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Learning curves for solid oxide fuel cells

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ABSTRACT

In this article we present learning curves for solid oxide fuel cells (SOFCs). With data from fuel cell manufacturers we derive a detailed breakdown of their production costs. We develop a bottom-up model that allows for determining overall SOFC manufacturing costs with their respective cost components, among which material, energy, labor and capital charges. The results obtained from our model prove to deviate by at most 13% from total cost figures quoted in the literature. For the R&D stage of development and diffusion, we find local learning rates between 13% and 17% and we demonstrate that the corresponding cost reductions result essentially from learning-by-searching effects. When considering periods in time that focus on the pilot and early commercial production stages, we find regional learning rates of 27% and 1%, respectively, which we assume derive mainly from genuine learning phenomena. These figures turnout significantly higher, approximately 44% and 12% respectively, if also effects of economies-of-scale and automation are included. When combining all production stages we obtain $lr = 35\%$, which represents a mix of cost reduction phenomena. This high learning rate value and the potential to scale up production suggest that continued efforts in the development of SOFC manufacturing processes, as well as deployment and use of SOFCs, may lead to substantial further cost reductions.

1. Introduction

Interest in power generation with solid oxide fuel cells (SOFCs), as well as R&D dedicated to this type of technology, has considerably increased over the past few years. Among the reasons are their high net electrical efficiency, in Alternative Current (AC), relative to conventional gas and coal based power units: even in comparison to for instance an integrated gasification combined cycle (IGCC) plant their efficiency is typically more than 10% higher [1]. Another explanation for the increased attention for SOFCs is the possibility of effectively recovering their exhaust heat, given the high temperatures under which they operate. As with other fuel cell systems, a combined heat and power (CHP) SOFC system consists of a stack of SOFCs and a balance-of-plant (BoP). The electrochemical reaction between oxygen and the fuel – such as hydrogen or a hydrocarbon gas like methane – takes place in the stack of fuel cells. The BoP supports the stack, drives the fuel and oxidant (i.e. air) to the fuel cells and can recover energy from the high-temperature exhaust gas. Main disadvantages of SOFC technology are the inabilities to rapidly start operation, switch off and to respond to unexpected variations in power demand.

Whereas their electric efficiency and ensuing economic benefits may be high, the fabrication costs of SOFCs and their resulting CHP systems, hence their purchase prices, are still significantly higher than strategically adopted target values. As a result, the cost of electricity generation with SOFCs are today well above those of most conventional alternatives. The development of SOFCs, however, is in the transition step between pilot and very early commercial stages and has not yet reached large commercial production. Progressively significant cost reductions are expected for the future when the technology transits through the various stages of maturation, as a result of likely improvements in the fabrication process, a probable enhancement of its performance by technical progress and the acquisition of experience at the stages of both manufacturing and commercialization. Learning is defined as the cumulative effect of each of the previously mentioned factors that generate stocks of knowledge, experience, (physical or institutional) infrastructures and skills. The impact of learning on manufacturing costs is usually expressed by the learning rate, a measure for the relative cost decrease of a technology with every doubling of produced or installed capacity. The representation of costs versus cumulative capacity or production of a technology results in a learning curve that in principle could allow for estimating the cost prospects of innovative technology and for determining the competitive breakeven point with respect to existing technology.

Schoots et al. [2] present an extensive analysis of global learning phenomena for several fuel cell technologies: proton exchange

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membrane fuel cells (PEMFCs), phosphoric acid fuel cells (PAFCs) and alkaline fuel cells (AFCs). The present work complements this recent fuel cell learning curve study, since so far no learning rates have been reported – or have been determined – for SOFCs. To our knowledge only Krewitt and Schmid [3] have attempted to determine a learning curve for SOFCs, but they found that insufficient information on produced SOFC capacity was available at the time to calculate a learning rate. Hence, their preliminary findings remained unpublished. We here report for the first time a reliable learning curve for SOFCs and describe how we performed our corresponding analysis. Apart from the fact that we studied a different type of fuel cell, our work distinguishes itself from the analysis reported in Schoots et al. [2] in that we obtained sufficient data from manufacturing facilities with enough detail to allow us to disentangle and measure the impact of learning on cost reductions at different stages of the fuel cell development process.

In Section 2 of this article we briefly recapitulate the general concept behind learning curves and explain how one calculates a learning rate. In Section 3 we present our study of SOFC costs and the effects of phenomena such as fuel cell production automation and economies-of-scale; we also describe in detail the cost model that we use for our analysis and the roles played herein by material, energy, labor and capital charges. On the basis of both literature and modeled data we determine learning curves for SOFCs in Section 4. In Section 5 we discuss our assumptions and evaluate the calculated learning rates in a broader perspective, in particular by unpacking the SOFC learning curves by production stage and cost reduction mechanism. We summarize our main conclusions in Section 6.

2. Learning curves

Since the development of the first learning curve for the aircraft industry in 1936 [4], many technologies have been subjected to learning curve studies, as a means to evaluate potential cost reductions based on realized progress in the past. Learning curves have been determined for a large range of different types of technologies and may serve company strategic purposes and as a tool for public policy making. Well known are learning curves for energy-related technologies, such as coal-burning power units [5], gas turbines [6], wind turbines [7] and photovoltaic modules [8]. A learning curve expresses graphically the cost decrease of a technology as function of cumulative production. The most common type of equation to correlate cost and cumulative production values in this area is a power law (see Eq. (1)). When cost and cumulative capacity data are represented in logarithmic form, the power law of a learning curve becomes a downward sloping straight line. The slope of this line is called the learning index (α) [9,10], which can be reformulated as the learning rate (lr) (see Eq. (2)). The latter expresses, usually in percentages, the relative cost reduction after each doubling of cumulatively produced items of a technology. The learning rate provides a quantitative measurement of the effect of (the aggregation of) various cost reduction drivers, among them in particular (but not necessarily exclusively) economies-of-scale and 'true' learning. The latter may originate from (1) the accumulated knowledge regarding the technological principles or the production and marketing processes of the technology and/or (2) implemented improvements in the overall infrastructure needed for the technology manufacturing procedure. In our case of fuel cells, the variables in Eq. (1) are the costs of SOFCs at time t (c_t), the costs of SOFCs in the time set as reference and referred to as $t = 0$ (c_0), the cumulated production of SOFCs at time t (P_t) and the total number of SOFCs produced until the time set as reference (hence at $t = 0$) (P_0). We express values of P either in number of SOFCs (typically for fuel cells) or in terms of their capacity (hence in kW, for example when referring to SOFC systems).

$$c_t = c_0\left(\frac{P_t}{P_0}\right)^{-\alpha} \quad (1)$$

$$lr = 1 - 2^{-\alpha} \quad (2)$$

A learning rate summarizes how cost reductions materialize when a manufacturer accumulates production or, alternatively, when it contributes to cumulative production of a technology thereby adding to the (global, regional or local) experience stock [11]. According to Lindman and Söderholm [11], learning is often not a public good, hence factors like the regional context, deployment and R&D support influence the cost reductions realized for a technology. The latter could be expressed by more complex mathematical learning curve expressions. Limited availability of data, however, prevents us from using more complex learning curve expressions than the one employed for this paper. In practice it proves difficult to distinguish between different cost reduction sources, as in our case with SOFC technology: the production process typically improves through several distinct ways, not only by the acquisition of experience based on manufacturing and deployment (learning-by-doing) but also via R&D efforts (learning-by-searching), and quite possibly from still other mechanisms such as technology spillovers [11–16]. Additionally to learning phenomena, effects of economies-of-scale, automation and market prices of raw materials eventually may contribute to costs reductions. Conventionally and erroneously these last elements are seen as part of learning, even though they are externalities not directly linked to a specific technology. Hence, in this work major efforts target to clarify the cost reduction of SOFCs by means of learning and non learning phenomena. It is conventional wisdom, and common practice in most studies, that learning rates are determined for technologies that have matured sufficiently and have reached advanced stages of commercial deployment – presently not yet the case for SOFCs – so that they mostly capture the effect of learning-by-doing. According to Ferioli and van der Zwaan [17], however, learning curves often apply only up to and including the early phase of commercial deployment. In those cases, as they argue, learning curves usually reflect several types of cost reductions, e.g. as associated with both learning-by-doing and learning-by-searching. Their observation, plus the asserted transition towards early commercial production of SOFCs over recent years, motivated our attempt to develop a learning curve for SOFC technology. Learning curve analysis can provide valuable insights for strategic planning and policy making, and can help determining or shaping indicators like total investment requirements and needs for financial support or deployment levels at which new energy technologies such as SOFCs become competitive with incumbent technologies.

3. Cost requirements for SOFCs

Since SOFC systems operate at temperatures above 900 K and present relatively long start-up times, they are principally considered for stationary and micro-stationary CHP generation purposes. Some specific mobile market applications exist, for example as auxiliary power supplies (APUs) in trucks. Apart from their high electric efficiency, other benefits are that they may be designed in a variety of distinct forms and set-ups, and can run on different types of fuel [18–20]. In the current early commercial production phase, planar and tubular geometries of SOFCs dominate triangular and other shapes. For all these geometries, individual fuel cells are assembled in stacks (planar) or modules (tubular) that are subsequently integrated with the BoP. An individual fuel cell consists of a multilayer device including the anode, electrolyte, cathode and interconnects. For an SOFC, the first three components are made of ceramics, such as respectively Nickel Oxide–Yttria Stabilized Zirconia (NiO–YSZ),