', in *Technological Change and Company Strategies: Economic and Sociological Perspectives*, Coombs, R, Saviotti, P and Walsh, V (eds,), Academic Press, 1992 (re-printed in MacKenzie, D, *Knowing Machines: Essays on Technical Change*, MIT Press, Cambridge, Mass., 1996)

Malerba, F (ed.), *Sectoral Systems of Innovation: Concepts, Issues and Analyses of six major sectors in Europe*, Cambridge University Press, Cambridge, 2004

Metcalfe, J S, 'Equilibrium and evolutionary foundations of competition and technology policy: New perspectives on the division of labour and the innovation process', in *Economies in Evolution: What can Governments do and Economists advise?*, Pelikan, P and Wegner, G (eds.), 2002

Mytelka, L and Smith, K, 'Policy learning and innovation theory: an interactive and co-evolving process', *Research Policy* 2002, 31, 1467-1479

Nelson, R, *National Innovation Systems: A comparative analysis*, Oxford University Press, New York, 1993

North, D C, *Institutions, Institutional Change and Economic Performance*, Cambridge University Press, 1990

OECD, *Managing National Innovation Systems*, OECD, Paris, 1999

OECD, *Dynamising National Innovation Systems*, OECD, Paris, 2002

OECD (2005), *Governance of Innovation Systems, Vol.1, Synthesis Report*, OECD, Paris

Pierson, P, 'Increasing returns, path dependence, and the study of politics', *American Political Science Review* 2000, Vol. 94, No.2, 251- 267

Pigou, A, *The Economics of Welfare* (4th Edition), Macmillan, London, 1932

Rennings, K, Kemp, R, Bartolomeo, M, Hemmelskamp, J and Hitchens, D, *Blueprints for an Integration of Science, Technology and Environmental Policy (BLUEPRINT)*, Final Report of 5th Framework Strata project, November 2003, available at http://www.insme.info/documenti/blueprint.pdf

Rhodes, R (1997), *Understanding Governance: Policy Networks, Governance, Reflexivity and Accountability*, Open University Press, Bucks

Rip, A and Kemp, R, 'Technological change', in *Human Choices and Climate Change, Vol. 2*, ed. S. Rayner and E.L. Malone, Battelle Press, Columbus, Ohio, 1998

Rosenberg, N, *Inside the Black Box: Technology and Economics*, Cambridge University Press, 1982

Simon, H A, 'A behavioral model of rational choice', *Quarterly Journal of Economics* 1955, 69, 1-18

Simon, H A, 'Theories of decision making in economics', *American Economic Review* 1959, 49, 258-28

Smith, K, 'Innovation policy in an evolutionary context', in Saviotti, P and Metcalfe, J S (eds.), *Evolutionary Theories of Economic and Technological Change: Present status and future prospects*, Harwood Academic Publishers, Reading, 1992

Smith, K, 'Innovation as a systemic phenomenon: Rethinking the role of policy', *Enterprise & Innovation Management Studies*, 2000, Vol. 1, No. 1, pp. 73-102

Utterback, J M, *Mastering the Dynamics of Innovation: How companies can seize opportunities in the face of technological change*, Harvard Business School Press, 1994

Weber, M and Hemmelskamp, J (eds.), *Towards Environmental Innovation Systems*, Springer, Berlin, 2005

Williamson, O E, *The Economic Institutions of Capitalism: Firms, Markets, Relational Contracting*, Collier Macmillan, New York, 1985