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Measuring the energy innovation process: An indicator framework and a case study of wind energy in China

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ABSTRACT

Whilst a well-established literature on metrics to assess innovation performance exists, relatively little work has linked it to the energy technology innovation process. This paper systematically brings together indicator sets and derives an indicator framework for measuring energy innovation, offering an important step forward in the quantitative evaluation of energy innovation performance. It incorporates *input*, *output* and *outcome metrics* that relate to different stages along the energy technology innovation chain, namely *research*, *development*, *demonstration*, *market formation* and *diffusion*. To test its efficacy, the indicator framework is applied to the case of wind energy in China, drawing comparisons against global market leaders such as Denmark, Germany and the USA. The paper finds that the framework enables a more rigorous comparative analysis of energy innovation between countries than currently offered by either the application of piecemeal indicators and complements contextually rich qualitative case studies. The empirical analysis shows that China has begun to lead across a range of innovation inputs (e.g. R & D expenditure) and outputs (e.g. publications) but lags considerably behind international competitors against other output and outcome indicators such as patents, revenue and exports.

1. Introduction

Energy technology innovation has been identified as critical to achieving a transition to a sustainable energy system (IEA, 2015; IPCC, 2014). The world's major economies' energy RD & D budgets have grown significantly in a bid to stimulate greater innovation following decades' of decline and stagnation (Breakthrough Energy Coalition, 2016; Mission Innovation, 2015; Skea, 2014). Given this growth in funding, it is necessary to assess the effectiveness of energy innovation support and the types of policy interventions that could accelerate innovation in the future. The first step in this direction is to develop an indicator framework capable of offering in-depth quantitative assessments of energy innovation performance (Freeman and Soete, 2009; OECD, 2005; OECD, 2015a).

The literature on energy innovation indicators is still in its infancy. The IEA emphasised that the "*ongoing evaluation of innovation effort is needed to assess success, accumulate learning experience and determine how to best support specific technologies*" (IEA, 2015, pp. 16). In a bid to advance the state-of-the-art on energy innovation indicators, this paper draws upon innovation systems theory to synthesise a wide-range of indicator sets to develop a comprehensive framework that allows for a more rigorous comparative analysis of innovation performance than currently offered both by the piecemeal quantitative indicators and contextually richer qualitative accounts of innovation studies.

The framework is employed to compare the performance of China, a relative newcomer to wind energy, versus other global market leaders, namely Denmark, Germany and the USA. As of 2015, China accounted for 33% of global wind power capacity (BP, 2016). However, few studies have measured its innovation performance and there are mixed opinions in the existing literature as to whether China has grown as a leading innovator in wind technology (see Gosens and Lu, 2013; Ru et al., 2012; Zhao et al., 2012; Zhao et al., 2014). The framework is applied to offer insights into whether China has technologically leapfrogged traditional industry leaders (Ru et al., 2012) or if its technological capability remains limited (Gosens and Lu, 2013; Klagge et al., 2012; Urban et al., 2015; Zhao et al., 2012). A more rigorous assessment of China's wind energy innovation performance relative to the world leading countries is offered.

The paper is structured as follows. Section 2 reviews the innovation systems literature. Section 3 reviews the key characteristics of pioneering indicator frameworks, synthesising them to present a new indicator framework to measure energy innovation performance. Section 4 mobilises the framework by presenting an international comparison of wind energy innovation to assess China's relative performance.

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Section 5 reflects upon the efficacy of the indicator framework. Section 6 presents conclusions and makes suggestions for future research.

2. Conceptual background

Innovation is a non-linear but systemic process (Fagerberg, 2005). Academic views on the innovation process have shifted from traditional linear models to the innovation systems (IS) approach (Rosenberg, 1982). A variety of IS approaches have emerged, including national innovation system (NIS) (Freeman, 1987; Lundvall, 1992; Nelson, 1993), regional innovation system (RIS) (Cooke, 1992), sectoral innovation system (SIS) (Malerba, 2002), technological innovation system (TIS) (Bergek et al., 2008; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007) and energy technology innovation system (ETIS) (Gallagher et al., 2012; Wilson et al., 2012; Wilson and Grubler, 2014). They can be regarded as variants of a generic IS approach, each adopting a different unit of analysis (i.e. national, regional, sectoral or technological) to suit the different research questions being posed (Edquist, 2005; Markard and Truffer, 2008). This paper is concerned with innovation occurring in a particular technological field within specific countries, so NIS, TIS and ETIS frameworks are most relevant. This section offers the theoretical background against which efforts have been made to measure, understand and explain the variations in innovation performance.

2.1. National innovation system

The NIS literature emerged in the early 1980s, with the theoretical foundation underpinned by key contributions from Freeman (1987), Lundvall (1992) and Nelson (1993). Freeman (1987) argued that the performance of an NIS can be affected by a variety of factors, among which the flexibility of institutions may perhaps be the most crucial element (Freeman, 1987). Nelson (1993) confirmed that institutions, universities, institutes and corporate R & D labs, as well as the connections among them, are essential for analysing NISs. Lundvall (1992) held that the core aim of an NIS is to create favourable institutions to incentivise the heterogeneous actors to interact with each other to generate, adopt and diffuse new concepts and technologies. In essence, NIS is used to explain the macro institutional and structural factors responsible for influencing technological change and the long-term economic growth of nations.

In recent years, NIS studies have begun to focus on competence-building (Borrás and Edquist, 2013; Lundvall, 2002), systemic problems (Chaminade et al., 2009; Edquist, 2011), dynamics of innovation (Lundvall, 2007; Lundvall et al., 2009) and international linkages of innovation systems (Carlsson, 2006; Marin and Arza, 2009; McKelvey and Bagchi-Sen, 2015). For example, Borrás and Edquist (2013) argued that the core tasks of innovation systems are to build, maintain and use competencies. In this sense, NIS can be seen as an evolutionary concept concerning how national systems create diversity, stimulate variation and select routines (Lundvall, 2007). In order to diagnose system failures that occur in developed and developing economies (Chaminade et al., 2009), Edquist (2005) presented a hypothetical list of functions similar to TIS. In general, NIS is mainly concerned with the national factors that positively or negatively contribute to innovation and technological change.

2.2. Technological innovation system

The TIS framework has gained much attention recently (Bergek et al., 2008; Bergek et al., 2015; Carlsson and Stankiewicz, 1991; Edquist, 2005; Hekkert et al., 2007; Jacobsson, 2004; Jacobsson and Johnson, 2000; Wieczorek and Hekkert, 2012). Different from the NIS approach, TIS focuses on the key functions that stimulate or hamper innovation activities in a specific technological area. According to the definition, "*a technological [innovation] system is a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilisation of technology*" (Carlsson and Stankiewicz, 1991, pp. 111). As a TIS typically involves fewer elements and relationships than an NIS, the structure and dynamics of the system can be mapped out. Also, geographical borders do not necessarily determine the boundaries of TISs.

A key feature of the TIS framework is the inclusion of TIS functions. These present a set of specific roles the TIS performs in support of the development and deployment of an emerging technology (Bergek et al., 2008; Hekkert et al., 2007). In essence, if a TIS system's functions are all performing strongly then it is assumed the technology is well-placed to progress towards commercialisation, assuming the engineering challenges are surmountable. However, should one or more functions perform poorly then the technology may fail to reach maturity (Edquist, 2001; Hekkert and Negro, 2009; Jacobsson and Johnson, 2000). Assessment of TIS function performance therefore helps us to identify weaknesses or 'bottlenecks' that are undermining energy innovation (Markard and Truffer, 2008; Ruud Smits, 2004). These functions are Entrepreneurial Experimentation, Knowledge Development, Knowledge Networks, Guidance of the Search, Resource Mobilisation, Market Formation, and Creation of Legitimacy (Bergek et al., 2008; Hekkert et al., 2007).

Scholars have begun to link the structure (e.g. *actors*, *institutions*, *networks*, *infrastructure*) with the functions of a TIS in order to diagnose systemic problems (Wieczorek and Hekkert, 2012). Each function involves one or more structural elements that have an important bearing on development, diffusion or use of innovations (Edquist, 2001; Hekkert and Negro, 2009; Jacobsson and Johnson, 2000). For example, the function of Knowledge Development is likely to perform poorly in the absence of key *actors* like universities and research institutes, *networks* that bring these together to foster collaboration and *infrastructure* such as test facilities and laboratories. In this sense, the structure acts as the foundation of the system upon which the functions are developed and work as 'intermediaries' towards the ultimate goals of the innovation system (Wieczorek, 2014).

2.3. Energy technology innovation system

Energy innovation results from research, development, demonstration, deployment and diffusion efforts (Gallagher et al., 2012; Grübler et al., 1999). The ETIS is an application of a systemic perspective on innovation to energy technologies (Gallagher et al., 2012; Wilson et al., 2012). It is developed in reaction to some of the characteristics specific to the energy system that together result in a relatively slow process of technology innovation and diffusion. These include: (1) capital intensiveness of energy technology investments; (2) longevity of capital; (3) extended time required to progress technology from invention to innovation; and (4) extended time for technology clustering and spill-over effects to emerge (Grubler et al., 2012).

The ETIS framework aims to capture these characteristically distinct innovation processes by emphasising the multi-dynamic feedbacks between different stages (Gallagher et al., 2006a; Gallagher et al., 2012; Grubler et al., 2012; Wilson and Grubler, 2014). It describes: a) the four analytical dimensions of ETIS (i.e. actors & interactions, resources, knowledge and adoption and use of energy technologies) (see Diagram 1); b) the stages of energy technology innovation process (i.e. research, development, demonstration, market formation and diffusion); c) the feedbacks between these stages; d) the drivers of energy technology innovation (i.e. technology-push and market-pull); and e) the relevance of energy supply and energy end-use technologies; (Wilson and Grubler, 2014).

The ETIS approach has absorbed core elements from different IS approaches like TIS, such as the focus on structural dimensions like knowledge, actors, networks and institutions. However, the central difference between ETIS and TIS is that the former is concerned with the historical stages of energy technology innovation process affected