Technological lock-in and the role of innovation

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1. Sustainability and the need for technological innovation

As the Chapters in this Handbook illustrate, despite increases in our understanding of the issues raised by the challenge of environmental, social and economic sustainability, movement has been frustratingly slow towards achieving levels of resource use and waste production that are within appropriate environmental limits and provide socially acceptable levels of economic prosperity and social justice.

As first described by Ehrlich and Holdren (1971), environmental impact (I) of a nation or region may be usefully decomposed into three factors: population (P), average consumption per capita, which depends on affluence (A), and environmental impact per unit of consumption, which depends on technology (T), in the equation (identity) I = P x A x T. Limiting growth in environmental impact and eventually reducing it to a level within the Earth's ecological footprint (Ch. 15) will require progress on all three of these factors. Ch. 18 discusses issues relating to stabilising population levels, and Ch. 28 addresses social and economic issues relating to moving towards sustainable patterns of consumption. This Chapter discusses the challenge of technological innovation required to dramatically reduce average environmental impact per unit of consumption. It draws on work by the author and colleagues from a project under the UK Economic and Social Research Council's Sustainable Technologies Programme (Foxon *et al*, 2004, 2005a,b,c).

Section 2 argues that individual technologies, and their development, are best understood of part of wider technological and innovation systems. Section 3 examines how increasing returns to the adoption of technologies may give rise to 'lock-in' of incumbent technologies, preventing the adoption of potentially superior alternatives. Section 4 examines how similar types of increasing returns apply to institutional frameworks of social rules and constraints. Section 5 brings these two ideas together, arguing that technological systems co-evolve with institutional systems. This may give rise to lock-in of current techno-institutional systems, such as high carbon energy systems, creating barriers to the innovation and adoption of more sustainable systems. Section 6 examines the challenge for policy-makers of promoting innovation for a transition to more sustainable socio-economic systems. Finally, Section 7 provides some conclusions and assesses the implications for future research and policy needs.

2. Understanding technological systems

The view that individual technologies, and the way they develop, are best understood as part of wider technological and innovation systems was significantly developed by studies in the late 1980s and early 1990s. In his seminal work on development of different electricity systems, Hughes (1983) showed the extent to such large technical systems embody both technical and social factors. Similarly, Carlsson and Stankiewicz (1991) examined the "dynamic knowledge and competence networks" making up technological systems. These approaches enable both stability and change in technological systems to be investigated within a common analytical framework. Related work examined the processes of innovation from a systems perspective. Rather than being categorised as a one-way, linear flow from R&D to new products, innovation is seen as a process of matching technical possibilities to market opportunities, involving multiple interactions and types of learning (Freeman and Soete, 1997). 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). Early work focussed on national systems of innovation, following the pioneering study of the Japanese economy by Freeman, (1988). In a major multi-country, Nelson (1993) and collaborators compared the national innovation systems of 15 countries, finding that the differences between them reflected 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. Innovation is the principal source of economic growth (Mokyr, 2002) and a key source of new employment opportunities and skills, as well as providing potential for realising environmental benefits (see recent reviews by Kemp (1997), Ruttan (2001), Grubler (2002), and Foxon (2003)).

The systems approach emphasises the role of uncertainty and cognitive limits to firms' or individuals' ability to gather and process information for their decision-making, known as 'bounded rationality' (Simon, 1955, 1959). Innovation is necessarily characterised by uncertainty about future markets, technology potential and policy and regulatory environments, and so firms' expectations of the future have a crucial influence on their present decision-making. Expectations are often implicitly or explicitly shared between firms in the same industry, giving rise to trajectories of technological development which can resemble self-fulfilling prophecies (Dosi, 1982; MacKenzie, 1992)[1].

3. Technological lock-in

The view outlined above suggests that the development of technologies both influences and is influenced by the social, economic and cultural setting in which they develop (Rip and Kemp, 1998; Kemp, 2000). This leads to the idea that the successful innovation and take up of a new technology depends on the path of its development - so-called 'path dependency' (David, 1985), including the particular characteristics of initial markets, the institutional and regulatory factors governing its introduction and the expectations of consumers. Of particular interest is the extent to which such factors favour incumbent technologies against newcomers. Arthur examined increasing returns to adoption, i.e. positive feedbacks which mean that the more a technology is adopted, the more likely it is to be further adopted. He argued that these can lead to 'lock-in' of incumbent technologies, preventing the take up of potentially superior alternatives (Arthur, 1989).

Arthur (1994) identified four major classes of increasing returns: *scale economies*, *learning effects*, *adaptive expectations* and *network economies*, which contribute to this positive feedback in favour of existing technologies. The first of these, *scale economies*, occurs when unit costs decline with increasing output. For example, when a technology has large set-up or fixed costs because of indivisibilities, unit production costs decline as they are spread over increasing production volume. Thus, an existing technology often has significant 'sunk costs' from earlier investments, and so, if these are still yielding benefits, incentives to invest in alternative technologies to garner these benefits will be diminished. *Learning effects* act to improve products or reduce their cost as specialised skills and knowledge accumulate through production and market experience. This idea was first formulated as 'learning-by-doing' (Arrow, 1962), and learning curves have been empirically demonstrated for a number of technologies, showing unit costs declining with cumulative production (IEA, 2000). *Adaptive expectations* arise as increasing adoption reduces uncertainty and both users and producers become increasingly confident about quality, performance and longevity of the current technology. This means that there may a lack of 'market pull' for alternatives. *Network* or *co-ordination effects* occur when advantages accrue to agents adopting the same technologies as others (see also Katz and Shapiro (1985)). This effect is clear, for example, in telecommunications technologies, e.g. the more others that have a mobile phone or fax machine, the more it is in your advantage to have one (which is compatible). Similarly, infrastructures develop based on the attributes of existing technologies, creating a barrier to the adoption of alternative technologies with different attributes.

Arthur (1989) showed that, in a simple model of two competing technologies, these effects can amplify small, essentially random, initial variations in market share, resulting in one technology achieving complete market dominance at the expense of the other – referred to as technological 'lock-in'. He speculated that, once lock-in is achieved, this can prevent the take up of potentially superior alternatives. David and others performed a series of historical studies, which showed the plausibility of arguments of path dependence and lock-in. The most well-known is the example of the QWERTY keyboard layout (David, 1985), which was originally designed to slow down typists to prevent the jamming of early mechanical typewriters, and has now achieved almost universal dominance, at the expense of arguably superior designs. Another example is the 'light water' nuclear reactor design, which was originally designed for submarine propulsion, but, following political pressure for rapid peaceful use of nuclear technology, was adopted for the first nuclear power stations and rapidly became the standard design in the U.S. (Cowan, 1990). Specific historical examples of path dependence have been criticised, particularly QWERTY (Liebowitz and Margolis, 1995), as has the failure to explain how 'lock-in' is eventually broken, but the empirical evidence strongly supports the original theoretical argument (David, 1997).

4. Institutional lock-in

As described in Section 2, the systems approach emphasises that individual technologies are not only supported by the wider technological system of which they are part, but also by the institutional framework of social rules and conventions that reinforces that technological system. To better understand the development of such frameworks, insights may be drawn from work in institutional economics, which is currently undergoing a renaissance (Schmid, 2004).

Institutions may be defined as any form of constraint that human beings devise to shape human interaction (Hodgson, 1988). These include formal constraints, such as legislation, economic rules and contracts, and informal constraints, such as social conventions and codes of behaviour. There has been much interest in the study of how institutions evolve over time, and how this creates drivers and barriers for social change, and influences economic performance. North (1990) argues that all the features identified by Arthur as creating increasing returns to the adoption of technologies can also be applied to institutions. New institutions often entail *high set-up or fixed costs*. There are significant *learning effects* for organisations that arise because of the opportunities provided by the institutional framework. There are *co-ordination effects*, directly via contracts with other organisations and indirectly by induced investment, and through the informal constraints generated. *Adaptive expectations* occur because increased prevalence of contracting based on a specific institutional framework reduces uncertainty about the continuation of that framework. In summary, North argues, “the interdependent web of an institutional matrix produces massive increasing returns” (North, 1990, p. 95).

Building on this work, Pierson (2000) argues that political institutions are particularly prone to increasing returns, because of four factors: the central role of *collective action*; the *high density* of institutions; the possibilities for using political authority to enhance *asymmetries of power*; and the *complexity and opacity* of politics. Collective action follows from the fact that, in politics, the consequences of an individual or organisation’s actions are highly dependent on the actions of others. This means that institutions usually have high start-up costs and are subject to adaptive expectations. Furthermore, because formal institutions and public policies place extensive, legally binding constraints on behaviour, they are subject to learning, co-ordination and expectation effects, and so become difficult to change, once implemented. The allocation of political power to particular actors is also a source of positive feedback. When actors are in a position to impose rules on others, they may use this authority to generate changes in the rules (both formal institutions and public policies) so as to enhance their own power. Finally, the complexity of the goals of politics, as well as the loose and diffuse links between actions and outcomes, make politics inherently ambiguous and mistakes difficult to rectify. These four factors create path dependency and lock-in of particular political institutions, such as regulatory frameworks. This helps to explain significant features of institutional development: specific patterns of timing and sequence matter; a wide range of social outcomes may be possible; large consequences may result from relatively small or contingent events; particular courses of action, once introduced, can be almost impossible to reverse; and, consequently, political development is punctuated by critical moments or junctures that shape the basic contours of social life.

5. Co-evolution of technological and institutional systems

The above ideas of systems thinking and increasing returns to both technologies and institutions may be combined, by analysing the process of co-evolution of technological and institutional systems (Unruh, 2000; Nelson and Sampat, 2001). As modern technological systems are deeply embedded in institutional structures, the above factors leading to institutional lock-in can interact with and reinforce the drivers of technological lock-in.

Unruh (2000, 2002) suggests that modern technological systems, such as the carbon-based energy system, have undergone a process of technological and institutional co-evolution, driven by path-dependent increasing returns to scale. He introduces the term 'techno-institutional complex' (TIC), composed of technological systems and the public and private institutions that govern their diffusion and use, and which become "inter-linked, feeding off one another in a self-referential system" (Unruh, 2000, p. 825). In particular, he describes how these techno-institutional complexes create persistent incentive structures that strongly influence system evolution and stability. Building on the work of Arthur (1989, 1994), he shows how the positive feedbacks of increasing returns both to technologies and to their supporting institutions can create rapid expansion in the early stages of development of technology systems. However, once a stable techno-institutional system is in place, it acquires a stability and resistance to change. In evolutionary language, the selection environment highly favours changes which represent only incremental changes to the current system, but strongly discourages radical changes which would fundamentally alter the system. Thus, a system which has benefited from a long period of increasing returns, such as the carbon-based energy system, may become 'locked-in', preventing the development and take-up of alternative technologies, such as low carbon, renewable energy sources. The work of Pierson (2000) on increasing returns to political institutions, discussed in Section 4, is particularly relevant here. Actors, such as those with large investments in current market-leading technologies, who benefit from the current institutional framework (including formal rules and public policies) will act to try to maintain that framework, thus contributing to the lock-in of the current technological system.

Unruh uses the general example of the electricity generation TIC, and we can apply his example to the particular case of the UK electricity system. In this case, institutional factors, driven by the desire to satisfy increasing electricity demand and a regulatory framework based on increasing competition and reducing unit prices to the consumer, fed back into the expansion of the technological system. In the UK, institutional change (liberalisation of electricity markets) led to the so-called 'dash for gas' in the 1990s – a rapid expansion of power stations using gas turbines. These were smaller and quicker to build than coal or nuclear power stations, thus generating quicker profits in the newly-liberalised market. The availability of gas-turbines was partly the result of this technology being transferred from the aerospace industry, where it had already benefited from a long period of investment (and state support) and increasing returns. This technological change reinforced the institutional drivers to meet increasing electricity demands by expanding generation capacity, rather than, for example, creating stronger incentives for energy efficiency measures. These insights were used in our study of current UK innovation systems for new and renewable energy technologies (ICEPT/E4Tech, 2003; Foxon et al., 2005a), in which we argued that institutional barriers are leading to systems failures preventing the successful innovation and take up of a wider range of renewable technologies.

6. Promoting innovation for a transition to more sustainable socio-economic systems

We conclude by examining some of the implications of this systems view of technological change and innovation for policy-making aiming to promote a transition to more sustainable socio-economic systems. As we have argued, individual technologies are not only supported by the wider technological system of which they are part, but also the institutional framework of social rules and conventions that reinforces that technological system. This can lead to the lock-in of existing techno-institutional systems, such as the high carbon fossil-fuel based energy system. Of course, lock-in of systems does not last for ever, and analysis of examples of historical change may usefully increase understanding of how radical systems change occurs.

A useful framework for understanding how wider technological system constrains the evolution of technologies is provided by the work on technological transitions by Kemp (1994) and Geels (2002). Kemp (1994) proposed three explanatory levels: *technological niches*, *socio-technical regimes,* and *landscapes*. The basic idea is that each higher level has a greater degree of stability and resistance to change, due to interactions and linkages between the elements forming that configuration. Higher levels then impose constraints on the direction of change of lower levels, reinforcing *technological trajectories* (Dosi, 1982).

The idea of a *socio-technical regime* reflects the interaction between the actors and institutions involved in creating and reinforcing a particular technological system. As described by Rip and Kemp (1998): “A socio-technical regime is the rule-set or grammar embedded in a complex of engineering practices; production process technologies; product characteristics, skils and procedures; ways of handling relevant artefacts and persons; ways of defining problems; all of them embedded in institutions and infrastructures.” This definition makes it clear that a regime consists in large part of the prevailing set of routines used by the actors in a particular area of technology.

A *landscape* represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society. As such, landscapes are even more resistant to change than regimes.

In this picture of the innovation process, whereas the existing regime generates incremental innovation, radical innovations are generated in *niches*. As a regime will usually not be totally homogeneous, niches occur, providing spaces that at least partially insulated from 'normal' market selection in the regime, for example, specialised sectors of the market, or locations where a slightly different institutional rule-set applies. Such niches can act as 'incubation rooms' for radical novelties (Schot, 1998). Niches provide locations for learning processes to occur, and space to build up the social networks that support innovations, such as supply chains and user-producer relationships. The idea of promoting shifts to more sustainable regimes through the deliberate creation and support of niches, so-called '*strategic niche management*' has been put forward by Kemp and colleagues (Kemp *et al.*, 1998). This idea, that radical change comes from actors outside the current mainstream, echoes work on 'disruptive innovation' in the management literature (Utterback, 1994; Christensen, 1997). Based on a number of historical case-studies, this argues that firms that are successful within an existing technological regime typically pursue only incremental innovation within this regime, responding to the perceived demands of their customers. They may then fail to recognise the potential of a new innovation to create new markets, which may grow and eventually replace those for the existing mainstream technology.

Geels (2002, 2005) examined a number of technological transitions, for example that from sailing ships to steamships, using the three-level *niche, regime, landscape* model introduced above (see also Elzen et al., 2004). He argued that novelties typically emerge in niches, which are embedded in, but partially isolated from, existing regimes and landscapes. For example, transatlantic passenger transport formed a key niche for the new steamship system. If these niches grow successfully, and their development is reinforced by changes happening more slowly at the regime level, then it is possible that a regime shift will occur. Geels argues that regime shifts, and ultimately *transitions* to new socio-technological landscapes, may occur through a process of niche-cumulation. In this case, radical innovations are used in a number of market niches, which gradually grow and coalesce to form a new regime.

Building on this work, Kemp and Rotmans (2001) proposed the concept of transition management. This combines the formation of a vision and strategic goals for the long-term development of a technology area, with transition paths towards these goals and steps forward, termed *experiments*, that seek to develop and grow niches for more sustainable technological alternatives. The transition approach was adopted in the Fourth Netherlands Environmental Policy Plan, and the Dutch Ministry of Economic Affairs (2004) is now applying it to innovation in energy policy. The Ministry argues that this involves a new form of concerted action between market and government, based on:

- *Relationships built on mutual trust*: Stakeholders want to be able to rely on a policy line not being changed unexpectedly once adopted, through commitment to the direction taken, the approach and the main roads formulated. The government places trust in market players by offering them 'experimentation space'.
- *Partnership*: Government, market and society are partners in the process of setting policy aims, creating opportunities and undertaking transition experiments, e.g. through ministries setting up 'one stop shops' for advice and problem solving.
- *Brokerage*: The government facilitates the building of networks and coalitions between actors in transition paths.

- *Leadership*: Stakeholders require the government to declare itself clearly in favour of a long-term agenda of sustainability and innovation that is set for a long time, and to tailor current policy to it.

In our project under the UK Economic and Social Research Council's (ESRC) Sustainable Technologies Programme (STP), the author and colleagues investigated some of the implications of the above ideas for policy-making to promote more sustainable innovation. This involved two project case studies (of UK low carbon energy innovation and of EC policy-making processes that support alternative energy sources in vehicles) and review of similar policy analyses in Europe (Rennings et al., 2003) and the U.S. (Alic et al., 2003). The final report for policy makers (Foxon et al., 2005) outlined five guiding principles for sustainable innovation policy, described briefly here.

The *first guiding principle* argues for the development of a ***sustainable innovation policy regime*** that brings together appropriate strands of current innovation and environmental policy and regulatory regimes, and is situated between high-level aspirations (e.g. promoting sustainable development) and specific sectoral policy measures (e.g., a tax on non-recyclable materials in automobiles). This would require the creation of a *long-term, stable and consistent strategic framework* to promote a transition to more sustainable systems, seeking to apply the lessons that might be gleaned from experience with the Dutch Government's current 'Transition Approach'.

The *second guiding principle* proposes applying approaches based on ***systems thinking and practice***, in order to engage with the complexity and systemic interactions of innovation systems and policy-making processes. This type of systems thinking can inform policy processes, through the concept of *'systems failures'* as a rationale for public policy intervention (Edquist, 1994, 2001; Smith, 2000), and through the identification and use of *'techno-economic' and 'policy' windows* of opportunity (Nill, 2003, 2004; Sartorius and Zundel, 2005). It also suggests the value of promoting a diversity of options to overcome *lock-in* of current systems, though the support of *niches* in which learning can occur, the development of a skills base, the creation of knowledge networks, and improved expectations of future market opportunities.

The *third guiding principle* advances the ***procedural and institutional basis*** for the delivery of sustainable innovation policy, while acknowledging the constraints of time-pressure, risk-aversion and lack of reward for innovation faced by real policy processes. Here, government and industry play complementary roles in promoting sustainable innovation, with government setting public policy objectives informed by stakeholder consultation and rigorous analysis, and industry providing the technical knowledge, resources and entrepreneurial spirit to generate innovation. *Public-private institutional structures*, reflecting these complementary roles, could be directed at specific sectoral tasks for the implementation of sustainable innovation, and involve a targeted effort to stimulate and engage sustainable innovation 'incubators'.

The *fourth guiding principle* promotes the development of a ***more integrated mix of policy processes, measures and instruments*** that would cohere synergistically to promote sustainable innovation. Processes and criteria for improvement could include: applying sustainability indicators and *sustainable innovation criteria*; balancing benefits and costs of likely economic, environmental and social impacts; using a dedicated *risk assessment* tool; assessing instruments in terms of factors relevant to the innovation process; and applying growing knowledge about which instruments work well or poorly together, including in terms of overlapping, sequential implementation or replacement (Porter and van der Linde, 1995; Gunningham and Grabowsky, 1998; Makuch, 2003a,b).

The *fifth guiding principle* is that ***policy learning*** should be embedded in the sustainable innovation policy process. This suggests the value of providing a highly responsive way to modulate the evolutionary paths of sustainable technological systems and to mitigate the unintended harmful consequences of policies. This would involve *monitoring and evaluation* of policy implementation, and the review of policy impacts on sustainable innovation systems.

7. Conclusions and ways forward

This Chapter has reviewed issues relating to the role of technological change and innovation in moving societies towards greater sustainability. Though the importance of technologies in helping to provide sustainable solutions is often promoted by commentators from all parts of the political spectrum, policy measures to promote such innovation have frequently failed to recognise the complexity and systemic nature of innovation processes. As we have seen, increasing returns to adoption in both technological systems and in supporting institutional systems may lead to lock-in, creating barriers to the innovation and deployment of technological alternatives.

This developing understanding of innovation systems and how past technological transitions have occurred could provide insight into approaches for promoting radical innovation for greater sustainability, for example, through the support of niches and a diversity of options. However, efforts to steer or modulate such a transition will also require significant institutional change in many countries. For example, the UK policy style has been based largely on centralised decision making processes and heavy emphasis on the use of market-based instruments without addressing other institutional and knowledge factors relating to the creation of markets for new technologies. This contrasts with a policy style of more decentralised and public-private collaborative decision-making, which has enabled the Netherlands to become a leader in practising and learning how a technology transition for sustainability could be promoted. Further practical experience and analysis will be needed for the implementation of the above ideas and principles for promoting sustainable innovation to overcome technological and institutional lock-in.

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[1] 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 in 1964, has held remarkably well from the first transistor in 1959 to present day chips, and may have guided the efforts of innovators in the semiconductor industry. See: www.intel.com/research/silicon/mooreslaw.htm

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