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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 nonlinear 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