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Diversity in solar photovoltaic energy: Implications for innovation and policy

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ABSTRACT

We undertake a qualitative empirical study of the solar photovoltaic (PV) industry in order to investigate the role of diversity in stimulating innovation and diffusion. Based on evolutionary-economic concepts, we identify the main dimensions and components of diversity in the solar PV industry. Using nine indicators and additional information about recent developments regarding technologies, markets and actors (countries and firms), the dynamic potential is assessed for the various solar PV technologies. It is concluded that the dominant trend is an increase or maintenance of diversity among solar PV technologies, which likely contributes positively to innovation and diffusion. We discuss the implications of taking into account the role of diversity of solar PV in the design of energy policies.

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1. Introduction

The threat of climate change and peak oil is stimulating investments in renewable energy options as widespread deployment of

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low-carbon technologies is required to tackle these challenges [1,2]. Solar photovoltaics (PV) is widely considered to be among the main options to play an important role in the long term. The reason is that it directly taps into solar energy, has no moving parts, and is consistent with decentralized and off-grid solutions [3]. This suggests that solar PV has long-term competitive potential compared to traditional and other alternative energy sources [1,3]. Grid parity-equality of the production costs of electricity from solar PV and of conventional sources—is considered to have already been achieved for some very specific technical and geographical conditions, while a broader realization of grid parity is expected in the next five to ten years [1,3].

Although the cost of solar PV has dropped by a factor of nearly 100 since the 1950s—more than any other energy technology in the same period [3,4], a main concern is how to maintain a rapid rate of unit cost reduction. Past cost reduction has been driven by a combination of technological improvements and gains of specialization [1,3].

From 2000 to 2014, solar PV was one of the fastest-growing renewable energy technologies worldwide, with an average annual growth of installed capacity of above 40% [3]. Solar PV is moving in the direction of being a mature technology. This raises the question of which degree of diversity is desirable to ensure steady progress, avoid undesirable lock-in, while also enjoying a sufficient level of increasing returns of adoption. Diversity is considered here-from an evolutionary-economic perspective-as having benefits next to costs, because it fosters evolutionary progress through innovation [5]. Diversity stimulates recombinant innovation and technological spill-overs, which speed up technological development.

This study aims to map diversity in the solar PV industry, as well as contribute to a better understanding of the role of diversity in stimulating an adequate pace of technical progress in terms of innovation and diffusion to mitigate climate change. By studying nine performance indicators, the various solar PV technologies are examined in terms of technology, market and actor (both country and firm) dynamics. Based on our findings, we draw policy recommendations for supporting solar PV development.

The structure of the paper is as follows. Section 2 introduces the framework and research method. Section 3 presents the results. Section 4 discusses the results and policy implications. Section 5 concludes.

2. Material and methods

2.1. An evolutionary economics' perspective on diversity

In recent years, a significant body of literature has emphasized the potential of evolutionary economics to analyze environmental problems [5], including those related to energy use and the energy sector [6]. Evolutionary economics departs from the concept of population (of agents, technologies, products, strategies, organizations or institutions) which are subject to selection and innovation dynamics [7]. Selection generally reduces existing diversity, whereas innovation increases it, and their interaction leads to complexity and (phases of) progress.

In evolutionary economics, diversity is generally seen as positively contributing to technological progress in terms of the speed of innovation and cost reduction [8]. By maintaining variety within a resource pool, diversity facilitates spillovers among distinct technologies. Keeping options open is beneficial to innovation when it reduces the lock-in to incumbent, dominant technologies, which have a competitive advantage from auto-reinforcing increasing returns to scale [9]. An example commonly seen in renewable energy technologies is the policy-driven creation of niche markets. Furthermore, by keeping options open, diversity enables higher system flexibility and increases the likelihood of finding good technical or organizational solutions in the face of high uncertainty about long-term (international) economic, political and social conditions [10]. Additionally, diversity increases the chance of recombinant innovation since it involves a larger number of different elements and therefore the likelihood of many possible connections to be created among them. In the case of solar PV, the diversity of technologies may spur innovation by allowing the combining of several pre-developed modules and components. Moreover, innovation (in such modules) benefits from diversity in system designs and regulations in different geographical areas around the world. Finally, diffusion of innovations can benefit from diversity since a pool of options improves system adaptability [11]. In the case of solar PV this is relevant because the conditions of installation and operation significantly change according to local circumstances, and in turn affect innovation and diffusion rates and direction.

Nevertheless, diversity seldom offers a 'free lunch' [12]. Higher levels of diversity may entail higher costs through foregone increasing returns to adoption. The higher the technological diversity, the lower the share of each technology in the market, and, hence, the lower the returns to scale that can be enjoyed. These arise on both the demand and supply sides of markets, and include economies of scale in production, compatibility with other technologies via standardization, learning effects, network externalities, and information externalities (more common products are better known and more trusted by consumers).

The challenge is to find a balance between these various benefits and costs of diversity [5]. The complete evolutionary picture is that innovation forces generating diversity are complemented by selection through competition, regulation and institutions. Nevertheless, through the process of repeated selection among diverse technologies, path dependency results which may give rise to lock-in to suboptimal technological options.

When considering the desirable or even optimal level of diversity in energy policy making and sustainable innovation, it should be noted that diversity is multidimensional. It has been defined by three main properties: variety, balance and disparity [10]. Variety refers to the number of categories into which a population can be portioned and can be seen to reflect the number of options within a system. Balance can be defined as the distribution of frequencies of each category or option within the population. Lastly, disparity relates to the degree of difference among, or distance between, the options. *Ceteris paribus*, the greater the variety, the higher the balance, or the more disparate the options, the greater the diversity.

There are still few systematic frameworks to assess, empirically or conceptually, the value of diversity. One idea is to explore the notion of optimal diversity, which reflects balancing the various short- and long-term costs and benefits of diversity, taking into account its three dimensions [5,13].

2.2. Research method

The framework of analysis used here to examine diversity and its role in the solar PV industry departs from the conceptualization of technological change in the solar PV industry by [14] and [15].

This approach, as summarized in Fig. 1, enables the study of selection and innovation processes involving the distinct technology options, their specific characteristics, strengths and weaknesses as well as their specific dynamics in the technology, market and actor dimensions.

For our analysis we proceeded in four major steps. First, to map the most relevant mechanisms of technological development in solar PV technologies, we performed an ample secondary data