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The experience curve theory and its application in the field of electricity generation technologies – A literature review

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ABSTRACT

The experience curve theory assumes that technology costs decline as experience of a technology is gained through production and use. This article reviews the literature on the experience curve theory and its empirical evidence in the field of electricity generation technologies. Differences in the characteristics of experience curves found in the literature are systematically presented and the limitations of the experience curve theory, as well as its use in energy models, are discussed. The article finds that for some electricity generation technologies, especially small-scale modular technologies, there has been a remarkably strong (negative) relationship between experience and cost for several decades. Conversely, for other technologies, especially large-scale and highly complex technologies, the experience curve does not appear to be a useful tool for explaining cost changes over time. The literature review suggests that when analysing past cost developments and projecting future cost developments, researchers should be aware that factors other than experience may have significant influence. It may be worthwhile trying to incorporate some of these additional factors into energy system models, although considerable uncertainties remain in quantifying the relevance of some of these factors.

1. Introduction

Access to electricity is widely regarded as a prerequisite for ensuring a high standard of living, yet more than one billion people globally still lack access to electricity [1]. One of the targets of the Sustainable Development Goals (SDGs) is, therefore, to "ensure universal access to affordable, reliable and modern energy services" by 2030 [2]. At the same time, decarbonisation scenarios for many different countries agree that substituting fossil fuel use with electricity in final energy demand (e.g. switching from conventional to electric vehicles) is a key element of decarbonisation strategies [3]. Electricity demand is, consequently, expected to continue to increase globally in the decades to come, while electricity supply will simultaneously need to undergo a transformation towards low or zero-carbon technologies.

As a wide variety of electricity generation technologies exist using either fossil fuels, nuclear energy or renewable energy sources, this leads to the following question: which technologies should be used to what extent to meet future electricity demand? Ideally, electricity supply should evolve in a way which allows electricity demand to be met at the lowest cost to society. Although the societal costs of electricity supply include system and external costs in addition to the plant level costs of generating electricity, the plant level costs are an important component of the overall societal costs.

A widely-used method for anticipating future changes in the costs of electricity generation technologies (as well as other technologies) is the experience curve approach. This approach assumes that technology costs decline as experience of a technology is gained through its production and use. Empirical evidence indeed demonstrates a strong negative correlation between experience and cost for various electricity generation technologies, with costs declining at a certain rate – the so-called learning rate – for each doubling of a technology's capacity. Based on assumptions about future deployment levels, this relationship can be used to anticipate future changes in the cost of electricity generation technologies, e.g. by assuming that the learning rates observed in the past will remain stable in the future. During the past two decades the experience curve approach has been used increasingly in energy modelling to endogenise future cost developments by representing an interrelationship between a technology's cost and its deployment [4–11].

This article reviews the literature on the experience curve theory and on its empirical evidence in the field of electricity generation technologies. A number of reviews of experience curve literature have previously been published, covering both electricity generation technologies in general [4,12,13] and individual technologies, such as wind [14–16] and solar PV [17]. This article aims to complement the existing literature and specifically the recent review study by Rubin et al. [13], by:

- providing a systematic overview of the differences in the characteristics of experience curves for electricity generation technologies;

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- providing a structured discussion of the limitations of the experience curve theory and the use of learning rates (including suggestions on how researchers can deal with these limitations);
- including additional and more recent empirical literature sources on experience curves for electricity generation technologies; and
- deriving plausible ranges of future learning rates for electricity generation technologies.

Section 2 introduces the experience curve theory and discusses the differences in experience curve characteristics, as well as the theory's limitations. Section 3 provides an overview and a discussion of the learning rates observed for electricity generation technologies in the past, distinguishing between onshore wind plants, offshore wind plants, photovoltaic (PV) systems, concentrating solar thermal power (CSP) plants, biomass power plants, nuclear power plants, coal power plants and natural gas power plants. Section 4 attempts to derive plausible ranges of future learning rates, drawing on the findings from Section 2 and Section 3. Finally, Section 5 draws conclusions and provides suggestions for future research in the field.

2. The experience curve theory

2.1. Deployment-induced learning and the experience curve theory

A large volume of empirical research indicates that specific costs fall as experience gained from the production and use of a particular technology increases. Initially, such learning was investigated at individual firm level, but, progressively, similar observations were made at industry level. These industry level observations suggest that a significant share of the knowledge gained by individual companies and their customers through experience can ultimately be appropriated by other companies and customers (i.e. the spillover effect). Alternatively, or additionally, some learning may take place at industry level; for example, through exchanges between company representatives within associations or at conferences.

The literature suggests that experience gained by deployment can lead to learning through at least three different channels:

- *Learning-by-doing:* as more and more units of a technology are produced, managers gain experience with the production process and may learn how to improve it, e.g. by increasing work specialisation or by reducing waste. Workers may become more efficient in their respective tasks as they continuously repeat their individual production steps.
- *Learning-by-using:* this can be regarded as the "demand-side counterpart" [18] of learning-by-doing. Users may gain experience by using a technology and learn how to install and operate it more efficiently. The existence of formal user groups who interact with each other can strengthen this kind of learning through networking effects [19].
- *Learning-by-interacting:* by informing them about problems related to the use of a technology, users enable manufacturers to learn from actual on-site experiences of the product. Manufacturers can use this information to improve their respective products [20,21]. Furthermore, companies, users and other stakeholders – such as research institutes and policy makers – can learn from one another through the formal and informal exchange of information [22–24].

A relationship between specific costs and experience has been empirically observed for numerous technologies in various fields [25–27]. As early as the 1930s, a negative correlation between specific costs and production volume was documented for airplanes by Wright [28]. He observed a steady decrease in the specific amount of labour and material input required as the cumulative construction of airplanes increased [28]. This relationship is nowadays referred to as a learning curve. Subsequently, the concept has typically been applied to the total costs of a product, including the combined effect of learning, scale and potentially other factors. The concept is now also commonly applied to entire industries, not only to single companies. The curves derived from this broader understanding of the concept can be referred to as *experience curves* [29].[1] Such experience curves can capture the three different channels of deployment-induced learning, as described above. However, they are not able to separate the individual effects of each channel of learning.

An experience curve typically describes the relationship between a technology's specific costs (expressed in real terms) as the dependent variable and the technology's experience as the independent variable.[2] The experience of a technology is depicted on the horizontal axis of a two-dimensional coordinate system, while the associated costs are depicted on the vertical axis. Typically, in the early stages of deployment, technology costs decrease more steeply for a set increase in production than in the later stages of deployment. Therefore, when costs are depicted on a double-logarithmic scale, experience curves tend to take a more or less linear form.

An experience curve can be described by either the learning rate or the progress ratio it depicts. The learning rate (LR) is the rate at which a technology's costs are found to decrease for each doubling of experience. The progress ratio (PR) is an alternative way of describing this relationship and can be defined as:

$$PR = 1–LR$$

It informs about the relative technology costs remaining after a doubling of experience.

Fig. 1 depicts two experience curves as examples. One of the curves shows the development of the average global PV module price from 1975 to 2015 and describes a learning rate of 22%. The curve's R^2 value is 0.93.[3] The other curve shows the development of wind power project costs in the USA between 1983 and 2015 and describes a learning rate of 6%. Its R^2 value is 0.33, considerably lower than that of the PV module price curve.

2.2. Different characteristics

Experience curves in the literature for electricity generation technologies differ in relation to various characteristics, as documented in Table 1.

2.2.1. Methodological issues

The traditional one-factor experience curve uses only experience as the independent variable to explain cost changes over time. However, this approach potentially suffers from the problem of omitted variable bias (as explained in Section 2.3 below) and, as a result, some authors have suggested the construction of multi-factor experience curves and associated learning rates. These curves aim to properly consider and isolate the combined effect of other relevant factors in order to derive a "true" learning rate [24]. While theoretically appealing, multi-factor experience curves are difficult to construct due to data limitations. For example, learning through research and development or spillover effects from other industries are difficult to reliably quantify. Furthermore, experience and other factors explaining cost changes often show high levels of multicollinearity, making it difficult to distinguish between the effects of experience and the other factors [40–43].

Most of the available empirical studies that construct experience curves for electricity generation technologies do not use technology costs as the dependent variable – as would be theoretically preferable – but instead use a technology's market price. Market prices are frequently used as a proxy for market costs, as the former are more

[1] However, as Junginger et al. [26] note, many authors today use the term "learning curve" as a synonym for "experience curve".

[2] While experience curves are typically used to investigate the relationship between costs and experience, other characteristics of technologies can also be related to experience. In the case of electricity supply technologies, for example, experience curves have also been constructed for the thermal efficiency of coal power plants [30], for the capacity factor of nuclear power plants [31] and for the energy required to manufacture PV modules and systems [32].

[3] R^2 is the coefficient of determination, a measure of the curve's goodness of fit. It takes on values between 0 and 1, with an R^2 of 1 indicating that the regression line perfectly fits the data.