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Learning curves for hydrogen production technology: An assessment of observed cost reductions

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ABSTRACT

At present three key energy carriers have the potential to allow a transition towards a sustainable energy system: electricity, biofuels and hydrogen. All three offer great opportunity, but equally true is that each is limited in different ways. In this article we focus on the latter and develop learning curves using cost data observed during the period 1940–2007 for two essential constituents of a possible 'hydrogen economy': the construction of hydrogen production facilities and the production process of hydrogen with these facilities. Three hydrogen production methods are examined, in decreasing order of importance with regards to their current market share: steam methane reforming, coal gasification and electrolysis of water. The fact that we have to include data in our analysis that go far back in time, as well as the uncertainties that especially the older data are characterized by, render the development of reliable learning curves challenging. We find only limited learning at best in a couple of cases, and no cost reductions can be detected for the overall hydrogen production process. Of the six activities investigated, statistically meaningful learning curves can only be determined for the investment costs required for the construction of steam methane reforming facilities, with a learning rate of $11 \pm 6\%$, and water electrolysis equipment, with a learning rate of $18 \pm 13\%$. For past coal gasification facility construction costs no learning rate can be discerned. The learning rates calculated for steam methane reforming and water electrolysis equipment construction costs have large error margins, but lie well in the range of the learning reported in the literature for other technologies in the energy sector.

1. Introduction

Recently, hydrogen has gained considerable interest as potential alternative fuel for zero-emission vehicles. Compared to the direct use in the transport sector of fossil fuels like oil and natural gas, however, the costs associated with the use of hydrogen are high at present. The overall costs of hydrogen usage can be split into four main components: production costs, distribution costs, storage costs and costs of end-use in, for example, fuel cells. In this paper we focus on the former, and present an analysis of hydrogen production cost reductions as achieved over approximately the past six decades. These observed cost reductions can be instructive for assessing the possibility of realizing hydrogen production cost improvements in the future and may provide an indication for the viability of establishing a hydrogen economy.

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We base our analysis on open literature data (as opposed to confidential company data). The costs we report below may be biased towards the lower end, because open literature cost data do regularly not report a variety of additional costs e.g. as related to the installation phase of hydrogen plants. Hydrogen can be produced through a number of different methods. In this paper we investigate three such techniques: steam methane reforming (SMR), electrolysis of water and coal gasification. Although we also addressed another important hydrogen production technology, the partial oxidation of heavy oil, we have not been able to retrieve enough reliable annual production data for this technique to independently determine the evolution of its employment over time; so we have discarded this alternative from our study. One of the possible explanations for the lack of production data for partial oxidation is the wide variety in feedstock for this technology. Also, quoted figures on hydrogen production through partial oxidation of heavy oil are sometimes diluted with amounts of hydrogen produced via the partial oxidation of natural gas, and the purity of the syngas produced by partial oxidation is not rarely left unrevealed, which leads to sizeable uncertainties in the precise amount of hydrogen produced via this method. These are additional reasons for not reporting on partial oxidation hydrogen production in this paper. The contributions of each of the other three main methods to their sum, in terms of both hydrogen production capacity and the global amounts of hydrogen produced, are shown in Figs. 1(a) and (b), respectively, as function of time since the origin of industrial hydrogen production.[1] The curves in these figures have been plotted with the assumption that the partial oxidation of heavy oil accounts for approximately 30% of the total of all methods combined, both for the global production capacity and for the amount of hydrogen produced.[2]

As the cumulative installed hydrogen production capacity increases, experience is obtained in both building production facilities and producing hydrogen with these facilities. The energy policy literature extensively reports that for many technologies these types of activities have resulted in (sometimes impressive) cost reductions. The observed relation between such cost reductions and the experience accumulated through deployment or employment activity is normally referred to as "learning-by-doing". The purposes of this article are to explore the existence of this learning phenomenon for hydrogen production technology and determine whether hydrogen production cost targets are achievable in the near future. The US Department of Energy target for the year 2017 for hydrogen fuel production costs from SMR is 2.00 US$ per gallon of gasoline equivalent (gge) and for electrolysis 3.00 US$ per gge. In both cases the production cost targets do not include taxes but do contain a cost target of 1.00 US$ per gge for delivery at the pump [3]. In terms of the hydrogen higher heating value (HHV), the production part (excluding taxes and delivery) of the US Department of Energy targets for hydrogen production costs are 0.025 US$/kWh for SMR and 0.05 US$/kWh for electrolysis.[3]

For many decades already, learning curves have been used as a suitable visualization of learning-by-doing. Learning curves express the hypothesis that the costs of a technology decrease by a constant fraction with every doubling of installed capacity or exercised activity. Hence, on a double logarithmic scale the relation between these technology costs and cumulated manufacturing or production involves a downward sloping straight line (see, for example, [4,5]). In 1936 the first learning curve was determined for the amount of labor hours spent on building aircraft [6]. Since then, analysts in commerce, consulting and academia have determined learning curves for a large range of industries and technologies.

Learning curves can be expressed as a power-law:

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

where c_t is the cost of the technology under consideration at time t, c_0 in principle the cost per item in the first batch of production (the point in time at which this occurs usually being referred to as $t = 0$), P_t the cumulated production of items at time t, P_0 the number of items in the first batch of production at $t = 0$, and α the learning index. P can be dimensionless, when its values are obtained by simply counting items of a certain technology, or may be expressed in a variety of different units (like MW, MWh or GJ, in the energy sector). In this paper P_t is either the cumulated installed hydrogen production capacity (which we express in GW) or the cumulated amount of hydrogen produced (which we express in TWh) at time t. P_0 refers to, respectively, the installed hydrogen production capacity or the amount of hydrogen produced at our choice for $t = 0$.

The progress ratio pr expresses the fraction to which costs are reduced with every doubling of, in our case, either the cumulated production capacity or the cumulated amount of hydrogen produced, and is related to α by

$$pr = 2^{-\alpha}. \tag{2}$$

The progress ratio is related to the more commonly used learning rate, lr, through $lr = 1 - pr$, and is, like pr, usually expressed in percentages. Typical values for lr and pr are, for example, 20% and 80%, respectively.

In spite of extensive research efforts, the mechanisms behind cost reducing learning phenomena are still poorly understood (see notably [7–11]), even while several studies point out the direction of search and other analyses have booked some progress in opening the black box of learning-by-doing (e.g. [12–14]). In the present paper we attempt to further unpack this black box. Learning curves can, by

[1] The total figures and the shares of individual methods have been independently retrieved from various sources in the open literature. As a result, depending on the year under consideration, the production capacities/amounts of the different methods do not always add up to 100%, but rather to typically about 97%. This difference can be explained by a few remaining processes that have hydrogen as by-product. The hydrogen co-produced in chlorine production explains most of the observed discrepancy (3.6% in 1983 and 3.0% in 1998; see [1]).

[2] The partial oxidation share of 30% is adopted from [2] and refers in principle to 2003 only. For ease of exposition, we assume that this share also approximately applies to other years.

[3] In this paper we use the HHV of hydrogen (39.41 kWh/kg). The US Department of Energy targets are based on the lower heating value (LHV) of hydrogen (33.33 kWh/kg).