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A multi-dimensional indicator framework for evaluating energy technology innovation system

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Abstract

Energy innovation is critical to the transition to a sustainable energy system. However, due to the lack of adequate metrics, the structure, functions and performance of energy technology innovation system (ETIS) have not been well established. This impedes our understanding of the status of ETIS as well as the implementations of policy interventions that should have been in place. Drawing upon innovation systems (IS) approach, this research developed a multi-dimensional indicator framework for evaluating the performance of ETIS. The wind turbine industries in China, Denmark, United Kingdom and United States were used as an example of a supply-side energy technology to quantitatively characterise the dynamics of knowledge and technology growth in wind energy. The results suggest a rapidly growing technological capability and closing innovation gaps to leading countries in the case of China's wind turbine industry. The multi-dimensional indicator framework enables to analyse the evolution of national innovation and technological capabilities.

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Abstract

Energy innovation is critical to the transition to a sustainable energy system. However, due to the lack of adequate metrics, the structure, functions and performance of energy technology innovation system (ETIS) have not been well established. This may impede our understanding of ETIS as well as the implementations of policy interventions that should have been in place. Drawing upon innovation systems (IS) approach, this research developed a multi-dimensional indicator framework for evaluating the performance of ETIS. The wind turbine industries in China, Denmark, United Kingdom and United States were used as an example of a supply-side energy technology to quantitatively characterise the dynamics of knowledge and technology growth in wind energy. The results suggest a rapidly growing technological capability and closing innovation gaps to leading countries in the case of China's wind turbine industry. The multi-dimensional indicator framework enables to evaluate ETISs in a systemic manner.

Key words: innovation indicators; innovation system; wind energy; China

1. Introduction

Driven by the concerns of climate change and energy security, energy RD&D expenditure by the world's major economies has increased again after decades of decline and stagnation (Skea 2014). Given this growth of spending, it is crucial to understand how well a nation's energy technology innovation system (ETIS) operates and identify what should be improved in order to proceed more effectively. An important step to achieving this aim is to develop adequate metrics as indicators can serve as a proxy or metaphor for stakeholders to assess status and make changes so that innovation resources and activities can be mobilized and implemented effectively under shared visions and strategies.

However, due to a lack of suitable indicators, the structure, functions and performance of ETIS across countries and technologies have not been well measured. In the last few decades, some countries have successfully taken the lead in certain novel energy technologies, others however failed to achieve the expected outcome although with higher levels of RD&D investment. The core question is therefore how do we most effectively apply human, financial and natural resources to stimulate innovation? Historical lessons imply that ignoring the systemic characteristics of technological change often leads to a partial view and fragmented (even contradictory) policies (Wilson et al. 2012, Grubler et al. 2012). This research attempts to draw lessons from IS approach particularly the ETIS as well as current innovation indicators to build a multi-dimensional indicator framework.

In order to test the validity of the proposed metrics, the wind turbine industries in China, Denmark, United Kingdom and United States were used as an example to quantitatively characterise their ETISs from multi-dimensions. The innovation stories of China are attracting wide interest, but not many studies have been conducted in an international comparative approach between China and Western leading countries, especially when China is currently in a technological catching-up phase. Then, wind power has developed as one of the most mature renewable energy technologies that is competitive against fossil fuels. Evaluation on wind technology innovation is important to accumulate learning experience and determine how to best support wind technology. Specifically, we intend to answer two research questions: 1) Which set of indicators may best describe the performance of ETIS? 2) What is the status of the Chinese wind technology innovation system compared with Denmark, United Kingdom and United States?

Section 2 reviews the theoretical research on innovation systems and innovation indicators. Section 3 develops a multi-dimensional indicator framework for measuring innovation system of wind technology. Section 4 carries out cross-country comparisons on wind technology innovation. Section 5 discusses the quantitative results, and theoretical contributions of this research. Finally, conclusions are drawn in section 6.

2. Theoretical bases

2.1 Innovation systems

Innovation systems (IS) approach is a useful tool for analysing systemic problems in innovation process. At present, IS approach has evolved into several branches, i.e. national system of innovation (Freeman 1987, Lundvall 1992, Nelson 1993, Fagerberg and Sapprasert 2011), regional system of innovation (Cooke, Uranga, and Etxebarria 1997, 1998, Asheirn 2007), sectoral system of innovation (Malerba 2002, Malerba 2004, 2005), and technological innovation system (Carlsson and Stankiewicz 1995, Hekkert et al. 2007, Bergek et al. 2008, Hekkert and Negro 2009). The NIS focuses on the macro level analysis of systemic structures and institutions. The RIS addresses regional productivity disparities caused by subnational regulations conditioned by trust, reliability and interactions. While the SIS emphasises sectoral differences in innovation processes and patterns, the TIS studies the structures and processes that stimulate (or hamper) innovation activities occurring in a particular technological area.

The multiple IS approaches coexist and complement each other. Whether the most adequate framework in a certain context should be national, regional, sectoral or technological, depends on the questions to be addressed (Edquist 2005). When the analysis is focused on a geographical dimension, a particular country or region determines the boundaries of the system. In other cases the main interest of dimension is a sector or technology. A major flaw of analysing NIS is that it is impossible to map out the dynamics of the system due to a vast amount of actors, networks and institutions involved. In comparison, TIS focuses on specific technologies, so the major actors, their activities and networks can be mapped out (Hekkert and Negro 2009). Also, as the prime focus of TIS is to understand how the system can identify, absorb and exploit technological opportunities, national boarders do not necessarily determine the boundaries of the system.

A TIS can be analysed at least three levels: a technology within a knowledge field, a product or artefact, or a set of related products aimed at a particular function such as health care or transport (Carlsson et al. 2002). With technology as the level of analysis, all entities having competence within a certain technological area (e.g. digital signal processing) will be included, regardless of its application (e.g. mobile phone and control engineering). It is more concerned with technological-problem solving activities, and the generation of new knowledge and technology. Taking a product or artefact as the perspective, the actors are those within an industry. The primary interest here lies in the diffusion and use of the technology, e.g. the links between a product and its customers. When it expands to a set of related products in a specific market, the actors may come from several industries, and the focus is on the actors and institutions supporting products to this market. Therefore, the choice of the level of analysis depends on the research questions raised.

But what determines the performance of an innovation system, what are the common problems occurring in energy technology innovations, and what lessons can be learnt from history? In studying Japan's rise as a major economic and technological leader in the post-war period, Freeman (1987) attributed Japan's success to a combination of technological, institutional, and social innovations. The way in which the resources were managed and organised at both enterprise and national levels was critical to speed up technical change in Japan and to improve international competitiveness of Japanese firms (Freeman 1987). Nelson (1993) argued that cross-country differences in innovation systems are major differences in economic, political circumstances and development priorities. These are partly caused by history, culture and social values, including the timing of entry into industrialisation, which profoundly influence a nation's institutions, laws and policies (Nelson and Rosenberg 1993). Some good practices have been diffused from a pioneering country to many other entities albeit with long time-lags, the successful absorption of these 'new' practices and their performance depend on the country's capability to learn from international experience and the flexibility of its existing institutions and framework conditions (Freeman 1987).

With regard to the energy sector, Negro, Alkemade, and Hekkert (2012) summarised five types of systemic problems that hamper the development and diffusion of renewable energy technologies, including (hard and soft) institutional problems, market failure, lack of capacity and capability, (knowledge and physical) infrastructure absence, and too weak or too strong interactions. The functions approach has been used to study the inducement or blocking mechanism of innovation system for various energy technologies (Negro 2007, Suurs et al. 2010, Vasseur, Kamp, and Negro 2013, Gosens and Lu 2013). Drawing upon 20 historical success and failure stories of energy technology innovations occurring in different market and policy contexts, Grubler and Wilson (2014) put forward the conceptual framework of ETIS to apply the necessary generality to assess energy technology innovation in a holistic manner. This paper is to understand how effectively a nation's ETIS operates rather than explain which factors have affected their innovation activities, so the ETIS seems more suitable for developing performance indicators.

2.2 Innovation indicators

Indicator is a measuring device that shows the state of a situation or how a situation is changing. In order to direct innovation efforts to achieve expected outcomes, evidence-based interventions from performance assessment through quantitative metrics are of prime importance. But, are the current indicators suitable for measuring the emerging innovation systems of RETs, and what lessons can be learnt from existing studies?

The OECD has a long history of developing science, technology and innovation indicators. The Frascati Manual (OECD 2015) and Oslo Manual (OECD and Eurostat 2005) set internationally agreed rules on how to collect and interpret innovation-related data. In recent years, the OECD (2010) introduced a number of experimental (or first-time) indicators to highlight the measurement gaps in innovation, and proposed actions for advancing measurement agenda. Existing indicators have been criticised for having several problems. Firstly, the majority of indicators have been limited to input and failed to take into account output and outcome of innovation which are of particular importance for wider social benefits (Lundvall 1992). Secondly, many indicators are not sector or technology-specific which may convey biased information as a nation's industrial mix have significant effects on innovation scores (Galindo-Rueda 2013). Thirdly, aggregate indexes have been used to benchmark countries but this is problematic as the selection, weighting and aggregation of individual indicators vary significantly among researchers (Grupp and Schubert 2010).

The literature on energy innovation indicators is nascent and not yet well defined, for which there are several reasons. Firstly, the indicators used to measure innovation activities are mostly designed for studying NIS, thus the majority of existing indicators are macro-level than sector or technology oriented. Secondly, rigorous study on energy innovation systems emerged only in recent years (Grubler et al. 2012, Gallagher et al. 2012, Hekkert et al. 2007, OECD 2006, Sagar and Holdren 2002), although the viewpoint that innovation processes and patterns vary considerably across sectors was proposed earlier (Malerba 2004, Malerba 2002, Malerba and Orsenigo 1997). Finally, current official statistics have not included sufficient data on energy innovations (Borup et al. 2013, Klitkou, Borup, and Iversen 2012, Grubler et al. 2012), which impedes the development of indicators as well as the associated empirical studies.

Energy innovation indicators are still taking shape. They have focused on R&D expenditures, publications, patents, adoptions of energy technologies, and employment in the energy sector (Gosens and Lu 2013, Borup et al. 2013, Klitkou, Borup, and Iversen 2012). Klitkou, Borup, and Iversen (2012) and Borup et al. (2013) categorised indicators into inputs, throughputs and outputs based on functions approach. In the *Global Energy Assessment*, Grubler et al. (2012) suggested to analyse ETIS with both quantitative and qualitative indicators. Three types of indicators – inputs, outputs and outcomes were proposed to cover the entire lifecycle of ETIS, from knowledge production to market formation and to technology diffusion. Wilson (2014) compared the advantages and disadvantages of some commonly used metrics, finding that no single metric can capture the entire process of energy technology innovation nor link inputs to outputs and broader outcomes.

The method of benchmarking has been employed for comparing NISs across countries. The OECD resists ranking countries' innovation performance via aggregate indexes as they do not adequately reflect the diversity and linkages of innovation actors and processes (OECD 2010). In contrast, the European Commission shows more interest in this approach which may be due to political agreements that "the European Union urged its Commission to work together with the EU-15 countries in order to develop indicators and a methodology for the benchmarking of national research policies" (Balzat 2003). The major shortcoming of benchmarking nations' innovation performances with composite indexes is that the selection, weighting and aggregation of indicators vary significantly by different researchers (Grupp and Schubert 2010). For example, China was ranked 19^{th} in the *National Innovation Index 2013* (Chinese

Academy of Science and Technology for Development 2014), but was 35th in *The Global Innovation Index 2013* (Cornell University, INSEAD, and WIPO 2013).

3. A multi-dimensional indicator framework

3.1 Rational for developing energy innovation metrics

A key message from the existing research is that "the appropriateness of a given set of indicators depends on its use" (OECD 2010). The validity of an indicator framework can be checked by two criteria: 1) Can the analytical framework well address the research question(s)? 2) Can the indicators be capable of measuring the specific dimensions defined by the analytical framework? The first criteria requires a clear and transparent structure and recognised concepts (Grupp and Schubert 2010), e.g. the core dimensions of innovation systems. The second criteria indicates that researchers should critically select indicators according to the proposed research question(s) as every indicator may have its own strengths and weaknesses (Grupp 1998).

Among the multiple innovation systems approaches, ETIS seems more suitable for evaluating the performance of energy technology innovation. It captures the fundamental aspects in the formation and evolution of innovation systems, which includes resources, knowledge, technology, and actors & institutions. Each dimension contains a range of contents, e.g. knowledge dimension can be analysed from the perspectives of knowledge stocks, knowledge depreciation and knowledge spill-overs, but the scope can be narrowed down according to real needs. If the dynamics of knowledge growth is of interest to be measured, then the estimation of knowledge stocks is very relevant. This enables stakeholders to monitor the achievement of an operational EITS and to identify potential gaps through international comparison.

Innovation differs across sectors in terms of characteristics, sources, processes and patterns (Malerba 2005, Pavitt 1984). The choice of individual technology-related policy instruments needs to be tailored to technology-and-locality specific circumstances (Wilson et al. 2012). Therefore, sector or technology-specific indicators can better evaluate successes and diagnose problems. Aggregate index may convey biased information as a nation's industrial structure has a significant impact on innovation rankings. For example, the United States has never been on the top in existing innovation rankings (Cornell University, INSEAD, and WIPO 2013, 2015), but it would not be disagreed that the country is strong in developing advanced technologies. In contrast, a few countries whose industry mix is less complex held a high position in the Global Innovation Index (GII). For wind power industry, the measurements of unit capacity of wind turbines (MW), capacity factor of wind power (%) and total cost of wind power projects ($/kW) are very relevant to capture the innovation outputs.

The ETIS indicates that energy technology innovation spreads over a series of inter-linked stages, from RD&D to market formation and diffusion (Grubler et al. 2012, Grubler and Wilson 2014). RD&D investment is required to generate technical knowledge that is often in the forms of publications and patents. These types of codified knowledge are then converted into advanced technologies and finally become commercialised. They can then be traded in the market as consumer products or intellectual properties for earning license fees and royalties. In the energy sector, it is essential to demonstrate new energy technologies particularly when end-user markets are highly fragmented or novel technologies cannot compete again established fossil fuels (Gallagher et al. 2011, Harborne, Hendry, and Brown 2007, Brown et al. 1993). When a promising technology becomes widely adopted and diffused across boarders or sectors, it may fulfil very important societal functions, e.g. scaling up electricity generation from renewables and cutting emissions of carbon dioxide and other air pollutants.

Low-carbon technology innovations in emerging economies are increasing rapidly. China has become a major exporter of green technologies such as solar photovoltaic (PV). But when the so called anti-subsidy and anti-dumping measures were acted, many Chinese solar PV makers went bankrupt. This may imply that Chinese solar PV manufacturers are not technology leaders nor their solar technologies are unique although they have dominated export market. In this sense, global value chain approach may represent a useful perspective to find how much value is added by emerging economies in international trade. It is meaningful to analyse the proportions of components or sub-systems that have been imported by emerging economies from technologically advanced countries to produce (sometimes assemble) the products which are then exported to the latter at significant numbers. A few countries have already began to collect this data, such as the US compiles historical data on imports and exports of heat pump and wind energy, but many other countries have not yet started.

3.2 Data gaps in energy innovation statistics

Assessing the performance of ETISs largely relies on energy innovation statistics, but current international categorization of products and technologies cannot meet the requirements (Borup et al. 2013). The lack of available and reliable data hampers the standardized and cross-comparable assessments of ETISs across technologies and countries (Grubler et al. 2012). Data collection on private RD&D, technology-specific investment, technology-specific trade and joint RD&D collaborations, knowledge spill-overs across sectors and at the international level, internationally comparable economic characteristics for energy technologies, as well non-OECD countries is much needed (Grubler et al. 2012).

In most cases, investment data is spread all over the innovation process. It is difficult to ascertain the accurate amounts of capital invested into the various stages (Sagar and Holdren 2002). While this may convey frustrating messages to researchers, efforts in interpreting quantitative indicators from existent statistics as the first step and then making use of qualitative methods (e.g. interviews, surveys, expert appraisal) to augment quantitative analysis would be able to produce satisfying results (Sagar and Holdren 2002). Besides, joint R&D activities across national borders are difficult to be captured by statistics, and thus measuring knowledge and technology spill-overs represent another challenge. Investigating the ownership of patents can be an alternative method to quantitatively map international flows of codified knowledge.

Given the limitations of data availability, it is important to derive energy innovation metrics from the existing economic, technical and social indicators (OECD 2013). It may be worth studying the already-available data, and from there working to identify which can be utilized to indicate the status of ETISs directly or indirectly. This research is an attempt of this effort. For example, it is difficult to figure out how many product and process innovations have been generated in China’s wind turbine industry, but it is able to analyse the historical changes of turbine sizes in manufacturing, installation and exportation.

3.3 Metrics for innovation system of wind technology

By drawing upon the implications from IS approaches particularly the ETIS and the existing research on innovation indicators, we proposed a multi-dimensional indicator framework for measuring wind technology innovation system (see table 1). At the initial stage, over 60 indicators were identified relevant but this number was reduced to 36 after careful considerations. The purpose is to focus on the indicators that may best describe the functionality of ETIS. It is clear that each indicator has two analytical dimensions. This distinguishes it from traditional indicator sets that focus on technological leadership or economic benefits, or neglect the cumulative nature of innovation. Instead, this multi-dimensional indicator framework is capable of conducting technology-specific analysis, understanding technology innovation process as a whole, making cross-country comparisons and identifying the specific areas that need to be improved.

This indicator set is not merely a combination of various indicators but also acts as a methodological framework that guides quantitative and qualitative analysis. While we aim to measure the performance of ETISs in a holistic manner, it is challenging to realise this now due to the complexity of systemic elements and data availability. For example, the measurement on the dimensions of actors and interactions, and institutions were not included in this research as we assumed that it may be more suitable to explain the causes for cross-country variations in energy technology innovations. But these two dimensions were included in this indicator framework in order to show a complete picture of how we may quantitatively characterise ETISs. Likewise, some data on private (RD&D) investment, and license fees and royalties were not available at the moment and thus the analyses on these aspects had to be dropped.

4. Research methods

4.1 Bibliometrics

Knowledge is a powerful driver for innovation and technological change (Powell and Snellman 2004, Lundvall 1992). From the completely tacit to the completely codified, and similarly for appropriability, knowledge can be in a variety of situations (Saviotti 1998, Nelson and Winter 1982). Codification of knowledge is essential in scientific progress, especially in natural sciences (Björn Johnson, Edward Lorenz, and Lundvall 2002). Codified knowledge takes various forms such as journal papers, books, magazines or other documentations, and is possible to be measured; while tacit knowledge often exists in our minds or embedded in artefacts, and is thus difficult to be written down and transferred to another person.

Technological innovation requires an accumulative process of knowledge production, but specific types of knowledge may not equally contribute to promoting science and technology advancement. Tödtling, Lehner, and Kaufmann (2009) evidenced that firms introducing rapid innovations relied more on advanced knowledge (e.g. scientific publications and patents) generated in universities and research institutes, while incremental innovations normally occurred in interaction with partners rooted in the business sector. Also, high-quality publications or patents tend to have higher citations and will create a bigger impact. Highly-cited publications or patents represent a good measure for exploring the quality of knowledge base.

Table 1 Metrics for innovation system of wind technology

<table>
<tr><th></th><th>Resources</th><th>Knowledge</th><th>Technology</th><th>Actors & Interactions</th><th>Institutions</th></tr>
<tr><td>Input</td><td>• Total investment in wind energy (1)
• Public investment in wind energy (1)
• Private investment in wind energy (1)</td><td>• Total RD&D expenditure in wind energy (1)+(5)
• Public RD&D budget in wind energy (5)
• Private RD&D expenditure in wind energy (1)</td><td>• Total expenditure for demonstrating new wind technologies (1)+(5)
• Public expenditure for demonstrating new wind technologies (5)
• Private expenditure for demonstrating new wind technologies (1)</td><td rowspan="3">Actors (measured by numbers and RD&D budgets):
• Regulators: national energy agency (10)
• Manufacturers: start-ups, SMEs, large firms and MNEs (10)+(15)
• Knowledge hubs: universities, research institutes, professional training organizations (10)+(15)
• Supporting facility: wind energy industry association, wind turbine standardization & certification bodies, wind turbine test centres (10)+(15)
Interactions (measured by closeness of networks):
• Formal & informal networks among various actors (6)+(15)+(16)</td><td rowspan="3">Institutions (assessed by observations):
Hard institutions
• Renewable energy laws (17)/(18)
• CO_2 reductions commitment (17)/(18)
• Wind power development targets, regulations and instruments (e.g. government subsidies, portfolio standards and feed-in tariffs) (17)/(18)
Soft institutions
• Top-down: Mutually shared expectations on wind power (17)
• Bottom-up: public acceptance on wind power (15)
• Culture: entrepreneurship in sustainable energy technology (15)</td></tr>
<tr><td>Output</td><td>• Market share of wind turbine manufacturers (2)
• Employees of wind energy RD&D personnel (3)</td><td>• Number of highly-cited publications in wind energy (6)
• Number of triadic patents in wind energy (7)</td><td>• Maximum unit capacity of wind turbine (10)
• Wind projects lifetime (10)
• Capacity factor of wind power (11)</td></tr>
<tr><td>Outcome</td><td>• Revenues from wind turbines (4)
• Balance of trade in wind-power generating sets (4)
• Employment in wind turbine industry (3)</td><td>• License fees and royalties of wind technology patents (8)
• Number of international standards and certifications in wind technology (9)</td><td>• Installed cost ($/kW) of wind power projects (12)
• Electricity generated from wind turbines (13)
• CO_2 emission reduction due to wind power diffusion (14)</td></tr>
</table>

Note: Data sources for the proposed metrics

(1) Bloomberg Desktop Database
(2) REN21 Renewables Global Status Report
(3) IRENA Renewable Energy and Jobs Annual Review
(4) UN Commodity Trade Database
(5) IEA R&D Database
(6) Web of Science Core Collection
(7) OECD Patent Database
(8) OECD Technology Balance of Payments Database (no technology-specific data)
(9) IECRE documents (data availability unclear)
(10) National statistics, e.g. Chinese Wind Energy Association
(11) IEA Wind Annual Report (or calculated from (10))
(12) IRENA Renewable Energy Technologies: Cost Analysis Series - Wind Power
(13) BP Statistical Review of World Energy
(14) Calculation according to IPCC CO_2 emission factor
(15) Surveys, interviews or expert appraisal
(16) Ownership analysis on patents registered by the EPO
(17) National government report(s)
(18) IEA Policies and Measures Databases

In order to quantitatively estimate the generation of specialised knowledge, bibliometrics and patent analysis (section 4.2) were performed with data retrieved from the Web of Science and OECD patent database. Besides, two types of measures were employed to quantify the strength of a country's knowledge base – country share of the world's total publications and country share of the world's top 1% publications. The former is to describe the volume of a nation's knowledge base, while the latter characterises the country's potential in producing high-quality knowledge measured by the number of forward citations.

A wind turbine consists of a large number of sub-components. The core ones include blade, generator, gear box, tower and inverter (IEA 2013). These elements require sophisticated technologies and comprise the majority of the total cost of a wind turbine (DOE 2015). Thus, these terms were included in query sets. 'Wind energy' and 'wind power' were also included because some technical articles or reviews study the systemic arrangements of wind power industry, e.g. business, economic or social issues, rather than individual parts of a wind turbine. In terms of timeframe, the data search started from 1970 when the US government funded NASA (National Aeronautics and Space Administration) to develop utility-scale wind turbines. A few years later, the world's first large (utility-scale) wind farms were constructed in California. By referring to this time period, it enables to better reflect the dynamics of knowledge and technology growth in wind energy.

Box 1 Query sets used in bibliometrics

> Search terms: TI = (wind energy Or wind power Or wind tech* Or blade Or generator Or gearbox Or tower Or inverter)
>
> Database: Web of Science Core Collection
>
> Document type: article, review, book chapter, proceedings paper
>
> Years: 1970-2014
>
> Language: English

4.2 Patent analysis

Patent is another type of codified knowledge and an important measure for technical inventions. The quality of patents registered across the world vary considerably. The patents registered at European Patent Office (EPO), United States Patent and Trademark Office (USPTO), and Japan Patent Office (JPO) have been most widely used to carry out patent analysis. However, there exists obvious 'home advantage effect' in these databases, which means that institutions and individuals located in the same region as the patent office often have higher contribution to patent publication (Li et al. 2007, Criscuolo 2006, Dernis and Khan 2004). American inventors have dominated patent grants at the USPTO, and European inventors have strong propensity to apply to the EPO (Dernis and Khan 2004).

In order to avoid 'home advantage effect', triadic patent families were built by taking patents from all these databases. Literally, triadic patent families is a set of patents filed at the USPTO, EPO and JPO by the same applicant or inventor for the same invention. There are two obvious advantages by using triadic patents. Firstly, international comparability of patents is improved as 'home advantage effect' is minimized. The second is that triadic patents are high-quality inventions to reflect the 'real value' of scientific knowledge. Multinational enterprises (MNEs) may not simultaneously file their patents with the EPO, USPTO and JPO, thus many patents are excluded but they are mainly low-value patents (Criscuolo 2006).

However, merely relying on the OECD triadic patent family may neglect the cumulative nature of knowledge as the quality of inventions may improve as the number of inventions grows. Japanese patents became more frequently cited than others before it rose to be a technological power (Narin and Carpenter 1986). This evidences that a catching-up country can make a shift from its relative weakness in fundamental science. To assess a country's potential to producing high-value patents, patent applications filed under the Patent Cooperation Treaty (PCT) were taken into account. PCT protects an invention simultaneously in 145 contracting countries, thus including a larger number of a country's inventions.

A negative aspect by using the OECD patent database is that citation and ownership analyses on patents become impossible. The number of citations a patent receives can reflect the degree of its technological and commercial potential (OECD 2009). Also, the ownership of patents can be analysed to track the collaboration between public and private sector or between domestic and foreign partners. In these two cases, the EPO Worldwide Patent Statistical Database (PATSTAT) can be used to explore the specific characteristics of patents. Another issue is that the triadic patent family covers patent applications only between 1985 and 2011, so it is not able to date back to 1970s as publications.

Box 2 Query sets used in patent analysis

Patents office & Triadic patents family: Triadic patents family (Or Patent applications filed under the PCT)

Reference country: Inventor(s)'s country(ies) of residence

Reference date: Priority date

Technology domains & IPC: Wind energy

Time: 1985-2011

5. The performance of China's wind technology innovation system

Energy innovation is to play a central role for China to sustain economic growth, enhance energy security, relieve environmental concerns and mitigate climate change. In recent years, the scale and speed of China in improving energy infrastructure and increasing human capital is higher than world leading countries (AEIC 2015). China's public budget on energy RD&D now ranks third globally only after United States and Japan (see figure 1)[1]. More broadly, the country's R&D expenditure as a percentage of GDP already climbs to 2.08% (OECD 2014), equivalent to the OECD average (2.12%). It is projected that China will become the top R&D spender by around 2019 (OECD 2014). Large amounts of RD&D investment can facilitate major technological innovations, but this finally depends on the functioning of China's (energy) innovation system

[1] It was estimated from the data produced by the IEA, World Bank and Chinese National Statistics Bureau. China's data was underestimated by the authors due to incomplete statistics.

5.1 Knowledge production

Institutional reforms have acted a crucial role in driving the state innovation machine operating in a more efficient manner. In 1978, the Chinese government delegation paid a visit to Western Europe. This extraordinary visit impressed Chinese policymakers on Western science, technology and business, and paved the way for cooperation between Chinese and Western enterprises afterwards. The well-recognised “Economic Reform and Opening-up Policy” was initiated to embrace foreign capital and technology. The accession to WTO enables Chinese firms to expand business and create technology linkages globally. The “Bringing in” and “Going out” deepens Chinese firms’ integration into global networks of production and innovation, through which they learn and develop technological and managerial capabilities. It is in this context that Chinese manufacturing sector including wind turbine industry develops rapidly.

Now among the world’s ten biggest wind turbine manufacturers, four of them are Chinese enterprises (REN21 2015). The innovation models of Chinese wind turbine manufactures have transformed from technology licensing and joint ventures to collaborative and indigenous innovations (Ru et al. 2012).Despite this, China still lags behind leading countries in knowledge accumulation measured by highly-cited (top 1%) publications and triadic patents (see figures 2-5). While the share of United States in producing high-quality publications declines, Denmark and United Kingdom are playing a more visible role. With respect to patenting activity, China’s performance is even poorer. United States and Denmark have been leaders in this area, but patents have failed to ensure United States as a global leader. This may imply that patents are a useful measure for estimating knowledge stock which is essential to facilitate technological innovation, but they cannot surely be converted into industrial leadership.

Literally, knowledge input should not be limited to RD&D but include all capital investment in the entire technology lifecycle. The current data infrastructure makes this impossible. RD&D activities cannot cover all innovation-related practices but they are the core to spur science and technology advancement. Another concern may be that the inputs fail to take into account human resources in science and technology (HRST). It should be acknowledged that R&D personnel play a vital role in generating knowledge and technology, but RD&D expenditure is an aggregate measure covering almost all the spending that support innovation activities, including human resources development. Therefore, HRST is excluded in inputs unless the stock of human capital or productivity of R&D personnel is of interest.

5.2 Resources accumulation

Resources are the key input to innovation. They can be financial and human resources, intellectual property, as well as time and effort invested by system actors (Grubler and Wilson 2014). Over the past forty years, United States spent about 2.5 billion dollars (public) in wind energy RD&D, which was nearly 4 times higher than that of Denmark (IEA 2015b). China’s public budget on wind RD&D is unavailable, but it is sure that number of wind energy R&D projects have been included in the country’s S&T programmes, such as " High Technology Research and Development Plan (863 Plan)", " Key Fundamental Technology Research and Development Plan (973 Plan)" and “National Key Technology Support Programme” (IEA 2015c).

Figure 2 Country share of scientific publications in wind energy

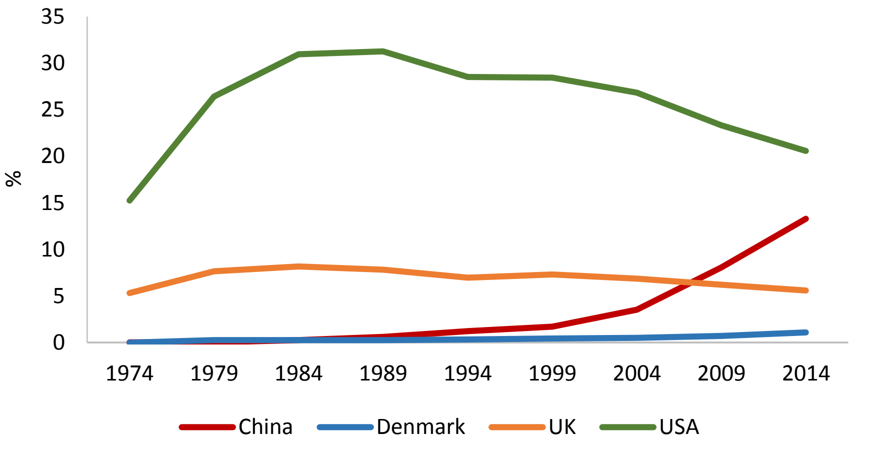


Figure 4 Country share of PCT patent applications in wind energy

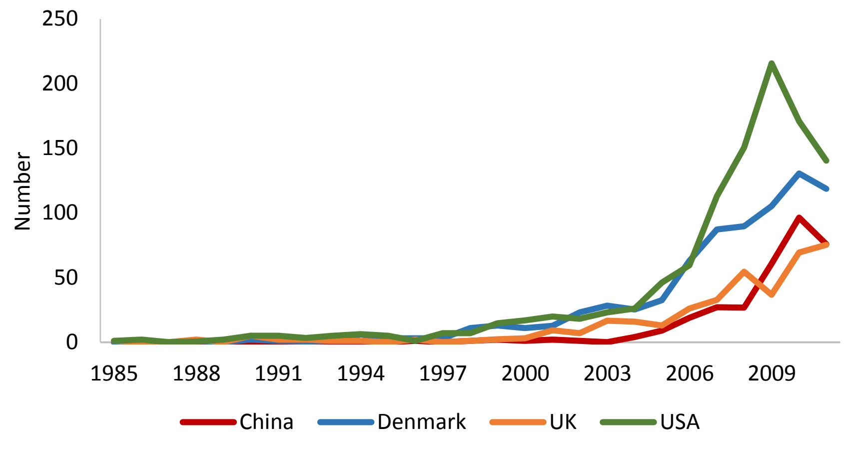


Figure 3 Country share of top 1% publications in wind energy

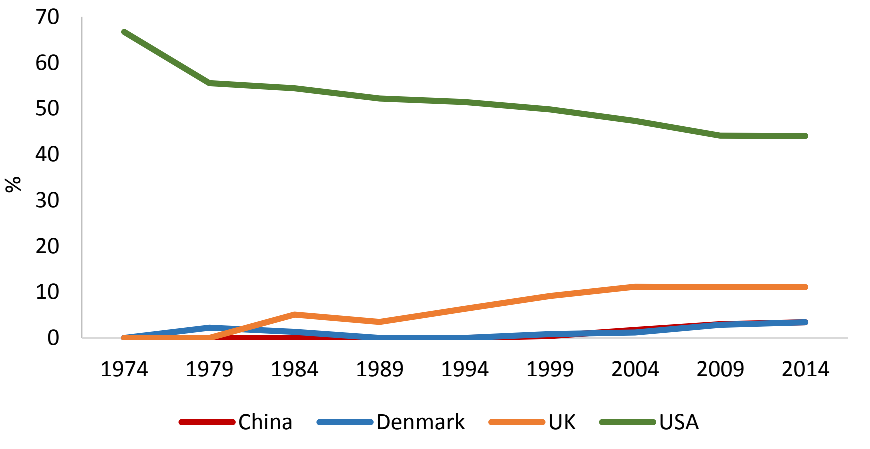
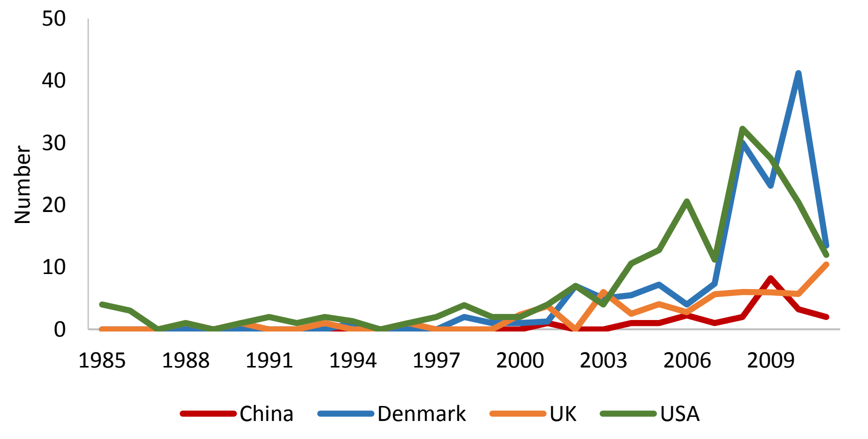


Figure 5 Country share of triadic patent applications in wind energy



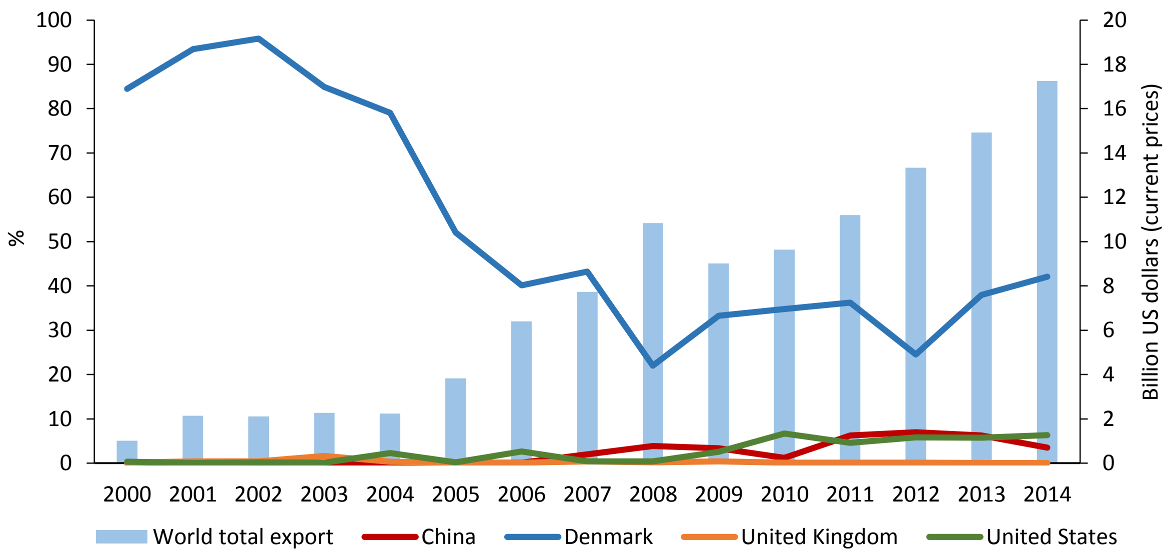
Source: Web of Science

Source: OECD patent database

The manufacturing capability of Chinese wind turbine makers has increased significantly. In the early2000s, less than 30% of the country's installed capacity was contributed by domestic wind turbine manufacturers (Shi 2003). Now their market share has grown to over 95%, with the remaining 5% shared by foreign firms and joint ventures (CWEA 2015). The annual additions of wind turbines in Chinese market by foreign manufacturers dropped from 2000 MW in 2009 to less than 50 MW by 2014 (CWEA 2015). In the meantime, Chinese manufacturers began to export wind turbines since 2007, mainly to United States, followed by Ethiopia and Austria (CWEA 2015). The average unit capacity of exported wind turbines varies considerably, but the dominant rated capacities have been 1.5 MW, 1.75 MW and 2.0 MW (CWEA 2015).

Danish manufacturers have been the leader in exporting wind-power equipment, taking up over 40% of the world's total export (United Nations 2015). In 2014, the export of wind turbines contributes a trade surplus of 7 billion USD for Denmark (United Nations 2015); in contrast, United States and United Kingdom have been a net importer of wind-power generating sets, and China have gradually balanced trade values (United Nations 2015). The balance of trade indicates value creations and focuses on manufacturing part. This may convey biased information as some countries only engages R&D activities and related business services. A deeper investigation into licence fees and royalties may be useful. Overall, the export performance indicator has proved to represent a good measure for indirectly evaluating technological capability of wind turbine manufactures.

Figure 6 Export of wind-power generating sets from China, Denmark, UK and US



Source: UN commodity trade database

Wind power has created millions of jobs globally. China accommodates almost half of the world's total employees in wind energy compared with 73,000 jobs in United States (REN21 2015). It should be noted that cumulative installed capacity of wind power in China hits at 114,609 MW, nearly 2 times higher than United States (BP 2014). This may imply that labour productivity of wind power industry in China is considerably lower than United States. While the labour market in wind energy sector is growing, there exists a critical shortage of skilled personnel. It is estimated that a shortage of 7,000 qualified personnel are required by the European wind energy sector annually, and this figure would tend to rise if the number of graduates taking relevant courses did not increase (Fitch-Roy 2013).

5.3 Technology development

In the early 1932, a German engineer proposed the idea of building giant wind turbines. The single wind turbine power would have a capacity of about 22 MW, standing at 1,400 feet, even higher than the Empire State Building. Today, the unit capacity of wind turbines has now increased from 75 kW in 1980s to 7.5 MW by 2011, growing by 100 times over the past thirty years. Today the state of art 10-20 MW wind turbine project is under research in Europe[2]. The R&D programme on the conceptual design and key components of 10 MW direct-drive wind turbines has been initiated in China (IEA 2015c). More recently, the American manufacturer Sheerwind announced its patented INVELOX™ which was claimed to be able to generate 25 MW wind power through a set of turbines in a funnel[3].

The sizes of Chinese wind turbines leapt from 600 kW in 1997 to 6 MW by 2011. The time lag between China and Denmark in manufacturing maximum unit capacity of onshore wind turbines is increasingly becoming shorter (see figures 7 and 8). In the past, there were usually 5-10 years' difference, now it is shortened to within 5 years. The United States installed relatively smaller onshore wind turbines, which may be due to the fact that offshore wind in the country has not developed yet. For economic benefit reasons, offshore wind turbines tend to have bigger capacity. The underdeveloped offshore wind may have caused negative impact on wind turbine industry in the US. However, this is not to say that countries with large offshore wind markets will perform better. For example, the UK is the world's largest offshore wind market but owns limited wind turbines manufacturing capability. Or put it differently, it seems impossible for a country to invest in all technological options.

Despite the progress, quality and reliability of wind turbines may undermine the further development of wind power in China. A typical example is that Sinovel was once the world's second largest wind turbines provider, but the company now has to cancel plans to build wind turbine manufacturing plants due to blind pre-expansion which causes serious quality problems (Windpower Monthly 2014). Chinese firms are seeking opportunities to explore international market, but this effort may not make obvious changes without improvement on quality and reliability. The maintenance cost can be huge if the turbines are less complete lifting of the reporting period.

In terms of offshore wind, the current progress of less than 700 MW installed capacity is far behind the target of completing 5 GW installation by 2015 as declared in the *12th Wind Power Development Plan (2011-2015)*. This may be partly due to the over-estimated target, but the main reasons lie in the high cost of offshore wind power projects, the lack of advanced construction equipment, complex climate conditions, and immaturity of offshore wind technologies. There are still big challenges for Chinese wind turbine manufacturers to transform from price competition to quality competition, and ideally to technology competition and to be able to provide customised products and solutions.

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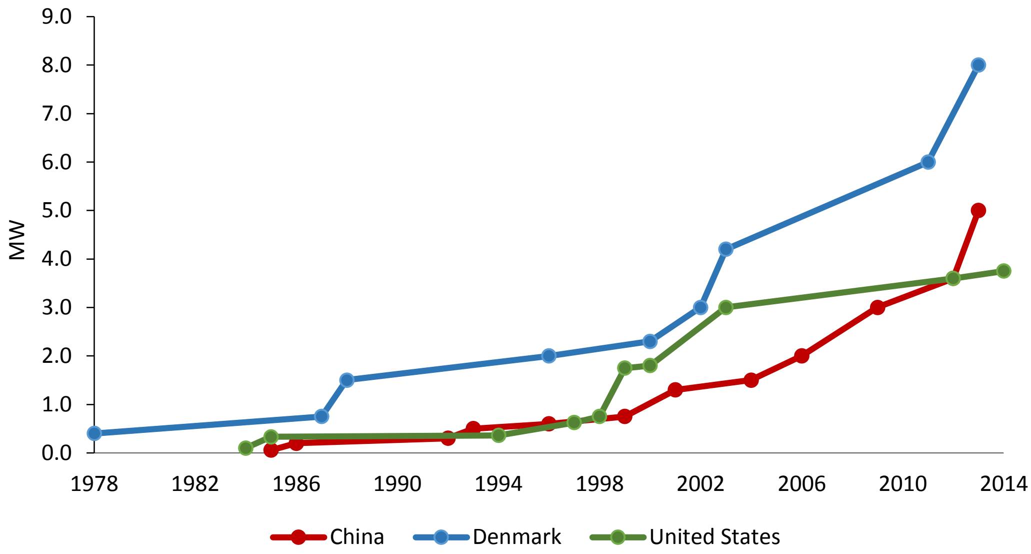
[2] The European 10-20MW offshore wind project can be found at http://www.innwind.eu/

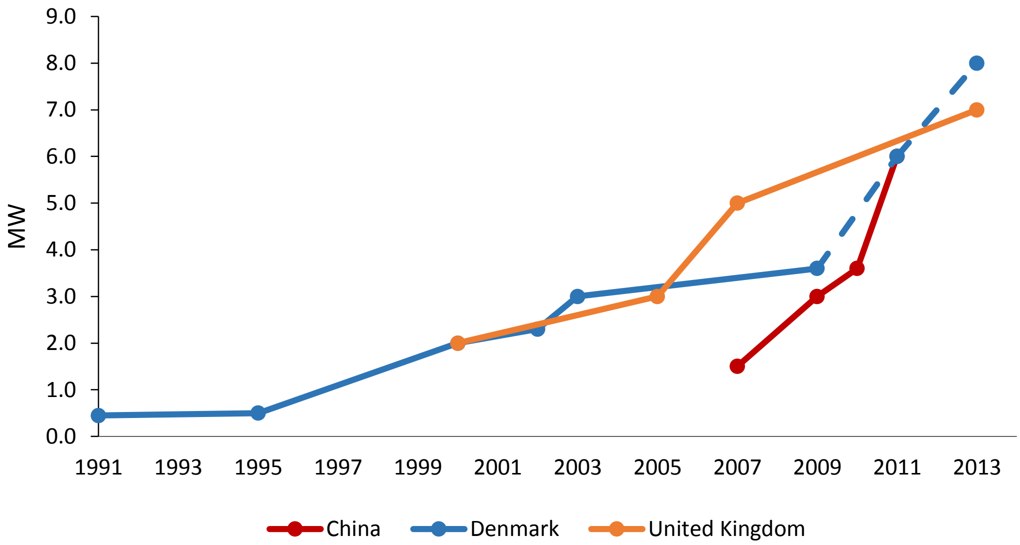
[3] More details about Sheerwind's INVELOX™ can be found at http://sheerwind.com/

Figure 7 Time lags in manufacturing maximum unit capacity of onshore wind turbines



Source: CWEA; ENS.DK; USGS

Figure 8 Time lags in manufacturing maximum unit capacity of offshore wind turbines



Source: CWEA; ENS.DK; UK Wind Energy Database

6. Discussion

Wind technology innovation in China is a typical example of "demand-pull" innovation (Chidamber and Kon 1994, Walsh 1984). Chinese wind turbine manufacturers are catching up rapidly with leading players, and their speed of technological innovation is accelerating (see figures 7-8). These largely owe to the government's favourable policies that support large-scale deployment of wind power to meet the demand for reducing air pollutions. There were little chance that China would develop wind technology for utility use without the concerns of severe air pollutions. At the same time, it implies that government's determination (or demand) to facilitate wind power has played a vital role in stimulating wind turbine manufacturers and wind farm operators to develop wind-related technologies.

An important observation is that high-quality patents do relate to innovation but the large number of ordinary patents may not ensure a country's industrial leadership. This has been clearly evidenced by the relationships between patenting activities and innovation achievements by Denmark and the US. The success of technological innovation depends on a variety of factors apart from cumulative patented technologies (Freeman 1979, Bartels et al. 2012). In some cases, patents can even harm downstream product development and the diffusion of upstream knowledge (Fabrizio 2007, Heller and Eisenberg 1998). Existing research shows that patent laws influence inventors' propensity to patent, the diversity of innovation, and the direction of technological change (Moser 2005). The recently established patent system in China has induced a stock of patents, but the key factor for this rapid growth of patents relied on the input of R&D personnel (Yueh 2009). It is understandable that large countries tend to have a larger number of patents.

It may be controversial whether Chinese wind turbine manufacturers have significantly improved their technological capability. Some argue that China has successfully transformed from technology licencing to indigenous innovation (Ru et al. 2012, Sun, Yang, and Ieee 2012); however more hold that China's wind industry still depends on international technology transfer and licensing (Gosens and Lu 2013, Klagge, Liu, and Campos Silva 2012). Although Chinese wind turbine manufacturers have attempted to grow technology through join R&D, and mergers and acquisitions, their innovation capability is still limited (Gosens and Lu 2013, Zhou et al. 2012). We herein suggest characterising a country's technological growth by measuring license fees and royalties, and the proportion of imported components in final products. Nevertheless, these two indicators are subject to data availability. An alternative method is to evaluate export performance.

Facing the grand challenge of global climate change, (clean) energy technology innovation is crucial to limit the increase in global temperatures (IEA 2015a). Traditional innovation indicators have often been constrained to economic growth, job creations and international competitiveness, but these may not meet today's expectations on innovation. A few new metrics that can reflect the impact of innovation on energy security, climate change mitigation, and environmental protection are needed. In order words, innovation should fulfil some new societal functions. This paper has attempted to experiment with these indicators, and shows that they can adequately evaluate the social impact of wind technology innovation across countries. For instance, China and the US are excellent users of wind technology by taking into account these aspects. As of 2014, approximately 158 TWh of China's electricity is generated from wind turbines, equivalent to the total electricity generation in Sweden (BP 2014). This means equivalent reductions of about 1.6×10^8 tons of CO_2, 9.2×10^5 tons of SO_2, 2.8×10^5 tons of NO_x, and 6.3×10^4 tons of $PM_{2.5}$ that may have been emitted into the air by China[4].

Having been tested with a case study on wind technology, the proposed indicator framework has proved to be useful for evaluating the performance of energy technology innovation system (ETIS) and making international comparisons. It captures the core dimensions of a well-functioning ETIS (Grubler and Wilson 2014), and enables to link together the inter-connected stages of a generic process of energy technology innovation, namely input, output and outcome. In addition, it explores new metrics that can measure the social impact of innovation. These indicators allow to analyse ETISs in a systemic manner and to avoid fragmented policies and adverse consequences (Wilson et al., 2012). The multi-dimensional indicator framework is contextually designed for wind power

[4] The calculations referred to the emission factors presented by Li et al. (2015).

industry, but it may also evoke new thoughts on how to adapt the indicators in order to be applied for other energy technologies.

7. Conclusion

The validity of indicators depends on the use. Indicators can be developed by tailoring existing indicators into research-objective oriented ones, or by exploring new indicators for which data limitations may occur. At current stage, indicators on the conditions and performance of energy technology innovation are still taking shape. This implies that there is much opportunity space to explore in this new area. The multi-dimensional indicator framework proposed in this paper fully considers the systemic nature of energy technology innovation, and enables to analyse ETISs in a systemic manner and learn successful and (or) failure lessons through cross-country comparisons.

It is of particular importance to avoid fragmented policies and poor alignment of national regulatory frameworks that often failed to spur energy technology innovation and wide-scale deployment of renewable energy (Grubler and Wilson 2014, Negro, Alkemade, and Hekkert 2012). The early efforts and successes by the National Aeronautics and Space Administration (NASA) on multi-megawatt turbine technologies have not ensured the US leadership in wind technology due to inconsistent energy policy. Instead, the success story of Danish wind energy stresses the importance of systemic approach to analyse and implement energy innovation policy (Wilson et al. 2012). The developed metrics can evaluate the functioning of resources mobilisation, knowledge production, and technology development, which helps imply systemic policy tools.

This research is an attempt to exploring quantitative metrics to assess energy technology innovation systems. Constrained by data availability, some areas were not covered in analysis. Improvement on data infrastructure is crucially important. Future research may discuss how to build a data-sharing system in the energy sector, or how likely it is to integrate multiple data sources into a one-stop platform, such as the Innovation Policy Platform jointed developed by the World Bank and OECD. Also, little attention was paid to explaining the reasons for cross-country variations in wind technology innovation. In-depth case study on institutional frameworks, research and training systems, and energy governance structures among countries will be fruitful research areas to answer this question.

Annex

Table 3 Summary on cross-country comparisons on wind technology innovation

	Knowledge	Resources	Technology
Input	• Public RD&D budget (Million $) in wind energy US (55) > UK (33*) > DK (32)	• Total investment in wind energy [Data unavailable]	• Public expenditure (Million $) for demonstrating new wind technologies US (21) > UK (17.1) > DK (0.8)
Output	• Share (%) of publications in wind energy US (21) > CN (13) > UK (6) > DK (1) • Share (%) of top 1% publications in wind energy US (44) > UK (11) > CN (3.4) > DK (3.4) • Share (%) of PCT patents in wind energy US (13) > DK (11) > CN (7) > UK (7) • Share (%) of triadic patents in wind energy DK (12) > US (12) > UK (9) > CN (2)	• Market share (%) of global top 10 wind turbine manufacturers CN (21) > DK (12) > US (9) > UK (0) • Share (%) of world export in wind-power equipment DK (42) > US (6) > CN (4) > UK (0.1)	• Maximum unit capacity (MW) of onshore wind turbine installed DK (8.0) > CN (5.0) > US (3.75) • Maximum unit capacity (MW) of offshore wind turbine installed DK (8.0) > UK (7.0) > CN (6.0)
Outcome	• License fees and royalties of wind technology patents [Data unavailable] • Number of international standards and certifications in wind technology [Data unavailable]	• Balance of trade (Billion $) in wind-power generating sets DK (7.2) > US (0.7) > CN (0.6) > UK (-1.2) • Employment (Thousand jobs) in wind turbine industry CN (502) > US (73) > DK (29) > UK (20*)	• Electricity generated (TWh) from wind turbines US (184) > CN (158) > UK (32) > DK (13) • Share (%) of wind power in total electricity consumption DK (41)> UK (9) > US (4) > CN (3) • Capacity factor of wind power (%) US (34) > DK (30) > UK (28) > CN (16)

Source: Calculated from multiple sources.

N.B. (1) *2013, otherwise it refers to the status in 2014; (2) Number round-up applies.

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