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Projections of electrolyzer investment cost reduction through learning curve analysis

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Contents

1 Introduction

Hydrogen might become an increasingly important energy carrier for the transformation of our energy system. Renewable hydrogen production costs are currently high but are likely to decline during the scale-up and deployment of production capacity. More insight in the costs of one of the main components, the expenditures for the electrolyzer, is valuable for policy makers and companies involved in hydrogen value chains. In this paper we sketch a picture of the possibly to be expected decrease in investment costs of electrolyzer plants to produce hydrogen through a learning curve analysis. During the various stages of technology development and deployment the corresponding experience increases. Technological progress and improvements are generally economically driven and optimization results in cost reductions. This learning-by-doing process can be expressed by an experience or learning curve. A technology learning curve provides information on how fast the costs (or another parameter) decline in relation to the cumulative installed capacity (McDonald & Schrattenholzer, 2001; Ferioli et al., 2009). A historical learning curve is based on empirical data and generally resembles a declining straight line if costs are plotted against the cumulative installed capacity on two logarithmic axes. Extrapolation of a historical learning curve indicates how technology costs may decline depending on the cumulative installed capacity. The learning rate (LR) specifies the rate (as a percentage) of cost reduction for each doubling in cumulative installed capacity. When the technology learning curve is non-existing or is not (yet) determined, an estimate can be made of the learning curve based on the current technology status. A learning curve of comparable technology might provide a good starting point for such assumptions.
To construct a learning curve for electrolyzer plants to produce hydrogen we use a few base parameters. In this study we apply the current cumulative installed capacity of electrolyzers, the current specific investment costs, the projected cumulative installed capacities for both 2030 and 2050, and information about the (historical) learning rate for electrolyzers and comparable technology to estimate future specific investment costs.

2 Methodology

To construct a learning curve for electrolyzer plants to produce hydrogen we use the following equations (Ferioli et al., 2009):

$$C_{Xt} = C_{X_0} (X_t / X_0)^{-b} \qquad (1)$$

$$LR = 1 - 2^{-b} \qquad (2)$$

In equation (1) X_0 and X_t are the cumulative installed capacities at respectively an arbitrarily chosen starting point *0* and at point *t* in time. Parameter *b* is a positive learning factor that relates to the learning rate (LR) as expressed in equation (2). $C(X_0)$ and $C(X_t)$ are the costs of the technology (or product) at X_0 and X_t, respectively. Below we explain how we determine these base parameters, such as the current cumulative installed capacity of electrolyzers (X_0), the current investment costs (C_0), the projected cumulative installed capacities (X_t) for both 2030 and 2050, and information about the (historical) learning rate (LR) for electrolyzers or comparable technology.

Base parameters

Today's global cumulative installed capacity is set at 20 GW (IRENA, 2020). We suppose here that experience from both water electrolysis and electrolytic chlor-alkali production since the 1950s contributes to the learning curve of electrolyzers. An alternative starting point can be chosen if only novel water electrolysis capacity that is installed during the last decade is considered. This accumulates to approximately 0.2 GW of capacity (IEA, 2019; Hydrogen Council, 2021). The latter, however, seems not a valid starting point as alkaline electrolysis, currently the cheapest technology option, is mostly inspired by technology development with which already 20 GW of experience is gained. Similar technology, such as fuel cells and (to a lesser extent) battery technology, may also be considered as part of the cumulative obtained experience, but we do not include this additional capacity, neither in today's numbers or in the projections. These potential spillover effects between batteries, fuel cells and electrolysers we do not analyze here, but they may accelerate further cost reductions for these technologies (IEA, 2020).

The current investment costs for electrolyzer plants are rather uncertain and available data covers a broad range. Often this range is influenced by the level of completeness of the analysed investment cost or capital expenditures (CAPEX). Some report only the equipment or system costs, while others describe total project costs (including cost items such as engineering, installation, owner's costs, and contingency). To calculate the levelized cost of hydrogen production, the total project costs are the most relevant and therefore are used for our initial CAPEX value. In the "eindadvies basisbedragen SDE++" for 2021 it is assumed that the total investments costs for a 20 MW (alkaline) electrolyzer amount to 1800 €/kWe (PBL, 2021). In the Hydrohub Innovation Program an estimate has been made of the costs for a GW scale electrolyzer if such a plant would be build today. The total project costs for a hydrogen plant based on alkaline electrolysis are determined at 1400 €/kWe of which nearly 800 €/kWe for the complete electrolyzer installation including balance-of-plant equipment (ISPT, 2020). In the same study the total project costs for a hydrogen plant based on PEM electrolysis amount to 1800 €/kWe of which 1000 €/kWe direct costs (ISPT, 2020). We use the values (1400-1800 €/kWe) from these two reports as the high and low end of our CAPEX range in 2020.

Projected cumulative installed electrolyzer capacity differs substantially between studies. The role of hydrogen in a future carbon neutral society becomes more significant in scenario studies that have been reported during the last couple of years. To reach the targets in such scenarios, projections range from 100 GW in the Planned Energy Scenario of IRENA, to 270 GW in 2030 in the Transforming Energy Scenario (IRENA, 2020). Installed capacity may grow to more than a TW in 2050 (IRENA, 2020; IEA ETP, 2020). Global installed electrolyzer capacities of around 80 GW in 2030 are reported based on announcements in plans and strategies in countries across the world (Hydrogen Council, 2021). In the recently reported net zero emission (NZE) scenario, an electrolyzer capacity of even 850 GW in 2030 and more than 3 TW in 2050 seems necessary to reach the climate goals (IEA, 2021). The rate of technology deployment is however highly uncertain as its current contribution is still minor. Electrolyzer manufacturing companies have currently reached a combined annual production capacity of roughly 2 GW/yr (NOW, 2018; IRENA, 2020). This capacity was an order of magnitude lower a few years ago, but many companies prepare themselves to be able to deal with the possibly rapidly increasing demand for electrolyzers. Most of the current production capacity comes from companies that for decades supply the electrolyzers for the chlor-alkali industry and already have the facilities and component supply chains in place (Air Products, 2021). Reaching the cumulative capacities as described in these outlooks necessitates a further rapid scale up of electrolyzer manufacturing industry.

The learning curve based on historical data of electrolyzer investment costs reveals a **learning rate** of around 18% (Schoots et al., 2008; Schmidt et al., 2017), while low and high estimates of 12 to 20% are used by others (Hydrogen Council, 2021). For other technologies, the historical learning rate also varies substantially. The learning rate for lead batteries, for example, is only 4%, while for portable lithium ion batteries a learning rate of 30% is reported (Schmidt et al., 2017). To accommodate for part of the uncertainty related to this analysis, we present our (single component) learning curve for electrolyzer CAPEX as a range. The high estimate starts from 1800 €/kWe in 2020 and declines with an LR of 12%, while the more optimistic projection starts at 1400 €/kWe in 2020 for which an LR of 20% is applied. We assume that all different electrolyzer types (e.g., alkaline, proton exchange membrane, and solid oxide) are covered by the range of our learning curve. In reality, current system costs for proton exchange membrane (PEM) and solid oxide (SO) electrolyzers are higher than for alkaline electrolyzers. We expect that these costs in the near future will come closer together or that one (or two) of the technologies will dominate the market. PEM differs from alkaline technology in its material usage but the manufacturing and assembly processes of the stacks are fairly comparable (NOW, 2018). The power unit (transformer and rectifier) will be nearly identical. Also other direct costs, such as the water supply system and the gas purification and drying installation, are not likely to differ significantly. An advantage of PEM compared to alkaline electrolyzers is that they allow operation at higher current densities. This characteristic results in lower space requirements for the installation and, thus, less plant area. One could argue that because currently PEM is still more expensive than alkaline, the latter will mainly be applied, and as a consequence PEM can never catch up. However, future cost reductions for PEM (and also SO) electrolysis might possibly profit from comparable developments in PEM (and SO) fuel cells, which are deployed in steadily growing amounts in transport and stationary applications. Considering all uncertainties and given the similarities between the technologies, we do not find it meaningful to project multiple learning curves and assume that our range covers all different electrolyzer types.

3 Results

The projected reductions in investment costs, based on the parameters as explained above, are plotted in Figure 1 versus the cumulative installed capacity of electrolyzers (the latter on a logarithmic scale). We indicate several points and ranges on the learning curve to illustrate the time aspect related to these learning curves.

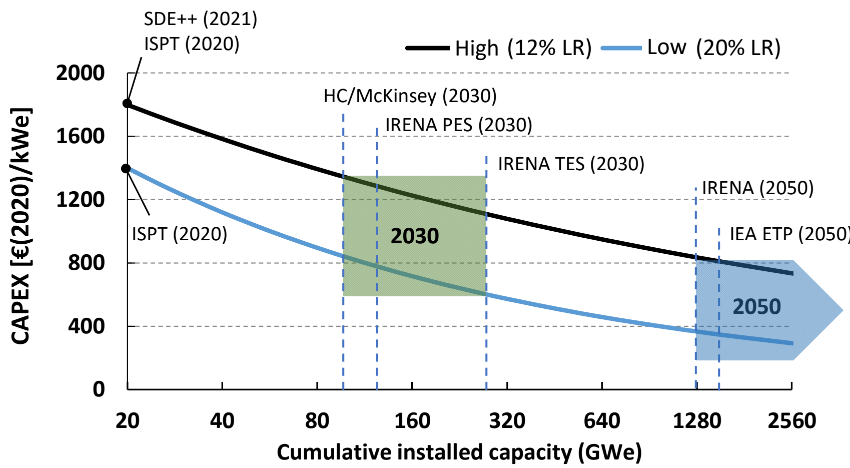

Figure 1. Projected single-component learning curves for electrolyzer investment costs.

In 2030, costs may have declined to 1100-1350 €/kWe under our more conservative assumptions, while the lowest estimate projects a reduction to 600-850 €/kWe. Our range matches well with data from the extensive study of Glenk & Reichelstein, who find an electrolyzer system cost range of 500-1400 €/kWe for 2030 (Glenk & Reichelstein, 2019). They based their analysis on cost estimates from manufacturers, journals, reports, and news for both PEM and alkaline systems. To reach a cumulative installed capacity of 100 GW in 2030, annual installations of today (<0.1 GW/year) should approximately double each year until 2030. This means that the estimated total electrolyzer production capacity of 2 GW/yr should double in approximately five years from now and increase twenty times by 2030.

Cost projections up to 2050 are highly uncertain but if renewable hydrogen really takes off as an important decarbonization option, more than a terawatt (TW) of cumulative capacity installations are likely required. This equals at least 6 and possibly even 8 doublings in cumulative electrolyzer capacity. Depending on the learning rate (12 to 20%), this may result in a reduction of the current costs of around 50 to 80%.

We also construct a three-component learning curve (Ferioli et al., 2009) in which we distribute the total project costs over three cost components, i.e. stacks & power supply, other direct costs (balance of plant), and other project costs. Based on reported breakdown of the costs (ISPT, 2020), we distribute the total projects costs in 2020 (1400-1800 €/kWe) over these components. Next, we apply different learning rates for each of these components. The stacks & power supply may experience a steep learning curve and we apply an LR of 20%. The other system components (balance of plant) are also implemented in other industrial plants, although their dedicated role in electrolyzer facilities may still result in an LR of 10%. A similar approach has been conducted by Böhm et al. (2019), who use learning rates of 5-18% for the module components and 7-13% for other equipment. Based on that data, they constructed a multi-component learning curve for the system costs. We conduct a simplified three-component breakdown of the total project costs to determine our learning curves. Other project costs (e.g. installation, engineering, contingency) experience the lowest learning rate (5%) as these type of costs are less likely to reduce rapidly. It is however possible that substantial cost reductions can be realized for this "other project costs" component. For example, automated installation can play a role and more experience in the execution of multiple similar projects can reduce engineering and contingency costs. The result of the three-component learning curves has been illustrated in Figure 2 in a similar fashion as for the single-component learning curves in Figure 1.

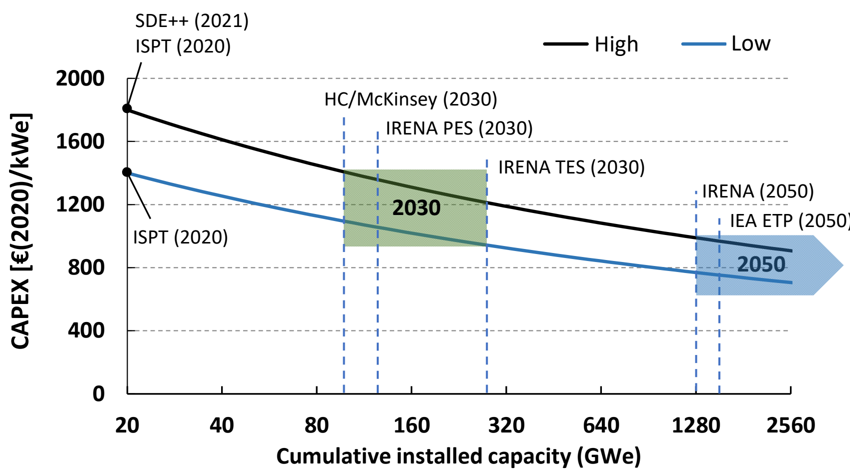

Figure 2. Projected three-component learning curves for electrolyzer investment costs.

Starting at a low initial CAPEX and reaching a high cumulative installed capacity, our three-component learning curve projects that in 2030 costs may have declined to approximately 950 €/kWe, while for a high initial CAPEX combined with less capacity installed, costs amount to around 1400 €/kWe. This range of 950-1400 €/kWe is slightly less optimistic compared to the range of 600-1350 €/kWe for single-component learning. A power law fit of the three-component learning curve reveals an LR of 9%, which is indeed lower in comparison with our most conservative single-component LR of 12%. In Figure 3 we show the cost breakdown of the three-component learning curves starting from 1800 €/kWe (left) and 1400 €/kWe (right) in 2020.

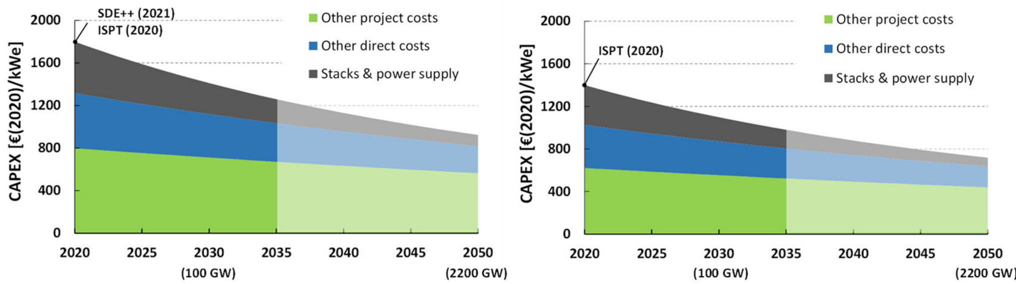

Figure 3. Cost breakdown of the projected three-component learning curves for electrolyzer investment costs, starting from 1800 €/kWe (left) and 1400 €/kWe (right). In this scenario, cumulative installed capacity grows to 100 GW in 2030 and 2200 GW in 2050. For a more detailed explanation of the three component categories we refer to the main text.

The relative contribution of stacks & power supply becomes smaller when time (and cumulative capacity) progresses thanks to the high LR of 20% compared to the LR's of the other cost components. An accelerated decline of the other project costs, as explained above, will lower the relative difference between the components and lead to an overall reduction in the total project costs. If we assume that announcements in current plans and strategies are realized and a cumulative installed capacity of around 100 GW is reached in 2030 (Hydrogen Council, 2021), electrolyzer CAPEX may decline to 1100 €/kWe in the optimistic case (Figure 3, right). Such a reduction in costs is considerable and likely requires significant scale up of both electrolyzer manufacturing facilities (to realize enough cumulative capacity) and hydrogen production plants (from MW to GW scale), as well as enough demand for green hydrogen. Continued scale-up and learning-by-doing towards 2050 would in this scenario reduce CAPEX further to approximately 700-900 €/kWe for a cumulative installed capacity of 2200 GW. At this stage, the direct costs components represent less than 40% of the total investment costs and other project costs dominate the CAPEX of an electrolyzer plant. As already mentioned, the uncertainty of cost projections up to 2050 is high and we recommend to continuously update such projections by using the latest available data. More datapoints, generated by the projects that are realized during the upcoming years, can substantially improve the reliability of these learning curve projections for the longer term.

4 Conclusions

The total investment costs of electrolyzer plants are likely to decline in the coming years. To what extent is uncertain and reported estimates cover a broad range. Here we apply a learning curve analysis to project the cost up to 2030 with an outlook towards 2050. A single component approach, for which we apply a learning rate of 12-20%, indicates that total project costs of an electrolyzer plant to produce hydrogen may reduce from currently around 1400-1800 €/kWe to approximately 600 €/kWe in 2030 under optimistic assumptions, while the conservative projection amounts to 1350 €/kWe. Current costs may reduce by around 50-80% up to 2050 if more than a TW of electrolyzer capacity has been deployed.

Distribution of the total project costs over three cost components, i.e. stacks & power supply, other direct costs (balance of plant), and other project costs, and applying learning curve analysis on each of these components aggregates to a fitted learning curve with a learning rate of 9%. According to this three-component learning curve, costs may reduce to 950-1400 €/kWe in 2030, which amounts to a slightly lower reduction in costs than observed for our single component approach. For 2050, CAPEX reduces further to approximately 700-900 €/kWe for a cumulative installed capacity of 2200 GW.

These results indicate that costs of electrolyzer plants can significantly reduce if learning-by-doing proceeds as projected. To reach the estimated cumulative capacities, electrolyzer manufacturing facilities should scale up as soon as possible to enable the deployment of enough electrolyzer plants. Such a deployment rate will only be justified if substantial incentive and demand for renewable hydrogen will develop in the coming years. If demand surpasses the maximum supply of the electrolyzer manufacturing industry, the price (and possibly also the costs due to scarcity of materials on the market) likely goes up. Such effects are difficult to project but can play a profound role during the scale-up phase of the renewable hydrogen industry.

We recommend to study these effects and to investigate the multi-component learning curves in more depth. It seems relevant to include possible spillovers from other electrochemical devices, such as fuel cells and batteries. A more detailed bottom-up assessment of the minimum equipment costs based on material usage would allow a better estimate of the floor costs of the learning curve. Such insights may help to further enhance developments and innovations in the electrolyzer industry.

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