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A review of experience curve analyses for energy demand technologies

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ABSTRACT

Transitioning towards a sustainable energy system requires the large-scale introduction of novel energy demand and supply technologies. Such novel technologies are often expensive at the point of their market introduction but eventually become cheaper due to technological learning. In order to quantify potentials for price and cost decline, the experience curve approach has been extensively applied to renewable and non-renewable energy supply technologies. However, its application to energy demand technologies is far less frequent. Here, we provide the first comprehensive review of experience curve analyses for energy demand technologies. We find a widespread trend towards declining prices and costs at an average learning rate of 18 ± 9%. This finding is consistent with the results for energy supply technologies and for manufacturing in general. Learning rates for individual energy demand technologies are symmetrically distributed around the arithmetic mean of the data sample. Absolute variation of learning rates within individual technology clusters of 7 ± 4%-points and between technology clusters of 7 ± 5%-points both contribute to the overall variability of learning rates. Our results show that technological learning is as important for energy demand technologies as it is for energy supply technologies. Applying the experience curve approach to forecast technology costs involves, however, unresolved uncertainties, as we demonstrate in a case study for the micro-cogeneration technology.

1. Introduction

Introducing renewable energy technologies and improving economy-wide energy efficiency are key strategies for a sustainable global energy system [1]. The quest for sustainable energy supply and demand is, however, complex and extremely challenging for various reasons. Given the magnitude of environmental and social problems associated with the current energy system, novel technologies must be deployed globally at large scale. Furthermore, investments into novel and efficient energy technologies are often unprofitable because current energy markets are distorted in favor of incumbent technologies [2]. Novel technologies in particular face the problem that they are relatively expensive at the point of their market commercialization. However, novel and efficient energy technologies might become cheaper due to technological learning, i.e., the combination of various mechanisms such as learning-by-doing, economies of scale, technological innovation, or factor substitution in manufacturing. Berglund and Söderholm [3] argue that technological learning as driver of cost decline for energy supply and demand technologies is likely to be the single most important factor for shaping our future global energy system. One widely applied tool for quantifying the cost dynamics of technologies is the experience curve approach.

The experience curve approach is an empirical concept that models production costs of technologies as a power–law function of cumulative experience, i.e., cumulative production. Cost dynamics are thereby quantified by learning rates, which indicate the rate of cost decline with each doubling of cumulative production. For several decades, experience curves have been widely used for strategic planning in manufacturing [4,5]. Since the 1990s, experience curves are increasingly applied to establish efficient energy

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technology policies and to forecast technology diffusion and technological change in energy and greenhouse gas (GHG) emission models [6–8].

In the context of sustainable energy supply, the experience curve approach has been widely applied and redefined for renewable and conventional energy supply technologies [9–13]. Neij [14] finds that the results of experience curve analyses on these energy technologies are generally reliable, i.e., consistent with the outcomes of bottom–up technology assessments. Using the extensive body of literature, comprehensive overview studies were prepared in the past with the aim of devising average technology-specific learning rates for energy supply technologies [7–9,15,16]. However, similar efforts for energy demand technologies are largely missing. Experience curves for energy demand technologies are scarce [17–20] and a comprehensive literature review is still unavailable to date. The absence of average learning rates for individual energy demand technologies or technology clusters makes it still necessary to devise individual experience curves for each energy demand technology in order to evaluate its prospects of cost decline. For the large and very heterogeneous group of energy demand technologies, this is a cumbersome and time consuming task.

In this article, we investigate whether it is possible to devise generic *ex-ante* learning rates for individual energy demand technologies and technology clusters. To address existing knowledge gaps, we first present a comprehensive literature review of experience curve studies on energy demand technologies. Based on this review, we quantify technology-specific learning rates and we compare our results with literature findings for energy supply technologies. We furthermore identify potentials and limitations of the experience curve approach to generate reliable *ex-ante* cost estimates for energy demand technologies. Such analysis can provide additional insights into the usefulness of the experience curve approach for energy policy and energy modeling.

In the next section, we briefly explain the experience curve approach and our research methodology. We present our results in Section 3 and we provide a discussion of our findings in Section 4. We draw conclusions in Section 5.

2. Methodology

The experience curve approach dates back to 1936, when Wright [21] found that unit labor costs in airframe manufacturing decline at a constant rate with each doubling of cumulative production. Wright [21] noted the particular relevance of his findings for the investigation of future cost developments in manufacturing. The graphical representation of Wright's discovery is nowadays referred to as *learning curve*, which applies to the effects of learning-by-doing, i.e., the decline in labor costs due to a reduction of working time requirements for manufacturing. Arrow [22] introduced the notion that declining labor costs are a result of growing experience. In 1966, the Boston Consulting Group extended the concept of technological learning by analyzing the dynamics of *total* production costs as a function of cumulative production [23]. This black-box modeling of total production costs as function of cumulative production is generally referred to as *experience curve* approach. Dutton and Thomas [5] differentiate *experience curves* and *progress curves*; the first represent average production costs of multiple manufacturer, whereas the second represent production costs at the level of individual firms. Here, we are interested in the price and cost dynamics of energy demand technologies. Technology-specific data in the literature generally refer to price and cost averages of various manufacturers in a specific country, region, or even on a global level. Hence, we uniformly use the term experience curves throughout this paper when referring to the graphical representation of prices and costs as a function of cumulative production.

The experience curve approach expresses production costs (and under specific preconditions also prices)[1] of technologies as a power–law function of cumulative production:

$$C\text{cum}_i = C_{0,i} \cdot (P\text{cum}_i)^{b_i} \quad (1)$$

where $C\text{cum}_i$ represents the price or costs at $P\text{cum}_i$, $C_{0,i}$ stands for the price or costs of the first unit produced, $P\text{cum}_i$ for the cumulative production, and b_i for the technology-specific experience index of technology *i*. By applying the logarithmic function to Eq. (1), a linear experience curve can be plotted with b_i as the slope parameter and log $C_{0,i}$ as the price or cost axis intercept (Fig. 1). A technology-specific progress ratio (PR_i) [%] and learning rate (LR_i) [%] can be calculated as rate at which the price or costs of a technology decrease with each doubling of cumulative production:

$$PR_i = 2^{b_i} \quad (2)$$

$$LR_i = 1 - PR_i = 1 - 2^{b_i} \quad (3)$$

Experience curves have been constructed for a wide range of products, technologies, and processes. Empirical results almost always indicate declining prices and costs with increasing cumulative production [24]. However, the rates at which production costs decline are technology dependent and even vary for identical technologies depending on the time period and the geographical

[1] In practical applications of the experience curve approach, production costs are often approximated by market prices because data availability is limited. This approximation introduces uncertainty as it is, strictly speaking, only valid, if profit margins of producers remain constant in the period of analysis (see discussion in Section 4.1).