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Assessing the performance of energy innovation systems: Towards an established set of indicators

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ABSTRACT

Energy innovation is essential for tackling climate change. However, an established set of indicators, that can support policy makers in their design of policy mixes, has not been developed for evaluating the performance of energy innovation systems. The purpose of this study is, therefore, to list and classify a large set of indicators of the performance of energy innovation systems at sectoral and technological levels. 120 listed indicators are evaluated using four usefulness criteria, demonstrating significant weaknesses in the available indicators. The indicators are also classified according to an innovation process categorization to see if they cover all aspects of an innovation system along the entire innovation chain. In order to illustrate their application, the Nordic countries are selected for an analysis at the sectoral level, demonstrating a variety in the dynamics of energy innovation systems among these countries. At the level of an individual technology, we show how 90 indicators match the seven functions in a technological innovation system and how they, therefore, can guide policy by helping to analyze the strength of each function. Policy making may be further supported by an understanding of the dynamic relations between different indicators. Finally, recommendations for further research are given.

1. Introduction

The diffusion of energy technologies with high efficiency is important for tackling climate change in the near future [1]. Various scenarios[1] show possible ways to eliminate emission of CO_2 equivalents, however, large-scale deployment of energy technologies with high efficiency is the basis for many of these scenarios [5].

Mitigating climate change needs, therefore, additional efforts in terms of research, development and demonstration (RD&D) of energy technologies [6]. In order to make energy RD&D more effective, while scaling it up, the assessment of public RD&D support instruments is essential [7]. Governments fund energy RD&D activities with numerous tools. The evaluation of relevant indicators, e.g. patents, publications and R&D funding, is a common method to assess these tools.

However, the innovation process consists of several steps, from research to, eventually, commercialization and large-scale deployment. As the innovation outputs are uncertain, feedback loops between different phases have an important role in influencing dynamics in a non-linear innovation process [8–10]. Hence, since the innovation process depends not only on RD&D but on an entire innovation system, a general framework is required to facilitate the assessment of the innovation process and associated government policies. This implies that additional indicators to those reflecting RD&D activities are needed.

Research into assessing indicators that can cover the numerous aspects of different energy innovation systems is, however, fairly new. Notable studies include: Gallagher et al. [11] who investigate different indicators of innovation processes (inputs, outputs, and outcome indicators) but do not offer an assessment framework; Wilson [12] who also categorizes innovation indicators into three types: input, output and outcome[2]. Borup et al. [13] who provide an overview of the most recent ideas concerning indicators of energy innovation systems and their dynamics and Gallagher et al. [14] who use four types of financial investments into energy supply and energy end-use components of energy systems as indicators of energy innovation system activity. Also several recent reports, such as Global Green Economy Index 2016 [15], Eco Innovation index [16], Global Cleantech Innovation Index [17] and Global Innovation Index [18] propose a set of innovation indicators in diverse frameworks to assess green growth and potential to develop clean technology in numerous countries.

An established set of metrics that cover the various aspects of energy

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[1] These scenarios do not aim to forecast what will happen, but rather to demonstrate the many opportunities to create a more sustainable and clean energy future, see [2], [3] and [4].

[2] Furthermore, he analyzes the wider societal benefits of energy technology innovation and detects some issues with the use of indicators to assess EIS.

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innovation systems has, however, not yet been developed. Further work in this field may have various benefits, e.g.:

- Help policy makers analyze and understand trends in energy innovation system activities and in particular product classifications (e.g. wind turbines).
- Help policy makers understand the innovation phenomenon (as systemic, interactive, complex) and identify drivers and barriers to energy innovation.
- An improved understanding may include assessment of investment flows into various stages of the innovation process which may show possible mismatches between resource needs and resource allocation. An improved understanding would facilitate the design of appropriate policy mixes.
- Enhance knowledge of energy innovation among companies and stakeholders which facilitates the design of strategies.

The purpose of this study is, therefore, to continue the work in this tradition by listing and classifying a large set of innovation indicators and also by proposing a comprehensive indicator framework has originated from stages of innovation process, to assess the performance of energy innovation systems at the sectoral and technological levels (henceforth EIS and TIS), indicators that can be used by policy makers, firms and other stakeholders.

The rest of this paper is organized as follows. Section 2 presents the analytical framework which includes the concepts of energy innovation system and technological innovation system. Methodological issues related to identifying, selecting and categorizing indicators are discussed in Section 3. In Section 4, indicators are (a) selected and classified according to four criteria of usefulness, (b) applied to seven TIS functions and (c) applied to sectoral EIS in the four Nordic countries. Section 5 contains a concluding discussion.

2. Analytical framework

This section begins with a brief discussion of linear and non-linear models of the innovation process. We proceed with the concepts of energy innovation systems and technological innovation systems.

2.1. Linear and non-linear models of the innovation process

Several conceptual models of the innovation process have been put forward over the years. A first was a linear one, comprising sequential stages from research to demonstration and diffusion in the market [19], a model in which the innovation process is seen as "flowing smoothly down a one-way street" [8]. Later, learning in one stage was linked to other stages in order to capture chain-linked interactions [20]. These interactions involve strong feedback loops between science, technology and markets [8]. Indeed, the various feedback loops, and their interactions, combine elements of supply push and demand pull and strongly contribute to the development of new technologies and more efficient outputs of the innovation process. It is now well accepted that the innovation process is not linear [21,22] and that R&D is not sufficient to drive the innovation process [23].

2.2. Energy innovation systems

Grubler et al. [24] improved the model further by linking various feedbacks among the diverse stages of an innovation process to the structural elements of an innovation system. Fig. 1 shows the improved model of the innovation process.

First, the innovation system concept emphasizes the collective and institutional aspects of the innovation process and, as Dodgson et al. [25] put it, "… the dynamic, emergent, and evolving nature of systems." The concept can be applied to different levels, e.g. national, sectoral, regional and technological. EIS is an application to energy technologies and applies, thus, a systemic approach to energy innovations, primarily at the sectoral level [26–28].

An innovation system consists of actors, networks and institutions. Networks are the result of linkages between various types of actors that facilitate the transfer of knowledge among these as well as coordination of various activities (e.g. investments and political lobbying); institutions are formal (e.g. property rights and laws) and informal rules (e.g. culture and tradition) that influence the activities and connections of actors within the innovation system [29].

Therefore, the development of an EIS involves dynamics in actors (e.g. firms and universities), networks (learning and political) and institutions (norms and regulations). For instance, an early market formation may stimulate new firms to enter an industry and venture capital firms, and other actors in the financial sector, to invest in it. The new entrants may strengthen networks between firms and between these and academia. These strengthened networks may influence learning processes but may also lead to changes in institutions (norms and regulations), e.g. the desirability of different technologies and the nature of government policy. Institutional change may, in turn, positively influence both market formation and actors' allocation of funding to RD&D in a context of more ambitious business strategies.

Second, the various stages in the energy innovation process are listed and all these include feed-backs. For example, the formation of early markets may not only enable firms to spend more money on RD&D through increased revenues, but may also stimulate such investments. Similarly, learning from deployment of an energy technology in new applications may guide and stimulate technical change. Hence, while in the linear model markets are formed after a technology is fully developed, in this model a technology co-evolves with diffusion.

A main lesson of the EIS framework is that we need to ensure that indicators cover all stages, elements and processes in the dynamics of such complex systems. In Section 3.3 we propose a categorization of indicators for assessing the performance of EIS that is influenced by Fig. 1.

2.3. Technological innovation system

An EIS at the sectoral level is made up by a number of TIS centered on individual technologies. A TIS is defined as "… network(s) of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology" [31]. The application of the TIS framework has emphasized the appearance of new technologies and the changes needed for the creation and development of a novel system [32,33]. Jacobsson and Johnson [34], as one of the pioneering contributions, investigate the diffusion of renewable energy technologies and examine barriers to their growth based on an innovation systems approach. Some prominent papers have followed since then, involving research on renewable energy technologies overall (e.g. [35]) and on specific technologies such as photovoltaics (e.g. [29,36]), biomass (e.g. [37–39]), wind energy (e.g. [40,41]), fuel cells (e.g. [42,43]) and biofuels (e.g. [44,45]).

In addition to the structural elements of an innovation system, the TIS framework includes a set of functions, or key processes [46] which means that the TIS provides a partly different framework to that of sectoral innovation systems. The addition of functions, as suggested by Bergek et al. [47] and Hekkert et al. [48], strengthened the original innovation system framework in examining the dynamics of innovation since these processes influence both the structural build-up and performance of a TIS [49,50]. Table 1 summarizes seven functions. For instance, a strengthened legitimation process may alter institutions which, in turn, may influence guidance of firm's search for business opportunities. This may induce new

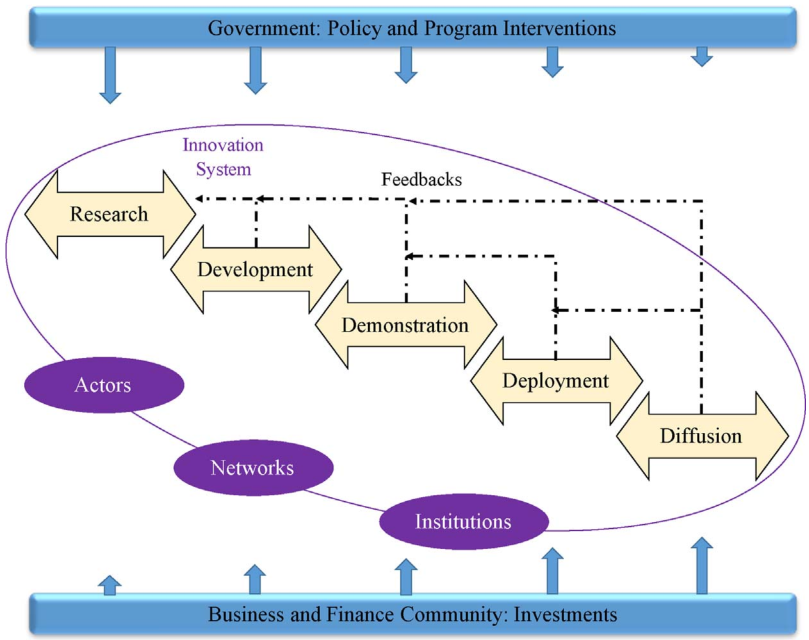

Fig. 1. The schematic representation of innovation with a chain-linked model of the innovation process.
Source: Adapted and modified from Grubb [30] and Grubler et al. [24].

Table 1
Functions of a technological innovation system (TIS).

Functions	Description
Knowledge development	refers to how knowledge is developed in the innovation system.
Knowledge diffusion	is the transfer of knowledge between actors and agents interacting, e.g. within various networks and across innovation systems.
Guidance of the search	covers the activities, incentives and mechanisms influencing the direction of search that affect firms' entry into an innovation system and exploration of specific applications of the technology.
Entrepreneurial activities	includes the innovative activities and business strategies required for testing new technologies to generate business opportunities. An innovation system without entrepreneurial activities will stagnate, because a technological system evolves under various uncertainties.
Market formation	includes the activities contributing to the emergence of markets and for new products. Three phases of market formation are normally considered, i.e. nursing, bridging and mass market.
Resource mobilization	covers the activities related to allocation of resources as an input function to innovation process. Key resources include financial capital, human capital and complementary assets such as network infrastructure.
Creation of legitimacy	is a matter of securing social acceptance of the technology and the actors. This function includes the activities that counteract resistance to improve the acceptance of new technologies.

Sources: Based on [47,56,48,57,58].

firms to enter into the system, which would strengthen resource mobilization and entrepreneurial activities.

The addition of a set of functions that underlay the development, commercialization and use of innovations means that policy makers can be guided by the strength and weaknesses of the various functions in their design of policy. It is, therefore, essential to have an established set of indicators of functional strength.

Various tools have been used to measure the strength of individual functions, including conventional indicators (e.g. [45]). Negro et al. [38] and Suurs and Hekkert [44] combine interview-based assessments with quantitative methods. Van Alphen et al. [51] use professional measurement to quantify the strength of the functions in several countries. Truffer et al. [52] illustrate that for development of novel technologies and linkages between TIS functions, a number of indicators are relevant. Gosens and Lu [53] suggest data types or indicators that may be used to map the emergence of domestic innovative activity. Vasseur et al. [54] investigate the development, demonstration and diffusion of photovoltaic (PV) technology in Japan and the Netherlands by collecting events and allocating those to individual functions. Finally, Bento and Wilson [55] summarize seven innovation system functions and develop a set of indicators to assess the spatial diffusion of energy technologies with reference to key innovation processes. In Table A.1 (Appendix A), we have listed the suggested indicators for each TIS function by these authors.[3]

3. Methodological issues

This section begins with a discussion of the method used to identify indicators of innovation systems in general. It proceeds with specifying four criteria for selecting useful indicators from a longer list and ends with proposing a way to categorize these indicators in terms of how they relate to the innovation process.

3.1. Method for identifying innovation system indicators

A variety of innovation studies include numerical metrics as part of their methodology. However, the number of these addressing the possibility of developing a complete set of indicators to assess the effectiveness of innovation systems is relatively small. So far, there is no full international consensus about a scheme involving a comprehensive set

[3] The majority of indicators in Table A.1 are gathered from the system functions elaborated by Bergek et al. [47] and Hekkert et al. [48].

of innovation system indicators [13]. This applies to both innovation systems in general and particularly to EISs. However, a number of suggestions have been made with contributions from researchers, statistics agencies and policy actors.

The set of indicators used in this paper is based on scientific publications listed in the *ISI Web of Science*. The following sentence was used in the search among the keywords, titles and abstracts of all publications: (*energy innovation* OR *innovation system*) AND (*indicator* OR *assessment*). We used generic keywords because we wanted to identify all types of indicators used in evaluations. In our search to construct a general database, we also benefited from manuals, organizational reports, regional sources and national-level quantitative data such as IEA [3,59] and OECD [60,61].

3.2. Criteria for selecting indicators

An important challenge in using indicators is to select an appropriate set among all possible indicators. To overcome this difficulty, several criteria to select or construct suitable indicators are needed. For innovation measurement and policy, data must be actionable, relevant, reliable and valid [62]. To select useful indicators to assess EIS, we propose four criteria. To identify these, we reviewed related publications about criteria to select proper indicators and then based on European Commission [63], GGGI et al. [64] and Zhu et al. [65], we selected four criteria. We found that these cover approximately all criteria proposed in the relevant literature:

- *Understanding*: indicators must be simple and easy to understand. This criterion focuses on simplicity instead of complexity and stresses acceptance by relevant stakeholders.
- *Availability*: indicators must be based on existing data and information. Availability ensures that the value of the indicators are available at national level and easy to obtain.
- *Relevance*: indicators are relevant if they mirror the goal of EIS assessment and energy sector's aspects. It differentiates between innovation systems in general and energy innovation systems.
- *Measurability*: indicators must be measurable. This criterion confirms possible scientific ways to measure indicators such as through using surveys.

There are, of course, other methods to filter indicators. For example, managers could select indicators based on qualitative and quantitative criteria or their own experience [66].

3.3. Categorization of indicators

In order to structure the assessment process, indicators can be organized in different ways. As mentioned in the Introduction, a common way is to categorize these into inputs, output and outcome indicators [12,67,68]. These can reflect either intangible features of the innovation system, such as ideas and knowledge stock, or tangible, such as number or types of active researchers and volumes of investments made.

However, this categorization fails to take into account policy, interactions among system elements and impacts of innovation, which are of particular importance for wider social benefits. Moreover, when an EIS is assessed all phases of the innovation process, from RD&D to market formation and diffusion, should be considered. For a comprehensive assessment, the indicators must, therefore, cover all aspects of an innovation system.

As a step towards reaching this goal, the indicators used in this study have been categorized inspired by the schematic dimensions of the non-linear generic innovation process, as depicted in Fig. 1, as well as by an input–output model developed by Klitkou et al. [69]. We include five categories of indicators in Fig. 2. Inputs into the innovation process are found to the left and outputs from the system to the right. Three additional categories that cover other aspects of the innovation process are policy, broader impacts and structural and system linkages.

Input indicators try to capture a diverse set of resources that enable a growth of the innovation system. These include indicators of financial, human and other resources, such as infrastructure, but also *number of new entrants* and *lobbying actions*. Policy indicators reflect diverse forms of policy instruments among nations [13], such as *Targets set by government*. Structural and systemic indicators consist of two parts. Structural indicators consist of the main country metrics that contain conventional measures to reflect national capacity, such as GDP, population and energy prices. Systemic indicators reflect any linkages and networks between actors in an innovation system [69]. The indicator *University/industry research collaboration* is an example of this category and may be used to analyze learning networks between firms and academia. Output indicators try to capture the desired end results of inputs into the innovation system [70], e.g. market penetration of green technologies. In this category we also consider throughput indicators. For instance, scientific publications and patents measure intermediate outcomes of the innovation process. In order to reflect the quality of scientific publications, we consider some indicators as output indicators such as *Citable documents H index* and *Number of highly-cited publications*. Finally, Impact indicators show broader benefits of energy innovation, such as jobs created and carbon emission reductions. Thus, for instance, the indicator *Employment in the energy industry* illustrates jobs created when innovation and development activities increase.

To sum up, the proposed energy innovation indicator framework focuses on the energy innovation process that covers the entire innovation chain including input, output and etc., and also incorporates indicators into the specific innovation stages from basic research to full commercialization.

4. Results and discussions

This section begins with an identification and classification of a large number of indicators according to four usefulness criteria (4.1). These are then applied to the functions of a TIS (4.2) and to sectoral EIS in the four Nordic countries (4.3).

4.1. Identification and classification of EIS indicators

Table A.2 (see Appendix A) presents all indicators identified by our generic keywords (as listed in Section 3.1), including their definitions. Table A.2 also includes the application of the four criteria listed in Section 3.2 to each indicator and how the indicators relate to the innovation process (see Fig. 2). The total number of indicators investigated is 120. As a synthesis of Table A.2, a histogram of indicators is given in Fig. 3. Fig. 3a illustrates the number of indicators meeting each criterion and the end column shows the number of indicators that meet all criteria. Fig. 3b shows the number of indicators organized according to the innovation process classification.

Many indicators meet one of the four criteria but only 12 match all four and among these, there is no systemic indicator. Hence, most indicators are problematic for assessing EIS. Moreover, only 32 out of the 120 meet the availability criterion. It is not easy to obtain all data from agents and actors and, therefore, most indicators were rejected based on this criterion. Other indicators were excluded because they were not directly relevant in an energy context. Regarding the innovation process classification, the input and output aspects have the largest number of indicators (37 and 30 respectively), and only 21 are related to structural and systemic aspects. The smallest number of indicators cover the policy and impact aspects.

In order to comprehend what indicators are rejected or included for EIS assessment, the application of the four criteria to the indicators in Table A.2 is further discussed.

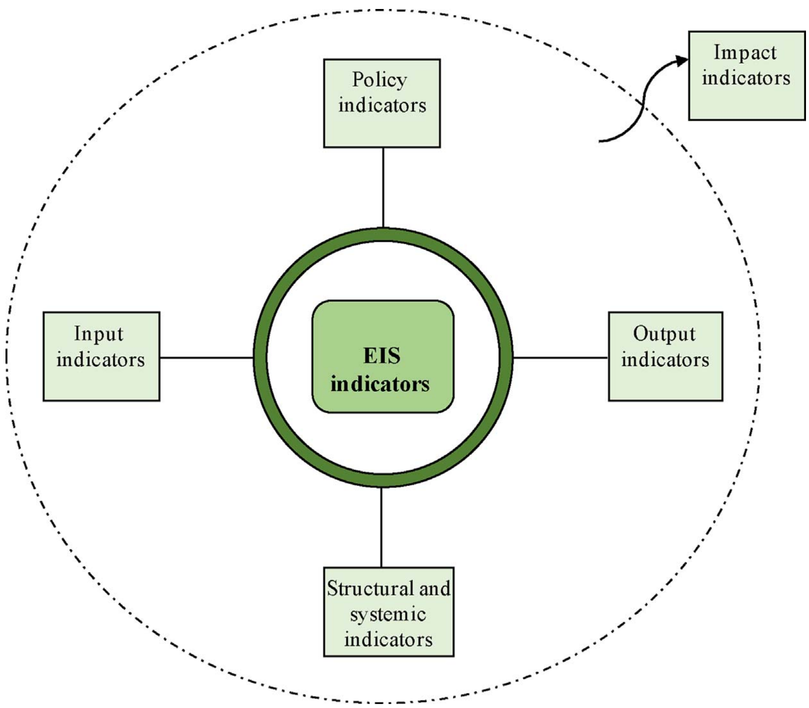

Fig. 2. Categorization framework of indicators.

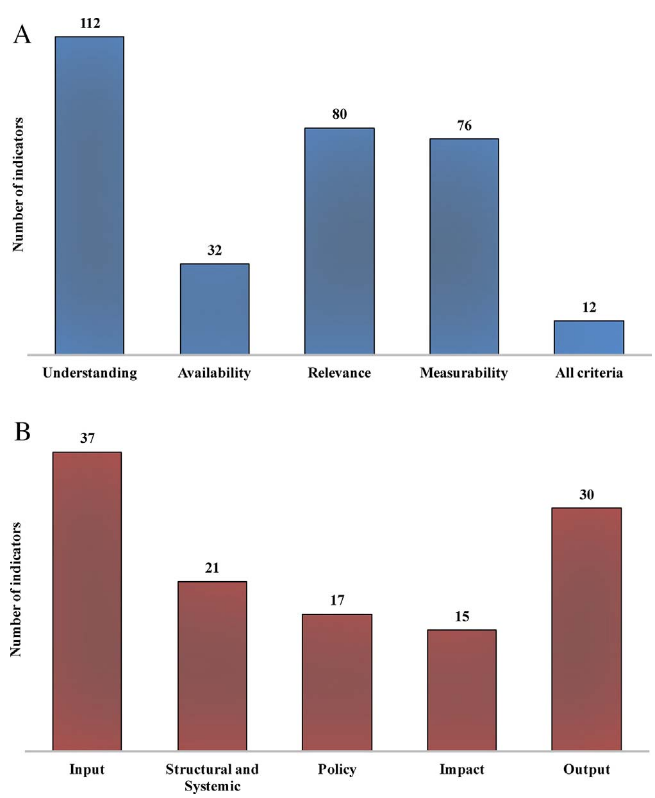

Fig. 3. Histogram of indicators based on two aspects. (a) Based on criteria of selection. (b) Based on innovation process classification.

4.1.1. Understanding

In general, if the definition of an indicator is hard to understand, it was rejected in this classification. Some indicators in the innovation system context have been linked to each other and developed into a new complex indicator. Thus, due to the high complexity they were rejected according to this criterion. For instance, Klitkou et al. [69], propose *a revealed symmetric comparative advantage* indicator reflecting the international specialization of energy RD&D combined with the specialization in energy supply. This type of indicator reflects a kind of complexity that is not easy to understand, so they were excluded.

4.1.2. Availability

For a comprehensive assessment, some indicators require detailed information and knowledge about several agents in the EIS. For instance, *cooperation patterns in R&D programs,* [13] which is one of these indicators, requires information about the number and types of collaborative projects between actors. All indicators that reflect these characteristics were rejected under this criterion because this information is not always available. We also assume that no deep information is available when performing the assessment, so, for example, the *ratio of energy-start-ups to incumbents* indicator [71], was excluded because of lack of availability. It is, however, essential to note that availability of data is flexible and can change this filter and selection of indicators over time.

4.1.3. Relevance

A group of indicators is focused on innovation without paying attention to the specifics of the energy area. As an example, the indicator *ICT access* [18] is very important for innovation as it measures the digital divide and compares ICT performance within and across countries and is, therefore, used by governments, researchers, operators, development agencies and others. This type of indicator does not focus on the energy sector in particular and was rejected under the criterion of relevance.

It is noteworthy that some indicators such as *high-tech exports* [72], are focused on innovation in general, but we can use these indicators in the energy area, e.g. energy technology exports.

4.1.4. Measurability

Indicators must be available in numerical terms, such as percentages, counts, ratios or proportions. Indicators are sometimes correlated with a size-related factor, such as gross domestic product (GDP) and population and will then be valid for cross-country comparisons. However, some indicators are not numerical, or not easy to measure, such as *Entrepreneurial culture* [17] or *Capacity to commercialize new products* [73]. Therefore, they were excluded under the criterion of

Table 2
Functions of TIS and their linkages to innovation process classification.

Functions	Input indicators	Policy indicators	Structural and systemic indicators	Impact indicators	Output indicators
Knowledge development	- R&D projects over time	- RD&D strategies - Research support			- Patents - Scientific publishing - Citable documents H index - No. of highly-cited publications - Learning rates
Knowledge diffusion	- R&D networks	- Development of communication centers - Facilitate the development of networks	- University and industry research collaboration - International scientific co-publications per million population - Public-private co-publications - Number of workshops and conferences - Cooperation patterns in R&D programs - Linkages among key stakeholders		- Knowledge-intensive services exports
Guidance of the search	- Policy action plans - Shared strategies and roadmaps - Perspectives of profits	- Targets set by governments or industries - Credible political support	- Debate-meetings/media - Strategy networks		- No. of press articles that raise expectations - Scenarios and foresight projects
Entrepreneurial activities	- No. of new entrants - Ratio of energy-start-ups to incumbents - Share of energy innovative firms of all firms - Entrepreneurial culture - Access to private nance for cleantech start-ups - Number of innovative activities - Number of diversification activities	- Ease of starting a business - Venture capital availability - Sustainable business models - Risk-sharing - Innovative firms support	- Innovative SMEs collaborating with others - Size of companies		- SMEs introducing product or process innovations - Market introduction of new technological products - Number of new businesses - Experimental application projects - Creative goods exports
Market formation	- Public market support - High-tech imports	- Green Tax - Tradable permits - Incentives and subsidies - Policy processes - Cleantech-friendly government policies - Transparency - Specific tax regimes	- Resource endowments - Proxies of size - Attractiveness of renewable energy infrastructure - Domestic market size index	- Environmental performance - Level of environmental impact on society - Renewable energy jobs	- Market penetration - High-tech exports - Installed capacity - Renewable energy production - Trade of energy technology and equipment - No. of niche markets - Environmental standards and certifications
Resource mobilization	- Investment in energy innovation - Graduates in science and engineering - Gross expenditure on R&D (GERD) - Domestic credit to private sector - Number of researchers in R&D per capita - Public energy RD&D budgets expenditures - Expenditure on education - Venture capital deals	- Financial sources support - Development of innovative financing - Infrastructural support	- ICT access	- Employment in knowledge-intensive activities - Employment in the energy industry	
Creation of legitimacy	- Lobby actions - Regulatory acceptance and integration - Technology support	- Regulatory quality - Intellectual property protection - Regulatory instruments - Political consistency	- Public opinions on energy technologies	- Executive opinion on environmental regulation - Recognition of benefits	

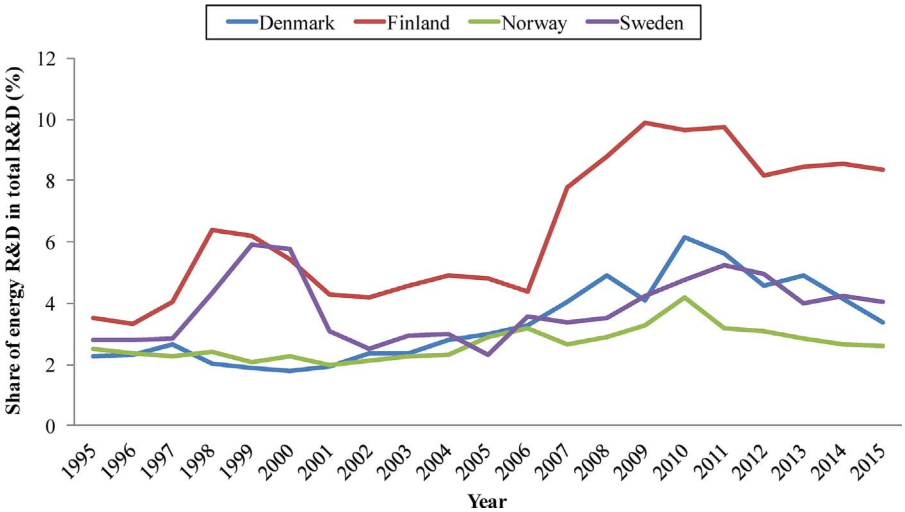

Fig. 4. Share of public energy R&D expenditures in all public R&D expenditures.
Source: IEA, 2015 [78].

measurability. However, since measurability sometimes requires detailed information from agents and actors participating in the innovation process, some indicators can be measurable with a survey approach [74].

4.2. Applying the indicators for assessing TIS functions

As mentioned in Section 2.3, the TIS approach has created a number of insights which are important for understanding system dynamics and for deriving policies to promote technology-specific EISs. In Table 2, we have taken the indicators from Table A.2, which are classified into the five categories of the innovation process (input, policy, structural and systemic, impact and output indicators, see Fig. 2), and allocated 90 relevant ones to the seven functions of a TIS (see Table 1).[4] This constitutes a list of possible indicators that may be used by a TIS assessment.

As can be observed in Table 2, for input indicators, *resource mobilization* dominates because financial, human and other resources are crucial inputs. For output indicators, *knowledge development* and *market formation* dominate, because scientific publishing and technology commercialization are vital results of innovation activities. For impact and structural/systemic indicators, *market formation* and *knowledge diffusion* have the most indicators respectively. Table 2 also shows that three functions are really well covered: *entrepreneurial activities*, *market formation* and *resource mobilization*.

We can also observe that each function has indicators that are classified into several categories of the innovation process. This reflects the nature of the improved model of the innovation process in Fig. 1 and reveals the contrast with the linear model in which primarily input indicators of knowledge development would be needed.

The wide range of indicators can clearly help in assessing the strength of the functions (given that more of them can eventually meet the four criteria), and therefore guide policy. Moreover, based on the strength and dynamics of TIS functions, the linkages between various indicators, and between policies aimed at strengthening the functions, can also be analyzed. Hence, the dynamics of innovation systems may be reflected in the dynamics of indicators, which would constitute a further guide for policy. For example, *market formation* has indicators in all categories and if these are strengthened, we would expect that indicators of both *entrepreneurial activities* and *resource mobilization* are strengthened, as firms are stimulated by a growing market. A strengthened business sector would also be expected to influence not only *knowledge development* but also *guidance of the search*, of both established and new firms, and associated indicators. Yet, policies aimed at other elements in the TIS, and associated indicators, may also be required, such as an educational policy to ensure the sufficient supply of human capital (*resource mobilization*) and an R&D policy that strengthens learning networks (*knowledge development and diffusion*) between industry and universities.

However, while we think that connecting the five categories of indicators to the TIS functions may be useful for understanding the dynamics between different indicators and help in the design of policy, more indicators are needed to fill Table 2.

Moreover, the indicators need to fulfill the four criteria discussed in Section 4.1, criteria that reduces the number of useful indicators rather drastically.

4.3. Applying the indicators to assess EISs in the Nordic countries

The aim of this section is to briefly illustrate how different metrics can be used to assess EISs. As a geographic area of analysis, the Nordic countries were chosen. Denmark, Finland, Sweden and Norway have advanced innovation ecosystems that invest in many energy technologies, particularly low-carbon technologies [75].

In order to increase relevance of this study and decrease its scope, only the most prominent indicators (based on their data availability) that meet the four criteria were analyzed. Furthermore, indicators included in the analysis were numerical and had to be relevant at national level. The eight selected indicators from Table A.2 include public energy RD&D budgets expenditures, RD&D budget distribution, scientific publishing, patents, technology exports, employment, installed capacity and CO_2 emissions.

4.3.1. Public energy RD&D budget expenditures

The Nordic countries play a prominent role in energy RD&D and policy makers have emphasized it by analyzing resource allocation to energy technology innovation [76]. Energy RD&D expenditure is, thus, considered an acceptable metric as input indicator [77] and energy R&D data are publicly accessible in IEA [78]. These statistics allow us to analyze differences between energy technologies over a long time period.

Public RD&D expenditure for energy technologies can be reported in different ways and then compared between countries, for instance, as absolute values, in relation to GDP, total RD&D or government RD&D expenditure. Fig. 4 shows the share of public energy R&D expenditures in all public R&D expenditures and Finland rates highest, reflecting a greater relative focus on energy R&D in Finland. However, Fig. 5 contains total public RD&D budgets for energy technologies and shows that

[4] Most of the 12 indicators meeting the four criteria are in Table 2 but, unfortunately, most of the 90 indicators in Table 2 do not meet all criteria.

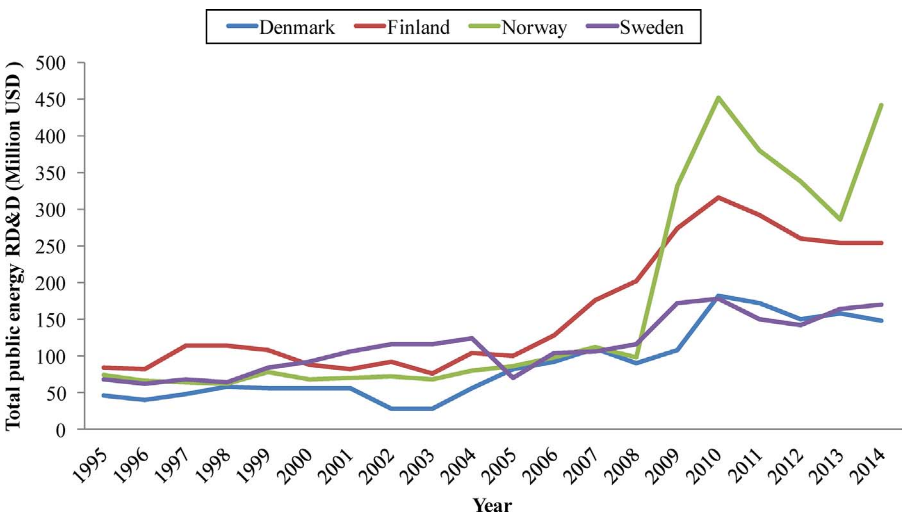

Fig. 5. Total public energy RD & D budget in the Nordic countries.
Source: IEA, 2015 [78].

Norway spends most on energy RD&D. In 2014, Norway invested 443 million USD in energy RD&D, compared to 252 million USD by Finland, 168 million USD by Sweden and 148 million USD by Denmark.[5]

4.3.2. RD&D budget distribution

The main groups of energy technology, as classified by the IEA, are shown in Fig. 6 which illustrates trends in public energy RD&D budget distribution. In the past 20 years, public energy RD&D has become progressively more diverse. Nuclear experienced a reduction in its share from 10% in 1995 to 5% in 2014. Renewables increased from 18% in 1995 to 23% in 2014 while energy efficiency ranked highest with about 40% in 2014.

As can be observed in Fig. 6, for Denmark funding of RD&D in nuclear and fossil fuels is negligible, while renewable energy sources dominate. Norway, on the other hand, has a large share of fossil fuels RD&D (due to notable domestic fossil resources) and focus to a lesser extent on renewable energy. For Finland and Sweden, the emphasis is on renewable energy sources and energy efficiency. Indeed, since 2007, the energy R&D budget has increased in the four countries through focusing on energy efficiency and renewable energy sources.

4.3.3. Scientific publishing

Scientific publishing is one of the output indicators for the EISs. In addition to indicate the strength of knowledge formation, detailed data can be used in several ways. For instance, *co-authorship patterns* can be used to help analyze learning networks between academia and industry and the *number of citations* of scientific publications to assess scientific impact.

In Fig. 7, bibliometric data has been obtained from the ISI Web of Science. It shows that in fuel cell and wind technology, Denmark and in photovoltaics, Sweden have the most scientific publications. The overall ranking in terms of three technologies based on this indicator is as follows: Sweden, Denmark, Finland and Norway.

4.3.4. Patents

Patent indicators are often used for assessment of technological progress at the national level and is an important output indicator of energy RD&D investment. At the national level, patent data for energy technologies is published regularly. Fig. 8 illustrates each country's share of all Nordic energy technology patents[6] and shows that Sweden and Denmark dominate,[7]

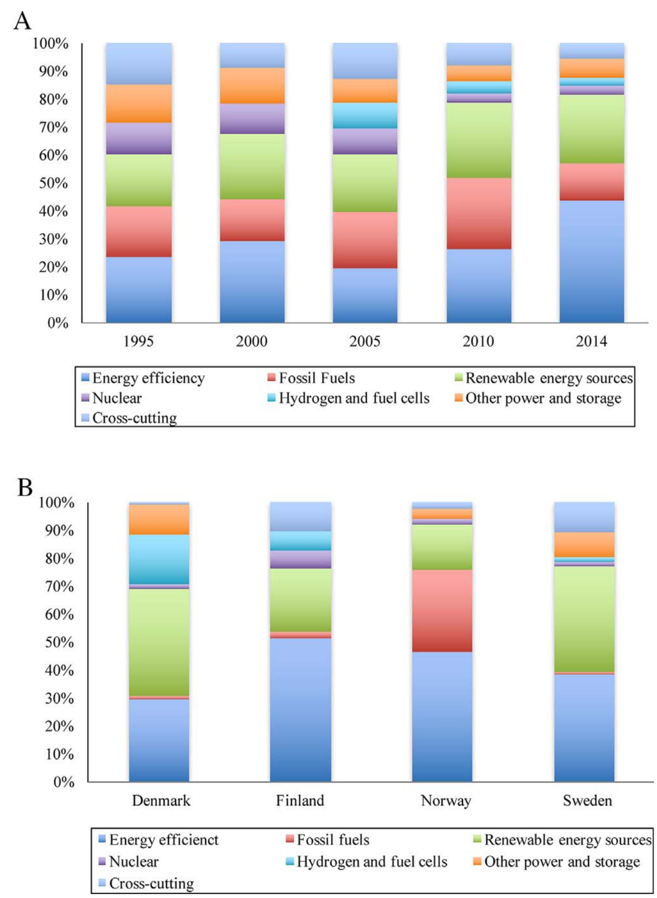

Fig. 6. Total public energy RD&D budget in the Nordic countries. (a) Total public energy RD&D budget for main groups over the time. (b) Total public energy RD & D budget in 2014.
Source: IEA, 2015 [78].

accounting for about 40 and 30% respectively in 2012. The high share of these two countries suggest that energy technologies may be an important area of innovation. Indeed, a Danish study of the green economy, shows that intellectual property rights and the trading of patents play a key role in green enterprises in comparison with in the overall economy [80].

4.3.5. Installed capacity

One of the key output indicators of EIS is installed capacity of individual technologies. In the case of wind power, Fig. 9 shows the

[5] With an average annual growth rate of 8.5 percent, between 1995 and 2014, these countries invested almost 10 billion USD in energy RD&D.

[6] Based on the energy area of the OECD Triadic Patents family.

[7] The Tekes (Finnish Funding Agency for Technology and Innovation) agency measures the total number of patents registered by provided innovation funding for companies, research organizations, and public sector service providers but does not offer a particular list for energy technologies [79].

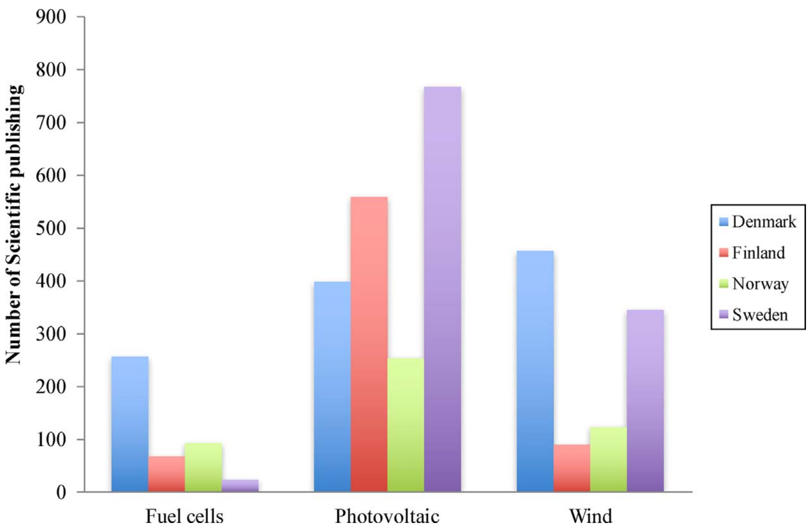

Fig. 7. Scientific publishing 2007–2013, in the Nordic countries.
Source: ISI Web of Science. *Note*: Included document types: article, review and proceeding paper.

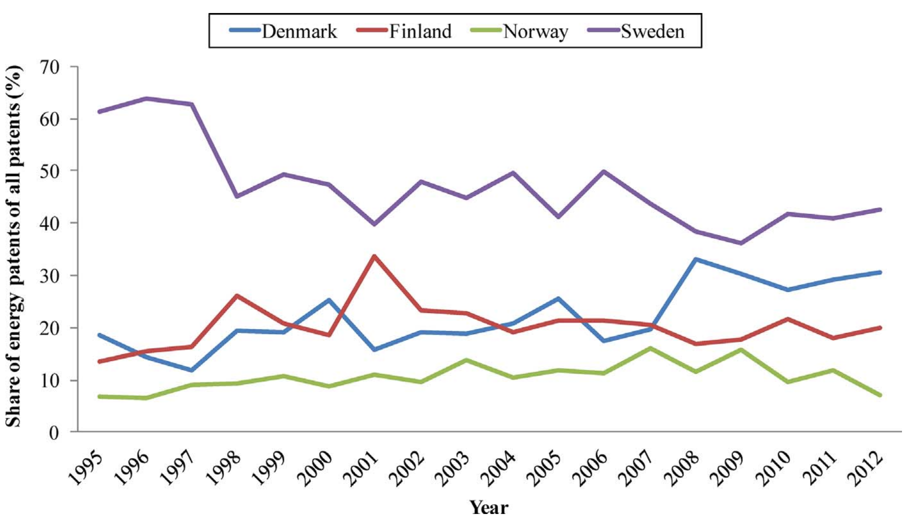

Fig. 8. Each country's share of all energy technology patents in the Nordic countries.
Source: OECD, 2016 [61].

installed capacity between 1997 and 2016. This increased from 1.2 GW in 1997 to almost 14 GW by 2016 [81]. In the 1980s and early 1990s, Denmark led the global development of wind energy technology [35]. The policy mix included a local market formation policy which explains the higher installed capacity in Denmark in 1997. However, a decade later, diffusion in Sweden took off. Indeed, the installed capacity in Sweden and Denmark increased from 122 MW and 1.1 GW in 1997 to 6.6 GW and 5.1 GW in 2016 respectively.

4.3.6. Energy technology exports

Energy technology export is one of the key output indicators of the EISs since dynamic EIS benefit the development of a local capital goods industry, as in the case of the Danish wind turbine industry. However, a significant challenge is that data is not available for all technologies. Based on the *UN database Comtrade*,[8] we use wind technology as an example. Fig. 10 shows the export from Denmark which amounted to as much as 3.2 billion USD in 2015, much more than other countries.

4.3.7. Employment

Another impact indicator to assess performance of EIS is employment in the energy technology industry. A recent account of employment in the energy area in Denmark specifies total employment to about 56,000. Among these, the wind technology industry dominates. Fig. 11 shows an upward trend in the employment from around 27,000 employees in 2006 to 30,000 in 2015.[9]

4.3.8. CO_2 emissions

CO_2 emissions is one of the most well-known impact indicators. Academics broadly investigate the role of technology diffusion policies for reducing CO_2 emissions. Indeed, the review of studies determined that emission reductions is not an indicator of success in itself but seen as a by-product of innovation system dynamics.

The development of CO_2 emissions from fossil fuel combustion in the Nordic countries is, therefore, a key indicator for evaluating the environmental effectiveness of public policies relating to energy technologies.[10] At the national level (especially in the Nordic countries), CO_2 emissions data is available.

Fig. 12 shows that CO_2 emissions have been reduced a bit in the past 15 years with the exception of Norway, presumably due to its domestic fossil resources. Indeed, in the last five years, the development of EIS helped Denmark and Finland reduce CO_2 emissions more than Norway and Sweden (almost 11.5 and 12 million tons respectively).

[8] Available from: http://comtrade.un.org/data/.

[9] Regarding this indicator, data for other countries in the Nordic is unavailable from existing data repositories.

[10] In order to reflect the economy of countries, this indicator is often presented in relation to GDP.

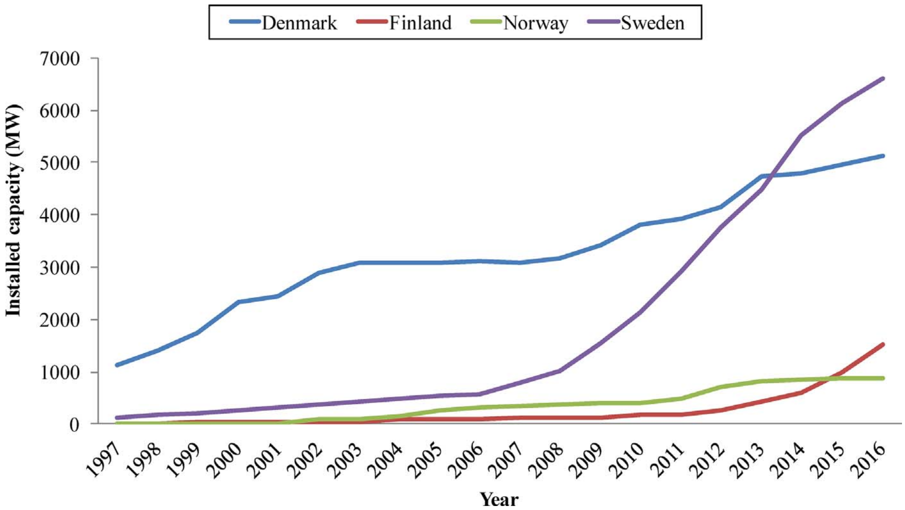

Fig. 9. Installed capacity of wind power in the Nordic countries.
Source: BP, 2016 [81].

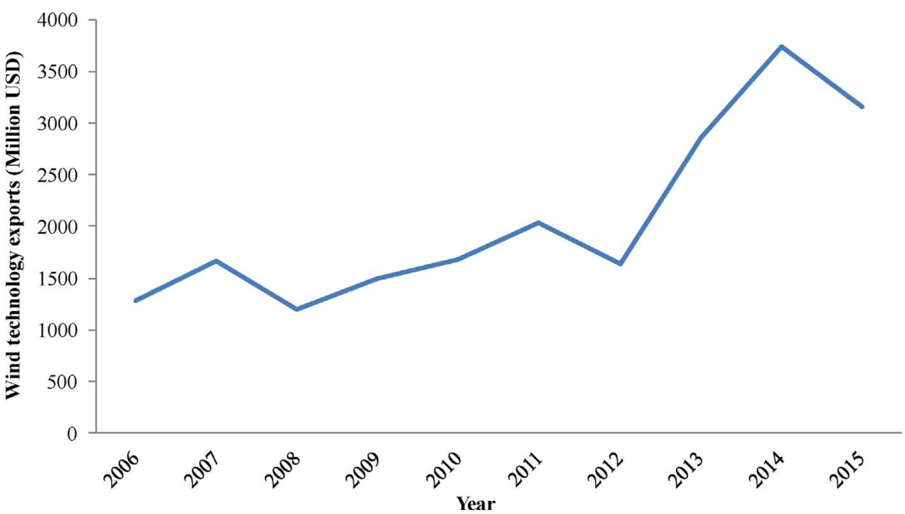

Fig. 10. Wind technology export from Denmark. Million USD.
Source: UN Comtrade Database.

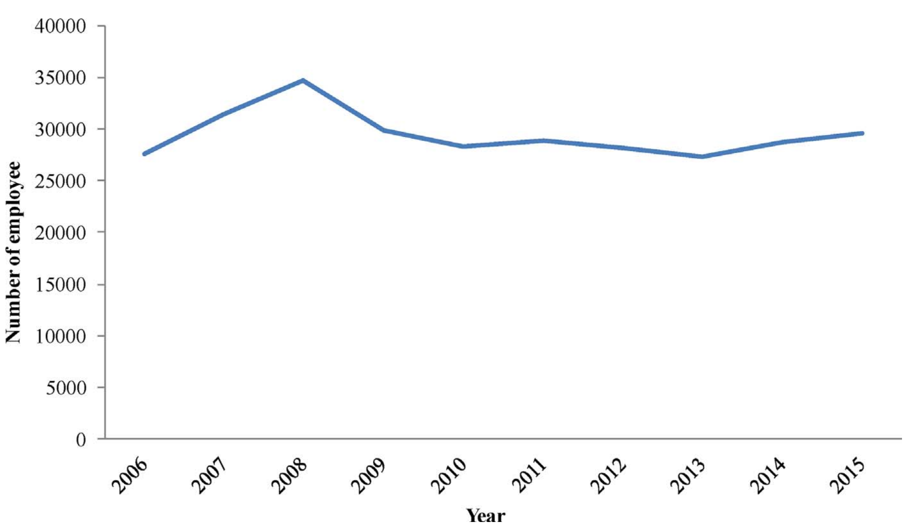

Fig. 11. Employment in the Danish wind industry.
Source: The Danish Wind Industry Association [82].

4.3.9. Summing up the cross-country comparison

In sum, applying only 8 indicators demonstrate the potential value of an enlarged set of useful indicators. We can assess a range of inputs and outputs e.g. a growing focus on energy efficiency in RD&D, an increased growth in installed capacity of desirable technologies and growth in technology exports. We can also see how the performance of EISs vary between countries (see Table 3). Table 3 summarizes the cross-country comparison and the numbers in the Table reflects the countries' rank in energy innovation indicators. For instance, Denmark leads in energy technology exports and employment (related to wind

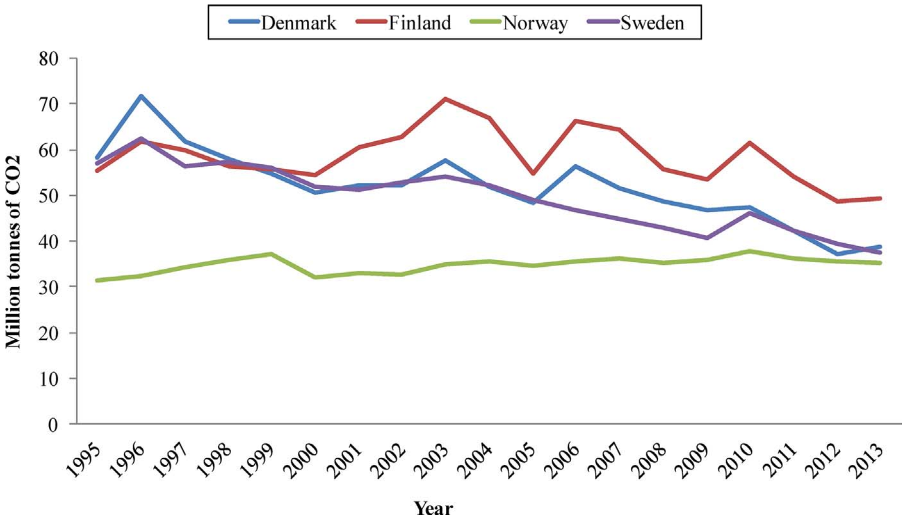

Fig. 12. Trends in CO_2 emission in the Nordic countries.
Source: IEA, 2016 [3].

Table 3
Ranking of the Nordic countries in energy innovation indicators, 2015.

Indicators	Type	Denmark	Finland	Norway	Sweden
Share of public energy R&D expenditures in all public R&D expenditures	Input	3	1	4	2
Total public energy RD&D budget	Input	4	2	1	3
CO_2 emissions	Impact	3	1	4	2
Patents	Output	2	3	4	1
Energy technology exports	Output	1	3	4	2
Employment	Impact	1	–	–	–
Scientific publishing	Output	2	3	4	1
Installed capacity	Output	2	3	4	1

power) while Sweden leads in patents, scientific publishing and installed capacity (of wind power). That means Denmark and Sweden are more successful in output and input indicators respectively. This point illustrates the high performance of the EIS and the importance of cumulative R&D in Denmark (i.e. comparing the level of outputs achieved with the level of inputs reflects the high efficacy of the innovation system).

By linking indicators, the dynamics of EIS can also be better understood, as noted in the Danish wind energy case. Indeed, if demand and supply side policies support a specific energy technology, even a small country, such as Denmark, can become a world leader. Moreover, weaknesses in the EIS can be identified which can provide further guide to policy makers. An example is Norway which appears to have the weakest EIS. Although it invests more than the other countries in energy R&D, it ranks lowest in all other indicators (Table 3). Finally, Sweden performs well in the inputs scientific publishing and patenting but is less successful in industrialization (and related export and employment indicators) which is linked to a lack of early market formation for new technologies given its tradable green certificate policy [83]. Yet, since Sweden has leapfrogged other countries in terms of installed capacity of wind power, the EIS works well in terms of diffusion.

5. Concluding discussion

The deployment of clean energy technologies is essential for mitigating climate change. Energy innovation is therefore crucial not only to sustain economic growth but also to constrain the increase in global temperatures in the years to come. The EIS is the application of an innovation system approach to energy innovations covering research into and, eventually, large-scale deployment of new technologies. An enhanced understanding of EIS and associated indicators is essential since it can help the investigation into, and design of, effective policies to support and stimulate innovation activities in the energy area.

Indicators of energy innovation needs to assess numerous aspects of innovation systems and a general framework is, therefore, important to facilitate this assessment. However, an established set of metrics has so far not been developed for this purpose. The main purpose of this study is, therefore, to list and classify a large set of innovation indicators, including developing a framework for categorizing them, to facilitate assessment of the performance of energy innovation systems at the sectoral (EIS) and technological (TIS) levels and to design effective policies.

Our attempt to categorize the indicators was driven by our understanding that for a comprehensive assessment the indicators must cover all aspects of an innovation system along the whole innovation chain. That is, the indicators should reflect the structural elements of an innovation system as well as the five stages of the innovation process so as to capture various feedbacks, e.g. how market formation impacts on the number of new entrants and how the addition of new firms increases allocation of funding to R&D.

A large set of innovation indicators were collected and four criteria were developed and applied to classify them in terms of their usefulness. One of the major results of this study is Table A.2 which includes the indicators, a categorization of these based on the innovation process model and an application of the four criteria to them. Applying the four criteria revealed that most indicators are problematic for assessing EIS because they do not meet all criteria. Availability and relevance are two important criteria that, unfortunately, exclude most indicators.

According to a TIS literature review, we then allocated indicators to seven TIS functions to enable assessment of their strength. We chose indicators from Table A.2, allocated them to the seven functions and then classified them in five categories based on the innovation process (Table 2). According to the innovation process classification, the results reveal the diversity of aspects of the innovation process and if the number of indicators is low in one category, additional indicators may be required. Indeed, the input and output aspects have the largest number of indicators and the policy and impact aspects have the smallest number of indicators.[11]

The results also show that for input indicators, resource mobilization is covered by most indicators and for output indicators the same applies to knowledge development and market formation. Of the seven functions, the three with the largest number of indicators are entrepreneurial activities, *market formation* and *resource mobilization*.

Eight indicators, which all met the four criteria, were then selected to assess EIS in the Nordic countries as a way to briefly illustrate what can be learned from applying these. The analysis clearly shows that Denmark leads in energy technology exports and employment, reflecting the strength of the innovation system centered on wind energy technology in Denmark, while Sweden leads in patents, scientific publishing and installed capacity. In contrast, Norway spends most on energy RD&D but appears to have the weakest EIS. Among the main groups of energy technologies, for Denmark and Norway, the focus of energy RD&D is on renewable energy and fossil fuels respectively whereas for Finland and Sweden energy efficiency and renewable energy sources dominate. Finally, except for Norway, CO_2 emissions have dropped in the past 15 years.

The findings in this study are subject to at least four limitations. First, quantitative analyses are limited by availability of information and data. It is not easy to obtain all data from agents and actors throughout an innovation system and, therefore, most of indicators are rejected based on availability criteria. Second, the study did not evaluate the use of qualitative indicators which seek to measure the impact and evaluate the long-term effects and benefits of an innovation system. Although we gathered some of them in the annotated list, they were not used to assess EIS in the Nordic countries because they didn't meet all criteria. Third, the indicators do not provide a micro-view of the EIS and therefore specific issues at the firm or project level may be overlooked. Fourth, the study did not include indicators' effectiveness compared with each other. To assess innovation system dynamics, each indicator has a specific effect and its effectiveness is different from the rest of indicators. In this study we assume all indicators in each categorize have same impact when assessing EIS and TIS.

It is recommended that further research be undertaken in the following areas:

- The indicators of Table A.2 can be used for comprehensive assessment of a country's innovation system. We did a cross-country comparison of the Nordic countries where the indicators were used to assess EISs. It would be interesting to compare other countries, particularly developing countries who need to combine high economic growth with emission reductions, to assess the different characters of energy innovation systems. It would also be valuable to focus on specific elements of an EIS, such as energy governance structures, research and training systems and institutional frameworks, to deepen our understanding of system dynamics and associated indicators.
- For policy makers, it would be of great help modeling dynamics between indicators because it provides feedback into the policy-making process which can then change in strategic focus and program design. For this purpose, analyzing the dynamics of indicators of TIS functions would be useful. In this study, the indicators associated with each function in a TIS is presented which may be valuable for such an analysis (see in particular Table 2). Indeed, because the dynamics and specific linkage schemes between each function have been analyzed in various forms (e.g. [48]), we believe this table may provide the beginning of a novel approach for future studies aiming to analyze the dynamics between the different indicators, and therefore, help designing policies aimed at strengthening the phenomena that the indicators reflect, such as entrepreneurial experimentation.
- Yet, a challenge is that most indicators in Table 2 do not fulfill the four criteria of usefulness. Indeed, only 12 match all four criteria and, moreover, only 32 out of the 120 meet the availability criterion. Hence, an additional opportunity for future research is to improve the data infrastructure, in part by surveys of energy innovation activities and interaction patterns. Improving the data infrastructure may also involve searching for additional indicators related to structural and systemic, as well as policy and impact aspects, which have much fewer indicators than input and output aspects.
- Future research on energy innovation systems should assess a key aspect of innovation systems that is still not investigated enough. This is to evaluate the interactions and collaborations between actors in energy systems because the innovation process involves such network interactions. There is also a need to find useful indicators of this aspect of the innovation process.
- There is the lack of reliable and stable data on private RD&D budgets, so an improved collection of such data is needed. In addition, further research might investigate how to integrate multiple data sources into a one-stop platform or how to provide a data-sharing system.
- Finally, as some aspects of the innovation process are difficult to find data of, it is important to supplement quantitative data with qualitative assessments undertaken by highly competent staff in terms of both analytical capabilities and domain-specific understanding. Indeed, a background that enables understanding the dynamics of innovation should be a prerequisite for policy makers and associated staff. Such a competence necessitates insights into both social science and engineering and this suggests the importance of conducting research that supports the development of an educational policy which integrates social science into energy programs [84]. Such a competence may also prove to be important for developing the desired set of useful indicators in the near future.

Acknowledgement

The authors would like to thank the anonymous reviewers for their valuable and constructive comments.

[11] The number of indicators in a category or function should not be understood as indicating the level of their importance or strength. Indeed, it is the value of indicators that reflect the strength of a function. The number of indicators rather gives us some information of how well a category or function is represented but it can also reflect the complexity of a target or category.

Appendix A. Indicators

Table A.1
Indicators used to measure TIS functions.

	Indicators	References
Knowledge development	- Basic R&D phase funding - Patenting and scientific publication numbers activities - Research and technological projects - Demonstration and pilot projects - Learning by doing and learning by using - R&D funding and activities - Scientific publication and patenting - Research networks (knowledge exchange)	[47,48,52]
Knowledge diffusion	- Network size and intensity - Activities of industry associations - Linkages among key stakeholders - Knowledge exchange in networks - Workshops and conferences - National knowledge exchange between organizations - International knowledge exchange (e.g. in joint research projects)	[47,52,54]
Guidance of the search	- Targets set by the government - Changes in regulatory frameworks - No. of press articles that raise expectations - Articulation of interest by leading consumers - Future outlook of alternative vs. traditional - Steering development towards specific technological alternatives - Expectations and opinion of experts (positive/negative)	[47,52,54]
Entrepreneurial activities	- No. of new entrants - No of diversification activities of incumbents - No of experiments - Experimentation and demonstration activities - Organizations or companies entering/leaving the market - Size of companies - Studies, demonstration pilots and field trials - Export activities	[48,54,55]
Market formation	- No. of niche markets - Specific tax regimes and regulations - Drivers of market formation (e.g. support scheme) - Size and types of markets formed - Financial market incentives (regulation/stimulation programs) - Regulations/tax regimes - Import share - Policies that stimulate market formation and expansion (e.g. protected niches, regulatory or fiscal instruments). - Sales, unit numbers - Installed capacity	[47,54,55]
Resource mobilization	- Availability of competence/human capital - Complementary assets for key actors - Financial resources (e.g. subsidies for - investments in the technology) - Physical resources - Foreign direct investment	[47,48,52]
Creation of legitimacy	- Rise and growth of interest groups and their lobbying activities - Political debate in parliament and media - Recognition of (societal) benefits of the technology - Extent to which the technology is promoted by organizations, government (awards, brochures, competitions) - Lobby activities for/against the technology - Technical assessment studies - Alignment of science and, technology policy	[47,48,52,54]

Table A.2
Indicators obtained though the research, and their type and criteria classification. I, Input; O, Output; S, Structural and Systemic; P, Policy; Im, Impact; U, Understanding; A, Availability; R, Relevance; M, Measurability.

Indicator names	Definition	Type	U	A	R	M	Ref.
Access to private nance for cleantech start-ups	It is the number of cleantech investors and cleantech focused funds recently raised weighted by GDP.	I	*		*		[17]
Actors in relation to energy technologies	It is the number of actors in relation to renewable and low-carbon energy technologies.	I	*		*	*	[13]
Capacity to commercialize new products	It is used to analyze the extent of ideas turn into commercially successful new products, services, or business models by companies.	I	*		*		[73]
Clean technology R&D institutions capacity	It is the number of clean technology R&D institutions, centers and university.	I	*		*	*	[85]
Distribution of energy RD&D budgets	It reflects the distribution of energy RD&D budgets over the main groups of energy technologies.	I	*	*	*	*	[13,69]
Domestic credit to private sector	It represents the financial resources provided to the private sector that establish a claim for repayment.	I	*			*	[18,73]
Energy and environmental expenditure in college/university research	It refers to the energy and environmental expenditure in college/university research.	I	*		*	*	[71]
Energy companies	It reflects the number of energy suppliers, energy grid operators, consumer organizations, etc.	I	*		*	*	[77]
Entrepreneurial culture	It describes the positive attitudes towards entrepreneurship and early stage entrepreneurial activity.	I	*				[17]
Expenditure on education	It measures the government expenditures in education.	I	*	*		*	[18]
Finance and investment institutions	It reflects the number of finance and investment institutions.	I	*		*	*	[77]
Foreign direct investment net outflows	It measures the foreign direct investment (FDI), net outflows.	I	*			*	[18]
GERD financed by abroad	It measures the percentage of gross expenditure on R&D financed by abroad.	I	*			*	[18]
GERD performed by business enterprise	It measures the gross expenditure on R&D performed by business enterprise.	I	*			*	[18]
Graduates in science and engineering	It measures the share of all tertiary graduates in manufacturing, engineering, and construction over all tertiary graduates.	I	*	*		*	[18]
Gross expenditure on R&D (GERD)	It measures the total domestic intramural expenditure on R&D during a given period.	I	*	*		*	[18]
High-tech imports	It measures the high-technology imports minus re-imports.	I	*	*		*	[18]
Human resources	It is the number of scientists and engineers engaged in energy R&D.	I	*		*	*	[12]
Investment in energy innovation	It measures the public, private or total investment in demonstration, early deployment and diffusion.	I	*	*	*	*	[12]
Lobby actions	It indicates the rise and growth of interest groups and their lobbying activities.	I	*				[52]
Number of new entrants	It is the number of new entrants into energy innovation process.	I	*		*	*	[47,48]
Number of diversification activities	It is the number of diversification activities of incumbent actors for new technology.	I	*		*	*	[47,48]
Number of innovative activities	It is the number of started and planned projects, experimentations and activities from incumbent actors for new technology.	I	*		*	*	[86]
Number of energy and environmental graduates, MScs or PhDs	It is the number of energy and environmental graduates, MScs or PhDs.	I	*		*	*	[71]
Number of researchers in R&D per capita	It is the number of researchers in R&D that engaged in the conception or creation of new knowledge, products, processes, methods, or system.	I	*			*	[73]
Percent of firms with environmental mission statements	It indicates the percentage of firms with environmental mission statements.	I	*		*		[71]
Perspectives of profits	It refers to perspectives of profits in the future for the new technology.	I	*		*		[86]
Policy action plans	It reflects the most urgent challenges and presents coherent policy responses to initiate a change of course.	I	*		*		[86]
Private RD&D investments	It measures the business and enterprise sector expenditure on energy R&D (BERD).	I	*		*	*	[69]
Public energy RD&D budgets expenditures	It reflects the share of estimated total budget as public energy RD&D budgets.	I	*	*	*	*	[13,69]
R&D expenditure in the business sector	It measures all R&D expenditure in the business sector (BERD).	I	*	*		*	[72]
R&D expenditure in the public sector	It measures all R&D expenditure in the government sector (GOVERD) and the higher education sector (HERD).	I	*	*		*	[72]
R&D expenditures for environmental protection	It measures R&D expenditure in environmental protection issues in industry.	I	*		*	*	[71]
R&D networks	It reflects R&D expenditure to create networks between projects.	I	*		*	*	[87]
R&D projects over time	It is the number of R&D projects over time.	I	*		*	*	[87]
Ratio of energy-start-ups to incumbents	It indicates the ratio of energy-start-ups to incumbents in the market.	I			*	*	[71]
Regulatory acceptance and integration	It is the formal adoption of a validated test method by a regulatory agency/authority.	I	*		*		[54]
Share of energy innovative firms of all firms	It indicates percent of all firms as energy innovative firms.	I	*		*	*	[71]
Shared strategies and roadmaps	It is the number of time-based plan that defines where a business is, where it wants to go, and how to get it there.	I	*		*	*	[54]
Technology support	It reflects the extent to which the technology is promoted by organisations, government (awards, brochures, competitions).	I	*		*		[54]
Venture capital deals	It refers to the venture capital per investment location.	I	*			*	[18]
Cleantech-friendly government policies	It refers to the government policies supporting clean energy including tax incentives, feed-in tariffs, renewable energy mandates and others.	P	*		*		[17]
Credible political support	It captures the perceptions of the ability of the government to create credible political support for the technology.	P	*				[88]
Development of communication centers	It reflects supporting the creation and functioning of training, extension and communication centers.	P	*				[88]
Development of innovative financing	It captures the perceptions of the ability of the government to facilitate the development of innovative and sustainable financing mechanisms for projects.	P	*			*	[88]
Ease of starting a business	It reflects the ease of starting a business (distance to frontier) by averaging the percentile rankings on the component indicators.	P	*				[18]
Facilitate the development of networks	It captures the perceptions of the ability of the government to facilitate the development of partnerships and networking among technology users and producers.	P	*				[89]
Financial sources support	It captures the perceptions of the ability of the government to support the provision of financial resources by local banks and micro-finance institutes and other financial sources.	P	*			*	[89]

(continued on next page)

Table A.2 (*continued*)

Indicator names	Definition	Type	U	A	R	M	Ref.
Green investment facilitation	It refers to the national efforts to facilitate green investment.	P	*		*		[15]
Green Tax	It measures the 'Green Tax' as a percentage of government budget.	P	*		*	*	[71]
Incentives and subsidies	It indicates the feed-in tariff and feed-in premium.	P	*		*		[69]
Infrastructural support	It captures the perceptions of the ability of the government to support infrastructural development needed for new technology development and diffusion.	P	*				[90]
Innovative firms support	It captures the perceptions of the ability of the government to encourage firms to undertake innovation activities.	P	*		*		[90]
Intellectual property protection	It is used to analyze the extent of intellectual property protected.	P	*				[73]
Policy processes	It indicates the white papers, action plans, strategies, agreements, public funds and programs.	P	*				[69]
Political consistency	It captures the perceptions of the ability of the government to encourage consistent political and institutional support across all TIS functions.	P	*				[33]
Quality of the education system	It will capture the overall quality of the education system and the extent it teaches the relevant skills.	P	*				[73]
RD&D strategies	It reflects the RD&D, technology programs and RD&D strategies.	P	*				[69]
Regulatory instruments	It indicates the acts, concessions and other regulations.	P	*				[69]
Regulatory quality	It indicates the capacity of the government to stimulate and support private-sector development.	P	*				[18]
Research support	It captures the perceptions of the ability of the government to support research programmes in technical schools and technology institutes.	P	*		*		[90]
Risk-sharing	It reflects public-private partnerships for risk-sharing in new business development.	P	*				[90]
Specific tax regimes	It reflects the specific tax regimes for new technologies.	P	*		*		[52]
Sustainable business models	It is the number of sustainable business models for technology diffusion.	P	*		*		[90]
Targets set by the government or industries	It refers to specific targets set by governments or industries (roadmaps) regarding the use of a specific technology.	P	*		*		[52]
Tradable permits	It indicates the green certificates, and quota policies or renewable energy obligations.	P	*		*		[69]
Transparency	It reflects providing transparent information on costs, performance and economic potential for the technology.	P	*				[90]
Venture capital availability	It is used to analyze the difficulty of start-up entrepreneurs with innovative but risky projects to obtain equity funding.	P	*				[73]
Attractiveness of renewable energy infrastructure	It indicates the national renewable energy markets, renewable energy infrastructures and their suitability for renewable energy technologies.	S	*		*		[17]
Cooperation and interaction	It is used to analyze the extent of collaborate and share ideas by people.	S	*		*		[73]
Cooperation patterns in R&D programs	It assesses the share of projects based on collaboration between different agents.	S	*		*	*	[13]
Debate – meetings/media	It includes the number of debates, meetings and media on energy technologies and systems.	S	*		*	*	[55]
Domestic market size index	It measures the gross domestic product plus value of imports of goods and services.	S	*			*	[73]
Efficiency enhancers	It measures factors that enhance countries in the efficiency-driven stage.	S				*	[85]
Energy mixes	It measures the gross electricity generation and primary energy production	S	*	*	*	*	[69]
GDP per unit of energy use	It evaluates GDP per kilogram of oil equivalent of energy use.	S	*	*	*	*	[18]
ICT access	It is a composite index that weights five ICT indicators (20% each).	S				*	[18]
Industrial specialization	It combines specialization of value added in mining and quarrying of energy producing materials and specialization in RD&D budgets on fossil fuels.	S		*	*	*	[69]
Innovative SMEs collaborating with others	It refers to sum of SMEs with innovation co-operation activities in the three years of the survey period.	S	*		*	*	[72]
Installed capacity	It describes the maximum capacity that a energy system is designed to run.	S	*	*	*	*	[69]
International scientific co-publications	It is the number of scientific publications with at least one co-author based abroad per million population.	S	*	*		*	[72]
Joint ventures deals	It refers to the joint ventures or strategic alliances deals.	S	*				[18]
Linkages among key stakeholders	It reflects the networks, correlations and linkages among key stakeholders in innovation system.	S	*		*		[52]
Number of workshops and conferences	It indicates the frequency of energy innovation workshops, conferences or other forums (social media) organized about the new technology and number of people attending.	S	*		*	*	[71]
Proxies of size	It evaluates the population and gross domestic product (GDP).	S	*	*		*	[69]
Public opinions on energy technologies	It includes the political and public opinions and debates on energy technologies and systems.	S	*		*		[72]
Public-private co-publications	It is the number of public-private co-authored research publications.	S	*	*		*	[72]
Resource endowments	It reflects the photovoltaic electricity potential in each country.	S	*	*	*	*	[69]
Revealed symmetric comparative advantage	It based on RD&D budget shares for energy RD&D and energy production shares for energy production.	S		*	*	*	[69]
Size of companies	It reflects the category of micro, small and medium-sized enterprises (SMEs) to describe a company with about 50 employees up to a few hundred.	S	*	*		*	[54]
Strategy networks	These are composed of inter-organizational ties that are enduring, are of strategic significance for the firms entering them, and include strategic alliances and joint ventures.	S	*		*		[86]
University/industry research collaboration	It is used to analyze the collaboration between industries and universities on research and development (R&D).	S	*		*		[18]
CO_2 emission intensity	It reflects the tCO_2 emissions, per unit of GDP.	Im	*	*	*	*	[12,85]
Employment in knowledge-intensive activities (manufacturing and services)	It is the number of employed persons in knowledge-intensive activities in business industries.	Im	*			*	[18,72]

(*continued on next page*)

Table A.2 (*continued*)

Indicator names	Definition	Type	U	A	R	M	Ref.
Employment in the energy industry	It assesses the employment in the energy technology industry in general and in the specific industry.	Im	*		*	*	[13]
Energy cost savings	It reflects economic growth by energy cost saving.	Im	*		*	*	[75]
Energy productivity	It assesses the GDP per gross inland energy consumption.	Im	*		*	*	[91]
Environmental performance	It ranks countries on 20 performance indicators tracked across policy categories that cover both environmental public health and ecosystem vitality.	Im			*	*	[18]
Executive opinion on environmental regulation	It refers to the stringency and transparency on environmental regulation.	Im	*		*		[71]
Exports of products from energy industries	It measures the exports of products from energy industries as percent of total exports.	Im	*		*	*	[91]
Jobs in green technology industry	It is the number of employees in green technology industry.	Im	*		*	*	[85]
Jobs per energy output	It is the number of employees per energy output.	Im	*		*	*	[75]
Level of environmental impact on society	It measures environmental health includes air pollution (effects on human health).	Im			*	*	[85]
Recognition of benefits	It refers to recognition of societal benefits (e.g. awards, competitions, brochures).	Im	*				[48]
Renewable energy jobs	It is the number of direct and indirect employees related to renewables by total labor force.	Im	*		*	*	[17]
SO*x* emissions intensity	It reflects the tSOx emissions, per unit of GDP.	Im	*	*	*	*	[12,85]
Water consumption intensity	It reflects the water withdrawal for each 1000 USD of GDP in cubic meters.	Im	*	*		*	[85]
Activeness of renewable energy utilization	It measures the contribution of renewable to total primary energy supply (TPES).	O	*		*	*	[85]
Citable documents H index	It is used to analyze the quality of scientific publications.	O	*	*		*	[18]
Creative goods exports	It refers to the total value of creative goods exports.	O	*			*	[18]
Energy intensity	It refers the gross domestic consumption of energy divided by GDP.	O	*	*	*	*	[12,13]
Energy technology export	It measures the exports of energy technology and equipment from each country.	O	*	*	*	*	[13,69]
Environmental standards and certifications	It reflects the new environmental standards that improve the chances for new environmental technologies.	O	*		*		[87]
Firm-level technology absorption	It refers to the extent of new technologies adoption by businesses.	O	*			*	[73]
Green patents	It reflects the environmental technology patent (patent grants by technology).	O	*		*	*	[85]
High-tech and medium-high-tech output	It measures the high-tech and medium-high-tech output.	O	*	*		*	[18,72]
Knowledge-intensive services exports	It refers to the exports of knowledge-intensive services and measured by the sum of credits in EBOPS.	O	*			*	[72]
Learning rates	It assesses the rate of cost reduction of a technology.	O	*		*	*	[12]
License and patent revenues from abroad	It refers to the export part of the international transactions in royalties and license fees.	O	*			*	[72]
Market capitalization of listed companies	It is the share price multiplied by the number of shares outstanding.	O	*			*	[73]
Market introduction of new technological products	It refers to introduction of new energy technology products or services in the specific period by companies in energy area.	O	*		*	*	[13]
Market penetration	It indicates the number or capacity of energy technologies sold or used.	O	*		*	*	[12]
Number of niche markets	It is the number of niche markets that have been introduced.	O	*		*	*	[52]
Number of press articles that raise expectations	It is the number of articles in professional journals that raise expectations about new technological development.	O	*		*	*	[52]
Number of highly-cited publications	It is the number of highly-cited publications in energy innovation subject.	O	*	*		*	[18]
Patents	It is the number of patents filed or granted.	O	*	*	*	*	[12]
PCT patent applications	It is the number of applications filed under the Patent Cooperation Treaty (PCT) per million population.	O	*			*	[73]
Renewable energy production	It measures the renewable energy production in each country, TJ.	O	*	*	*	*	[13]
Revenue of cleantech companies	It reflects the value-added from cleantech manufacturing as a proportion of GDP and revenue of low carbon and environmental goods and services companies as a proportion of GDP (PPP).	O	*		*	*	[17]
Scenarios and foresight projects	It is the number of foresight projects in relation to innovation system.	O	*		*		[52]
Scientific publishing	It refers to the number of scientific and technical journal articles in relation to energy technology.	O	*	*	*	*	[12,13,69]
Share of renewable energy in the total consumption of energy	It assesses the percentage share of renewable energy from total consumption of energy.	O	*	*	*	*	[13]
SMEs introducing product or process innovations	It is the number of SMEs who introduced a new product or a new process to one of their markets.	O	*			*	[72]
Technology characteristics	It refers to the ratios of technical to service characteristics.	O			*	*	[12]
Technology output	It is the number of energy technologies commercialized.	O	*		*	*	[12]
Trade of energy technology and equipment	It refers to the goods supply, imports/exports, and market for energy technologies and equipments in each country.	O	*		*	*	[13]

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