EPSRC Supergen XIV: WP 4.2

Delivery of Sustainable Hydrogen

Working Paper 1:

Models of Innovation, their Policy Implications and Hydrogen and Fuel Cells (HFCs) Literature

A Review

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1.0 Introduction

The EPSRC SUPERGEN XIV "Delivery of Sustainable Hydrogen" consortium brings together a multidisciplinary team of leading UK researchers with the aim of addressing both the scientific and the socio-economic challenges facing the development of hydrogen as an energy vector.

Within this broad multidisciplinary programme of research, Work Package 4.2 draws upon theoretical and methodological approaches from the fields of innovation studies and socio-technical transitions research, with the aim of providing both: i) insights for policy regarding the promotion and development of a low carbon economy; and ii) a robust empirically and theoretically grounded evidence base to underpin the sustainable innovation, knowledge transfer and the rapid commercialisation of hydrogen technologies.

This first working paper therefore provides a brief overview of the literature on theories of innovation, seeking to highlight the differing policy implications of the various conceptual models considered, before going on to explore how these various theories of innovation inform the empirical literature on hydrogen and fuel cells. t

The paper is structured as follows. Section 2 deals with linear models of innovation. Section 3 with systems models, Section 4 with innovation systems models, whilst Section 5 considers models of innovation dynamics from the field technological expectations. Finally Section 6 reviews a selection of key papers from the hydrogen and fuel cells innovation studies literature and illustrates how each relates to this broader theoretical landscape.

2.0 Linear Models of Innovation

A debate emerged in the 1960s and 1970s over the factors that are most influential in terms of the rate and direction of technological change (Dosi, 1982). An earlier school of thought from the 1930s and 1940s suggested that advances in science, so-called ‘technology push’, are most influential (Schumpeter, 1947). However, around the same time, another school of thought countered this with evidence of the strong impact of market demand on technological development (Nemet, 2009). By the 1980s, a number of researchers were suggesting that there is evidence for both of these linear processes (Mowery and Rosenberg, 1979; Rennings, 2000; Taylor, 2008). This combined approach is termed the ‘technology push-demand pull’ model. This so-called ‘linear model’ of innovation, which posits a straight developmental line from basic R&D to finished products, has since come to be regarded as an overly simplistic, linear heuristic. However, it nevertheless remains influential in some policy circles (Dosi, 1988; Chidamber and Kon, 1993; Kemp, 1997; Nemet, 2009).

2.1 Technology Push: Description

The technology-push argument suggests that advances in scientific understanding determine the rate and direction of innovation (Nemet, 2009). This linear model suggests that there is a progression of knowledge from basic science to applied research to product development and ultimately commercial products (Bush, 1945a, b; IIT, 1968). The technology push hypothesis further suggests that innovation originates from individual entrepreneurs or firms that are prepared to take financial risks with radically new product innovations (and/or process innovations) in the hope of gaining at least a temporary monopoly position (Coombs et al, 1987; Antonelli and de Liso, 2003).

2.1.1 Technology Push: Policy Implications of Theory

Policy instruments based on the technology push approach are illustrated in Figure 1. Public R&D funding, for example, is central to innovation policy based on the technology-push approach. This focus can help prevent underinvestment in R&D (Peters et al, 2012). Such an approach can also include tax credits for companies which invest in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects (Nemet, 2009). The theory behind the technology-push model also implies the need to identify, in the absence of demand, which emerging technologies to choose to spend R&D funds on.

Figure 1: Theoretical Approaches to Innovation and Associated Policy Measures

Theoretical Approach	**Associated Policy Measure**
Technology Push	Public R&D funding, tax credits for companies investing in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects.
Demand Pull	Tradable permits, feed-in tariffs, intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, taxes on competing technologies and command and control regulation inducing demand through standard setting.
National Systemss of Innovation (NSIs)	Investments in technological learning activities by institutions, the links amongst them as well as incentive structures and competencies avoiding low corporate R&D spending and low spending in terms of workforce skills.
Regional Systems of Innovation (RSIs)	Incentives and support schemes need to fit the functionality of the system as well as its phase of development (formative or growth phase). Recommendations include: support advocacy coalitions to overcome a weak legitimacy; create visions and strategies to guide the directions of search; support experiments and demonstration projects to create and diffuse new knowledge and reduce the risk of entrepreneurial experimentation. Other measures include: attractive regional tax and welfare arrangements and general economic development policies.
Sectoral Systems of Innovation (SSIs)	Invest generically and thematically in basic science and R&D. Foster application of knowledge. Improve science education and the stock of qualified scientists and engineers. Invest in technological product and process (TPP) and non-technological innovation. Support improved innovation management skills. Promote innovation culture and the networking or firms in clusters.
Technological Innovation Systems (TISs)	Support firms to increase and diffuse knowledge. Support experiments with new applications. Develop standards. Develop research and education policies. Supporting advocacy coalitions.
Strategic Niche Management (SNM)	Stimulate the co-evolution of supply and demand to produce desirable outcomes in the short- and long-term. Develop a portfolio of protected spaces for certain applications of a new technology.
Transition Management (TM) / Multi-level Perspective (MLP)	Employ joint decision-making and network management via ‘visions’ and ‘roadmaps’. Use problem structuring methods to deconflict alternate frames of reference. Use portfolio management, risk assessment, technology assessment (TA) and monitoring of effects to reduce uncertainties associated with long-term system effects of a technology. Also use flexible designs, adaptive management and the use of capital-extensive solutions with relatively short life times.
Enactors and Selectors	Policymakers should remain open to different options and progressively drop failing applications/technologies instead of picking winners.
Hype Cycles	Institutions should not invest in a particular technology solely on the basis of an upswing of hype. Conversely, institutions should not ignore a technology if it is not matching early over-expectations.

2.2 Demand Pull: Description

In the 1950s and 1960s, a number of academic studies suggested that, in fact, demand is a more significant driver of the rate and direction of innovation that technology *per se* (Nemet, 2009). Changes in market conditions accordingly create new investment opportunities for firms to help them satisfy new and unmet needs. Schmookler's work on investment, stocks, employment and inventive activity in the US railroad, refining, agriculture and paper-making industries in the late 19th and early 20th Centuries suggested a close link between the making of investments and subsequent patenting (Schmookler 1954, 1957, 1962), according to Coombs et al, (1987). In this way, Rosenberg (1969) suggests that demand "steers" firms to focus on certain technical problems.[1]

2.2.1 Demand Pull: Policy Implications of Theory

The kinds of market based instruments deployed by state institutions as part of demand-pull innovation policies include tradable permits, feed-in tariffs, intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, taxes on competing technologies and command and control regulation inducing demand through standard setting (Jaffe et al, 2002; Nemet, 2009). Demand-pull policies can help to lower the financial uncertainty of R&D investments via the creation of markets. Such policies may also compensate for competitive disadvantage from negative external effects (Peters et al, 2012).

3.0 Systems Models of Innovation

The debates in the 1960s and 1970s over the relative merits of the technology push and demand pull approaches to innovation suggested to some researchers that a new, more systematic perspective needed to be developed. In the 1960s, Freeman et al, (1963, 1965, 1968) undertook large-scale empirical studies of the innovation-diffusion process in the global electronics, plastics and chemical industries. These confirmed the early views of Schumpeter (1934) that markets are essentially dynamic and do not move towards stasis and equilibrium, as neoliberal economic theory predicts. This led to the conclusion for Freeman and other like-minded neo-Schumpeterian economists that innovation is absolutely crucial for firms. They must keep pace with other firms and continually move forward in search of competitive advantage. As Freeman (1974, 256) says: "[N]ot to innovate is to die". He similarly notes that because of the dynamic nature to markets, large firms will become trapped on an innovative treadmill (Freeman, 1974).

[1] Note that while Schmookler (1962, 1966) is typically quoted as the leading exponent of the demand pull hypothesis of innovation, he nevertheless believed that there are other determinants to inventive and innovative activity technology other than simply the demand of market (cf. Coombs et al, 1987).

In terms of innovation theory building at the macroeconomic level, the neo-Schumpeterians put forward advanced theoretical models all essentially based on Kuhn's (1962) work on 'paradigm shifts', the idea that the basic assumptions shared by scientists (so-called 'normal science') can eventually be overturned by a rival set of basic assumptions in an evolutionary way. The output of two key papers in innovation studies, Nelson and Winter (1982) and Dosi (1982) swiftly coalesce and become the 'Nelson-Winter-Dosi' model of innovation. Although macroeconomic in outlook, the 'Nelson-Winter-Dosi' model also points towards the need to understand microeconomic activity with its pronounced separation of the creation and the selection of innovation (Ehret, 2004).

With the groundwork laid for further theoretical evolution in innovation studies in the 1990s and 2000s, a typology of national, regional, sectoral and technological innovation system heuristics has emerged. Further insights in innovation studies are incorporated from elsewhere: evolutionary economics, 'path dependence' and 'path creation', science and technology studies (STS) and economic geography. With innovation studies moving further into the mainstream economic analysis in the 1990s, policymakers have increasingly taken note of the policy prescriptions of its leading researchers. Most recently, researchers are highlighting the need to strengthen conceptions of power, place and territory in these heuristics (Clark and Christopherson, 2009, Fløysand and Jakobsen, 2011; Truffer and Coenen, 2012).

3.1 National Systems of Innovation (NSIs): Description

The first approach in the typology of innovation systems shown in Figure 1 is National Systems of Innovation (NSIs). Since the neo-Schumpeterian revival in the 1960s, evolutionary economists (as well as economic geographers and others) have been interested in how certain nations might 'catch up' with others in terms of their economic development (Freeman et al, 1963, 1965, 1968; Rosenberg, 1976, 1982). In the context of concerns that globalisation potentially erodes nation-states' innovative capabilities, the neo-Schumpeterians proposed a "national innovation system" (NIS), or "national system of innovation" (NSI), a heuristic approach that stresses the importance of national comparative advantages (cf. List, 1841).

The NSI is defined as:

> "the networks of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies" (Freeman, 1987, 4)

Institutions including business firms, universities, other education and training institutions, and governments form a subsystem of the national economy where innovative activity is seen as the result of various organizations and institutions interacting making the institutional environment a key focus (Nelson, 1983; Lundvall, 1985; Freeman, 1987; Fagerberg, 2003; Balzat and Hanusch, 2004). The NSI approach therefore has a systemic view of innovation-diffusion based on non-linear and multi-disciplinary innovation processes (Abrunhosa, 2003). The NSI concept is first formerly introduced in the mid-1980s (Lundvall, 1985; Freeman, 1987; Dosi et al, 1988) and since then, the concept has been continuously refined (Lundvall, 1992; Nelson, 1993; Edquist, 1997; Fagerberg et al, 2007). However, as with the other innovation systems approaches described below, there have long been unresolved concerns with NSIs about where the boundaries lie for such systems (Kaufman and Tödtling, 2001; Carlsson et al, 2002). This is especially the case given the ability of certain institutions and actor-networks, like transnational corporations (TNCs), to operate in a variety countries and at a number of scales.

3.1.1 National Systems of Innovation (NSIs): Policy Implications of Theory

In policy terms, an NSI approach stresses the more intangible investments in technological learning activities by institutions, the links amongst them as well as incentive structures and competencies (Patel and Pavitt, 1994). Such activity is designed to avoid low corporate R&D spending and low spending in terms of workforce skills. Both of these help determine long-term economic growth rates and national demand for basic research and associated training activities (Patel and Pavitt, 1994).

3.2 Regional Systems of Innovation (RSIs): Description

A lack of regional innovation policies in centralised Western economies spurred the development of the second leading heuristic in the typology of innovation system approaches shown in Figure 1: 'regional innovation systems' (RISs) or 'regional systems of innovation' (RSIs), which first appeared in the early 1990s. According to Lundvall (2007, 6) this approach: "is the one that resembles most original versions of the national system of innovation". It attempts to define where an innovation system is localised in more precise geographical terms than a NSI (Park, 2009). Weber (2007, 114) cites Braczyk et al (1998) when he defines the RSI approach:

> "[It] recognises … the spatial and cultural proximity as relevant elements of the economic analysis of innovation, thus drawing the attention of the local and regional 'tissue' in which innovations are embedded."

Some of the first researchers to put forward the RSI concept were economic geographers in the United States, e.g. Saxenian (1985, 1994) and Audretsch and Feldman (1996). They analysed several geographically localised sectors including Silicon Valley in California (Park, 2009). The central role played by the interaction between universities, firms and governments in regional and local knowledge agglomeration is emphasised in particular by Ohmae (1993), Braczyk et al (1997, 1998), Keeble (1997), Etzkowitz and Leydesdorff (2000) and Cooke (2001) and Cooke et al (1997, 2007).

3.2.1 Regional Systems of Innovation (RSIs): Policy Implications of Theory

An RSI approach to innovation policy suggests a focus on the entrepreneurial culture and the level of innovation activity in a region (Fritsch and Mueller, 2007). While overarching national policies will be important, regional development strategies and policy measures need to account for region-specific factors. Factors stimulating entrepreneurship, like regional tax and welfare arrangements as well as general economic development policies are thought to be important (Van Stel and Stunnenberg, 2004). Large businesses can also make a significant contribution to regional development as incubators for spin-offs (Klepper and Sleeper, 2005; Agarwal et al, 2004; Klepper, 2001; Sorenson, 2003). However, precisely how to achieve a balanced combinations of both small businesses and incumbent enterprises remains "still rather unclear" in policy terms according to Fritsch and Mueller (2007, 312).

3.3 Sectoral Systems of Innovation (SSIs): Description

The Italian economists Stefano Breschi and Franco Malerba first refer to the third leading approach in the typology of innovation systems approaches shown in Figure 1: "sectoral innovation systems" (SISs) (Breschi and Malerba, 1997, 130), later known as 'sectoral systems of innovation' (SSIs). SSIs represent a significant advance in understanding of the large and persistent differences across industries and sectors in the ways that innovation and knowledge diffusion takes place (Fagerberg, 2003).

Breschi and Malerba (1997, 131) define an SSI as a:

> "[S]ystem (group) of firms active in developing and making a sector's products and in generating and utilizing a sector's technologies; such a system of firms is related in two different ways: through processes of interaction and cooperation in artefact-technology development and through processes of competition and selection in innovative and market activities."

Here, the three major functional components of a SSI are the knowledge base, actors and networks, and sectoral institutions and they evolve in a co-evolutionary fashion, i.e. each exerts selective pressures on the other, thus affecting each other's evolution (Nelson, 1994). The central actors are private firms and the key concern is the overall dynamics of their population in terms of entrants to and exits from the industry. The geographical boundaries analysed are the same as those in the NSI and RSI approaches (Breschi and Malerba, 1997; Breschi, 2000). An SSI is an innovation system (IS) approach that evolves from earlier research work into Dosi's (1982, 1988) ideas about technological regimes (Malerba, 1992; Malerba and Orsenigo, 1990, 1993, 1995, 1996, 1997; Breschi, 1995).

3.3.1 Sectoral Systems of Innovation (SSIs): Policy Implications of Theory

According to Malerba (2002, 29), policymakers pursuing an SSI approach need to:

> "[F]acilitate the self-organisation of the sectoral innovation system within the relevant policy domain"

This involves policy measures on a number of fronts including prioritising investment into basic science and R&D activities, as with other innovation studies approaches. Such broad measures could also include generic and thematic research funding programmes, bridging/linking policies to foster the application of knowledge, and improving science education and the stock of qualified scientists and engineers (Reid and Miedzinski, 2008).

Specifically in terms of innovation policy, an SSI approach suggests increasing the quantity and efficiency of innovation activities in enterprises, measures boosting investment invest in technological product and process (TPP) and non-technological innovation, support for improved innovation management skills and the promotion of innovation culture (Reid and Miedzinski, 2008). Regarding sectoral innovation policy, measures include improving the organisation of the sectoral innovation system (networks, etc.), increasing the understanding of sectoral-specific drivers and barriers, tailoring general measures to sectoral needs or launch sectoral innovation policy measures, and improving the institutional conditions regulations, IPR, etc.) specific to the sector (Reid and Miedzinski, 2008). Lastly, where the sector is showing signs of spatial clustering, policymakers can attempt to strengthen the linkages between the enterprises and related organisations of a cluster with a view to increasing joint R&D, innovation, export, training, etc. activities and identify and remedy specific institutional, framework, etc. barriers to the development of the cluster (Reid and Miedzinski, 2008).

3.4 Technological Innovation Systems (TISs): Description

The fourth heuristic from innovation studies shown in Figure 1's typology is Technology Innovation Systems (TISs). These were originally referred to as Technology Systems (TSs) (Carlsson and Stankiewicz, 1991; Carlsson, 1995, 1997; Freeman, 1995) and more recently are known as Technology-Specific Innovation Systems (TSISs) (Hekkert et al, 2007; Suurs, 2009). The developers of the TIS concept focus on internal system dynamics and especially the potential for positive feedback (Bergek, 2002; Jacobsson and Bergek, 2004; Negro et al, 2007, 2008). Proponents do not feel that the boosting of knowledge flows, as in the SIS approach, is sufficient, in of itself, to bring about technological change and economic growth. Knowledge created in the innovation process, it is felt, must be exploited to give rise to new business opportunities. For this reason, actors (institutions) are now regarded as key sources of innovation (Carlsson and Stankiewicz, 1991, 111):

> "[TSs] are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks. In the presence of an entrepreneur and sufficient critical mass, such networks can be transformed into development blocks, i.e. synergistic clusters of firms and technologies within an industry or a group of industries."

An approach related to TISs has since emerged from this literature and is called the 'functions of innovation systems'. Ever since Carlsson and Stankiewicz (1991) introduced the concept of a Technological System (TS), an increasing number of innovation studies researchers have focused on internal system dynamics. A recurring theme within these studies is the notion of cumulative causation between systems functions – market formation, entrepreneurial experimentation, influence on the direction of search, resource mobilisation, knowledge development and legitimation – all of which are closely linked to the earlier idea of virtuous and vicious feedback circles.

3.4.1 Technological Innovation Systems (TISs): Policy Implications of Theory

In terms of policy, Bergek et al (2008) suggest that the healthy feedback between system functions is often impeded by 'blocking mechanisms'. These include uncertainties of needs among potential customers, inadequate knowledge of relations between investments and benefits, lack of capability and poor articulation of demand, lack of standards, few relevant university programmes for skills and a weak advocacy coalition. Remedying these deficits in policy terms involves increasing user capability, supporting users to increase and diffuse knowledge, supporting experiments with new applications, developing standards, altering research and education and supporting an advocacy coalition (Bergek et al, 2008).

4.0 Systems Innovation Models

While the overall Innovation Systems (ISs) approaches were evolving into the typology outlined above, a new approach to innovation began to emerge in the early 1990s. 'Systems Innovation' (SI) models are similarly heuristic approaches, but instead are based on the concept of sustainability transitions, i.e. normative shifts towards the development of more sustainable technologies. It is a hybrid approach that draws on both Science and Technology Studies (STS) and Innovation Studies. An initial approach known as Constructive Technological Assessment (CTA) helped to pave the way for another evolutionary perspective, Strategic Niche Management (SNM), in which government policymakers must make strategic judgements about which technologies to develop. They are encouraged to do this via the technological assessment of technical feasibility, economic opportunities, user demand and competitive advantage over alternative technologies (Kemp, 1994; Kemp et al, 1998). The focus in the literature is on public-private sector cooperation that may shape the future direction for so-called 'pathway technologies'.

By the late 1990s, the SNM approach evolved into another potentially powerful heuristic for researchers and policymakers known as the 'Kemp-Geels model'. This approach to technological transitions, especially in moves towards more sustainable energy, combines the work of two Dutch researchers, René Kemp, an evolutionary economist and developer of the Transition Management (TM) approach, and Frank Geels, a science philosopher and historian, who expanded Kemp's TM model into the Multi-level Perspective (MLP). All three of these models – SNM, TM and MLP – are described below along with their policy implications.

4.1 Strategic Niche Management (SNM): Description

SNM, shown in Figure 1's typology, examines the social, economic, legal, cultural, and political factors that create conflict with the introduction and expansion of new technologies (Kemp, 1994; Kemp et al, 1998). It works to establish a niche in which new technological factors and societal factors can develop and advance together. Park (2009, 70) points out that:

> "From the viewpoint of the technology supplier, the innovation subjects (the technical community developing and supporting specific technologies) that strategically foster new technologies in the niche carry out 'technology learning' activities. They also carry out

activities to obtain socio-political legitimacy and cognitive legitimacy, which over time may enable their technologies to become the dominant design and socially legitimate, and form policies that support the technologies they are developing."

Because of the wide range of socio-technical actors and structures, SNM focuses on potential conflicts when introducing new technologies, a focus that is highly relevant to the development of many radical technologies, including hydrogen.

4.1.1 Strategic Niche Management (SNM): Policy Implications

With SNM, policymakers need to stimulate the co-evolution of supply and demand to produce desirable outcomes in the short- and long-term. This will not be achieved by laying down requirements, but rather via process management to help steer and keep sociotechnical change on track (Kemp et al, 1998). Instead, SNM offers a concentrated policy effort to develop protected spaces for certain applications of a new technology. This gives it a chance to develop from a demonstration project to one that is actually in use (Kemp et al, 1998).

This approach is linked to the proliferation of a range of technological niches. Some of these survive, establish themselves and even come to shape the selection environment for others – so-called technological regimes - but then they lose their niche protection:

> "Once the technology is sufficiently developed in terms of user needs, and broader use is achieved through learning processes and adaptations in the selection environment, initial protection may be withdrawn in a controlled way." (Kemp et al, 1998, 185)

4.2 Transition Management (TM) / Multi-level Perspective (MLP): Description

Based on the SNM approach, Transition Management (TM) is a co-evolutionary heuristic that advocates increasing returns and the avoidance of path dependencies. TM emerges largely from the work of Kemp (Kemp, 1994; Kemp and Soete, 1992) and his ideas about creating a more sustainable energy system (work which remains highly relevant to current thinking about hydrogen transitions). Kemp (1994, 1997) and Rip and Kemp (1998) tackle radical system change – or system transitions - in a way that innovation studies does not do with its focus on incremental shifts. Kemp (1994) recognises that socio-technical barriers need to be overcome in order to bring about the kinds of normative technological changes that policymakers seek in an era of sustainable development. Kemp develops the concept of a 'technological regime' which he uses to explain how a 'transition' involves a shift from one regime to another. Kemp examines the transformation of existing large-scale technologies (cf. Hughes, 1986) and proposes a model of TM that has a much longer time frame and a wider analytical scope than CTA (Kemp et al, 1998; Rip and Kemp, 1998).

Advancing on Kemp's socio-technical systems perspective, Geels (2002, 2004) puts forward his own more advanced, unified theory that claims to provide a better understanding of technological changes and transitions in terms of both the techno-economic aspects and the social aspects. In proposing a heuristic model of socio-technical system transitions, which he calls the Multi-level Perspective (MLP) (Geels, 2002, 2004), Geels (2004) critiques the shortcomings of SISs. The MLP is essentially a more detailed version of Kemp's TM approach and both models are now termed the 'Kemp-Geels model' both of which are bracketed together in Figure 1. The one essential difference between Kemp and Geels' models is that the latter has two transition levels – technological niches and socio-technical regimes - instead of three.

4.2.1 TM & MLP: Policy Implications of Theory

TM aims to show policymakers how they might 'steer' technological change in a normative fashion. The literature suggests that governments should utilise available policy levers to achieve its ends and avoid transition failures. Given the failure of top-down, command-and-control policies in the past, this, it is suggested, can only be achieved via joint decision-making and network management where visions and roadmaps hold together networks of stakeholders in a particular technology. Kemp et al (2007) suggest that problem-structuring methods (cf. Mingers and Rosenhead, 2001) may help stakeholders with conflicting frames of reference to discuss shared problem definitions about unsustainable aspects of current systems. Portfolio management overcomes the dilemma of which technologies to support. From there, risk assessment, technology assessment and monitoring of effects can help with the uncertainty associated with long-term system effects of a technology. Kemp et al (2007) also suggest that if reactions are required to keep a technological pathway on track this can be aided via flexible designs (Verganti, 1999), adaptive management (c.f. Lee, 1993; Walker et al., 2001), the use of portfolios and the use of capital-extensive solutions with relatively short life times (Collingridge, 1980). Carrot and stick approaches, as seen previously with CTA, e.g. grants for technology testing, are also advocated with the Kemp-Geels approach.

5.0 Models of Technological Expectations

Technological promises or expectations about future technological performance have an important role to play in mobilizing the variety of resources needed for advancing any new technology (Alkemade and Suurs, 2012). Expectations and visions about the future performance of a technology are felt to be a resource in themselves that can help create and bolster niches that protect an application in the early stages of research, development and demonstration (RD&D) from the full rigours of the marketplace (Geels and Smit, 2000). Heuristic models of expectations that stakeholders have with regard to particular technologies are traceable back to early work on rates of technological diffusion (Rogers, 1962; Freeman et al, 1963, 1965). Beyond visions and roadmaps of a technology's future - a key tool for those working with technological expectations – there are two leading heuristic models in this area: technological hype cycles and 'enactors and selectors'.

5.1 Enactors and Selectors Model

Different technologies are adopted – or diffuse – at differential rates between different places (Rogers, 1962; Freeman et al, 1963, 1965). Neoclassical economics regards such outcomes at the micro and macro levels of actors and economies respectively as 'irrational'. Rosenberg (1976), however, built on early diffusion research and suggested that two factors at the micro level, in particular, that might better help explain it. Firstly, there are varying technological promises (or expectations) made by entrepreneurs, and, secondly, these promises then intersect with the different levels of risk aversion held by decision-makers who may or may not fund further development of the technology.

A social constructivist 'sociology of expectations' (SOE) literature has since developed in this area (cf. van Lente, 1993; Garud and Ahlstrom, 1997; van Lente and Rip, 1998; Borup et al, 2006) in which Rosenberg's idealized vision of the interplay between entrepreneurs and decision-makers has been further refined into a heuristic model known as 'arenas of expectations' which involves 'enactors' (entrepreneurs) and 'selectors' (decision-makers) as its protagonists. As before, the technological promises being made by enactors are continually being constrained and revised by the financial risk aversion of selectors but this is now conceived as taking place within 'arenas of expectations'. It is also worth noting that arenas of expectations are not regarded as level playing fields for actors. Negotiations between them are thought to be subject to power relations as characterised in Latour's (1987) concept of 'trials of strength' where actor-networks form and try to build a case for a technology by building political legitimacy through the enrolling, aligning and coordinating of other enactors and resources (van Lente, 2012; Alkemade and Suurs, 2012). Visions and roadmaps of potential future developments for a technology are thus considered especially powerful tools for enactors and selectors given their dual ability to assist enactors - by enrolling, aligning and coordinating the support and resources of others – and yet also constrain them (Eames et al, 2006). Expectations thus need to be seen as a key means of linking the micro-economic perspective of actors to the macro-economic perspective of innovation systems, particularly technological innovation systems (TISs). Expectations stimulate the fulfillment of other key processes in technological innovation systems such as the mobilization of resources. This role of expectations is strongest in the earliest phases of the life cycle of a technology which is characterized by uncertainty regarding future performance and possible applications.

5.1.1 Policy Implications of Enactors and Selectors Model

In policy terms, later-stage developments for many technologies require a protective niche so that final research, development and demonstration (RD&D) can be completed and market demand can be met or developed. Very strong positive expectations can assist public and private agencies to create and maintain such technological niches and as such, strong expectations may well ensure that a technology is more positively evaluated (Konrad, 2006; Eames et al, 2006; Alkemade and Suurs, 2012). Shared, or aligned, expectations may reduce the financial uncertainty perceived by selectors (decision-makers). This guides the process of technological change in ways that have been formalized in the private and public sectors of many developed nations via technological foresight/vision reports (e.g. roadmaps) which are now seen as a standard policy tool.

5.2 Hype Cycles

Over time, collective negotiations over technological promises, or expectations, have been shown to lead to so-called 'hype cycles' – rises and falls in the shared expectations actors have in a technology or group of technologies (Alkemade and Suurs, 2012). Heuristic modelling of this process, also termed the Gartner hype cycle, has been developed commercially by the US information technology research and advisory company, Gartner, Inc. The Gartner hype cycle characterizes the way emerging technologies move from a period of user and media over-enthusiasm for a technology to swift disillusionment with it. However, ultimately, an understanding of a technology's position in the marketplace emerges (Fenn and Raskino, 2008). The Gartner hype cycle attempts to offer a more detailed description of the early stages seen in the broader S-curve model of technological diffusion pioneered by Rogers (1962).

5.2.1 Policy Implications of Hype Cycles

In practical terms, hype cycles allow a comparison to be made of a particular technology's evolution against Gartner's generic analysis of how a technology is maturing. As a policy tool, hype cycles suggest very careful judgements need to be made by entrepreneurs and their investors. For the entrepreneurial institutions, legitimacy is key to raising further investment funds and building markets. Not being able to deliver on technological promises will seriously undermine credibility and investor confidence. For investing institutions, the logic of hype cycles suggests that they should not invest in a particular technology solely on the basis of an upswing of hype. Conversely, these same institutions should also not ignore a technology if it is not matching early over-expectations (Fenn and Raskino, 2008). The applications of many new technologies take longer than initially expected to successfully get through the design, prototyping and manufacturing stages.

6.0 Innovation Models and HFC Literature

Having covered a range of theoretical models of innovation from the linear heuristics of the 1950s to the non-linear, systems approaches of the late 20^{th} Century, Figure 2 matches these to a selection of HFC studies from the 1990s to the present. The diagram shows that the total number of studies is not large for these particular approaches. However, for other innovation perspectives not covered here, like technological assessment (TA) for example, the volume of HFC studies is greater.

6.1 Linear Models

Of the linear approaches to innovation identified in Figure 1, Figure 2 shows that HFC studies exist which are 'technology push' only, 'demand pull' only and a combination of the two. These types of studies are outlined below.

6.1.1 Technology Push and HFC Literature

In the selected literature on HFCs shown in Figure 2, two references fall into the first category of 'technology push' alone (Bockris, 2002; Al-Ahmed et al, 2010). The analysis here of the need for, and the means to, achieving a 'hydrogen economy' (Bockris, 2002) or a 'hydrogen highway' (Al-Ahmed et al, 2010) is strong on technological determinism, but lacking in an appraisal of the demand factors that can allow state agencies to help spur innovation (while working in partnership with private enterprise). These studies also do not assess the socioeconomic or sociotechnical barriers that can hinder the development of a hydrogen economy or highway.

6.1.2 Demand Pull and HFC Literature

The second category in Figure 2 covers studies which solely analyse policies based on a demand pull approach for HFCs. The assessment by Chen et al (2011) of the optimal

Figure 2: Innovation Models and Hydrogen and Fuel Cell (HFC) Literature

Innovation Model	**Literature**
Technology Push	Al-Ahmed et al (2010), Bockris (2002)
Demand Pull	Chen et al (2011)
Technology Push & Demand Pull	Brey et al (2007), Dunn (2002), Gutierrez-Martin & Guerrero-Hernandez (2012), Haeseldonckx and D'haeseleer (2011), Hugo et al (2005), Murray et al (2007), Rifkin (2002)
Innovation Systems (general)	Bleischwitz and Bader (2010), Bleischwitz et al (2010), Brown et al (2007), Ekins and Hughes (2007), Foxon et al (2005), Markand and Truffer (2008)
National Systems of Innovation (NSIs)	Haslam et al (2012), Mans et al (2008), Park (2009)
Regional Systems of Innovation (RSIs)	Bleischwitz et al (2008), Godoe and Nygaard (2004), Holbrook et al (2010), McDowall (2010), Madsen and Andersen (2010)
Sectoral Systems of Innovation (SSIs)	Choi et al (2011)
Technological Innovation Systems (TISs) / Functions of Innovation Systems	Bleischwitz et al (2008), Madsen and Andersen (2010), Markand and Truffer (2008), Musiolik and Markard (2011), Suurs et al (2009)
Strategic Niche Management (SNM)	Agnolucci and Ekins (2007), Ehret and Dignum (2012), Park (2010, 2011)
Transition Management (TM) / Multi-level Perspective (MLP)	van den Bosch et al (2005), Farla et al (2011), Hodson et al (2010), Kohler et al (2010)
Expectations	Eames and McDowall (2005, 2010), Hodson and Marvin (2005, 2010), McDowall (2012), McDowall and Eames (2004, 2006)
Enactors and Selectors	Bakker (2010b, 2011), Bakker et al (2010, 2012)
Hype Cycles	Alkemade and Suurs (2012), Bakker (2010a, 2011), Ruef and Markand (2010)

patent strategy for the global fuel cell industry reflects demand-pull policy advice regarding securing intellectual property protection, a measure identified in Figure 1.

6.1.3 Technology Push-Demand Pull and HFC Literature

The third category in Figure 2 refers to research reflecting both technology push and demand pull policy measures. All are strongly technologically deterministic about what HFCs may achieve in rolled out into the marketplace, but there is also a recognition of the socio-economic constraints of external changes in demand. In policy terms, Dunn (2002), for example, advocates state involvement in R&D for HFCs (technology push) and public-private partnerships in greening energy infrastructure (demand pull). At the same time, Dunn (2002) recognises the importance of potential socio-technical barriers to HFC uptake such as the public acceptance of these technologies.

6.2 Innovation Systems (General) and HFC Literature

The fourth category in Figure 2 covers HFC literature from a general Innovation Systems (IS) perspective, i.e. not specifically NSIs, RSIs, SSIs or TISs. These studies refer to innovation studies approaches generically. Those with case studies, like Markand and Truffer (2008) and Brown et al (2007), present data within a systems framework consistent with the work of IS researchers like Jacobsson and Bergek (2004).

6.2.1 National Systems of Innovation (NSIs) and HFC Literature

In the NSI category, the study of Mans et al (2008, 1384) offers an analysis of self-declared HFC 'clusters' within an NSI framework for the Netherlands which tallies with the kind of policy measures outlined in Figure 1:

> "Just labelling a cluster is not expected to be enough … For policymakers, this suggests that cluster policies … [need] to include incentives for the cluster partners to actually function as a cluster … Stimulating cooperation can be done by anticipating on initiatives arising in the market, and subsequently facilitating these initiatives by assuming the role of broker in the exchange of knowledge."

This point is precisely in line with the approach pursued more widely in Supergen XIV's WP4.2 which gauges the relative health of the national hydrogen and fuel cells innovation systems in the UK and Germany.

6.2.2 Regional Systems of Innovation (RSIs) and HFC Literature

The RSI category in Figure 2 contains HFC literature that includes Bleischwitz et al's (2008) focus on encouraging the healthy growth of European HFC clusters. This is advocated via the boosting of functional activities such as knowledge transfer and coordination. In terms of the economic geography of these HFC clusters in Europe, Madsen and Andersen (2010, 5380) report that: "geography and cluster aspects seem to matter in establishing a European H2FC technology innovation system". They also claim that regions which are active in pursuing HFC deployment are generally innovative and, somewhat counter-intuitively, that there is only a weak connection between existing hydrogen-production capacities and pipeline infrastructure and the early adoption of HFCs in the regions (Madsen and Andersen, 2010). Such insights from an IS approach matter to policymakers who need to decide both how and *where* to deploy their resources to encourage the growth of a healthy HFC innovation system.[2]

6.2.3 Sectoral Systems of Innovation (SSIs) and HFC Literature

The SSI literature highlighted in Figure 2 includes Choi et al's (2011) study of the South Korean HFC SIS. They point out that Malerba's (2002, 2004) identification of three key components of an SSI: knowledge and technologies, actors and networks, and institutions, can be regarded as a 'knowledge network' which acts as a precursor to an emerging economic sector like HFCs. In this, as with policy for NSIs and RSIs, Choi et al (2011) see a dual role for government in terms of being an investor in R&D and a facilitator/organiser of knowledge networks.

6.2.4 Technological Innovation Systems (TISs) and HFC Literature

In the TIS category in Figure 2, Suurs et al (2009) pursue an analysis of the Dutch HFC sector between 2004 and 2008. They focus their analysis on the drivers of and barriers to change for actors, institutions and technologies within the sector and claim that the linear model of innovation is still the dominant approach for many. However, to advance with HFCs in the Netherlands, Suurs et al (2009) suggest parallel system developments in policy are more appropriate: develop visions, use technology assessment (TA) in conjunction with policy development, facilitate learning and communication, procure HFC technologies and regulate niche markets.

[2] It is worth noting that the RSI approach is generally used as an analytical tool to direct regional innovation policy. It offers a more holistic view on a region's production structure than the cluster approach (Bleischwitz et al, 2008).

6.3 Systems Innovation and HFC Literature

Figure 1 showed that, despite the theoretical similarities between the SI approaches of Strategic Niche Management (SNM), Transition Management (TM) and the Multi-level Perspective (MLP), there are significant policy differences between SNM and TM/MLP. More detail of these differences, in terms of the HFC studies based on these approaches, is given in the next two sub-sections below.

6.3.1 Strategic Niche Management (SNM) and HFC Literature

In Figure 2, Park's (2011) study of Iceland's hydrogen energy policy development is undertaken with SNM's sociotechnical approach. Because Park knows *post hoc* that certain straightforward technology choices were made in favour of HFCs in the 1990s, there is relatively little elaboration on the state's role in renewable energy technology selection and how it maintained its portfolio of niche technologies, something advocated in SNM theory. Instead, Park enlarges upon some of the policy instruments also associated with TM/MLP - visions and expectations, network development and alignment, policy-making and negotiation - as being key areas for state agencies and other stakeholders to be involved in. Just in terms of visions and expectations, for example, Park (2009, 10452) notes that "Iceland aimed to be a 'global exemplar'" in HFCs, an aspiration which, for a variety of reasons, has so far not come to pass.

6.3.2 Transition Management (TM), Multi-level Perspective (MLP) & HFC Literature

In Figure 2, van den Bosch et al's (2005, 1034) TM study of bottom-up, civic initiatives for fuel cells in transport in Rotterdam found that: "incremental, feasible innovation steps, which are widely supported by stakeholders … are more effective in terms of budget, time and stakeholder commitment. … small steps encourage learning-by-doing … an important characteristic of transitions". van den Bosch et al (2005, 1034) conclude that:

> "a long-term vision, commitment and a pro-active role of both industry and (local) government are crucial in starting transitions or system innovations. Furthermore, there might be a challenging role for universities and other independent institutes in facilitating stakeholder interactions and mobilizing stakeholders to set up transition projects."

Linked to this, is Farla et al's (2011, 16) TM study on transitions in Dutch mobility, which concludes in cautionary terms for policymakers that:

> “The transition management idea to execute small-scale experiments which can be developed into mass markets, seems to be rather difficult for transition paths in which the build-up of new physical infrastructures plays an important role. One reason is the need for large and typically irreversible investments, even for small-scale experiments. This seems to hinder the involvement of small entrepreneurs and newcomers.”

However, Köhler et al (2010), using an adapted integrated transport policy assessment model (ASTRA) and a transitions approach, report the reverse of this, stating: “the provision of a hydrogen distribution (as well as production) infrastructure is not a major economic barrier to the adoption of hydrogen vehicles”.

6.4 Expectations and HFC Literature

Research into technological expectations for hydrogen and fuel cells has been developed using a sociotechnical approach. This combines insights from the Multi-level perspective (MLP) heuristic with those from the Sociology of Expectations (SOE) literature (McDowall and Eames, 2004, 2006; Eames and McDowall, 2005; McDowall, 2012). At its heart, this work suggests that:

> "It is expectations about, and visions of, the future of hydrogen that are currently driving investment and research" (Eames and McDowall, 2010, 95).

Through their forecasting work done for the UKSHEC project (McDowall and Eames, 2004, 2006; Eames and McDowall, 2005), Eames and McDowall (2010) have identified four scenarios each of which would lead to the greater use of hydrogen and fuel cell technologies in a national energy economy. Each scenario entails different policy implications for national and regional governance structures and, as the SOE literature makes clear, each scenario is contested by rival stakeholder groups who struggle to build legitimacy for their own preferred vision.

A leading potential weakness of this work stems from the aspatial nature of the MLP heuristic and the Sociology of Expectations literature. Both suggest that, in the case of hydrogen and fuel cell innovation, this could take place anywhere in economic space. Empirical case studies show that this is not the case given the uneven distribution of resources. Instead, place-specific expectations for hydrogen and fuel cells held by actors and institutions have been investigated by Eames et al (2006) and Hodson and Marvin

(2005, 2010) which makes use of a geographically-specific typology of where hydrogen and fuel cell innovation typically occurs (Hodson et al, 2008).

6.4.1 Enactors and Selectors and HFC Literature

In a study of competing expectations within a niche community of actors developing hydrogen vehicles, Bakker (2011) uses Garud and Ahlstrom's, (1997) quasi-evolutionary heuristic model of innovation known as 'enactors and selectors' to address the nature of competition between different technological options. In terms of making policy judgements about the competing performances of different technological options, Bakker et al (2012) use a case study of the US Department of Energy's hydrogen and fuel cells programme. They conclude that: "For a contested path or sociotechnical vision, the process of technology selection is thus not so much one of picking winners, but rather one of dropping losers." (Bakker et al, 2012, 1070)

6.4.2 Hype Cycles and HFC Literature

In their case study of stationary fuel cells in Germany, Ruef and Markand (2010) observe how media attention increased strongly at the end of the 1990s at a time when highly optimistic expectations about the short-term prospects for commercialising stationary fuel cells were being made by proponents. As Bakker (2010) notes in the case of hydrogen and fuel cell automobility, the original equipment manufacturers (OEMs) are deliberately involved in the hyping process which is necessary to attract attention, create legitimacy and so find further funding. The hype in stationary fuel cells peaked in 2001 at which point public interest evaporated. Ruef and Markand (2010) report that expectations were then adjusted significantly but innovation activities nevertheless continued after the peak. Ruef and Markand (2010) suggest three reasons for this:

i) attention and expectation cycles may coincide but are not necessarily coupled,
ii) some types of expectations may be sharply adjusted after hype while others remain unchanged,
iii) the effect of disappointments on the innovation process also depends on structural developments in the field.

As the previous section makes clear, Bakker (2010, 2011) draws on the sociology of expectations literature to explain the role of expectations in the innovation process. This approach makes the role of hype in innovation processes more explicit and points to a particular policy conclusion:

> "Without neglecting the positive outcomes of hype on public and private funding for R&D efforts, more modest promises could serve the development of sustainable mobility better. Be it for the revival of hydrogen or the current surge of battery-electric vehicles, for policy makers the challenge is to remain open to different options instead of following hypes as they come and go." (Bakker, 2010, 6544)

Finally, Alkemade and Suurs' (2012) study of the patterns of expectations that surround three renewable technologies - biofuels, hydrogen and natural gas powering sustainable mobility in the Netherlands – highlights the role of hype-cycled expectations within the technological innovation systems (TIS) heuristic. They Alkemade and Suurs' (2012, 452) report that:

> "the expectation dynamics for hydrogen as a transport fuel ... shows a pattern with first a large increase in positive expectations and a subsequent decrease, an indicator for hype cycle dynamics ... [but] the hydrogen system is not yet ready to move to the next stage of development, the stage of commercialisation (of a dominant design)."

More broadly, this research suggests that hype cycles offer insights into the dynamic changes taking place within a technological innovation system as it evolves. Alkemade and Suurs' (2012) conclude that foresight and scenario studies based upon such innovation dynamics – like the hydrogen and fuel cell forecasting work done for UKSHEC by Eames and McDowall (2005) – have particular utility for policymakers.

7.0 Conclusion

The aim of Supergen XIV's Work Package 4.2 is to identify theoretically informed recommendations regarding the major long-term socio-technical barriers that need to be overcome when moving towards a hydrogen economy. In reviewing the literature on theories of innovation, related innovation and energy policies, and how these can be applied to hydrogen and fuel cells (HFCs), this first working paper has laid the groundwork for the case-study-led analysis of the second working paper.

In terms of finding a successful 'theory of agency' for innovation (cf. Giddens, 1979), this literature review suggests that a combined use of three approaches offers key insights into a co-evolutionary, enacted, relational, and interactional view of the nature of innovation:

i) the technological innovation systems' (TISs) heuristic,

ii) the functions of innovation systems approach, and
iii) the sociology of expectations (SOE) literature.

This suggests that innovation is a quasi-evolutionary process centred on the learning that takes place inside and between institutions. To a degree it may be able to be directed at the micro-level by the strategic participation of individual institutions in actor-networks, but at the macro-level the kind of collective activity required to bring about significant infrastructural investments requires the long-term alignment of these actor-networks behind guiding visions of the future which, despite the peaks and troughs in hype cycles in different territories and at different time, continues apace in the case of the global hydrogen and fuel cell technological innovation system (McDowall, 2012).

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