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Explaining technological change in the US wind industry: Energy policies, technological learning, and collaboration

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ABSTRACT

This paper examines the drivers of technological change in the US wind industry from perspectives of technological learning, collaboration, and energy policies. Using a panel of 576 utility-scale wind farms between 2001 and 2012, this paper estimates the impacts of different learning mechanisms—learning through research and development in wind turbine manufacturing, learning from a wind farm operator or a turbine manufacturer's previous project experience, learning through collaboration among wind project participants, and knowledge spillovers—on technological change of wind power, measured as improved capacity factor. Empirical findings suggest that a wind farm's performance has improved over time as the project operator accumulates more experience. Moreover, its collaboration with turbine manufacturers and the transmission system operator leads to greater performance improvement, particularly when the transmission system is coordinated by an independent system operator or a regional transmission organization (ISO/RTO). This finding supports the institutional change in the US electricity market deregulation—the creation of ISO/RTOs. The ISO/RTO-governed transmission networks promote wind power integration through regional collaboration and coordination. In addition, evidence of knowledge spillovers on wind farm operation at the state level provides justifications for state energy policies that subsidize wind power generation.

1. Introduction

As the world's major energy consumer and greenhouse gas emitter, the United States is striving to increase the share of renewable energy in its electricity supply so as to address climate change and energy security concerns. Among all renewable energy sources, wind energy has great potential to provide a significant share of electricity generation. During the last two decades, the US has experienced tremendous technological change in wind power. By the end of 2016, the cumulative wind installed capacity reached 82,184 MW, which was almost 20 times the total installed capacity in 2001 (Global Wind Energy Council, 2017). With the development of larger wind turbines, better siting technologies, and improvement in power transmission, the average capacity factor[1] of wind farms in 2015 has become approximately 43% greater than the average performance of wind farms installed before 1998 (Wiser and Bolinger, 2012; US Energy Information Administration (EIA), 2017). This immense progress has been driven by various policy instruments that both the federal government and state governments have implemented to encourage investment in wind energy. Understanding how these energy policies affect different actors in the wind power sector to develop and deploy wind energy is important for future renewable energy policy design.

In this paper, I use utility-scale wind farms in the US over the period 2001–2012 to examine what has led to technological change in the US wind industry. Technological change in the wind power sector is defined as improved performance of wind power (Arrow, 1962; Grubler, 1998; Grubler et al., 1999; Ibenholt, 2002). I analyze this research question from a technological learning perspective (Junginger et al., 2005), which focuses on how knowledge related to wind power is acquired and diffused among different actors in the wind industry (Tang and Popp, 2016). Those actors include wind power equipment manufacturers, wind farm operators, transmission system owners, and

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[1] Capacity factor is the ratio of power actually produced by a wind farm in a given period to the potential output if it was operated at its full capacity. It is a commonly used measurement for wind farm performance.

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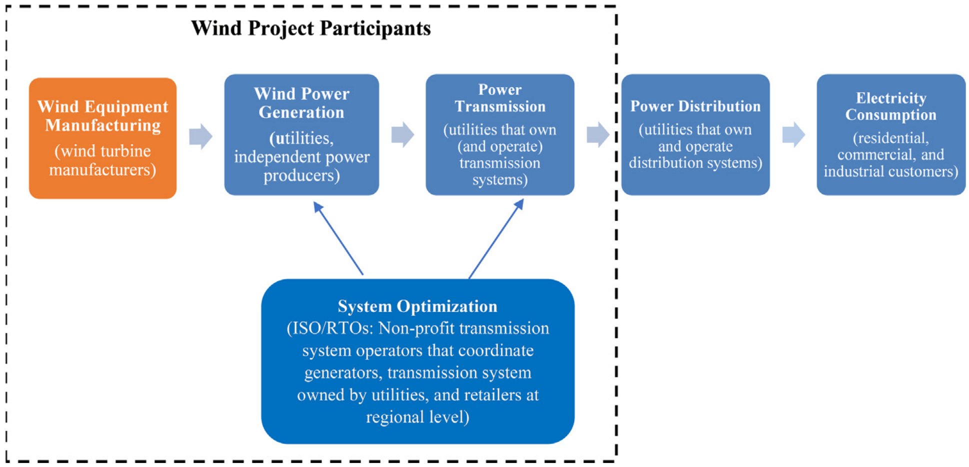

Fig. 1. Segments and key actors in the US wind industry. Note: Except for wind equipment manufacturing, the wind industry is embedded in the US power sector. In addition to participants in wind projects, this figure also shows other segments in the power sector (segments in blue are all in the power sector) so as to present a whole picture of the wind industry. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

transmission system operators (Fig. 1).[2] Specifically, I am examining the following channels of technological learning. I ask whether wind farm performance is improved after a wind project operator or its turbine manufacturer has more project experience (**learning-by-doing**). In addition to internal experience, I test whether wind farm performance benefits from industry-wide wind power development (**spillover effect**). I also investigate if wind farm performance is improved when there has been more research and development (R&D) activities in wind turbine manufacturing (**learning-by-searching**). Moreover, I examine if wind farm performance is improved after repeated collaboration among project participants (**learning-by-interacting**).

This paper can inform policymaking regarding renewable energy technology innovation and electricity transmission in the US. Focusing on the roles of various actors engaged in the US wind power sector, this paper can help policymakers target policies to different learning channels and make wind power a more cost-effective generation option to reduce carbon emissions in the power sector. First, the evidence of knowledge spillovers from other wind projects justifies the subsidies to wind generators, such as production tax credits or other forms of financial incentives. These subsidies may offset private investors' incentives to freeride on the learning benefits from early adopters. Consequently, they can encourage more wind power generation and further reduce wind power costs over time through learning-by-doing. Second, this paper addresses the emerging challenge of integrating intermittent renewable energy by highlighting the importance of learning-by-interacting through regional collaboration on transmission system operation. The empirical findings suggest that a regional transmission network, coordinated by an independent system optimizing agency, can improve wind power utilization through mobilizing and pooling resources from different electricity market participants in the transmission network.

In addition to the policy implications, this paper also contributes to technological learning literature and studies on renewable energy policies. Built on existing literature that tests various learning effects in the wind industry (Junginger et al., 2005; Taylor et al., 2006; Nemet, 2006; Söderholm and Klaassen, 2007; Söderholm and Sundqvist, 2007; Qiu and Diaz Anadon, 2012; Patridge, 2013; Kim and Kim, 2015; Tang and Popp, 2016; Grafstrom and Lindman, 2017), this paper has been the most comprehensive analysis of different learning mechanisms in the US wind industry. Particularly, it provides the first empirical evidence of learning-by-interacting effect in the US wind power sector. Findings of this paper highlight the importance of collaboration among participants in a wind project and collaboration in a regional transmission network to wind farm performance improvement. Among studies that examine the impacts of renewable energy policies on technological change, most existing empirical research focuses on the impacts of policy instruments on two stages of technological change (Jaffe et al., 2002; Popp et al., 2010), which are technological innovation measured by patenting activities (Johnstone et al., 2010; Peters et al., 2012; Dechezleprêtre and Glachant, 2014; Nesta et al., 2014; Lindman and Söderholm, 2016), and technology diffusion in the form of installed capacities or renewable generation (Menz and Vachon, 2006; Carley, 2009; Yin and Powers, 2010; Hitaj, 2013; Shrimali et al., 2015). However, there are few studies that investigate the impacts of renewable energy policies on the ultimate technological change, in terms of cost reduction or performance improvement in power generation (Nemet, 2012; Tang and Popp, 2016). The only research that examines the influence of energy policies on wind farm performance in the US uses wind projects in California to test learning-by-doing and knowledge spillovers (Nemet, 2012). With a more representative sample of wind projects in the US, this paper provides a cross-state analysis and examines the impacts of multiple learning channels on technological change in wind power.

The remainder of the paper is organized as follows. Section 2 briefly introduces the institutional context for the US wind industry. Section 3 reviews the theoretical foundations for various learning mechanisms in the wind industry and proposes the hypotheses. Section 4 describes the data and major variables, and Section 5 presents the empirical models and discusses the results. The last section concludes the major findings and discusses their policy implications.

2. Institutional context for wind power technological change in the US

The learning process and technological change of the US wind industry are embedded in the sophisticated institutions of the power sector, which are highly heterogeneous across states and regions. These multilayer institutions affect the development, deployment, and performance of wind technologies.

2.1. State renewable energy policies and the development of wind power in the US

To reduce carbon emissions and diversify the energy portfolio in the power sector, state governments in the US have taken initiative to

[2] In this paper, I use the definitions from the US Energy Information Administration (EIA). In the US, the institutional settings in the power sector are heterogeneous across regions. Transmission system owners are utilities that own the transmission facilities to which each wind farm is connected. Transmission system is operated by its owner in regions that are not governed by independent system operators or regional transmission organizations (ISO/RTOs). In contrast, transmission system operators and transmission system owners are separate organizations in ISO/RTO-governed regions. In these regions, the transmission systems are owned by utilities and operated by ISO/RTOs. Section 2 introduces more details about ISO/RTOs.