Supporting renewable energy in Latin America and the Caribbean: lessons to learn from innovation theory

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Introduction

Theoretical approaches to innovation have evolved considerably from the linear models proposed in the first half of the twentieth century. Contemporary theories of ‘ innovation systems’ are highly pertinent to the energy sector, yet the policy debate surrounding renewable energy is still influenced by early linear concepts and focussed on addressing market failures – ignoring the importance of wider ‘system failures’. In addition, innovation theory has, for the most part, been developed and applied in the context of OECD countries, with relatively little consideration of the differing needs, capabilities, barriers and opportunities for innovation in developing countries.

This working paper provides an overview of the development of innovation theory and its relevance to renewable energy technologies in a developing country context. It has been written in support of a project currently being undertaken by the IRENA Innovation and Technology Centre (IITC), which will investigate cooperation strategies to support renewable energy innovation in Latin America and the Caribbean (IRENA, 2013a). The paper considers the challenges of both technological and socioeconomic development, along with the benefits and difficulties of applying theoretical frameworks to studies of innovation. An analysis of case studies of the Brazilian biofuels industry demonstrates the insights that theory can bring to research in the field.

Section 2 outlines the development of innovation theory from Schumpeter in the first half of the twentieth century to the present day. This is based on the earlier ICEPT working paper ‘*Innovation Theory: A review of the literature’,* by Greenacre, Gross and Speirs (2012).

Section 3 considers some of the key challenges for innovation in renewable technologies and developing countries, and discusses the relevance of theory of innovation systems.

Section 4 analyses the contribution of theoretical insights to four case studies of the Brazilian biofuels industry.

Section 5 presents the conclusions of the working paper.

The development of innovation theory

Innovation theory is not rooted in a single discipline or school of thought (Gross, 2008). 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. Theoretical approaches have evolved considerably, from the linear models proposed in the first half of the twentieth century to more recent fully-systemic perspectives.

These theories share an understanding that technologies themselves typically undergo several stages of commercial maturity starting with *basic and applied research and development (R&D)*. Following this will be a *demonstration* stage which includes prototypes; a fairly broad *pre-commercial* stage where multiple units are installed for the first time, and/or where the first few multiples of units move to much larger scale installation; and then a *market development* stage where technologies are rolled out in substantial numbers, commonly within a niche market or with the support of market instruments. If successful, this results in a final *commercial diffusion* stage in which a technology competes unsupported across wider markets, within the broad regulatory framework (Hekkert and Negro, 2009, IRENA, 2013b).

The remainder of this section will outline the development of innovation theory, explaining the key constructs that continue to shape academic perspectives of innovation today.

1930s to 1960s: Linear models

Beginning in the 1930s with Joseph Schumpeter, early theoretical perspectives viewed the innovation process as a relatively simple, one-directional journey from basic research through applied research to technology development and diffusion (Schumpeter, (1911/1934), Stenzel, 2007). 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 *research and development* (R&D) (Nemet, 2007). 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. More recent theoretical approaches accept the importance of both (ibid.), but also stress the importance of more complex, systemic feedbacks between the supply and demand sides (Foxon, 2003).

1970s to 1990s: Induced innovation, evolutionary economics and path dependency

In the second half of the 20th century innovation theory was in particular furthered by three approaches to understanding technological change: induced innovation, evolutionary economics, and the path-dependent model (Ruttan, 2001). The induced innovation approach analyses the impact of changes in the economic environment on the rate and direction of technical change. Market drivers, particularly changes in the relative prices of production elements, are seen as crucial in steering technical developments (Foxon, 2003). The evolutionary and path dependency approaches stress the importance of past decisions which may constrain present innovation (ibid.). They are associated with several concepts that are fundamental to contemporary innovation theory, discussed below.

Evolutionary economics

The evolutionary economics approach characterises technological change as slow-moving and incremental, arising as a result of numerous interlinked economic, social, institutional and technological variables. Changes in one dimension create tensions with the others, triggering additional changes and thus creating continuous feedback loops between the different dimensions (Stenzel, 2007). The approach builds on the Schumpeterian understanding of innovation and the concepts of 'uncertainty' and 'bounded rationality', discussed below. Both bounded rationality and uncertainty result in mind-sets that in general favour incremental innovations to current products or processes, rather than radical and disruptive ones (Greenacre et al., 2012).

- Uncertainty is intrinsic to innovation decisions and particularly relevant to technologies in the early phases of development. It may be present at various levels: technological, resource, competitive, supplier, consumer and political (Meijer et al., 2007). For the firm or entrepreneur, uncertainty signifies both the large variety of opportunities that a new technology may bring, but also the threat of being unable to determine ex ante the success or failure of a technological path (Greenacre et al., 2012). .
- Bounded rationality emphasises that decision makers have a limited ability to gather and process information. Rather than being absolutely rational profit-maximisers, they make decisions that satisfy their most important criteria whilst foregoing others (Nelson, 1982). Thus the default goal of innovation becomes achievement of minimum criteria, rather than the pursuit of the optimal or maximally efficient solution (Greenacre et al., 2012).

Path dependency

The path dependent model explains how the set of decisions faced by an entity for any given circumstance is limited by the decisions made in the past, even though past circumstances may no longer be relevant (David, 1985, Arthur, 1994). It 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 economies and learning by doing and will typically give rise to cost reductions and incremental improvements (Greenacre et al., 2012). 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 (Kemp and Foxon, 2007, Gross, 2008).

1970s to 1990s: Early concepts of systems theory

Alongside induced innovation, evolutionary economics and path dependency, the 1970s to 1990s saw the emergence of several key perspectives that would lay the foundations for a more general systems theory of innovation (Greenacre et al., 2012).

Regimes and trajectories

The evolutionary approach was adapted by Nelson and Winter into a more general theory of innovation, underpinned by the concepts of uncertainty and institutional structure (which provides incentives or creates barriers to innovation) (Nelson, 1982, Nelson, 1977). This sees R&D as being guided by both technology-push and demand-pull factors to generate a variety of possible solutions. These are tested in an environment containing both market and non-market (institutional) elements. The prevailing set of technologies and institutions form a 'technological regime', which steer the R&D process along particular 'trajectories', typically favouring incremental innovations to existing products or processes (Nelson, 1977). This idea is closely related to path dependency.

Life cycle and dominant design

Nelson proposed that new technologies exhibit a 'life cycle' of development. In the early stages of development there are a variety of competing designs, but as advantageous features favour a certain design, so that design will be increasing taken up. If the market grows, institutional change may gradually occur as the institutional regime adapts to match the needs to the new technology. Assuming the combination of improved technological capability and the adapted institutional framework is compelling, the new technology will spread until it achieves the status of a 'dominant design'. From this point on, only incremental improvements will be made to the technology design. Many firms will cease to invest in learning about alternative design architecture, instead investing to refine their competencies related to the dominant architecture (Schilling and Esmundo, 2009).

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*, depicted in Figure 0.1. The model recognises the existence of feedbacks between each innovation stage, and between the product users and the design and production phases, however its narrow definition of 'system' takes no account of the wider economic, political, social and cultural landscape (Foxon, 2003). In particular, the model promotes three key concepts (OECD, 1997):

- the importance of maintaining effective links between phases of the innovation process to ensure an innovation's success;
- the uncertainty and unpredictable nature of both technological capabilities and user needs;
- the role of R&D, not as the source of inventive ideas, but as a form of problem-solving to be called upon at any point.

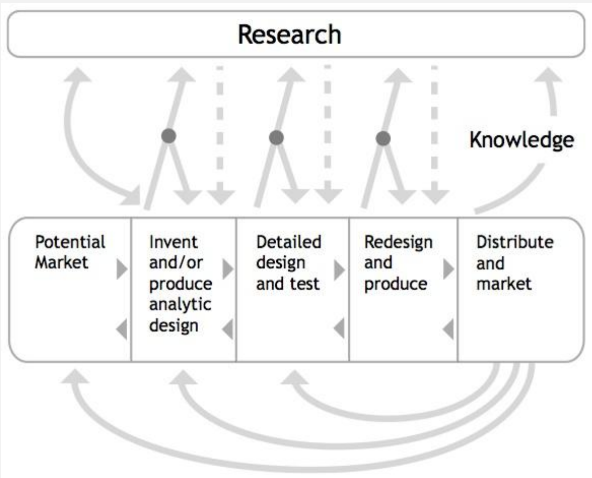

Figure 0.1 An interactive model of the innovation process: The chain-linked model (Source: (Kline, 1986)). Interactions relating to the processes occurring within a given firm, or a network of firms acting together are depicted in the lower part of the figure. Relationships between the individual firm and the wider science and technology system within which it operates are shown in the upper part.

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: Innovation systems

The latter years of the 20th 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. Several additional approaches were proposed, in particular the 'Innovation System Frame' at the level of the firm or the enterprise (OECD, 1997) and various national, regional and sectoral perspectives.

The Innovation System Frame

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

- framework conditions (including educational, communications, financial, economic, legislative, market and industrial context);
- science and engineering base;
- transfer factors (influencing information and learning);
- innovation dynamo (factors that shape the innovative capacity of a firm or entrepreneur).

The framework presents the innovation dynamo – and so the firm or entrepreneur - as being central to innovative activity. The propensity of the firm to innovate is considered to be dependent on the availability of technological opportunities and the ability of the firm to recognise and exploit these (OECD, 1997).

National Innovation Systems

The National Innovation Systems (NIS) approach focuses 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 are found at the national level. The concept was first developed in the late 1980s by Freeman and Perez (1988), who defined the NIS 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 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; and a high level of education and scientific culture, combined with practical training and frequent up-dating in industry. Lundvall (1988) and (1992) further stressed the role of interactions between users and producers, which rely on mutual trust and behaviour codes due to the fundamentally uncertain nature of innovation. An empirical study of national innovation systems in fifteen countries by Nelson (1993) concluded that 'differences in innovation systems reflect differences in economic and political circumstances and priorities between countries'. These are linked to institutional conditions such as university 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 actors and institutions, notably competition (incentivising innovation through rivalry), transaction (traded knowledge), and networking (knowledge transfer through collaboration and cooperation) (Speirs et al., 2008).
- The incentives for innovation created by the institutional set-up.

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' - geographic concentrations of interconnected innovating entities. This concept is similar to that found in other innovation conceptualisations, particularly that of 'National Innovative Capacity', discussed below (Speirs et al., 2008).

National Innovative Capacity

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, 2002). 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. This location-bias is at the heart of the concept of the national innovative capacity and NIC theory has concluded that the registration of international patents per capita provides the best measure of realised innovation (Speirs et al., 2008). NIC theory is characterised by three main elements (ibid.):

- Common Innovation Infrastructure (analogous to the 'framework conditions' referred to in the 'innovation system frame' of the 'Oslo Manual')

- Cluster-Specific Conditions (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. 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).

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.

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 (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 (Stenzel, 2007).

1990s to present day: Systemic and hierarchic innovation

Advances in innovation theory in recent years have gradually moved closer to a fully systemic, dynamic, non-linear process involving a range of interacting actors. Examples of specific, recently developed approaches include 'technological innovation systems', 'technological transitions', and the 'multi-level perspective'. Although these still acknowledge the existence of stages of technology development, they put these in a wider context, emphasising the role of multiple agency and distributed learning mechanisms in technological change (Winskel and Moran, 2008). Attention is given to aspects such as 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.

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 paths, while often throwing up barriers to more radical change (Foxon, 2003). The importance of feedbacks between different parts of the system 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).

Technical Innovation Systems

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 et al., 2006). Hekkert and Negro (2009) note 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, 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 regional and national system scopes, and the dynamic interactions of actors and knowledge flows within the institutional environment of all these contexts remains fundamental.

The TIS approach attempts to analyse innovation systems by assessing 'functions of the innovation system' (Speirs et al., 2008), i.e. processes that directly influence the development, diffusion and use of new technology and, thus, the performance of the innovation system. According to Hekkert et al. (2006), this approach 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. Hekkert et al. (2006) and Bergek et al. (2008) propose seven functions for describing and analysing technological innovation systems: entrepreneurial activities; knowledge development and diffusion; guidance of the search (e.g. policy targets, expectations); market formation; resource mobilisation; creation of legitimacy/counteract resistance to change; and development of positive externalities. It is expected that the more these system functions are fulfilled, the better the performance of the innovation system will be.

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 (Jacobsson and Bergek, 2004). Given the potential for incumbent actors to block development, government policy is seen as a key cornerstone to aid the formation of the functions mentioned above. 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).

Niches and niche cumulation

Innovation literature has increasingly emphasised the importance of niches, in which new technologies may be more able to compete with incumbent rivals. Niches provide insulation from 'normal' market selection and space to build up the social networks that support innovation (Geels, 2002). Technological niches are 'protected spaces', where regular market conditions do not prevail because of special conditions created through subsidies and alignments between various actors. They can develop into market niches, applications in specific markets in which regular market transactions prevail. Technologies in niches benefit from relatively rapid penetration and learning-by-doing, thus reducing costs and improving performance.

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. They 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 to manage and expand the social networks. Geels (2002) argues that while socio-technical regimes account for stability, niches are the building blocks for transitions. Whilst existing regimes generate incremental innovation, radical innovations are generated in niches. Geels suggests that regime shifts may occur through a process of niche-cumulation, whereby a number of initially separate niches are created and gradually grow and come together to form a new regime.

Investment in niches is inherently risky for firms. 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). There may be a role for policy support for the development and cumulation of niches, through 'strategic niche management', discussed below.

Radical and disruptive innovation

There has also been much interest in the differences between incremental, radical and disruptive innovations, and in how industry structure is related to them.

Incremental innovation builds on and improves existing technology but does not significantly alter it. Radical innovation does produce significant change but is not necessarily disruptive, i.e. it does not necessarily displace the dominant, incumbent technology or process. 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). Disruptive innovations are innovations that eventually overturn the existing dominant technologies, products or processes. The innovation fulfils 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.

Smaller firms, outside the mainstream and with less invested in the old system, are more likely to attempt riskier, more radical approaches assuming they have the resources. Larger firms are more likely to have the R&D capacity to generate new ideas but have traditionally focused on incremental improvements along the existing technological trajectory (Foxon, 2003). This is beginning to change, with larger firms establishing semi-autonomous divisions to research and develop more radical innovations. Nonetheless, 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. Policy interventions may be needed to make established firms consider deploying new technologies 'against their inclination' (Winskel and Moran, 2008).

Transition theory

Research into transition theory has been another important development. This focuses on the detailed process of technological change, which is not simply incremental but represents a radical, possibly even disruptive, shift in products and processes (Gross, 2008). Transitions theory emphasises the importance of technological and market niches by which an innovation can be protected from normal market conditions and nurtured for a period of time.

Three main theoretical approaches have emerged (Foxon et al.):

- The 'multi-level perspective' acknowledges that transitions do not only involve changes in technologies, but also changes in user practices, regulation, industrial networks, infrastructure and symbolic meaning or culture (Geels, 2002). Geels explores these at three explanatory levels: 'micro' technological niches, 'meso' socio-technical regimes and 'macro' landscapes. At the niche-level the lack of 'size' and impact of innovations mean that they 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. 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, to new regulations or newly emerging markets, or they may ride along with growth in particular markets.
- 'Strategic niche (or transitions) management' recognizes that government and firms, as well as other stakeholders, have a central role to play in a system change and that there is a need for policy-makers to manage the dynamics of possible transitions in order to avoid early lock-ins (Maréchal, 2007). Instead of the use of specific economic instruments it focuses on the different ways of

interaction between entities, the mode of governance, and goal seeking (Rennings et al., 2004).

- ‘Socio-technical scenarios’ “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” (Gross, 2010).

Summary

Prevailing perspectives in 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).

Innovation theory for renewable energy in developing regions

Innovation theory and development economics have been studied little in combination (Lundvall et al., 2009), however efforts to promote renewable energy innovation in developing countries must marry the learnings of both disciplines. This section separately discusses some of the key issues affecting innovation in the context of renewable energy and developing countries. We then consider the relevance of the systemic approach to research and policymaking in this area.

Challenges for renewable energy innovation

Renewable technologies represent a departure from the regime of fossil fuel technologies that characterise most incumbent energy systems. They are affected by major uncertainties, such as long run costs, geopolitics and the extent of GHG emissions reductions required to manage climate change (Anderson et al., 2001). In combination with the existence of path dependency these lead to three inter-related dilemmas for policymakers keen to promote renewable energy innovation (Gross, 2008):

- How to avoid premature path choices when the relative long term merits of different technologies are unknown.
- The need to avoid delaying choices excessively, to avoid low carbon options being ‘locked out’.
- The fact that small changes in the near future give rise to much larger long-term impacts. Hence a relatively small amount of early intervention 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.

Given the difficulties of selecting technological pathways, discussion of low carbon innovation has commonly asserted that policymakers are not best placed to decide which technologies to fund. Rather than ‘picking winners’ by providing targeted support to particular technologies, it has been suggested that governments should set general frameworks to encourage widespread innovation (Watson, 2008, Foxon, 2003). Watson (2008) challenges this argument on a number of grounds. First, the resources that governments can devote to sustainable energy innovation are limited – without prioritisation, there is a risk that resources will be spread too thinly. Second, the urgency of climate change demands rapid innovation and deployment in low carbon technologies; generic incentives such as carbon markets may be too slow. Third, generic policy incentives such as carbon prices tend to favour near market technologies, so they are unlikely to be sufficient to develop those technologies that are not already close to commercial status. In addition, Gross (2008) highlights the need for policy to ensure, perhaps paradoxically, 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 (Gross, 2008).

Innovation and technology transfer in developing countries

There is a growing body of literature that addresses innovation in developing countries – and particularly its potential to help countries ‘catch up’ (Crespi and Zuniga, 2012, Furtado et al., 2010, Aguayo et al., 2010, Lundvall et al., 2009). It is widely asserted that the acquisition and imitation of technologies developed abroad – technology transfer

- has a more significant impact than endogenous R&D in this respect (Bell and Pavitt, 1993, Crespi and Zuniga, 2012, Katz, 1986). Research has indicated that the introduction of new products and processes to the firm or national market may represent a more significant proportion of innovations in developing countries than 'world firsts' (OECD and INSEAD, 2011), and that that the majority of indigenous R&D focuses on incremental (rather than radical) developments (Furtado et al., 2010).

Technology transfer to developing countries presents challenges and opportunities in addition to those previously highlighted for renewable energy innovation. Gerschenkron's theory of economic backwardness explains that 'latecomer' countries adopting an already-mature technology 'leapfrog' the early phases of its development, installing a more sophisticated infrastructure from the outset (Gerschenkron, 1962). In practice, however, latecomer effects are neither entirely beneficial nor automatic. Whilst latecomers tend to adopt innovations more rapidly than inventor countries, they also tend to attain lower technological levels (GEA, 2012). Significant domestic expertise is required to select the most appropriate technology for adoption, absorb associated explicit and tacit knowledge, and adapt the technology to local operating conditions; the value of imported innovation can therefore be seen as dependent on the skills and absorption capacity of domestic actors (Crespi and Zuniga, 2012). However, Humphrey and Schmitz (2002) argue that active involvement in the formative stages of R&D is important for developing these same skills. From a technological development perspective, broadening a technology's market increases the opportunity for scale economies, which may hasten the passage from niche to commercial application (GEA, 2012).

The systemic approach

The systemic approach is dominant in modern intellectual thought surrounding innovation. It is particularly pertinent to renewable technologies. Fossil-fuel based energy systems have undergone a process of co-evolution and increasing returns, leading to the current dominance of high carbon technologies. These are 'locked in' by the accumulation of knowledge, capital outlays, infrastructure, available skills, production routines, social norms, regulations and life styles, which have developed around them (Unruh, 2000). Such factors provide a formidable barrier to entry for low carbon technologies and substantial disincentives for radical, low carbon innovation. Further, the primary driver for renewable energy - climate change - is unlikely to be effectively addressed by fragmented innovation strategies focussed on individual technologies (e.g. wind or PV) or drivers (feed-in tariffs or R&D). Decarbonisation goals demand an approach to innovation that considers the entire energy system – including demand and supply, low carbon and fossil fuel, and different scale technologies (GEA, 2012).

Despite this, many policymakers in the low carbon arena still subscribe to the underlying theories of the linear model, notably that greater levels of support will automatically result in more new technologies reaching the market (IEA, 2012, Suurs et al., 2009, GEA, 2012). In addition, policies commonly focus on market failures, taking insufficient account of the impact of wider systemic failures. For example, renewable energy policy in industrialised nations has been heavily influenced by the twin market failures of the social cost of carbon emissions, and under-investment in private sector innovation due to suboptimal intellectual property compensation (Greenacre et al., 2012). These have often led to the development of policy frameworks that emphasise market mechanisms which provide government funding for R&D (ibid.). However, government support is needed for other stages of the innovation process (Watson, 2008), and there are rationales for intervention that stem from more than just market failures. These 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 that hinder the effective networking of the system components (Foxon et al., 2005).

In contrast, the relevance of systems failures to innovation in developing countries is commonly implicit in policy reports, with recommendations often concentrating on non-market instruments and institutions (Altenburg, 2009). However there has been relatively little explicit application of the systemic approach to developing countries (Furtado et al., 2010), even though its emphasis on context – actors, institutional conditions and networks – makes it highly adaptable and applicable to research in a wide range of situations. Further, those studies that have explored developing countries' innovation systems have not always applied the theory with due care: a significant proportion fail to show practical appreciation of developing countries' characteristics (Altenburg, 2009). According to Altenburg (ibid.) three key areas are commonly ignored:

- Socioeconomic concerns. Issues such as poverty reduction and distributional effects need to inform innovation strategies, to mitigate the adverse effects of disruptive innovations on poor, unskilled communities implicated in the incumbent system.
- Political economy. The impacts of inefficiency, corruption or favouritism on the propensity of the government to promote social good, must be considered where policy recommendations rely on state guidance and support.
- The sufficiency of basic market institutions. These should not automatically be assumed to be efficient or effective.

Innovation systems theory has evolved in the context of OECD countries as the product of many academic disciplines (Gross, 2008). Its application to developing countries should therefore also draw on insights (such as the above) from development economics, and other related fields of study. While contextual focus is a key strength of the systemic approach, its benefits will not be realised by research that limits the scope of context studied, albeit unintentionally.

Summary

Policies to encourage renewable energy innovation in developing countries need to consider the range of issues that challenge both technological and socioeconomic development. For example, while policy debate has historically disfavoured targeted support for technologies, this may be necessary in the case of renewable technologies, which need to develop rapidly to reduce the greenhouse gas emissions of the energy sector. Innovation in developing countries tends to focus on incremental, rather than radical, developments, and the transfer of foreign technologies. Particular challenges are associated with garnering and stimulating growth in local technological capacity. Thus whilst push-pull market interventions are important to incentivise R&D, progressive policy should also seek to build capacity, improve the institutional framework and facilitate interactions between actors at all levels of the innovation system. The systemic approach to innovation is well-suited to describe developments in the energy sector and can – in theory – be adapted to a wide range of contexts, including developing countries. However, efforts must be made to ensure that lessons learned from the wider field of development studies are reflected in its application.

Theoretical approaches to analysing innovation in the Brazilian biofuels industry

Relatively few studies have explicitly applied innovation theory to the analysis of renewable energy systems in Latin America and the Caribbean (LAC), particularly less-successful innovation efforts (Aguayo, Gallagher et al. 2010). Of the studies that have employed innovation theory, several focus on the highly successful biofuel, and particularly bioethanol, industries in Brazil. This section examines the results of four such investigations, considering the particular insights that have been afforded by the analytical frameworks employed. The findings of all four studies are presented together thematically. They are grouped according to some of the key innovation constructs that have been identified as being influential in the sector's development, notably: institutional conditions, actors, linkages, technological clustering and non-linear feedbacks. This is not intended to be a fully comprehensive analysis of all the constructs encompassed in the studies, but rather a summary of those that are most influential.

The case studies under examination are as follows:

- A generic innovation systems approach, employed by Aguayo, Gallagher et al. (2010) to conduct a macro analysis of energy across the Hispanic world. Brazil's successes in biofuels are a key focus of the study.
- Sectoral innovation approaches, employed by Furtado, Scandiffio et al. (2010) and GEA (2012). The former study focuses on the sugarcane and bioethanol agroindustry whilst the latter considers the role of bioethanol within wider energy technologies.
- An analysis of the technological, commercial and social uncertainties surrounding Brazilian biofuels, conducted by Hall, Matos et al. (2010). The scope of study is extended beyond the conventional value-added innovation system to include secondary stakeholders, developing a methodology first proposed by Hall and Martin (2005) and taking account of latecomer and global value chain discourses. The methodology is based on the assumption that radical innovations are often controversial and thus sensitive to public pressure (ibid.).

Case study findings

Brazil's bioethanol industry has expanded rapidly, with production rising from 0.6 million cubic metres in 1975 to 12.6 million in 2002 (Furtado et al., 2010). This volume is bettered by the USA, however Brazilian bioethanol is more cost competitive and generates lower levels of GHG emissions than its American counterpart; as such it is considered by some to be the more successful industry (ibid.). As we discuss below, these achievements are not merely the result of natural competitive advantage, but sustained developmental efforts and dynamic responses to economic, institutional and technical challenges.

Institutional conditions

All of the studies note that innovation in biofuels has benefitted from supportive institutional conditions (Furtado et al., 2010, Aguayo et al., 2010, Hall et al., 2010, GEA, 2012). Barring a hiatus in the 1990s, innovation in the sugarcane and later bioethanol industries has received sustained, long-term political and financial support since the early twentieth century. The Sugar and Alcohol Institute (IAA) was established by the federal government in the 1930s. R&D efforts intensified in 1975 with the launch of a national alcohol subsidy programme (ProAlcool) as joint response to the near-concurrent oil crisis and collapse in global sugar prices (GEA, 2012, Furtado et al., 2010, Hall et al., 2010). The National Alcohol Commission (CNAL) was subsequently established to promote alcohol production, create a guaranteed market and improve the credit environment (Aguayo et al., 2010). Alongside these sector-specific programmes, the

Brazilian Development Bank (BNDES) was critical to establishing the biofuels industry and continues to support innovation activities through both concessionary loans and grants. The latter are specifically geared to strengthen cooperation between public research organisations and the private sector (ibid.).

Actors

The importance of actors' behaviours is well illustrated through changes to investment sources, which have influenced innovation trajectories. In the 1990s several decades of federal support for bioethanol innovation were brought to a halt, a result of changes to Brazil's political and economic situation and the effects of the oil counter-shock (Furtado et al., 2010, Hall et al., 2010, GEA, 2012). Remarkably this removal of funds did not engender a proportional decrease in R&D, as the private sector responded by increasing the level of its own investment. The resulting realignment of innovation priorities led to improved interactivity and efficiency in the system, and focussed efforts on incremental developments to the existing technological base (Furtado et al., 2010). Although these have enabled Brazil to become a world leader for both sugar exports and bioethanol production, current aims to expand worldwide ethanol sales will require more radical innovations. Recognising that these are unlikely to be funded by the private sector alone, the federal government has recently redoubled its publically-funded innovation efforts, assuming a strategic niche management role (ibid.). This departure and subsequent return of focus to radical innovation illustrates the impacts of both corporate expectations and the guiding role of government.

Linkages

The role of strong linkages between actors and institutions is also emphasised by the studies, most notably though application of collaboratively-developed automotive technology to cultivate the bioethanol market (GEA, 2012, Hall et al., 2010). Brazilian car manufacturers worked with foreign-owned multinationals to develop affordable flex-fuel engines. This technology alleviated serious consumer concerns about the fluctuating availability and price of ethanol, thereby playing a decisive role in the development of a large and stable domestic ethanol market. By 2008 81% of new light vehicles registered in Brazil were equipped with flex-fuel engines (ANFAVEA, 2008). The collaboration also facilitated the transfer of technological skills to the domestic automobile industry, and has helped to pave the way for future expansion of the global bioethanol market – with associated export activity for Brazil.

Technological clustering

Cluster conditions in the state of São Paulo are considered to have significantly accelerated the development of the bioethanol industry (Furtado et al., 2010, Aguayo et al., 2010). Sugarcane production grew rapidly in the region during the earlier twentieth century, thanks to good energy and transport infrastructure, ready access to markets, and a large and good quality land resource. Publically-funded research institutions were established in the state to support the sector's development. In combination these created a strong regional innovative capacity which bolstered subsequent bioethanol developments. Successful collaborations between producers, public – and later private - research institutions and manufacturers have enhanced the dynamism of local R&D.

Non-linear feedbacks

Non-linear feedbacks between the different stages of innovation are observed through the influence of secondary stakeholder groups and the interactions between different biofuel technologies. In recent years activist groups and the media have lobbied sugarcane producers, the government and the leading ethanol distributor (Petrobras), to improve the working conditions of plantation labourers and to address the exclusion of small-scale farmers from production. While this has led to an increase in labourers' wages, it is also driving R&D to further process mechanisation, with resultant social exclusion feedbacks (Hall et al., 2010). Similarly, weighty concerns regarding the social and environmental uncertainties of soybean biodiesel have been used to justify alternative investment in (less publically controversial) castor biodiesel (ibid.).

Summary

All four of the studies examined adopt a broadly systemic approach to analysing innovation in Brazilian biofuels, considering the impacts of actors, institutional conditions and linkages between these. The value of this approach lies in its comprehensive investigation of the wide range of factors that may influence innovation, enabling a fuller understanding of past experiences and so more accurate identification of best practices. Events such as switch from public to private investment in the 1990s, and the current switch back to public funding (creating niches to encourage radical innovation), would be difficult to explain with a simple theoretical frameworks, such as the linear model (Furtado et al., 2010). The studies commonly note that strong, sustained guidance from the state, learning effects from other industrial sectors in Brazil and abroad, and a dynamic private sector driven by positive expectations for future market, political and technological conditions. The similarity of conclusions across the studies supports the perception of innovation systems as a robust framework for policy analysis.

Conclusions

Innovation theory has developed significantly since the linear models proposed during the early twentieth century. Prevailing contemporary views may be regarded as variants of a 'systemic approach', under which innovation systems are seen to comprise three main components: actors, institutional conditions and networks. They consider the rationale for policy intervention to extend beyond the correction of market failures to include wider 'systemic failures', such as deficiencies in the provision of infrastructure, institutional failures, and the difficulties of technological transitions and 'lock-in'.

The systemic approach to innovation is well-suited to describe developments in the energy sector, where the dominance of incumbent fossil fuel technology - and the frameworks that support it - is a major barrier to low carbon innovation. Although largely developed in and for OECD counties, the focus of the systemic approach on contextual factors should in theory make it suitable for adaptation and application in developing countries. It appears that relatively few studies have investigated innovation in renewable technologies in Latin America and the Caribbean (LAC), confirming the need for additional study to understand the opportunities and barriers to technological development in the region. In particular, very few studies have applied theoretical frameworks to the examination of less successful programmes in LAC, nor identified the system failures which have prevented or slowed renewable energy innovation. Whilst there are clearly important lessons to learn from successful programmes, there is also value in understanding the reasons for failure.

Several authors have applied the systemic approach to analysis of the highly successful Brazilian biofuels industry. This paper analyses the contribution of the theoretical framework to four such studies, concluding that the systemic approach has facilitated understanding of the causality of innovative developments in each case. For example, cluster conditions boosted the collaborative development of end-use technology, which in turn increased market demand and thus fostered additional innovations in bioethanol production. Although the results of all four studies are in agreement, the scope of findings of each is affected by the specific choice of systemic framework applied. Researchers working with innovation systems should consider – and if necessary adapt - the approach most suited to their investigation, taking account of both the objectives and scope of study and the resources available for its execution.

Some authors have raised concerns regarding the rigour with which innovation systems theory is applied to developing countries. Most applications of the systemic approach relate to industrialised countries – by and which it was developed. It has been suggested that studies employing a systemic approach have ignored contextual factors that are influential in developing countries, the relevance of which has been highlighted by wider fields of study. Given that contemporary innovation theory is itself the product of many disciplines, it is important that its practical application (and on-going theoretical development) remains open to lessons learned from wider development studies.

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