Energy Policy 33 (2005) 133–150

ENERGY POLICY

www.elsevier.com/locate/enpol

Global experience curves for wind farms

M. Junginger*, A. Faaij, W.C. Turkenburg

Department of Science, Technology and Society, Utrecht University, Padualaan 14, Utrecht 3584 CH, The Netherlands

Abstract

In order to forecast the technological development and cost of wind turbines and the production costs of wind electricity, frequent use is made of the so-called experience curve concept. Experience curves of wind turbines are generally based on data describing the development of national markets, which cause a number of problems when applied for global assessments. To analyze global wind energy price development more adequately, we compose a global experience curve. First, underlying factors for past and potential future price reductions of wind turbines are analyzed. Also possible implications and pitfalls when applying the experience curve methodology are assessed. Second, we present and discuss a new approach of establishing a global experience curve and thus a global progress ratio for the investment cost of wind farms. Results show that global progress ratios for wind farms may lie between 77% and 85% (with an average of 81%), which is significantly more optimistic than progress ratios applied in most current scenario studies and integrated assessment models. While the findings are based on a limited amount of data, they may indicate faster price reduction opportunities than so far assumed. With this global experience curve we aim to improve the reliability of describing the speed with which global costs of wind power may decline.

Keywords: Experience curve; Wind energy; Technological learning

1. Introduction

The wind energy sector is one of the fastest-growing energy sectors in the world. From 1991 until the end of 2002, global installed capacity has increased from about 2 GW (EWEA, 1997) to over 31 GW (Milborrow et al., 2003), with an average annual growth rate of about 26%. During this period, both prices of wind turbines and cost of wind-generated electricity have been reduced (Turkenburg et al., 2000). In spite of these developments, electricity derived from wind is not yet able to fully compete with electricity produced from fossil fuel. However, this may change in the near future (Turkenburg et al., 2000). To forecast future cost development of both wind turbines and wind electricity, use is made of the so-called experience curve concept. This concept analyzes cost development of a product or a technology as a function of cumulative production. On the basis of recorded data on these parameters, a historic experience curve can be devised. If the trend of this curve may be extrapolated into the future, it can help policy makers to estimate when a technology may reach a certain price level.

The technical and economic performance and productivity of a technology typically increase substantially as producers and consumers gain experience with this technology. This phenomenon was first described in literature by Wright (1936), who reported that unit labor costs in airframe manufacturing declined significantly with accumulated experience of the workers. Technological learning has since then been described for many different industries (see e.g. Dutton and Thomas, 1984; Argote and Epple, 1990).

The concept of experience curves has also been applied widely within the energy technologies area. Recent examples are PV modules (Harmon, 2000), combined cycle gas turbines (Claeson et al., 2002), fuel cells (Tsuchiya, 2002), ethanol production (Goldemberg, 1996) or carbon sequestration technologies (Riahi et al., 2002). An overview of studies concerning energy technologies is given by McDonald and Schrattenholzer (2001). Especially for the wind energy sector, experience curves have been devised for Denmark (Neij, 1999a, b), Germany (Durstewitz and Hoppe-Kilpper, 1999), the United States (Mackay and Probert, 1998), and other countries (Lund, 1995; Ibenholt, 2002; Klaassen et al., 2002).

*Corresponding author. Tel.: +31-30-2537613; fax: +31-30-2537601.

E-mail address: m.junginger@chem.uu.nl (M. Junginger).

0301-4215/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0301-4215(03)00205-2

Experience curves can be used for the following different purposes:

- Experience curves are used on a *company level* to project future costs and to formulate corporate strategy (see e.g. Abell and Hammond (1979). The first experience curves (in fact: learning curves[1]) were used to measure the influence of different inputs on the production costs of a standardized product within a factory.
- *National policy makers* may use experience curves to evaluate the effect of past subsidies such as R&D subsidies or investment subsidies. Also, experience curves can be used to estimate learning investments, i.e. the future investments required to 'buy down' the costs of a technology to a certain price level until it can compete with conventional technologies. A discussion of experience curve for various technologies and their application for policy is given by Wene (IEA, 2000).
- Experience curves are also utilized to construct *scenarios* for global wind energy technology development. An example is the recently published Wind Force 12 by EWEA and Greenpeace (2002).
- *Energy models and climate change models* increasingly make use of experience curves to endogenize technological learning and associated cost reductions of renewable energy technologies. Examples of energy models using endogenous learning are ERIS, MESSAGE, MARKAL (Seebregts et al., 1999) and DEMETER (van der Zwaan et al., 2002).

The scope of using experience curves can range from a single manufacturer of wind turbines with a time horizon of a few years (see for example Milborrow, 2002a) to global energy models with a time horizon of up to a century (Seebregts et al., 1999). However, we observe that a number of problems occur with using experience curves for the above mentioned applications. For example, there are different types of experience curves, like for wind turbines, wind farms, wind electricity, which cannot be compared directly. Also, local policy support measures or geographical differences may be sources of uncertainty. Yet, in many scenarios and energy models, global cost reductions of wind turbines are modeled by experience curves based on *national* results.

In this article, we attempt to set up a *global* experience curve for global wind farm price development. The applicability of this curve in energy models and scenarios is also discussed. In order to do so, we will give a brief introduction to the experience curve theory and some general methodological issues in Section 2. In Section 3 we look at the underlying factors that have caused price reduction of wind turbines and wind farms in the past, and we attempt to identify which key factors may be responsible for future price reductions. Subsequently, we evaluate possible methodological pitfalls (especially concerning setting correct system boundaries) in Section 4. Based on these considerations we develop an approach for a global experience curve in Section 5. In Section 6, we describe the data selection for the global experience curve, while in Section 7 we present and discuss the results of the global experience curve for wind farms. Finally, in Section 8, we draw conclusions on the developed methodology and on the global experience curve.

[1] The term learning curve refers to the cost reductions of a standardized product within a single firm, while an experience curve may also describe cost reductions of non-standardized products on a national or global level (Neij, 1999a, b).

2. A brief introduction to experience curve theory and technological learning

2.1. General experience curve theory

A basic experience curve can be expressed as (Neij, 1999a, b):

$$C_{\mathrm{Cum}} = C_0^* \,\mathrm{Cum}^b, \tag{1}$$

$$\log C_{\mathrm{Cum}} = \log C_0 + b \log \mathrm{Cum}, \tag{2}$$

$$\mathrm{PR} = 2^b, \tag{3}$$

$$\mathrm{LR} = 1 - 2^b, \tag{4}$$

where C_{Cum} is the cost per unit; C_0 the cost of the first unit produced; Cum the cumulative (unit) production; b the experience index; PR the progress ratio and LR the learning rate.

The definition of the 'unit' may vary: in many cases a unit is a product (for example a car or an airplane). In relation to energy technologies, more often the unit is the capacity of an energy technology (e.g. the capacity of a gas turbine) or the amount of electricity produced by a technology (see also Section 4.1). The progress ratio (PR) is a parameter that expresses the rate at which costs decline each time the cumulative production doubles. For example, a progress ratio of 0.8 (80%) equals a learning rate of 0.2 (20%) and thus a 20% cost decrease for each doubling of the cumulative capacity. The advantage of using the term 'learning rate' rather than the term 'progress ratio' is that a 'higher' learning rate means a faster decrease of costs, while a 'higher' progress ratio means a slower decrease of costs and thus is somewhat misleading. However, as the term PR is used more frequently in literature, we will use it throughout this paper.