Innovation Theory: A review of the literature

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Glossary

CCS	Carbon capture and storage
ETAP	EU Environmental Technologies Action Plan
LR	Learning rate or ratio
NIC	National Innovative Capacity
NIS	National Innovation System
OECD	Organisation for Economic Co-operation and Development
PR	Progress ratio
R&D	Research and Development
RO	Renewables Obligation
TIS	Technological Innovation System

Overview

This report was funded by BP and forms part of the Technology Innovation workstream of BP's Energy Sustainability Challenge (ESC) project. The aim of the report is to provide a review of the academic literature that focuses on innovation theory, especially in the low carbon arena, with a view to applying innovation concepts to environmental remediation and adaptation to climate change. The workstream includes a particular focus on (i) the industrial exploitation of water arising from meeting the demand for energy goods and services and (ii) use and scarcity of potable water, especially the impact on energy demand arising from the need to pump, transport and/or desalinate water due to the impacts of climate change.

Innovation theory is not rooted in a single discipline or school of thought. Rather, conceptual strands are drawn from a variety of academic disciplines and research areas. Beginning in the 1930s, early theoretical perspectives viewed the innovation process as a relatively simple, one-directional journey from basic research to applied research to technology development and diffusion. This so-called 'linear model' suggests that advances in science determine the rate and direction of innovation and that the optimal way to increase the output of new technologies is to increase the input of new inventions by simply putting more resources into R&D. This is the process of technology-or supply-push. An alternative perspective, demand-pull, gained traction in the 1950s, arguing that demand for products and services is more important in stimulating inventive activity than advances in the state of knowledge. Both the technology-push and demand-pull perspectives have since been challenged as over-simplistic, and more recent theoretical approaches accept the importance of both.

In the second half of the 20th century innovation theory was in particular furthered by three approaches to understanding technological change: induced innovation, the evolutionary approach, and the path-dependent model. The evolutionary and path dependency approaches stress the importance of past decisions which may constrain present innovation whilst the induced innovation perspective emphasises the importance of changes in relative prices in driving the direction of technical change.

These approaches are associated with several concepts that are fundamental to contemporary innovation theory. The evolutionary model includes the concept of 'uncertainty' at various levels - technological, resource, competitive, supplier, consumer and political - and also the idea of 'bounded rationality' which emphasises that decision makers have a limited ability to gather and process information. The suggestion is that both bounded rationality and uncertainty result in mindsets that in general favour incremental innovations to current products or processes rather than radical and disruptive ones.

The path dependent model is underpinned by the idea of increasing returns to adoption whereby the more a technology is taken up by users or the more an institution becomes established, the more likely it is to be further adopted. The process is supported by factors such as scale effects and learning by doing and will typically give rise to cost reductions and incremental improvements. However, at both a technological and an institutional framework level, path dependency can result in technological dominant design, institutional inertia, and the 'lock-in' of incumbent technologies and systems and the 'lock-out' of innovations that may be more optimal.

The latter years of the 20^{th} century saw an increasing theoretical interest in developing the older linear model of innovation into something which more accurately reflected the complexity and interdependency of the innovation process. This evolving 'systems perspective' has been characterised by a number of related approaches but each has tended to emphasise the importance of knowledge flows between actors; expectations about future technology, market and policy developments; political and regulatory risk; and the institutional structures that affect incentives and barriers. One of the most developed theories is the Technological Innovations Systems approach. This emphasizes the importance of recognising not only the structural components of a system i.e. the overall framework conditions and the multiple entities involved within it but also the dynamic interactions of those actors with each other and with the knowledge flows.

Another important development has been the research into transition dynamics where technological change is more than simply incremental but represents a radical, possibly even disruptive, shift in products and processes. Here, the importance of technological and market niches is emphasised by which an innovation can be protected from normal market conditions and nurtured for a period of time.

One of the most significant outcomes of the evolution in innovation theory has been the recognition that innovation should not simply be fostered via technological R&D but also implies a role for policy to improve the institutional framework and the opportunities for interactions so as to better incentivise innovation. This correcting for 'systems failures' in the innovation system is particularly pertinent to the low carbon arena where the incumbent, carbon-intensive energy system displays very substantial increasing returns, path dependency and lock-in. Here, assets are long lived and capital intensive, incumbent fossil-fuel technologies have benefited from decades of development, and the system has co-evolved into compatible networks of fuels, end use devices, vehicles, delivery infrastructure and institutions. These factors provide a formidable barrier to entry for low carbon technologies and substantial disincentives for radical, low carbon innovation – at both the technological and systems level.

Advances in innovation theory have afforded insights into the structures and processes of energy systems and have proposed theoretical approaches with which to further eco-innovation and the radical transition to more sustainable energy systems. By contrast, the relative paucity of literature addressing remediation and adaptation to climate change from the perspective of innovation theory suggests that more research in these areas could be equally valuable. Despite obvious differences, energy and remediation/adaptation share important common ground in terms of their relevance to environmental care and sustainability. Innovation theory has been successfully applied to the energy arena and might also be usefully applied to remediation and adaptation. It is therefore worth investigating how key concepts from innovation theory might be brought to bear on remediation and adaptation innovation.

Introduction

Advancing technological knowledge has been identified as the single most important contributing factor to long-term productivity and economic growth (Grubler et al., 1999). Consequently, the innovation process and the identification of actions required to effect technological change continue to be of paramount interest to businesses, governments and academics. Moreover, innovation is increasingly considered crucial to deal with the negative side effects associated with that same productivity and economic growth. Influencing the direction of innovation towards more sustainable directions is therefore high on many political agendas (Hekkert and Negro, 2009).

Innovation, notes Slade and Bauen (2009), is something of a catch all term. It is sometimes differentiated from invention (defined by Schumpeter as the first discovery of new products or processes) but may be used interchangeably with technological change to describe the steps required to get a new product to market. It may refer to a new product itself, to a stage in a product's lifecycle, or to an iterative process of invention and application that links technical, societal and political change. Innovation may be classified as incremental, radical, or disruptive depending upon whether it originates within, or outside, the mainstream, and whether it renders an incumbent technology (or process) obsolete.

Innovation theory is not rooted in a single discipline or school of thought (Gross, 2010). Rather, conceptual strands are drawn from a variety of academic disciplines and research areas including the economics of increasing returns; behavioural economics; 'business school' analysis of competitive advantage; analysis of national systems; and socio-technical regimes.

Notwithstanding the nuances and differences of the various theories of innovation, there is a shared understanding that the technologies themselves typically undergo several stages of commercial maturity starting with *basic and applied R&D*. Following this will be a *demonstration* stage which includes prototypes, financed largely through R&D grants; a fairly broad *pre-commercial* stage of development where multiple units of previously demonstration-stage technologies are installed for the first time, and/or where the first few multiples of units move to much larger scale installation for the first time; and then a *supported commercial* stage where, given support measures (such as the Renewables Obligation in the case of UK renewables), technologies are rolled out in substantial numbers. If successful, this results in a final *commercial* stage in which a technology competes unsupported within the broad regulatory framework (Foxon et al., 2005).

As we shall see however, the above stages are no longer interpreted as a one-way linear flow. As innovation theory has developed, it has become accepted that knowledge flows in both directions, for example, as information from early market applications feeds back into further research. This means that the conventional drivers of technology-push from R&D, and market-pull from customer demand, can be reinforced or inhibited by feedbacks between different stages and by the influence of framework conditions, such as government policy and the availability of risk capital.

A significant consequence of this is that contemporary innovation theorists do not simply frame the barriers to innovation in terms of a 'market failure' whereby an innovation which is relatively expensive compared to incumbent alternatives struggles to be adopted by consumers because the benefits are societal (e.g.

environmental) rather than private. Instead, framing the problem is expanded to incorporate the concept of a wider 'systems failure' in the innovation arena as a whole, which may include failures in infrastructure provision, transition and lock-in failures, and institutional and regime failures (OECD, 2002).

This report reviews the literature on innovation theory, using a broadly chronological framework of theoretical development in order to do so. The structure of the remainder of this report is as follows:

- Section 2 examines the evolution of innovation studies in general, from Schumpeter in the first half of the 20th century up to the present day.
- Section 3 looks more specifically at the application of innovation theory to the environmental arena - so-called eco-innovation – and the low carbon sector, in particular.

Section 4 considers how advances in innovation theory might suggest valuable lines of thinking and questioning if applied to the field of remediation and adaptation to climate change, especially with regard to energy demand and water use.

The development of innovation theory

The older linear models

Pre-1950: Schumpeter

The first systematic effort by an economist to analyse the process of innovation was undertaken by Joseph Schumpeter in the first half of the twentieth century. He identified three stages of the process: invention, innovation and diffusion. For Schumpeter, invention is the first demonstration of an idea; innovation is the first commercial application of an invention in the market; and diffusion is the spreading of the technology or process throughout the market. Typically, the diffusion process is represented by an S-shaped curve, in which the take-up of an innovative process or technology starts slowly with the focus on market positioning, then gathers momentum achieving rapid diffusion, before slowing down as saturation level is reached, with the focus shifting to incremental improvements and cost reductions (Schumpeter, (1911/1934)); (Stenzel, 2007). S-curves of technological improvement have been well documented in a range of technologies, including disk drives, cars, sailing ships, semiconductors, steam engines and many more (Schilling and Esmundo, 2009).

This three-stage journey of slow start-up, gathering momentum, and finally diminishing returns underlies what is often referred to as the 'linear model of innovation', a more-or-less continuous flow through the three stages, from basic research to applied research to technology development and diffusion. The model suggests that advances in scientific understanding determine the rate and direction of innovation and that the optimal way to increase the output of new technologies is to increase the input of new inventions by simply putting more resources into R&D (Nemet, 2007). This is the process of *technology*- or *supply-push*.

In his analysis of the drivers of innovation, Schumpeter's early work stressed the importance of the individual entrepreneur (Xu, 2007). Later work gave more emphasis to the role of large firms with the resources to conduct extensive R&D and support new technologies. Schumpeter's concept of 'creative destruction' which describes the replacement of old firms and old products by innovative new firms and products has been widely influential in inspiring more recent understandings of the innovation process. However, critics argue that Schumpeter was more interested in the consequences of innovation than its causes and that none of his works "contain anything that can be identified as a theory of innovation" (Ruttan, 2001).

1950s and 1960s: Technology push versus demand pull

A central critique of the technology-push argument was that it ignored prices and other changes in economic conditions that affect the profitability of innovations. Another - later – criticism, as we shall see, is that the emphasis on a unidirectional progression within the stages of the innovation process was incompatible with more complex emerging ideas about feedbacks, interactions, and networks (Nemet, 2007).

The alternative perspective - that demand for products and services is more important in stimulating inventive activity than advances in the state of knowledge - so-called *demand-pull* - was first put forward in the 1950s and 60s. Here, it is economic factors that drive the rate and direction of innovation. Changes in market demand create opportunities for firms to invest in innovation to satisfy unmet needs i.e. demand "steers" firms to work on certain problems (Nemet, 2007).

One important criticism of demand-pull was that demand explains incremental technological change far better than it does discontinuous (disruptive) change, so it fails to account for the most important innovations. Both the technology-push and demand-pull perspectives have since been challenged as over-simplistic, and more recent theoretical approaches accept the importance of both (Nemet, 2007), but also stress the importance of more complex, systemic feedbacks between the supply and demand sides (Foxon, 2003).

1950s and 1960s: organisational and national level research

During the 1950s and 60s, theoretical research on innovation also began to broaden its perspective on the sources of innovation. In part, it focused on how to promote innovation in organizations through effective management of R&D departments and their activities (Xu, 2007). In addition, the macro-economic importance of understanding innovation was explored in the work of Robert Solow and others investigating the relative significance of different factors to the growth of national economies (Solow, 1957). Solow estimated that the largest contribution to growth did not come from increases in labour or capital productivity, but from a residual element which he identified broadly as technical change i.e. advances in knowledge resulting in economic applications. Indeed, Solow argued that this accounted for approximately 40% of the total increase in US national income per head.

Still using the linear model of innovation, Richard Nelson in 1959 and Kenneth Arrow in 1962 examined the question of whether investment levels in R&D were sufficient to meet national economic needs (Nelson, 1959); (Arrow, 1962). They concluded that the social returns to R&D investment exceed the private returns made by the individual firm. The reason for this is that an innovative process or technology created by a firm or entrepreneur may be easy and cheap (or costless) for competitors to copy i.e. a firm may often not be able to fully appropriate the fruits of its investment because advances in knowledge 'spill over' to other firms and consumers. This in turn can reduce private incentives below those needed for a socially optimal level of innovation (Foxon, 2003). This 'market failure' is a commonly recognised potential barrier to innovation although the problem of appropriability may be temporarily mitigated by the patent and copyright.

1970s to 1990s: some conceptual approaches

In the latter part of the 20th century innovation theory continued to evolve, and was in particular furthered by three approaches to understanding technological change: *induced innovation, evolutionary approaches,* and *path-dependent models* (Ruttan, 2001). The evolutionary and path dependency approaches stress the importance of past decisions which may constrain present innovation whilst the induced innovation perspective emphasises the importance of changes in relative prices in driving the direction of technical change (Foxon, 2003).

In addition, these approaches are associated with several concepts that are fundamental to contemporary innovation theory. The path dependent model, for example, arises from the idea of increasing returns to adoption and also includes the concepts of learning curves and 'lock-in'. The evolutionary model includes the concepts of 'bounded rationality' and uncertainty. We now examine these approaches and the main concepts associated with them in more detail.

Induced innovation approach

The induced innovation approach analyses the impact of changes in the economic environment on the rate and direction of technical change. It puts emphasis on market drivers and hence demand-pull mechanisms are seen as important. A key insight is that a change in the relative prices of factors of production motivates innovation directed at economising the use of the factor that has become relatively expensive. If, for example, labour becomes relatively more expensive compared to capital, then innovation will be directed towards more labour-saving technologies (Foxon, 2003).

Evolutionary economics approach

This perspective on technical change built on the Schumpeterian understanding of innovation, and on the ideas of '*bounded rationality*' and '*uncertainty*'. The evolutionary perspective characterised technological change as slow-moving and incremental, arising out of the interlinked nature of a number of variables from the economic, social, institutional and technological sphere. Changes in one dimension create tensions with the others, thus triggering further changes and creating continuous feedback loops between the different dimensions (Stenzel, 2007).

Bounded rationality

The idea of bounded rationality suggests that decision makers, either individuals or firms, have a limited ability to gather and process information. Rather than being absolutely rational profit-maximisers, they make decisions that satisfy whatever are their most important criteria while foregoing, or sacrificing, others, i.e. they '*satisfice*' rather than optimize (Nelson, 1982). This modus operandi of achieving certain minimum criteria rather than trying to find the best imaginable solution becomes what Nelson (1982) terms a '*routine*' i.e. any technical, procedural, organisational or strategic process or technique used by a firm as part of its normal business activities, for example, its R&D strategy.

Routines typically change gradually via a process of searching for better techniques. Because firms have bounded rationality, such search processes will usually look for incremental improvements (perhaps by imitation of the practices of other firms), and will be terminated when firms satisfice by attaining a given aspiration level. Thus, any equilibrium reached cannot be assumed to be optimal or maximally efficient.

An important implication of bounded rationality is that firms' expectations of the future are a fundamental influence on current decision-making. Innovation is necessarily characterised by uncertainty about future markets, technology potential and regulatory environments (see below). Firms' expectations of these factors will influence the directions of their innovative searches, and as expectations are often implicitly or explicitly shared between firms in the same industry, this helps to explain why the technologies follow particular trajectories (Foxon, 2003).

Uncertainty

The intrinsically uncertain character of innovation decisions is particularly true for innovation decisions concerning emerging technologies, i.e. technologies that are still in an early phase of development (Meijer et al., 2007). For the firm or entrepreneur, this represents something of a double-edged sword. On the one hand, the high degree of uncertainty signifies the large variety of opportunities that a new technology may have to offer. On the other hand, this uncertainty poses a threat of not knowing what comes next and not being able to ex ante determine the success or failure of a technological path.

Uncertainty will arise not only about the technology itself but also about the socio-institutional setting in which the emerging technology will be embedded. In the early stages, technology developers will perceive uncertainty about user requirements and market demand, whereas potential users will perceive uncertainty about what the new technology might have to offer. In addition, current regulation is aligned with established technologies and may not provide room for the introduction of new technologies, creating uncertainty about which institutional regulations and support mechanisms will emerge for the new technology. Thus, uncertainties in the development and implementation of emerging technologies are of several types: technological, resource, competitive, supplier, consumer and political (Meijer et al., 2007).

Both bounded rationality and uncertainty result in mindsets that in general favour incremental innovations to current products or processes. This is closely related to the idea of path dependency and the associated concept of lock-in which are examined in more detail in sub-section 0. First however, we consider the role of increasing returns to adoption and learning effects which are usually pre-conditions for dependency and lock-in.

Increasing returns to adoption

It is widely acknowledged in the literature that both technologies and institutions tend to show increasing returns to adoption i.e. the more a technology is taken up by users or the more an institution becomes established, the more likely it is to be further adopted. Arthur (1994) identified four major classes of increasing returns: *scale economies, learning effects, adaptive expectations* and *network economies*.

Scale economies arise from the reduction in unit costs as fixed costs are spread over increasing production volumes, causing demand to increase. *Learning effects* reflect product improvements and cost declines as experience is gained in the production and application of a technology (see below for more on learning effects). *Adaptive expectations* are produced as increasing adoption reduces uncertainty and both users and producers become more confident about quality, performance and longevity of the current technology. *Network or co-ordination effects* occur for technologies for which the more users there are, the more useful the technology becomes. Mobile phones and the internet are good examples.

It is not only technologies (and the firms developing them) that are subject to reinforcement by increasing returns. Institutions can follow similar patterns of development and innovation (or inertia) (Foxon, 2003). According to Ruttan (2001): "Institutions are the social rules that facilitate co-ordination among people by helping them form expectations for dealing with each other. They reflect the conventions that have evolved in different societies regarding the behaviour of individuals and groups.” The definition of institutions also embraces forms of property rights, rules governing market behaviour such as contracts, and non-market forms of co-ordination between actors.

Learning effects and learning curves

A fundamental constituent of increasing returns to adoption is the effect of learning (not only on technological innovation but also on production and diffusion). Three key types of learning are typically identified in the literature: *learning-by-doing*, *learning-by-using* and *learning-by-interacting.*

The concept of *learning-by-doing* was first articulated by Theodore Wright in the 1930s who observed that the labour cost of producing an aircraft frame declined with the number of frames produced. This idea was formalised in a paper by Kenneth Arrow in 1962 which proposed that the productivity of a firm increases as the cumulative output for the industry grows (Arrow, 1962). *Learning-by-using* refers to the gains in knowledge from subsequent use of the product by consumers. *Learning-by-interacting* arises between producers and users and is “mediated not merely by price mechanisms, but also by closer interactions involving mutual trust and mutually respected codes of behaviour” (Foxon, 2003). Thus, when difficulties occur in technological systems, communication between the needs of users and the capabilities of producers is required, in order to effect mutually beneficial learning. This gives rise to process or product innovations.

These three types of learning occur within a current technological system or regime, and therefore generally giving rise to incremental innovation. More recent thinking argues that most radical innovations develop from niches outside the current dominant regime. In addition, a fourth type of learning – *learning by researching* - should also be included. This too may give rise to radical innovation though it often results in less dramatic incremental development as well.

Learning curves

The idea of the learning or experience curve is closely related to but broader than the concept of the technology S-curve. Whereas technology S-curves refer specifically to technological improvements that are embodied in product or process design, experience curves refer collectively to many additional sources of efficiency also gained through the production and use of a product (e.g. workers becoming more skilled, or improvements in relations with suppliers, for example) (Schilling and Esmundo, 2009).

The concept originates from empirical observations of technological change, specifically that technology unit costs often decrease at a more or less fixed rate - the progress ratio (PR) - with every doubling of cumulative production. The learning (or experience) curve model operationalises the explanatory variable ‘experience’ using a cumulative measure of production or use. Changes in cost typically provides a measure of learning and technological improvement, and represents the dependent variable. The central parameter in the learning curve model is the exponent defining the slope of a power function, which appears as a linear function when plotted on a log-log scale. This parameter is known as the learning coefficient and can be used to calculate the progress ratio (PR) and its inverse, the learning ratio (LR) (Nemet, 2007).

The learning curve can be an important tool for modelling technical change and for informing policy decisions (Nemet, 2007). In particular, it provides a method for evaluating the cost effectiveness of public policies to support new technologies and for weighing public technology investment against environmental damage costs. The concept has been widely applied to the manufacturing sector including energy technologies (Slade and Bauen, 2009) and energy supply models now use learning curves to endogenate improvements in technology (Nemet, 2007).

Path dependency approach

The idea that the innovation and take-up of a new technology depends on the path of its development was promoted in the work of Brian Arthur and Paul David in the 1980s and 90s (David, 1985); (Arthur, 1994). In essence, path dependence explains how the set of decisions faced by an entity (individual, firm, institution or whole system) for any given circumstance is limited by the decisions made in the past, even though past circumstances may no longer be relevant. As we have seen, increasing returns to adoption mean that the more a technology is adopted, the more likely it is to be further adopted. The same process can also hold for entire systems such that the more an institutional rule or framework is applied, the more stable it is likely to become. This in turn can have a significant influence over the development path of a technology and vice versa (Foxon, 2003). As such, technologies, innovating entities and institutional frameworks can all become path-dependent. The pathway itself includes the particular characteristics of initial markets, the institutional and regulatory factors governing its introduction and the expectations of consumers.

The innovative process is thus both a product of – and reinforces - the so-called path dependency. 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 (Foxon and Pearson, 2008). The technologies and institutions co-evolve and reinforce each other. This process of mutual adaptation of the innovation and the environment in which it is produced leads to so-called socio-technical regimes (Kemp and Foxon, 2007) where the institutions are the social rules and where for significant innovation to occur there must be changes in the rules and the overcoming of potentially considerable inertia.

Dominant design and lock-in

Several significant outcomes are associated with increasing returns and path dependence:

- First, a dominant design/configuration may 'capture' a market or sector, even if a range of alternative options were equally feasible when a new system or market began to emerge.
- Second, timing matters since early developments are more significant in defining the development path than later ones.
- Third, particularly where a network or infrastructure tailored to the dominant design emerges, infrastructural lock-in can result; over time it becomes very difficult and costly to change the system.
- Fourth, the dominant design may not be the best, as relatively unimportant early events may shape developments and hence the 'locked-in' system or technology might turn out to be suboptimal in some way (Gross, 2008).

Thus, while increasing returns represents a seemingly 'virtuous circle' for the incumbent technology or system, from the point of view of aspiring new entrants to market and to society in general this lock-in has potentially detrimental effects. One technology may achieve complete market dominance at the expense of another potentially superior alternative. While allowing incremental innovation of dominant technologies and systems, the status quo serves to 'lock out' more radical 'disruptive' innovation i.e. a technological or systemic step-change. Lock-in is therefore generally defined as the consequence of path dependence whereby technologies and technological systems follow specific paths that are difficult or costly to escape (Gross, 2008).

1970s to 1990s: towards a systems approach - additional concepts

Ruttan (2001) argues that the models of induced innovation, evolutionary economics, and path dependency developed from the 1970s onwards represent complementary elements of a yet to be articulated more general systems theory of innovation. In fact, during the same period such a development was beginning to take place, characterised by the emergence of some key additional perspectives.

Regimes and trajectories

Within the evolutionary perspective (see 0 above), Nelson and Winter in the 1970s and 80s started attempts to build a more general theory of innovation underpinned by two main concepts (Nelson, 1977); (Nelson, 1982):

- As discussed, a core feature of innovation is *uncertainty*, particularly early on when there is diversity of options for addressing a technological problem or user needs.
- The *institutional structure* is important for providing incentives or creating barriers to innovation.

Based on this, R&D is viewed as a process of searching for solutions, guided by both technological capabilities (supply-push) and user needs (demand-pull), generating a variety of possibilities. These are tested in an environment consisting of both market and non-market elements. The non-market element arises from the current institutional structures e.g. regulations and codes of behaviour. Together, the prevailing set of technologies and institutions form a *technological regime*. This steers the R&D process along particular *trajectories*, which typically favour incremental innovations to current products or processes (Nelson, 1977). This idea is closely related to the concept of path dependency whereby increasing returns reinforce existing patterns of innovation methodology, of resource allocation to R&D, and of institutional structures and modus operandi (see sub-section 2.2.5 above).

Life cycle and dominant design

Nelson proposed that due to the cumulative nature of the innovation process, new technologies exhibit a *life cycle* of development (Nelson, 1994). In the early stages of development, there are a variety of possible competing designs. Advantageous features will then favour a certain design, often in a particular niche market, and that design may begin to be taken up. If the market grows, often at the expense of a current technology, institutional change may gradually occur as the institutional regime adapts to match the needs of the new technology. Assuming the combination of improved technological capability together with an adapted institutional framework is compelling, then the new technology will spread until it achieves the status of a '*dominant design*' (Utterback, 1994). From then on, only incremental improvements will be made to the technology design.

During this extended phase of incremental change, many firms cease to invest in learning about alternative design architectures, and instead invest in refining their competencies related to the dominant architecture (Schilling and Esmundo, 2009). Most competition focuses on improving components rather than altering the architecture and thus like their predecessors, such firms become institutionally embedded.

The 'chain linked 'model

An early attempt to represent the systems feedbacks within the innovation process was made by Kline (1986) in the *'chain linked' model*. This model, shown graphically in Figure 0.1 below represents the feedback loops between: (i) research; (ii) the existing body of scientific and technological knowledge; (iii) the potential market; (iv) invention; and (v) the various steps in the production process.

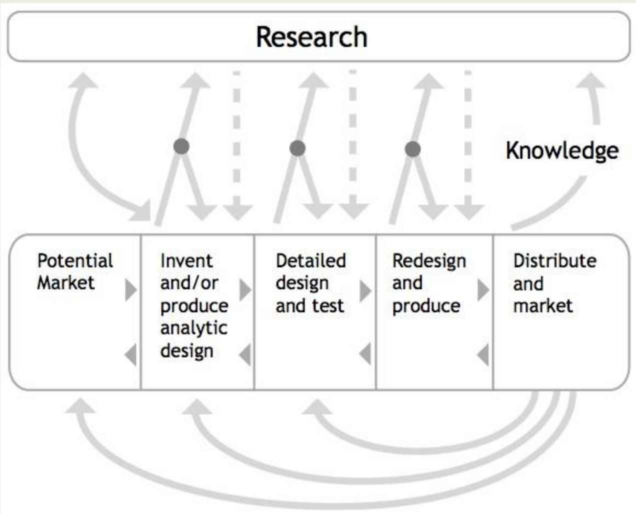

Figure 0.1 An interactive model of the innovation process: The chain-linked model (Source: (Kline, 1986))

The chain-linked model combines two different types of interaction. The first (in the lower part of the figure) relates to the processes occurring within a given firm (or a network of firms acting together). The second (upper part of the figure) expresses (some of the) relationships between the individual firm and the wider science and technology system within which it operates. Note that it is a relatively narrow definition of 'system' and unlike later theories takes no of the wider economic, political, social and cultural landscape (Foxon, 2003). Nevertheless, the model represents an advance in complexity of understanding. It recognizes there are feedbacks between each innovation stage and, importantly, feedbacks between the product users and the design and production phases.

A key element, according to the model, in determining the success (or failure) of an innovation project is the extent to which firms manage to maintain effective links between phases of the innovation process. The chain linked model emphasizes, for instance, the central importance of continuous interaction between marketing and the invention/design stage (OECD, 1997). Another key feature is the uncertainty and unpredictable nature of both technological capabilities and user needs. Finally, for the chain-link approach, R&D cannot be seen simply as the work of discovery which precedes innovation. Instead, research is viewed not as the source of inventive ideas but as a form of problem-solving to be called upon at any point (OECD, 1997).

Four level taxonomy of innovation

Also moving towards a more complex, systems-based perspective, Freeman and Perez (1988) proposed the following taxonomy of the innovation process:

(i) *Incremental innovations* occur continuously in any industry or service activity, often as a result of learning- by-doing or learning-by-using, rather than because of specific R&D activity.

(ii). *Radical innovations* come from outside the current mainstream, as a result of R&D activities in enterprises and/or in university and government laboratories, or from smaller firms. These innovations can bring about structural change, but their economic impact is relatively small and localised unless a whole cluster of radical innovations are linked together in the rise of new industries and services.

(iii). *Changes of 'technology system'* are far-reaching changes in technology, caused by technically and economically inter-related innovations, combining clusters of radical and incremental innovations, together with *organisational* and *managerial* innovations affecting more than one or a few firms.

(iv). *Changes in the 'techno-economic paradigm'('Technological revolutions')* go beyond engineering trajectories for specific process or product technologies, and affect the cost structure and conditions of production and distribution throughout an economic system.

1980s to 2000s: towards a systems approach – innovation systems

The latter years of the 20th century saw an increasing theoretical interest in evolving the older linear model of innovation into something which more accurately reflected the complexity and interdependency of the innovation process. In addition to the ones already discussed, several further approaches were proposed, in particular the Innovation System Frame at the level of the firm or enterprise, and also various national, regional, and sectoral perspectives.

The Innovation System Frame

The OECD's guideline document known as 'The Oslo Manual,' (OECD, 1997), (OECD, 2005) covers technological product and process innovation at the firm or enterprise level. The manual uses the conceptual framework of a so-called 'Innovation System Frame' to classify system conditions into four separate domains relating to innovative capacity (Speirs et al., 2008). These domains are as follows:

- **Framework Conditions** - the external area in which the firm is situated:
    - basic educational system

- communication infrastructure
    - financial institutions determining access to capital
    - legislative and macro-economic settings
    - market accessibility, including market size and ease of access
    - industry structure including the existence of supplier firms in complementary industry sectors
- **Science and Engineering Base** – science and technology institutions underpinning the business innovators
- **Transfer Factors** – the factors influencing information transmission to firms and learning by firms
- **Innovation Dynamo** - the complex system of factors that shape the innovative capacity of a firm or entrepreneur i.e. the propensity to innovate.

The four domains and their interaction are represented graphically in Figure 0.2:

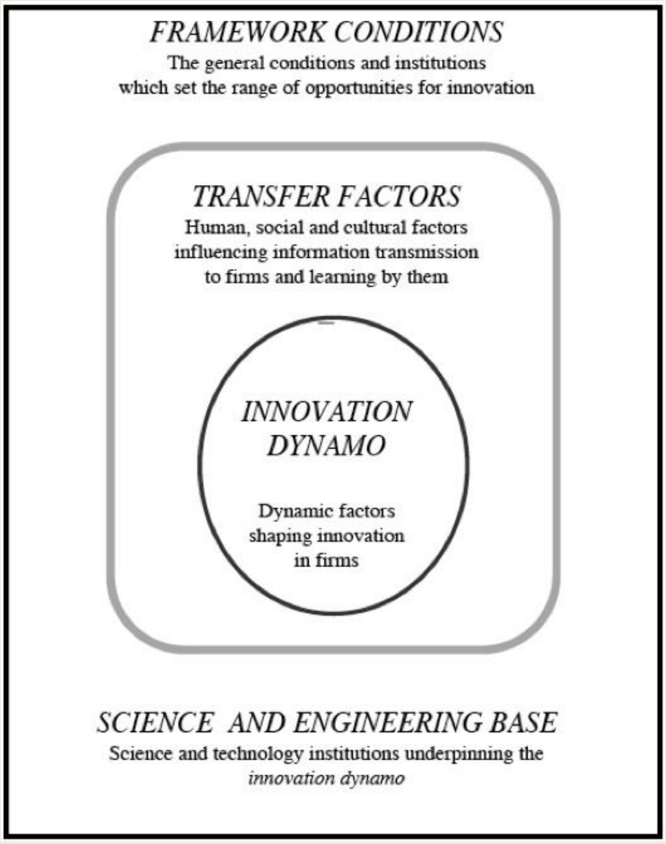

Figure 0.2 The Innovation System Frame as presented in the second edition of the Oslo Manual (Source (Speirs et al., 2008)).

Note that placing the innovation dynamo at the centre of the system frame map recognises the importance of the firm (or entrepreneur) for an economy to be innovative. OECD (1997) explores what characteristics make firms more or less innovative and how innovation is generated within firms. The propensity of a firm to innovate, it suggests, depends on the technological opportunities it faces. In addition, firms differ in their ability to recognise and exploit technological opportunities. In order to innovate, a firm must figure out what these opportunities are, set up a relevant strategy, and have the capabilities to transform these inputs into a real innovation – and do so faster than its competitors.

National Innovation Systems

In the *National Innovation Systems* (NIS) approach the research focus is on individual and comparative analyses of the innovation systems in different countries, across a range of technologies. In particular, the idea is that key institutional drivers would be found at the national level. The concept of a national system of innovation was first developed in the late 1980s in a study of the then successful Japanese economy. Freeman and Perez (1988) defined a national system of innovation as "the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies." Their study stressed the positive role of government - working closely with industry and the science base - to provide:

- direction and support for development and marketing of advanced technologies;
- an integrated approach to R&D, design, procurement, production and marketing within large firms;
- a high level of education and scientific culture, combined with practical training and frequent up-dating in industry.

Meanwhile, Lundvall (1988) and (1992) stressed the role of interactions between users and producers, facilitating a flow of information and knowledge linking technological capabilities to user needs. Because of the fundamental uncertainty of innovation, Lundvall argued these interactions go beyond pure market mechanisms, and rely on mutual trust and mutually respected codes of behaviour.

Further insight came from Nelson (1993)'s analysis of an empirical study and comparison of the national innovation systems of 15 countries. This concluded that "to a considerable extent, differences in innovation systems reflect differences in economic and political circumstances and priorities between countries." These differences reflected the differences in the institutional set-ups between different countries, including systems of university research and training and industrial R&D, financial institutions, management skills, public infrastructure and national monetary, fiscal and trade policies (Foxon, 2006).

Following these early studies the national innovation systems approach to innovation theory has been developed and used extensively by the OECD (OECD, 1997); (2002). Here, the innovation process is characterised by the different actors and institutions (small and large firms, users, governmental and regulatory bodies, universities, research bodies), the interactions and flows of knowledge, funding and influence between them, and the incentives for innovation created by the institutional set-up. The report 'Dynamising National Innovation Systems' (Remoe and Guinet, 2002) summarises it as follows: "The NIS approach rests on the interactive model of the innovation process that puts an emphasis on market and non-market knowledge transactions among firms, institutions and the human resources involved".

Remoe and Guinet (2002) and OECD (2002) come to several overarching conclusions regarding national innovation systems:

- The building block of innovation is the innovative firm but a firm's innovative capacities are limited due to market and systemic failures.
- A firm's innovative capacity is linked to its ability to combine knowledge from external and internal sources. It must therefore develop linkages and transition management becomes vital.

- Firms have a range of innovation modes to choose from and it is important to adopt the one that fits their own learning needs.
- Technological innovation plays a crucial role but non-technological forms of innovation deserve more attention.
- A firm's innovation may be characterised in terms of process or product innovation but *ultimate innovation behaviour implies a reinvention of the firm itself* (Nokia & Siemens are cited as examples)**.**

The OECD work on NIS acknowledges the firm as the founding unit of the innovation system. It goes on to draw heavily on the concept of 'clusters' of innovating firms and involved entities. This concept is similar to that found in other innovation conceptualisations, particularly that of 'National Innovative Capacity' (see next sub-section) (Speirs et al., 2008). Figure 0.1 below present a generic model of national innovation systems:

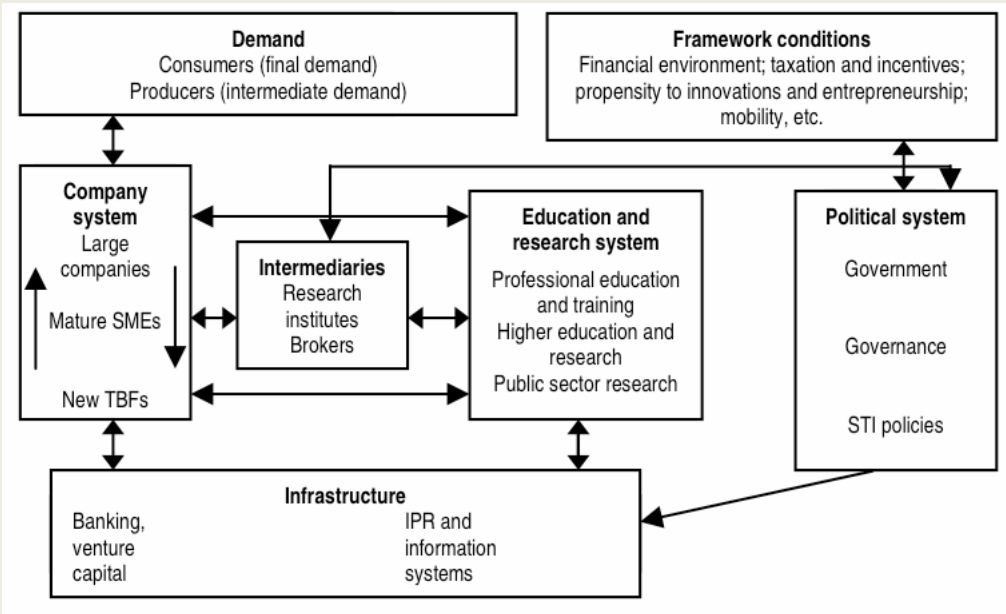

Figure 0.3 Generic model of national innovation systems presented in Arnold & Kuhlman (2001) (Source: (Speirs et al., 2008)).

This generic model of innovation can be summarised as:

- clusters of innovative entities;
- the interactions between these innovative entities; and
- the framework conditions within which these entities operate.

The concept of clusters involves an inherent dependence on interactions and these interactions are central to the goals of NIS (i.e. to generate a non-linear model of innovation). The interactions include three basic ideas:

- Competition, creating incentives for innovation through rivalry between innovating firms.
- Transaction, representing traded knowledge between actors including tacit and technology embodied knowledge.
- Networking, or knowledge transfer through collaboration, co-operation and long-term networking arrangements" (Speirs et al., 2008).

National Innovative Capacity

Related to the National Innovation System model is a concept developed by Porter (2002). *National Innovative Capacity* (NIC) refers to a country's potential “as both a political and economic entity to produce a stream of commercially relevant innovation”. Porter observes that significant innovative activity concentrates in a relatively small number of countries and that although R&D expenditure is common to all jurisdictions, biases in expenditure are evident. Patent registrations also display similar differences across jurisdictions, with some regions or countries registering significantly more patents per capita than others. This location-bias is at the heart of the concept of the national innovative capacity and NIC theory has concluded that international patents provide the best measure of realised innovation. The data gathering method of NIC implies a focus on the firm or enterprise level (Speirs et al., 2008).

NIC theory is characterised by three main elements (Speirs et al., 2008):

- Common Innovation Infrastructure - the human and financial resources devoted to innovation, the policies impacting on innovation, and the economy’s level of technological sophistication (analogous to the ‘framework conditions’ referred to in the ‘innovation system frame’ of the ‘Oslo Manual’)
- Cluster-Specific Conditions - a characterisation of innovation at the enterprise level where the innovating ‘cluster’ is defined as a geographic concentration of interconnected companies and institutions in a particular field (expands on the idea of the ‘innovation dynamo’ found in ‘the innovation system frame’).
- Quality of Linkages – the relationship between the common infrastructure and the industrial clusters. This, it is argued, is a two-way relationship since clusters contribute to and benefit the infrastructure as well as vice versa.

One important example of linkages is a nation’s university system, which provides a strong bridge between technology and companies. Without strong linkages, a nation’s scientific and technical advances can diffuse to other countries more quickly than they can be exploited at home (Porter and Stern, 2001).

Finally, corporate behaviour and national innovative capacity in the business environment tend to move together. Porter and Stern (2001) found that successful innovation depends not just on a favourable business environment but also on supportive company operating practices and strategies (an aspect of the so-called ‘Porter Hypothesis’. The implication is that companies should adjust their competitive approaches to attain higher levels of innovative output.

Regional and sectoral perspective on innovation systems

During the 1990s, research on innovation systems expanded its focus from the national level to also consider the regional level. However, this was mostly directed towards the IT and biotechnology sectors (Winskel and Moran, 2008). There has also been some focus on the idea of sectoral innovation systems. Here, the research examines, within a particular sector, a set of new and established products and the set of agents involved in the creation, production and sale of those products. This concept transcends both specific technological and national boundaries, with sectors being located sometimes in small regional clusters, yet sometimes also spanning global networks, as, for example, within multinational corporations (Stenzel, 2007).

1990s to present day: systemic and hierarchic innovation

The systems perspective of innovation

Advances in innovation theory recent years have gradually moved closer to a fully systemic, dynamic, non-linear process involving a range of interacting actors. This perspective emphasises the knowledge flows between actors; expectations about future technology, market and policy developments; political and regulatory risk; and the institutional structures that affect incentives and barriers.

Thus, while conceptual and methodological specifics vary, these more recent innovation systems approaches tend to emphasise the role of multiple agency and distributed learning mechanisms in technological change. Rather than all-powerful firms or unidirectional knowledge flows, the focus is on inter-organisational networks and feedbacks (Winskel and Moran, 2008). The system perspectives still acknowledge the existence of stages of technology development but they attempt to put these in a wider context. For example, Carbon Trust (2002) includes a graphic representation of how actors interact with the different stages of the innovation process:

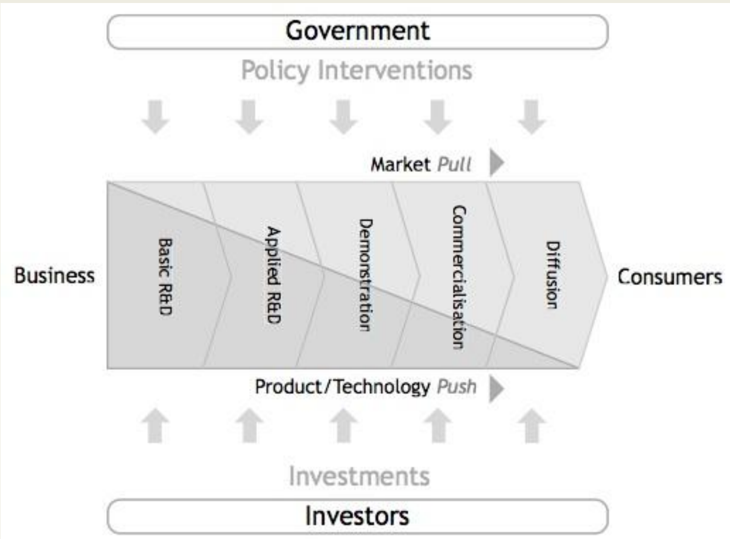

Figure 0.4 Roles of Innovation Chain Actors (Source: (Carbon Trust, 2002))

In particular, the role of institutions at all levels in establishing and maintaining the 'rules of the game' is a key theme since institutions may constrain choices, driving innovation along certain - possibly sub-optimal - paths, while often throwing up barriers to more radical change (Foxon, 2003). The importance of feedbacks between different parts of the system – both positive and negative - is also emphasised as are the links between technological and institutional change. A well functioning system vastly improves the chances for a technology to be developed and diffused (Negro et al., 2008). Hence, the guiding principle of innovation studies is that if we can discover what activities and contexts foster or hamper innovation (i.e. how innovation systems function) we will be able to intentionally shape the innovation processes (Hekkert et al., 2006).

Examples of research work on systemic innovation over the last decade or so include 'technological innovation systems', 'technological transitions', and the ‘multi-level perspective’. These approaches may differ somewhat in their focus but they all consider technological change not just in terms of developments of physical technologies but as a process interacting with changes in wider socio-economic structures such as the market environment and consumer preferences (Stenzel, 2007).

Technological Innovation Systems (TIS)

Technological innovation systems theory has been developed with the aim of improving on systems-style analysis of the innovation process. In part, TIS theory can be distinguished from national (or regional) systems theory by the differences in basic starting point. National innovation systems principally start from the notion that innovation is geographically heterogeneous whereas TIS begin with technology and technological change as the starting point (Speirs et al., 2008).

However, according to Hekkert et al. (2006), theories focusing on the national or regional structure of innovation systems have proved insufficient in fully informing the study of the innovation process. Hekkert and Negro (2009) notes that when innovation systems are studied on a national level, the dynamics of the process are difficult to map due to the vast amount of agents, relations, and institutions. Therefore, many authors who study national systems of innovation focus on structure not on mapping the emergence of innovation systems and their dynamics.

By contrast, in a TIS the number of agents, networks, and relevant institutions are generally much smaller than in a national innovation system, which reduces the complexity. This is especially the case when an emerging TIS is studied. Generally, an emerging innovation system consists of a relative small number of agents and only a small number of institutions are aligned with the needs of the new technology. Thus, by applying the TIS approach it becomes possible to study the dynamics and to come to a better understanding of what really takes place within innovation systems (Hekkert and Negro, 2009). That said, the scope of a TIS does overlap with sectoral, regional and national system scopes and the dynamic interaction of actors and knowledge flows within all these contexts remain fundamental (see Figure 0.5).

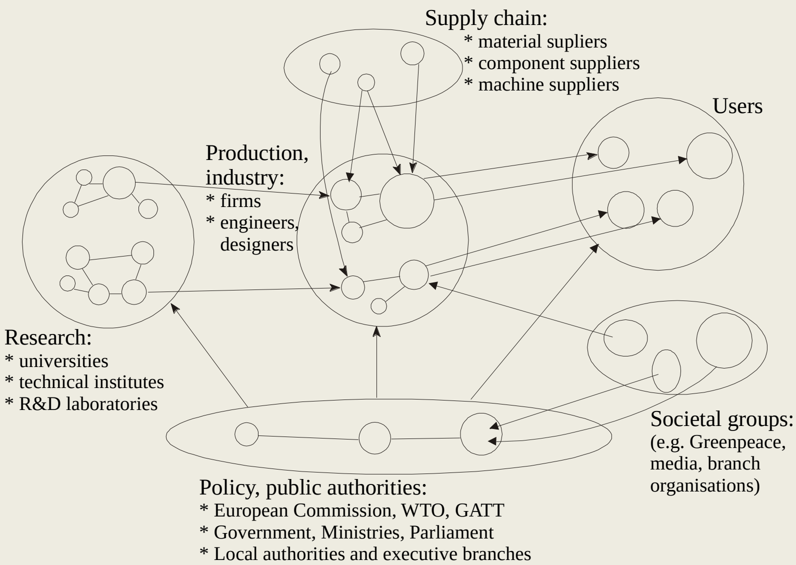

Figure 0.5 Interacting Groups in Technological Innovation Systems (Source: (Geels, 2002))

Jacobsson and Bergek (2004) define the three main elements of technological innovation systems as:

- Actors (and their competencies), including firms, users, suppliers, investors, and other organisations (comparable to the idea of clusters).
- Networks, defined as the channels for the transfer of tacit and explicit knowledge (comparable to the idea of transfer factors or linkages).
- Institutions, being the entities that govern and dictate the environment within which all actors operate (comparable to framework conditions or innovation infrastructure).

Note that, in general, innovation system frameworks tend to adopt a broad definition of institutions, including not only formal rules in market, regulatory and planning systems, but also informal 'norms, rules and values' in organisations and society which shape the way different agents collaborate and compete. Informal institutions also play an important role in innovation processes (Winskel and Moran, 2008).

TIS functions

The TIS approach attempts to analyse innovation systems by assessing what is termed 'functions of the innovation system' (Speirs et al., 2008), i.e. certain processes deemed important to the success of an innovation system (see below). This approach, says Hekkert et al. (2006), addresses two flaws in earlier innovation systems concepts: that they lack sufficient attention to the micro level; and that they are too static due to their focus on structure.

This view is supported by Bergek et al. (2008a) who contend that most of the literature discussing innovation system failure tends to focus on perceived weaknesses in the structural composition of a system. But the question remains as to whether the existence of, say, a particular actor network is a strength (e.g. a source of synergy) or a weakness (e.g. a source of lock-in or "group-think"), without identifying its influence on the innovation process and its key sub-processes. Thus, in order to be able to identify the central policy issues in a specific innovation system, a structural focus needs to be supplemented with a process focus.

Jacobsson and Bergek (2004) proposed an analysis of the processes of a technological system by considering how five essential 'functions' are served within the system, functions that directly influence the development, diffusion and use of new technology and, thus, the performance of the innovation system. More recently, Hekkert et al. (2006) and Bergek et al. (2008a) have put forward a modified list of seven functions (see Figure 0.6) for describing and analysing technological innovation systems:

- *Entrepreneurial activities*: The existence of entrepreneurs in innovation systems is of prime importance. Without entrepreneurs innovation would not take place and the innovation system would not even exist.
- *Knowledge Development* including 'learning by searching' and 'learning by doing' and Knowledge Diffusion: R&D and knowledge development are prerequisites within the innovation system. In addition, the essential function of networks is the exchange i.e. diffusion of information.
- *Guidance of the search*: an example being the announcement of a policy goal to aim for a certain percentage of renewable energy in a future year. This grants a certain degree of legitimacy to the development of sustainable energy technologies and stimulates the mobilisation of resources. Expectations are also included, as expectations can generate a momentum for change.

- *Market formation*: the formation of niche markets or manipulation of market conditions via economic instruments such as favourable tax regimes or minimal consumption quotas.
- *Resource mobilisation*: resources, both financial and human, are a basic input to all the activities within the innovation system.
- *Creation of Legitimacy/Counteract Resistance to Change*: in order to develop well, a new technology has to become part of an incumbent regime, or has to even overthrow it. Advocacy coalitions can function as a catalyst to create legitimacy for the new technology and to counteract resistance to change.
- *Development of positive externalities* (e.g. technology 'spill-over').

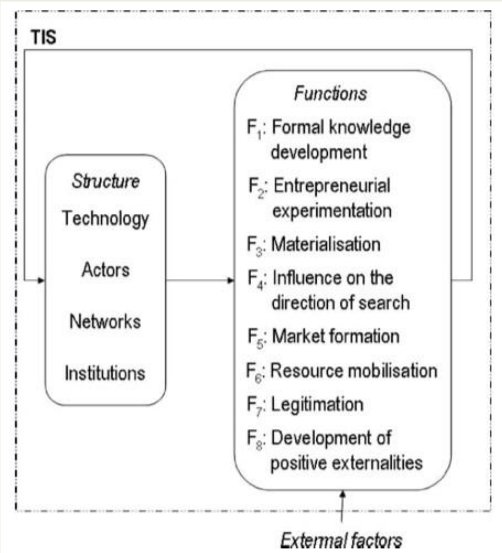

Figure 0.6 Relations between external influence, structural elements and functions. (Bergek et al., 2008b)

It is expected that the more these system functions are fulfilled, the better the performance of an innovation system will be, resulting in better chances for a successful development, diffusion, and implementation of new technologies. Both the individual fulfillment of each system function and the interaction dynamics among the functions are of importance. Virtuous interaction patterns between functions could lead to a reinforcing dynamic within a system, whereas flawed interactions could cause its collapse. An example in this respect could be the cutback of a national subsidy program and its negative impacts on the expectations over the possible success of the technology. This could cause entrepreneurs to stop their activities, thus further decreasing the expectations, which eventually would lead to the abolishment of the remaining subsidies (Negro et al., 2008).

TIS and transition

A key theme in the TIS literature is the competition between established systems and newly emerging ones. Hence, functions of new innovation systems are analysed in terms of 'inducement' and 'blocking mechanisms' for their further development. On the one hand, a new firm's entry is seen as unambiguously inducing the development of key functions such as the creation of new knowledge, the supply of resources and the formation of markets. On the other hand, "ambiguous" behaviour by established firms is seen as having the reverse effect of blocking the development of such functions (Jacobsson and Bergek, 2004).

Given this potential for (understandable) obstruction by incumbent actors, government policy is seen as a key cornerstone to aid the formation of the functions mentioned above. Especially in the early stages of a technology's life-cycle, support for knowledge creation, the supply of resources and (niche) market formation are seen as critical for the creation of a self-sustainable innovation system (Stenzel, 2007).

Recent research into TIS theory

The most recent research in TIS has developed methods for the analysis of specific systems, and the comparative assessment of different technologies and systems (Winskel and Moran, 2008). This analysis is aimed at providing useful outputs for technology developers and policymakers and can be used by them to analyze a TIS and determine the key policy issues and set policy goals. Bergek et al. (2008a) define a 6-stage method for TIS performance assessment:

- Define system taking into consideration the choices to be made between a knowledge field and product focus; breadth and depth; and the spatial domain.
- Identify the structural components of the TIS which include the actors, networks and institutions.
- Map the functional pattern of the TIS based on the seven functions (see (Hekkert et al., 2006) and (Bergek et al., 2008a) above): knowledge development and diffusion, influence on direction of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization and development of positive externalities.
- Assess the functionality of the TIS and set process (policy) goals. This step is where the relative 'goodness' of the functional pattern is assessed.
- Identify inducement and blocking mechanisms.
- Specify key policy issues which aim to fix poor functionality by strengthening inducement mechanisms and weakening blocking mechanisms.

Niches, niche cumulation, and disruptive innovation

Niches and niche cumulation

Innovation literature has increasingly emphasised the importance of occupying niches, in which new technologies may be more able to compete with incumbent rivals. They do so by benefiting from relatively rapid penetration and learning-by-doing, thus reducing costs and improving performance. Because niches are in some way insulated from 'normal' market selection, they act as 'incubation rooms' for radical novelties. They also provide space to build up the social networks that support innovations, e.g. supply chains and user-producer relationships (Geels, 2002).

Geels (2002) categorises niches into two (partly overlapping) forms: technological niches and market niches. *Technological niches* are 'protected spaces', where regular market conditions do not prevail because of special conditions created through subsidies and alignments between various actors. These technological niches are often played out in the form of experiments like those with electric vehicles in various European countries and cities. These experiments with real-life users are suitable locations for learning processes. Technological niches can develop into *market niches*, applications in specific markets in which regular market transactions prevail.

In terms of rules and social networks, niches are different from technological regimes in two ways. First, while rules in regimes are stable and specific, rules in niches are fluid, broad and diffuse. Protagonists are typically guided by 'diffuse scenarios' about the potential of future technologies. These general rules and visions become more specified and stable as more is learned about the technology and its use. Second, while regimes consist of large social networks, niches are carried by small and precarious networks. An important part of the work of niche protagonists is thus to manage and expand the social networks, in particular to enrol other actors.

Geels (2002) argues that while socio-technical regimes account for stability, niches are the seeds for change and the building blocks for transitions. And whereas an existing regime generates incremental innovation, radical innovations are generated in niches. Geels suggests that regime shifts, and ultimately transitions to new socio-technical landscapes, may occur through a process of niche-cumulation. This means that a number of initially separate niches for the new technological system are created, and these gradually grow and come together to form a new regime.

However, investment in niches is inherently risky for firms compared to concentrating on existing mainstream customers (if they have them). This can represent a form of 'systems failure', in which current market mechanisms fail to give sufficient incentives, and where public support could be used to create a more favourable risk/reward climate for niche development (Foxon, 2003). This suggests that there may be a role for policy support for the development and cumulation of niches, through '*strategic niche management*' (see sub-section 0).

Radical and disruptive innovation

As well as the necessity of niche markets, there has also been much interest in the differences between incremental, radical and disruptive innovations, and in how industry structure is related to them. Within industry, larger firms are more likely to have the R&D capacity to generate new ideas but this will typically be focused on incremental improvements along the existing technological trajectory (Foxon, 2003).
Incremental innovation builds on and improves existing technology but does not significantly alter it. Kemp and Foxon (2007) notes that incremental innovations are nevertheless important source of productivity and of environmental improvements and are not necessarily of lesser importance than radical ones.

Smaller firms, outside the mainstream and with less invested in the old system, will be more likely to attempt riskier, more radical approaches assuming they have the resources. Radical innovation does produce significant change but is not necessarily disruptive (sometimes called 'discontinuous') i.e. it does not necessarily displace the dominant, incumbent technology or process. Fuel-injection is an example in the internal combustion engine regime of a radical innovation which is not a disruptive technology.

By contrast, disruptive innovations are innovations that eventually overturn the existing dominant technologies, products or processes. The innovation fulfills a similar market need but does so by building on a new knowledge base (Schilling and Esmundo, 2009). The result may be that the firms which have been the market leaders are unable to adapt and could go out of business. An example of potentially disruptive innovation is in-wheel electric propulsion which may one day render the internal combustion engine and the specific activities around it obsolete (Kemp and Foxon, 2007).

This understanding of niches and disruptive innovation has become important for larger firms and is now feeding back into their behaviour. They have begun to recognise the potential in establishing semi-autonomous divisions or spinning out companies to research and develop more radical innovations. The incentive structure and risk profile for radical innovation is different from that of incremental innovation and while the likelihood of initial failure is higher and the need for learning is greater, the potential for generating breakthroughs is higher (Stenzel, 2007).

That said, it should be recognised that firms in mature sectors such as the energy system operate in embedded socio-technical networks, and tend to re-invest in existing competencies. Disruptive technologies rarely 'make sense' to such established firms, so that development of these technologies may be left to the small, outsider organisations. Alternatively, as noted above regarding niches, policy interventions may be needed to make established firms consider deploying new technologies 'against their inclination' (Winskel and Moran, 2008).

Transitions theory

Recent research into innovation systems has, in particular, focused on the detailed process of technological change which is more than simply incremental but represents a more radical, possibly even disruptive, shift in products and processes. This strand of analysis goes beyond economics and includes sociology, history and engineering and is sometimes referred to as 'transitions' theory (Gross, 2008).

Technological change and the transition process can be investigated from a number of different perspectives but with the common aim of trying to anticipate and manage future transitions. Fouquet (2010), for example, reviews past energy transitions by sector and service to identify features that may be useful for future transitions. The main economic drivers identified for energy transitions were the opportunities to produce cheaper or better energy services. Typically, the existence of a niche market willing to pay more for these characteristics enabled new energy sources and technologies to be refined gradually until they could compete with the incumbent energy source. Other factors cited by Fouquet (2010) as common features of successful energy transitions are:

- A successful 'learning curve' allowing costs to decline.
- An S-shaped growth model of technological diffusion into a new market or the substitution in an existing one.
- 'Technological clusters' (which will eventually lead to dominance and ultimately to 'lock-ins' such that the innovative technology becomes the embedded incumbent).

(Foxon et al. (2010 (In press)) reports that research under the transitions approach has developed along three main lines:

Multi-level perspective of the transition process

Using the idea of a hierarchy of levels of innovation and working within the evolutionary approach, Geels (2002) put forward a multi-level perspective of how transitions to radically new technological systems could occur and how policy support (i.e. transition management) might facilitate this. This multi-level perspective is important for an understanding that breakthroughs of innovations are dependent on multiple processes in the wider contexts of regimes and landscapes (Geels, 2002).

According to Geels (2002), transitions do not only involve changes in technology, but also changes in user practices, regulation, industrial networks (supply, production, distribution), infrastructure, and symbolic meaning or culture. Geels uses three explanatory levels: *technological niches* at the 'micro' level, *socio-technical regimes* at the 'meso' level, and *landscapes* at the 'macro' level, as first proposed by Kemp (1994).

A socio-technical regime reflects the interaction between the actors and institutions, and the resultant routines and practices, involved in creating and reinforcing a particular technological system (Winskel and Moran, 2008). These practices include: "engineering practices; production process technologies; product characteristics, skills and procedures embedded in institutions and infrastructures (Foxon et al., 2010 (In press)). Thus, in so far as firms differ in their organisational and cognitive routines, then there is variety in the technological search directions of engineers. In so far as different firms share similar routines, these form a regime. Technological regimes produce *technological trajectories*, because the community of engineers searches in the same direction. Technological regimes thus create stability in the direction of technical development (Geels, 2002). This is closely related to the concepts of path dependency and lock-in.

Technological trajectories are in turn located within a landscape consisting of a set of deeper structural trends and changes. Both regime and landscape are structures or contexts for interactions of actors, but in a different way. Where regimes refer to social structures and rules that enable and constrain activities within communities, the function of the concept 'socio-technical landscape' is that it accounts for technology-*external* factors that influence its development (Geels, 2002). The landscape represents the broader political, social and cultural values and institutions that form the structural trends of a society. They are a set of heterogeneous factors, such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems that have an impact on innovation and production processes without being influenced by the outcome of innovation processes on a short to mid term basis (Markard and Truffer, 2008).

As such, landscapes are even more resistant to change than regimes. Each higher level has a greater stability and resistance to change, due to interactions and linkages between the elements. Higher levels impose constraints on the direction of change of lower levels thereby reinforcing trajectories (Foxon, 2003). However, if change does arise, it tends to be initiated at the niche level, and then may spread and become embedded in regimes, possibly leading on to regime (and even) landscape transformation (Winskel and Moran, 2008).

The actual dynamics of technological transitions is described by Geels (2002) as follows:

At the niche-level, work is being done on innovations. However, lack of 'size' and impact mean that the innovations are not yet noticed on the regime-level. They remain 'hidden novelties' and usually have a hard time breaking through because of the inertia of the incumbent socio-technical regime. However, innovations break out of niches when they can link up with processes at the regime- and landscape-level. They may link to the established technology as an auxiliary device (add-on) or as a hybridisation; or they may be linked to new regulations or newly emerging markets. Indeed technological transitions tend to be rooted in the linking of *multiple* technologies. In addition, new technologies break out of niches by riding along with growth in particular markets. (For example, the case-study used by Geels – the transition from sailing ships to steamships - showed that the take-off phase of steamships was associated with strong growth in Atlantic passenger transportation). Finally, such transitions do not just involve technology and market share but also changes on wider dimensions such as regulation, infrastructure, symbolic meaning, social and industrial networks.

Strategic Niche or Transitions Management

Alongside the multiple-level perspective has emerged the proposal for 'transitions management' and 'strategic niche management' by governments in order to promote and protect the development and use of promising technologies (Fouquet, 2010). Strategic niche management differs from simple ''technology-push'' policies, particularly in the role that states undertake (Maréchal, 2007). Echoing the multiple-level perspective, there is a recognition that government and firms, as well as other stakeholders, have a central role to play in a system change and, for example, in the diffusion of low carbon technologies and that there is a need for policy-makers to manage the dynamics of possible transitions in order to avoid early lock-ins.

According to Rennings et al. (2004), transition management is not so much about the use of specific economic instruments but more about different ways of interaction between entities, the mode of governance, and goal seeking. If innovation and learning are the aims of transition management then this requires a greater orientation towards outsiders, a commitment to change and clear stakes for regime actors.

Thus, strategic niche management is larger than simple niche promotion in that niches are managed (i.e. created, developed then phased out), taking into account the broader context in which niches evolve (i.e. acknowledging that social and institutional factors do contribute to reinforce the locking-in of the incumbent technological system) (Maréchal, 2007). This management process involves creating shared visions and goals, mobilizing change through transition experiments, and learning and evaluating the relative success of these experiments (Foxon et al., 2010 (In press)).

Socio-technical scenarios

The third main line of research under the transitions approach is to develop 'socio-technical scenarios'. Such a scenario "describes a potential transition not only in terms of developing technologies but also by exploring potential links between various options and by analysing how these developments affect and are affected by the strategies (including policies) and behaviour of various stakeholders" (Foxon et al., 2010 (In press)).

Elaborating on the socio-technical scenarios method, Foxon et al. (2010 (In press)) offers a theoretical approach to developing transition pathways. Three main steps to specifying transition pathways are identified:

- Characterise key elements of existing regime (socio-technical, actors, and landscape).
- Identify key processes that influence dynamics and stability, especially at the niche level.
- Specify interactions giving rise to or strongly influencing transition pathway.

Summary

Prevailing perspectives on the innovation arena exhibit some significant similarities. All are an attempt to create an integrated, systems-based concept of innovation in order to understand the structures and processes in a comprehensive way. Three core concepts in particular unite these theories (Speirs et al., 2008):

- The firm (analogous or closely related to the 'innovation dynamo', 'cluster', 'actor').
- The conditions (analogous or closely related to 'framework conditions', 'innovation infrastructure', and 'institutions').
- The linkages (analogous or closely related to 'transfer factors', 'quality of linkages' and 'networks').

Arguably the core insight that the more recent innovation literature has provided is the importance of systems thinking. The systems approach goes beyond the old linear model of innovation, whereby an increase in R&D will automatically lead to new products and services emerging at the end of the process. It also suggests that the rationale for government intervention to support innovation goes beyond a simple 'market failure' argument, whereby support reflects the difference between the private rate of return to R&D and the social rate of return. Instead, the rationale also includes correcting for wider 'systems failures' (OECD, 2002).

None of this diminishes the role or importance of traditional R&D in generating innovation, but it provides a more complex picture of the drivers of successful innovation, and the barriers that can prevent it. The picture that emerges is of an innovation process and system which consists of a range of actors that interact through both market mechanisms and flows of knowledge and influence, within an institutional set up which creates incentives for different types or rates of innovation. This implies a role for policy to improve the institutional framework and the opportunities for interactions so as to better incentivise innovation. This correcting for 'systems failures' in the innovation system includes failures in infrastructure provision, transition failures, lock-in failures, and institutional failures (OECD, 2002).

In the next chapter, the report considers how innovation theory has been used to examine issues arising more specifically in the eco-innovation arena, particularly with regard to low carbon/renewable energy technologies.

Eco-innovation

Introduction

Eco-innovation as a specific concept within the innovation theory arena is relatively recent, first appearing in the mid-1990s (Kemp and Foxon, 2007). Denmark's government defines eco-innovation as innovation leading to an eco-efficient technology. Eco-efficient technology means all technologies which directly or indirectly improve the environment. It includes technologies to limit pollution, more environmentally friendly products and production processes, more effective resource management, and technological systems to reduce environmental impacts.

Eco-innovation is defined by Kemp and Foxon (2007) as "the production, application or exploitation of a good, service, production process, organisational structure, or management or business method that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of resources use (including energy use) *compared to relevant alternatives*." The innovation may result in a lowering of the costs of achieving an environmental improvement or result in a greater environmental gain than an older model. It may also be new technology for a new environmental problem.

Types of eco-innovation

Eco-innovation and resultant environmental gains may be achieved via innovation in technology, processes, organisations, and wider system changes. A transition to a renewable energy system is an example of the latter. Andersen (2005) distinguishes the following five categories of eco-innovations:

- Add-on innovations (pollution and resource handling technologies and services)
- Integrated innovations (cleaner technological processes and cleaner products)
- Eco-efficient technological system innovations (new technological paths)
- Eco-efficient organizational system innovations (new organizational structures)
- General purpose eco-efficient innovations e.g. renewable energy technologies and ICT.

Kemp and Foxon (2007) proposes the following list of environmental technologies:

- Pollution prevention measures in existing processes
- Cleaning technology e.g. bioremediation of polluted soils
- Cleaner technology
- Process internal recycling i.e. re-use of material waste, heat and water
- Measurement technologies of pollution and processes.

Kemp and Foxon (2007) builds on this to produce a detailed taxonomy of eco-innovation with three different 'classes' and multiple sub-categories (see Kemp and Foxon (2007) for further details of these).

As already noted in Chapter 2, a distinction can also be made between those innovations which are disruptive and those which are incremental and sustaining.

Disruptive innovations are innovations that eventually overturn the existing dominant technologies or products in the market (Christensen, 1997)). By contrast, sustaining innovations build on previous knowledge within the innovating company, servicing existing product markets and users. Sustaining technologies are often incremental improvements in established products. An example of a sustaining eco-innovation is the catalytic converter which helped to improve the environmental performance of the internal combustion engine and so maintain the dominance of that technology (Kemp and Foxon, 2007).

Benefits of eco-innovation

Rennings et al. (2004) notes that environmental regulation can be good for business and is consistent with economic growth – a concept sometimes known as 'ecological modernisation'. Kemp and Foxon (2007) sees the direct benefits for the eco-innovating firm as being:

- Operational advantages such as cost savings from greater resource productivity and better logistics
- Sales from commercialisation

Indirect benefits for the eco-innovator include:

- Better image
- Better relations with suppliers, customers and authorities
- Enhanced innovation capability due to contacts with knowledge holders
- Health and safety benefits
- Greater worker satisfaction

These benefits must be weighed against costs for the company. The majority of companies know very little of either the costs or benefits of their environmental activities. This leads many of them to believe that environmental considerations are a burden rather than an asset – an attitude that is a significant barrier to eco-innovation. Own or others' experiences (about net benefits from eco-efficiency) are therefore instrumental in changing the mind set (Kemp and Foxon, 2007).

In 2000, a review of 52 case studies showed that the non-energy benefits of certain efficiency measures could be of the same order of magnitude as their energy benefits (Maréchal, 2007). This, suggests Maréchal, enhances the credibility of the ''Porter hypothesis'', which argues that investments undertaken to reduce environmental impacts may trigger productivity gains. This may well have applied in the case of BP. According to Maréchal (2007), between 1998 and 2001, BP reduced its emissions by 18%, while gaining $650 million of net present value - a gain that occurred because the bulk of the emission reductions came from the elimination of leaks and waste.

Eco-innovations should also be valued from a societal point of view. From a social welfare point of view, eco-innovations are desirable if they contribute to overall welfare in the sense of wellbeing (not economic growth). Society has a net increase in welfare if the environmental benefits for society plus the benefits for companies exceed the costs of achieving those benefits (which consist of the costs for the companies involved and the administrative costs related to the use of policy instruments involved).

Drivers of eco-innovation

The main drivers for eco-innovation include regulation, cost reduction, improving technical efficiency, increasing market share, profits from commercialisation, pressure from communities, green ethos, and improving the company image (Kemp and Foxon, 2007). In the case of renewable energy regulation, the primary driver behind this is the market failure of uncosted carbon dioxide (and other greenhouse gas) pollution (energy security and diversity may be a potential secondary driver). In cases for which reducing environmental impact offers no operational benefits or commercialization benefit, then regulation may be the clearest driver for eco-innovation.

In many cases, firms find that the generation of waste and pollution in production processes is also cost-inefficient and they have achieved large cost savings through process and system innovations (Kemp and Foxon, 2007). Firms may also gain first mover advantage if an innovation is subsequently widely diffused. Moreover, as consumers become increasingly aware of the environmental impacts of their purchasing choices, they begin to exert pressure on firms to reduce these impacts.

Barriers to eco-innovation

Market failure of IP inappropriability

As noted in sub-section 0 a firm may often not be able to fully appropriate the fruits of its investment – its intellectual property (IP) - because advances in knowledge ‘spill over’ to other firms and consumers without adequate compensation. This can reduce incentives below those needed for a socially optimal level of innovation (Foxon, 2003). This is a commonly recognised potential barrier to innovation although the problem of appropriability may be temporarily mitigated by the patent and copyright.

Ironically, from the point of view of other firms and of society as a whole, such knowledge spillover represents a positive externality – one of Bergek et al. (2008a)’s ‘functions’ of a technological innovation system.

Cost

One of the strongest obstacles to the commercialisation of a new technology - and therefore a major barrier to innovation – is its relative cost. Rehfeld et al. (2004) found that a perception of expense amongst consumers of environmental products was a much more significant factor than attitudes towards reliability or quality. Economic rather than ‘soft’ factors appear to be the major obstacles to the commercial exploitation of environmental products and therefore also to environmental product innovations (Rennings and Ziegler, 2006).

Systems failure and related barriers

As we have seen in Chapter 2, increasing returns to adoption arising from learning and scale effects etc. can result in path dependency and technological and systems inertia, leading to the lock-in of incumbent technologies, institutional and policy regimes and landscapes, and to the lock-out of innovative technologies and systems.

This issue is argued to be particularly acute in the energy arena (Gross, 2008) where carbon-intensive, fossil fuel-based energy systems have benefited from a long period of increasing returns and have therefore become locked-in. Fossil-fuel based energy systems have undergone a process of co-evolution, leading to the current dominance of high carbon technologies and the accumulated knowledge, capital outlays, infrastructure, available skills, production routines, social norms, regulations and life styles which support these (Unruh, 2000). Foxon (2003) further argues that electricity generation is contextualised by institutional factors - for example, the desire to satisfy increasing electricity demand and a regulatory framework based on reducing unit price – which feed back into expansion of the technological system.

Thus, persistent market and policy failures inhibit the diffusion of carbon-saving technologies despite their environmental and possibly economic advantages.
The evidence for what Unruh terms *carbon lock-in* is compelling says Schmidt and Marschinski (2009): economists have argued for many years that greenhouse gas emissions should have a price. However, few countries have so far implemented effective carbon prices, and many countries still subsidize the use of fossil fuels - a paradox that can be explained by techno-institutional lock-in.

Similar arguments could be made for technologies with high environmental impacts more generally. This leads to the conclusion that eco-innovation requires not only technological change but also institutional change and, hence, that measures of eco-innovation should encompass both technological and institutional factors (Kemp and Foxon, 2007).

At a 'macro' level, barriers and failures with respect to environmental technologies have been summarised by ETAP (the European Commission's Environmental Technologies Action Plan) as follows:

- Economic barriers;
- Regulations and standards acting as barriers to innovation;
- Insufficient research efforts;
- Inadequate availability of risk capital;
- Lack of market demand (Kemp and Foxon, 2007).

Similarly, using an innovation theory framework, Jacobsson and Johnson (2000) summarises the factors that represent potential barriers to eco-innovation:

- Actors and markets
  - Poorly articulated demand
  - Established technology supported by increasing returns
  - Market control by incumbents
- Networks
  - Poor connectivity
  - Wrong guidance with respect to future markets
- Institutions
  - Legislative failures
  - Failures in the educational system
  - Skewed capital markets
  - Underdeveloped organisational and political power of new entrants.

Looking at the barriers and failures at a more 'micro' level, Vincent (2006) suggests that there are various ways in which, and stages at which, the innovation and commercialisation of new and emerging low carbon technologies can fail including:
(i) funding inadequacies at the demonstration and pre-commercial stages;
(ii) failures at the planning stage for commercial developments;
(iii) insufficient attention to setting industry standards and test regimes for new and emerging products;
(iv) a focus on grant support schemes to address the initial capital cost premium from the consumer's perspective whilst paying insufficient attention to working with manufacturers on ways to move their new and emerging products faster down the cost curve to commercial viability;

(v) insufficient attention to maturing the supply chain; and
(vi) unsettling of investor confidence brought about by regulatory uncertainty and inconsistency.

Hence, says, Vincent (2006), there is no single 'valley of death' for new and emerging low carbon technologies which deliver a societal good but have weak consumer and market pull. Government intervention at multiple stages is therefore essential to overcome the various valleys of death a technology may face.

Supporting eco-innovation

Government policy and regulation

The twin market failures of (i) the social cost of carbon emissions not being internalised and (ii) under-investment in innovation in the private sector because of less than optimal IP compensation tend to lead to a typical policy response. This is to create a policy framework that emphasises market mechanisms (such as emissions trading) that price carbon emissions and provides government funding for R&D However, Watson (2008) argues that government technology eco-innovation policies have to do more than fund basic R&D and internalise the social costs of carbon emissions. There is a need for government to support other stages of the innovation process such as the so-called valley of death as technologies move from demonstration or prototype phase to commercialization.

Moreover, beyond this, there are rationales for intervention that stem from more than just market failures. These rationales arise from the innovation systems perspective where the rationale for policy intervention shifts from simply addressing market failures that lead to underinvestment in R&D towards one which focuses on ensuring the agents and links in the system work effectively as a whole, removing blockages and barriers (i.e. systems failures) that hinder the effective networking of the system components (Foxon et al., 2005).

As discussed, environmental innovation policy regimes have evolved from the so-called '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. This still forms the basic mindset of many policy practitioners says Suurs et al. (2009). However, as we have seen, contemporary innovation theories offer a more complex picture of innovation as a systemic, dynamic, non-linear process, involving significant uncertainties.

Major areas of uncertainty within the low carbon arena include the long run relative costs or feasibility of emerging technologies (Anderson et al., 2001); the emergence of entirely new technologies; consumer behaviour and preferences; and geopolitical uncertainty, which may affect fuel prices or the political acceptability of some technologies or fuels such as nuclear power or natural gas. The implications of climate change are of themselves uncertain and will affect the scale of emissions reductions expected in future (Gross, 2008).

Such uncertainties combined with the existence of path dependence leads to three inter-related dilemmas for policymakers, says Gross (2008):

- The first is how to avoid premature path choices when the relative long term merits of different environmental technologies are unknown. If systems are path dependent there is a danger that the 'wrong choice' might lead to lock-in to sub-optimal options and systems.

- On the other hand policymakers may need to avoid excessive delay, otherwise low carbon options may be locked out because strategic decisions are not taken, such that lock-in to the incumbent technology or system happens 'by default'.
- Finally, small changes in the near future give rise to much larger long-term impacts. The issue for policy then is that a relatively small amount of early intervention (subsidy, regulation, R&D etc) may be sufficient to 'tip' the energy system in a particular direction. This may be both less costly and more practical/successful than delayed intervention, but early action risks a direct conflict with the first dilemma, above.

The existence of path dependency and of lock-in/lock-out means that the adoption of low carbon technologies may well require both technological change and also institutional change. For example, the diffusion of smart metering technology is not just a simple technical challenge but also implies a new approach to information provision to energy consumers and new information-technology infrastructure. Carbon capture and storage (CCS) technologies require new collaborations between utilities, oil and gas companies and power equipment companies. Plug-in hybrid vehicles require planning and co-operation between vehicle manufacturers and electricity companies. Novel technologies such as CCS can also require amendments to existing regulations (e.g. those that govern marine pollution) (Watson, 2008).

Philosophy of government involvement

Watson (2008) analyses the role of governments in supporting the eco-innovation process and takes as a starting point the common assertion that governments should avoid providing targeted support to particular technologies. Instead, they should set general frameworks to encourage more sustainable innovation, for example by creating carbon markets. In the early 2000s, Foxon (2003) noted the prevailing argument that whilst government did not need to pick winners, it did need to create the conditions in which winners could emerge and attract sufficient investment from industry and skeptical capital markets. The practice of 'picking winners', so the argument ran, should be avoided because governments are not best placed to decide which technologies to fund.

According to Watson (2008), this argument is now challenged on a number of grounds. First, the resources that governments can devote to sustainable energy innovation are limited. If there is no attempt to prioritise, there is a risk that resources will be spread too thinly. Second, the urgency of climate change means that innovation and deployment may be too slow if there is an over-reliance on carbon markets which have yet to demonstrate they are strong enough to promote significant low carbon innovation. Third, even if there were a high carbon price, it is unlikely that this would be sufficient to develop those technologies that are not already close to commercial status. Generic policy incentives such as carbon prices tend to favour near market technologies. In any case it is not clear what carbon price might be required in order to achieve the uptake of near market technologies nor longer term innovation investment.

Gross (2008) agrees that some mainstay assumptions of existing policy may need to be reassessed, including especially the notion that policy should not seek to 'pick winners'. Policy needs to create the conditions that allow a variety of low carbon options to emerge and prosper. But, perhaps paradoxically, policies will also need to ensure that the most promising low carbon options can themselves benefit from increasing returns to adoption. The same processes that created lock-in to a high carbon energy system can be harnessed to reduce the costs and improve the performance of low carbon technologies.

Whether, directly picking winners or not, governments can encourage eco-innovation in two primary ways: by implementing measures that reduce the private cost of producing innovation i.e. technology-push; and by implementing measures that increase the private payoff to successful innovation i.e. demand-pull (Nemet, 2007).

Examples of technology push policies include: government sponsored R&D, tax credits for companies to invest in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects. However, critics of such policies note their mixed record of success, the possibility that public spending crowds-out private investment, and their tendency to isolate scientific understanding from technical knowledge.

Examples of demand-pull policies include: intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, regulatory standards, and taxes on competing technologies. Both types of instruments appear necessary given the complex, uncertain, and iterative nature of the eco-innovation process in which different policies are needed at different stages of maturity (Nemet, 2007).

Innovation theory and application in reality

Several researchers in the field of innovation have applied theoretical insights to specific case studies in the renewable energy sector. Jacobsson and Bergek (2004), for example, used systems theory to contrast the relative success of wind and solar PV development in Germany (using feed-in tariffs) with the relative failure of wind and solar thermal development in Sweden and the Netherlands. Bergek employed technological innovation systems (TIS) thinking to examine the functional and structural development and 'legitimation' of the solar PV sector in Sweden (Bergek et al., 2008b). Suurs et al. (2009) also used the TIS approach, specifically to describe how the absence of a TIS function can result in the breakdown of a system – in this case, the Dutch wind energy innovation system which was well developed in the 1980s but collapsed as the result of an important deficiency, namely the absence of Knowledge Diffusion between the emerging turbine industry and potential users.

In the UK, Foxon employed innovation theory to analyse UK innovation systems for six new and renewable energy technologies: wind; marine; solar PV; biomass; hydrogen from renewable sources; and district and micro-CHP (Foxon et al., 2005). Foxon applied a framework for analysis based on the OECD National Systems of Innovation (NIS) approach and also introduced two novel features for this type of analysis: the detailed characterisation of innovation system failures in relation to stages of technological maturity; and the use of innovation system 'maps' to describe and summarise flows of knowledge, influence and funding within innovation systems. The findings support the picture of innovation systems as nonlinear, dynamic systems involving feedbacks between different stages of development in the commercial maturity of a technology.

As we have seen in Chapter 2 these more recent systems-style strands of innovation theory argue that policies need to take the stages of development of technologies into account as well as their context. In particular, this case has been made through the framework of strategic niche management – essentially the creation of "protected spaces" (Tsoutsos and Stamboulis, 2005). This framework allows nascent technologies to be protected from normal competitive pressures for an appropriate period to allow them to develop and mature, whilst fostering new networks of firms and other actors. Specific examples include the aforementioned case study by Jacobsson and Bergek (2004) of solar PV and wind energy in Germany which revealed technology-specific approaches that include R&D, demonstration programmes and market support through the feed-in tariff system. The result was policies that provided steady, tailored support to each technology as it moved from one stage of innovation to the next.

The UK's Renewables Obligation – which has been used instead of a feed-in tariff to support renewables deployment - provides a contrasting example (Watson, 2008). Whilst this policy instrument can, in theory, support a range of technologies including wind power, wave and tidal power and domestic scale photovoltaics, it has largely supported the cheapest near-market technologies. Winners under this policy include onshore wind, co-firing of biomass in conventional power plants and landfill gas.

The RO can be thought of as creating a niche for renewable generation in the electricity supply market. However, the design of the RO fails to take into account that different renewables technologies are at different stages of development and commercialisation, and so it fails to create niches for early stage technologies in particular (Foxon and Pearson, 2007). This shortcoming led the government to introduce 'bands' within the Renewables Obligation so that early stage technologies would receive a greater level of support. However, the feed-in tariff model retains one key advantage – its predictable nature offers more certainty (and hence, a lower risk) to investors (Watson, 2008).

Key policy implications and lessons

Winskel and Moran (2008) finds that several policy lessons can be drawn from international case studies of low carbon/renewable energy innovation:

- A significant period of R&D and building-up networks is necessary during the preparation phase ahead of industry take-off.
- During this period, policies must strike a balance between concentrating support on upscaling and progressing one or two leading prototypes, versus supporting a wide range of novel device designs.
- Some specific formal institutions and measures have proved important during the preparation phase:
    - Dedicated R&D grants to support individual device development
    - Technology-specific 'feed-in' tariffs to stimulate market growth
    - R&D networks linking industry, universities and research institutes
    - Well-supported testing and accreditation centres to compare different designs and generate community-wide knowledge
    - Powerful industry associations to disseminate knowledge
    - Advocacy groups to build political influence and legitimacy for renewables
    - Common backgrounds or shared understandings between technology developers, researchers, and suppliers (but building 'trust' is an informal issue and difficult to transfer between regions/nations).

Failures in low carbon/renewable energy system building, says Winskel (2006), have been associated with partial or inflexible policies and institutions. In some cases potentially important actors were excluded, leading to lack of design variety, whilst weak system feedbacks resulted in an over-emphasis on technical refinement or lock-in around unsuccessful designs. In other cases, weak or narrow support for renewables inhibited policy interventions and blocked the transition to industry take-off. Elsewhere, policy inconsistency or a prevailing commitment to market liberalisation led to loss of innovative capacity.

Alongside formal institutions and policy mechanisms, case study research also highlights a number of informal institutional and cultural influences on system building. For example, Winskel and Moran (2008) argues that the most effective policies during the experimental phase of innovation have emerged from an inclusive and participatory policy style able to mobilise the potential of different actors dispersed across the system, rather than top-down directives or measures restricted to a few insider organizations.

Certainly in Europe, say Winskel and Moran (2008), the most successful experiences have been associated with a gradual building-up of eco-innovation networks over time from the bottom-up. These networks have featured a prominent role for public intermediary agencies, such as the Danish Risoe testing and research centre for wind turbines. Centres of this kind make their impact by encouraging interaction between research groups, technology developer firms, project developers and policymakers.

Meanwhile, Negro and Hekkert (2008) find that the practical relevance of the technological innovation systems framework is that policy initiatives directed at stimulating sustainable change of the energy system, should focus on stimulating weak system functions to increase the chances of virtuous feedback taking place. Additionally, by identifying the underlying tendencies of the occurrence of flawed cycles, appropriate policy recommendations can be developed to prevent or resolve the occurrence of those cycles in the future.

In summary, Watson (2008) proposes five key implications for energy eco-innovation policy, relevant both to the UK and to other countries:

- First, government funding for sustainable energy technologies needs to be increased and rebalanced. Rebalancing means giving greater support to technologies facing, in particular, the 'valley of death' between demonstration and commercial deployment.
- Second, government funding needs to be more technology-specific. Generic incentives such as carbon emissions trading schemes are necessary but not sufficient. Research shows that technology-specific approaches work. However, policy makers will need to decide when to discontinue support.
- Third, the process of deciding which technologies to prioritise needs to be more transparent.
- Fourth, policy needs to strengthen its capacity for evaluation of technology support programmes.

Finally, innovation policies need to deal with the locked in-nature of current energy systems. Whilst energy infrastructures, institutions and policies were developed to meet important social goals, radical change is likely to be required to tackle climate change effectively. Government policy therefore needs to open up energy systems to more radical technologies and business models, and ensure that institutions and common infrastructures facilitate their deployment.

Eco-innovation and the private sector

At the micro-level of the individual firm, the pursuit of eco-innovation is seen as a strategic management issue (Slade and Bauen, 2009). The focus is on companies' decision-making processes and behaviour in the face of technological change. The research is underpinned by four fundamental concepts: bounded rationality, organisational routines (i.e. dominant behaviour), capabilities, and strategy (i.e. determination of goals and/or defence against competition).

In the face of competition strategic decisions may include: becoming a cost leader; seeking to differentiate products; and vacating highly competitive markets. If a defensible position within an existing market cannot be found, another option is the lobbying of government to change the rules so that competition is reduced or so that existing capabilities can be exploited more profitably.

In addition, of course, firms may eco-innovate since investments in R&D (and learning by working) which generate new sustainable technologies and processes may improve a firm's competitive position. Investments in new technology may also provide a hedge against uncertain and unforeseen risks (Slade and Bauen, 2009).

Similarly, Stenzel (2007) suggests that a firm's responses to the threat/opportunity of innovation and transition cannot be explained by systemic changes alone but needs to be complemented by an understanding of decision-making at the firm-level. As we have seen, for 'incumbent' firms innovation research and investment will tend to be incremental in nature. Incumbents tend to be good at doing innovative activity that builds on their existing technology portfolio, either where new technologies build on the same capabilities in a company, or where the resulting innovations serve the needs of an incumbent's established customers. Organizational capabilities are difficult to create and costly to adjust, a fact that favours incremental or sustaining innovations over radical or disrupting ones (Stenzel, 2007).

Successful innovation, says Porter and Stern (2001), depends not just on a favourable business environment but also on supportive company operating practices and strategies. Innovative capacity and corporate behaviour tend to move together and hence companies must adjust their competitive approaches to attain higher levels of innovative output. Porter and Stern (2001) employs the systems approach of national innovative capacity to examine the innovation process at the level of the firm and to make recommendations. The study characterises the primary shifts in corporate practices that are associated with countries that produce the highest output of international patents:

- First and foremost, firms in innovator countries have strategies that aim for unique products and processes rather than relying on low cost labour or natural resources.
- Firms in these countries are willing to invest heavily in R&D, and have moved beyond extensive use of technology licensing.
- Companies focus on building their own brands, controlling international distribution, and selling globally, all of which are complementary to innovation-based strategies.
- Firms from innovator countries engage in extensive training of employees, delegate authority down the organization, and make greater use of

incentive compensation than firms in countries with lower innovation output.

In addition to the above, contemporary systemic eco-innovation theory puts a greater emphasis than in the past on stakeholder participation and regulator/regulated relationship enhancement (Speirs et al., 2008). This is something that may become fundamental to the success of eco-innovation policy making as other guiding principles cover issues contrary to the typical aspirations of industry such as technology diversification and public policy intervention.

Innovation theory and remediation

Eco-innovations are all technologies and services which contribute to a better environment (Andersen, 2005). Two broad categories of eco-industry are identified: (i) pollution- and resource handling technologies and services; (ii) all technologies, products and services which are more environmentally benign than their relevant alternatives. (Kemp and Foxon, 2007) categorises 'Remediation & Clean-Up of Soil & Groundwater' as a specific eco-industry sub-sector. It is defined as the production of equipment, technology or specific materials, or the design, operation of systems or provision of other services to reduce the quantity of polluting materials in soil and water, including surface water, groundwater and sea water. It includes absorbents, chemicals and bio-remediators for cleaning-up, as well as cleaning-up systems (in situ or installed), emergency response and spill cleanup systems, water treatment and dredging of residues.

Note that the Technology Innovation workstream of the ESC project encompasses both environmental remediation and adaptation to climate change, and includes a particular focus on (i) the industrial exploitation of water arising from meeting the demand for energy goods and services and (ii) use and scarcity of potable water, especially the impact on energy demand arising from the need to pump, transport and/or desalinate water due to the impacts of climate change.

In Europe, the "Lisbon process" of 2000 heralded (at least in theory and intention) a new era of environmental policy where environmental protection systems alone were seen as insufficient for handling an increasingly complex set of challenges (Andersen, 2005). With the introduction of the 2004 European Environmental Technologies Action Plan (ETAP) promoting eco-innovation and the use of environmental technologies, for the first time there was an intention that environmental and innovation policies be aligned.

However, whilst the last decade may have seen a greater emphasis on the linkages between innovation theory and environmentally-oriented public and private sector activities, most of the research has tended to concentrate on the low carbon/renewable energy arena. The literature search for this report revealed very little that directly addresses innovation thinking and environmental remediation. According to Nentjes et al. (2007), much of the literature on the relation between pollution and innovation tends to concentrate on the ranking of different environmental policy instruments with respect to their incentives to innovate in advanced *abatement* technology as opposed to *remediation*. Carrión-Flores and Innes (2010), for example, examine the relationship between environmental innovation and air pollution targets (i.e. abatement). Moreover, where the focus is on remediation innovation, in Spira et al. (2006) for example, little or no use is made of a theoretical framework rooted in innovation thinking to assist the work. As noted, such an application has instead tended to be a feature of the energy sector, in particular the low carbon/renewables arena.

Clearly, remediation and energy generation differ in several obvious, 'high level' ways. Remediation activity is an energy consumer with its principal aim being the improvement of an impaired environment. The energy sector is an energy provider where a significant by-product may be environment-damaging emissions depending on the generation technology employed. Temporally and spatially, remediation goals are shorter term and more localised than the clean energy generation objectives of mitigating globally dispersible carbon emissions over a period of decades. At the regulatory and political level, remediation is generally less difficult to garner support for and to enforce. Society has been aware of non-greenhouse gas types of pollution and associated remediation for far longer than climate change and the potential responses to it.

Application of innovation theory to remediation

Despite significant differences, energy and remediation/adaptation share important common ground in terms of their relevance to environmental care and sustainability. Innovation theory has been successfully applied to the energy arena and might also be usefully applied to remediation and adaptation. Going forward, during the upcoming innovation workshop and thereafter, it is worth investigating how key concepts from innovation theory might be brought to bear on remediation and adaptation innovation. For example:

- To what extent is the market failure represented by IP inappropriability and knowledge spillover a barrier to remediation/adaptation innovation?
- Does so-called 'bounded rationality' cause potential remediation/adaptation innovators to 'satisfice' and settle for sub-optimal routines in a corporate system?
- How much does uncertainty in technological outcomes, in customer demand, and in the stability of the regulatory environment inhibit innovation?
- Have increasing returns and path dependency led to technological and systems inertia and lock-in? And what potential is there for radical, disruptive change as well as incremental innovation?
- What lessons can be drawn from comparisons of national innovative capacity in remediation/adaptation? How do actors, institutions and linkages compare?
- What additional impetus is required at what stages of the innovation chain (whether via corporate strategy or government policy or both)?
- To what extent could niche promotion and cumulation counter a potentially sub-optimal status quo?

Chapter 2 of this report noted the contribution of Bergek et al. (2008a) which defined a 6-stage method for TIS performance assessment. Whilst this work is more specifically directed at policymakers, it might be instructive to use at least some of its stages at the corporate level. The six stages of assessment are as follows:

- Define system taking into consideration the choices to be made between a knowledge field and product focus; breadth and depth; and the spatial domain.
- Identify the structural components of the TIS which include the actors, networks and institutions.
- Map the functional pattern of the TIS based on the seven functions (see Hekkert et al. (2006) and Bergek et al. (2008a)): knowledge development and diffusion, influence on direction of search, entrepreneurial

experimentation, market formation, legitimation, resource mobilization and development of positive externalities.

- Assess the functionality of the TIS and set process (policy) goals. This step is where the relative 'goodness' of the functional pattern is assessed.
- Identify inducement and blocking mechanisms.
- Specify key policy issues which aim to fix poor functionality by strengthening inducement mechanisms and weakening blocking mechanisms.

Some concluding and summarising observations

In the last two decades, the systemic nature of technological innovation, including eco-innovation, has been articulated by a number of related approaches. Notwithstanding differences in detail, all emphasise that innovation is a dynamic, systemic process, arising out of the interplay between actors and institutions, and involving both knowledge flows and market interactions in a context of inherent uncertainties.

One of the most persistent themes in modern innovation studies is the idea that innovation by firms cannot be understood purely in terms of independent decision-making at the level of the firm. Rather, innovation involves complex interactions between a firm and its environment, with the environment being seen on two different levels (Kemp, 2000). On one level, there are interactions between firms - between a firm and its network of customers and suppliers. The second level is wider, involving broader factors shaping the behaviour of firms: the social and cultural context, the institutional and organizational framework, infrastructures, the processes which create and distribute scientific knowledge, etc.

Thus, more recent perspectives on innovation structures and processes emphasise the systemic character of technological innovation. This helps to explain why technological change is often a very slow process and why it is difficult to influence (Hekkert et al., 2006). The rate and direction of change is not so much determined by the simple competition between different technologies, but also by the competition between various existing innovation systems, both fully developed and emerging ones. The inertia of technology-innovation system combinations is quite large, which can lead to a lock-in that results in relatively rigid technological trajectories.

Energy systems may exhibit a particularly acute form of lock-in (Unruh, 2000). As Gross (2008) emphasises, currently we are locked into a carbon intensive energy system and largely carbon intensive technologies. Assets are long lived and capital intensive, incumbent technologies have benefited from decades of development, and the system has co-evolved into compatible networks of fuels, end use devices, vehicles, delivery infrastructure and institutions. It is also argued that the locked-in system emerged before the carbon problem was recognised and/or low carbon alternatives could be promulgated.

Advances in innovation theory have afforded insights into the structures and processes of energy systems and have proposed theoretical approaches with which to further eco-innovation and the radical transition to more sustainable energy systems. By contrast, the relative paucity of literature addressing remediation/adaptation from the perspective of innovation theory suggests that more research in these areas could be equally valuable.

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