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Invention, innovation and diffusion in the European wind power sector☆

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ABSTRACT

The purpose of this paper is to provide an economic analysis of the technology development patterns in the European wind power sector. The three classic Schumpeterian steps of technological development, invention, innovation and diffusion, are brought together to assess the relationship between these. Three econometric approaches are used, a negative binomial regression model for inventions approximated by patent counts, different learning curve model specifications that have been derived from a Cobb-Douglas cost function to address innovation, and a panel data fixed effect regression for the diffusion model. We suggest an integrated perspective of the technological development process where possible interaction effects between the different models are tested. The dataset covers the time period 1991–2008 in the eight core wind power countries in Western Europe. We find evidence of national and international knowledge spillovers in the invention model. The technology learning model results indicate that there exists global learning but also that the world market price of steel has been an important determinant of the development of wind power costs. In line with previous research, the diffusion model results indicate that investment costs have been an important determinant of the development of installed wind power capacity. The results also point towards the importance of natural gas prices and feed-in tariffs as vital factors for wind power diffusion.

1. Introduction

Anticipated increases in global energy demand, following predictions and realizations of fast economic development and population growth in the developing world, may exacerbate environmental degradation (Suganthi and Samuel, 2012). In order to avoid the threat of climate change largely generated by the growing accumulation of greenhouse gases from increased energy use, the development of new carbon-free energy technology should be prioritised (Stern, 2007).

It is frequently argued that energy system modelers and analysts do not possess enough knowledge about the sources of invention, innovation and diffusion to properly inform policy-makers in technology-dependent domains such as energy and climate change (e.g., Gillingham et al., 2008). Technological change has often previously been considered a non-economic, exogenous variable, where economic incentives and policies are assumed to have no or little impact on technological development. Specifically, in exogenous representations technological change is reflected through autonomous assumptions about, for instance, cost developments over time and/or efficiency improvements (Löschel, 2002).

Even if most economic and energy system models rely on exogenous characterizations of technological change, the literature has increasingly stressed the fact that technical progress is endogenously determined following considerable development efforts, much of it done by private firms. Over the last couple of years energy researchers have therefore shown an increased interest in introducing endogenous (induced) technical change into energy system models and other impact assessment models, every so often with the purpose of analyzing explicitly the impact of technological change on energy systems (Gillingham et al., 2008). Thus, in such representations technological change is allowed to be influenced over time by energy market conditions, policies, as well as expectations about the future.

Endogenous technological change is often introduced into energy system models through so-called learning rates. The focus is then on cost reductions driven by the cumulative experience of the production and use of the technology. Innovations have therefore often been empirically quantified through the use of learning curves specifying the investment cost as a function of installed cumulative capacity (e.g., Isoard and Soria, 2001; Junginger et al., 2010). The cost reductions are thus the result of learning-by-doing, i.e., performance improves as capacity and production expand. Another set of studies concentrates on the invention step of technological change, where inventions often are approximated by the number (counts) of patents (granted or applied). For instance, Popp (2002) and Johnstone et al. (2010) used patent count data to empirically investigate different aspects of public policies that

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drive technological development. Yet another set of studies focuses on the diffusion of new technology, where the gradual adoption of a technology is assumed to be influenced by, for instance, policy instruments, cost developments, market size etc. For example, Stoneman and Diederen (1994) analyzed the importance of policy intervention for diffusion. In spite of this rich empirical literature, though, few previous studies address the interaction between the invention, innovation and diffusion phases of technological development. Söderholm and Klaassen (2007) did a first attempt to combine two of these technological development steps by combining an innovation (learning) model and a technology diffusion model in the empirical context of European wind power. A later attempt was made by Kim and Kim (2015) where all three development steps were included in a wind power and solar PV setting.

The purpose of this paper is to provide a quantitative analysis of the main determinants of technological change in the European wind power sector. The paper takes inspiration from the Schumpeterian framework with the three development steps; invention, innovation and diffusion, to model technological change. These steps are recognized as the foundations for the gradual development of new technology (Jaffe and Stavins, 1995). They should thus not be studied in isolation (see also Kline and Rosenberg, 1986).

For example, technological innovation and diffusion could be viewed as being endogenous, and thereby simultaneously determined. On the one hand cost reductions will be achieved gradually as a result of learning-by doing as capacity expands, but on the other hand capacity expansions will largely take place as a result of past cost reductions. Furthermore, unlike wind power output, innovations do not come out of the thin air. Instead they stem from the development of previous inventions into something that can be taken to the market (see further Section 2.1). It is therefore motivated to investigate how innovations (cost reductions) are affected by the knowledge build-up over time through inventions. In brief, our paper contributes to an improved understanding of the dynamics between these three distinguished steps of technological change.

Empirically we focus on wind power. This choice is motivated by the fact that wind power represents a key energy supply technology in complying with existing and future climate policy targets, and there exists a wide variation of policy instruments used worldwide to encourage wind power expansion. During the last decades, there has been an outstanding development in the wind power industry with declining costs and increasing electricity output. The learning process, even though there are still disagreements regarding the role and the significance of technology learning (e.g., Lindman and Söderholm, 2012), has reduced the cost per produced unit of wind-generated electricity. Wind power generation is now estimated to provide more than 3% of the world's electricity demand operating in 100 countries (WWEA, 2013). Globally, in 2012, a record 44.8 Gigawatt (GW) of wind power capacity was added, bringing the total to more than 280 GW (GWEC, 2013).

To our knowledge, the only previous attempt to assemble all three development steps in a quantitative (econometric) setting was made by Kim and Kim (2015). They use 3SLS models for all steps, and analyze dynamic impacts of renewable energy policies in wind power and solar PV. Our paper is different in several important aspects. We present different econometric approaches in line with previous research in respective technological development step. Our paper only focuses on wind power, covers a longer time period and considers to some extent other dependent and explanatory variables.

In the present paper an invention-, innovation-, and diffusion approach is taken, inspired by the innovation- and diffusion models by Söderholm and Klaassen (2007). The diffusion model is in turn a modified version of the rational choice model by Jaffe and Stavins (1994, 1995). We combine a rational choice model of technological diffusion with an innovation model of dynamic cost reductions, and add an invention model which builds on the use of wind power patent counts.

The dataset, covering the time period 1991–2008, includes the eight countries[1] in Western Europe where most inventors of wind power patents reside. There is a significant gap between these selected countries and other European nations, both in terms of granted patents and accumulated installed wind capacity. However, the development of wind power among the selected countries also varies, both when it comes to the diffusion record, and the use of public policies implemented to promote innovation and market penetration of wind power.

By doing the above, the paper fills at least two research gaps identified in the literature. Firstly, it brings the three major steps of technological change together in one paper, thus providing a more in-depth understanding of how these development steps can be linked together. In spite of the empirical focus on wind power, the approach should also generate important general insights into the determinants of technological change in the energy sector. Secondly, with a dataset spanning from 1991 to 2008, it covers a period during which the wind power industry developed rapidly, thus embracing both the technology's infancy and its maturity phase, which allows for a sufficiently large time frame in order to address and measure also the diffusion aspect adequately (Bettencourt et al., 2013).

The paper proceeds as follows. In the next section we outline the theoretical framework used in the paper, and present an invention-, innovation- and diffusion approach to wind power. Section 3 discusses data and model estimation issues, while the empirical results are presented in Section 4. The paper ends in Section 5 with some concluding remarks.

2. An invention, innovation, and diffusion model of wind power

2.1. A simultaneous equation approach

This paper draws inspiration from a Schumpeterian framework to model technological change in the wind power sector (Schumpeter, 1934, 1942), thus specifying three development steps: invention, innovation and diffusion.[2] The concepts of invention and innovation are often somewhat erroneously[3] used synonymously today with the diffusion concept treated separately. In this article, the steps are defined and mainly used as follows (Rosenberg, 1990).[4]

Invention is defined as: “The creation of new products and processes through the development of the new knowledge or from new combinations of existing knowledge. Most inventions are the result of novel applications of existing knowledge,” (Grant, 2002, p. 333). One illustration of this is the jet engine patented by Frank Whittle in 1930; which employs the old Newtonian principles of forces. From patent to civilian customer commercial use it took 27 years; the first jet airliner, the Comet, started to operate in 1957.

Innovation is defined by Grant (2002, p. 334) as: “[t]he initial commercialization of invention by producing and marketing a new good or service or by using a new method of production”. Innovations do not necessarily have to consist of new inventions. They can instead, like the personal computer or the smart phone, consist of several older inventions that are packaged together to a new product. Cost reductions are considered a product of an innovation process where existing knowledge put together can create more efficient use or production of existing technology.

[1] These countries include Denmark, France, Germany, Italy, the Netherlands, Spain, Sweden and the United Kingdom.

[2] The formalization of Schumpeter's ideas into a sequential model arose later than Schumpeter's seminal work with other economists patching together a formalized model. Schumpeter was building on previous technological change ideas by adding concepts of innovations (Godin, 2006).

[3] Schumpeter himself had a strong opinion regarding the importance of separation of the concepts “Innovation is possible without anything we should identify as invention, and invention does not necessarily induce innovation, but produces of itself … no economically relevant effect at all,” (Schumpeter, 1939, p. 81).

[4] For a further discussion about the steps, see for example Ruttan (1959).

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