Projecting the future cost of PEM and alkaline water electrolysers; a CAPEX model including electrolyser plant size and technology development

Anita H. Reksten [a,], Magnus S. Thomassen [a,b], Steffen Møller-Holst [c], Kyrre Sundseth [c]*

[a] SINTEF Industry, Forskningsveien 1, 0373 Oslo, Norway
[b] Hystar, Veritasveien 5, 1363, Høvik, Norway
[c] SINTEF Industry, Richard Birkelands vei 3, 7034 Trondheim, Norway

HIGHLIGHTS

- A cost model for water electrolyser plants including both plant size and technology improvements has been developed.
- Steeper learning rates for PEMEL and AEL have been estimated than previously reported.
- Electrolyser plant size is an important parameter to include when estimating the learning rate of PEMEL and AEL technologies.
- The CAPEX gap between AEL and PEMEL technology decreases significantly towards 2030.

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ABSTRACT

The investment costs of water electrolysis represent one key challenge for the realisation of renewable hydrogen-based energy systems. This work presents a technology cost assessment and outlook towards 2030 for alkaline electrolysers (AEL) and PEM electrolysers (PEMEL) in the MW to GW range taking into consideration the effects of plant size and expected technology developments. Critical selected data was fitted to a modified power law to describe the cost of an electrolyser plant based on the overall capacity and a learning/technology development rate to derive cost estimations for different PEMEL and AEL plant capacities towards 2030. The analysis predicts that the CAPEX gap between AEL and PEMEL technologies will decrease significantly towards 2030 with plant size until 1–10 MW range. Beyond this, only marginal cost reductions can be expected with CAPEX values approaching 320–400 $/kW for large scale (greater than 100 MW) plants by 2030 with subsequent cost reductions possible. Learning rates for electrolysers were estimated at 25–30% for both AEL and PEMEL, which are significantly higher than the learning rates reported in previous literature.

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Introduction

The deployment of intermittent renewable energy in recent years, and the subsequent increased need for flexibility for the electric power system, has led to an increased focus on green (i.e., produced from renewable energy sources) hydrogen. Hydrogen is a flexible energy carrier with the potential application in many sectors. It can be used for long term storage and as balancing services for fluctuating renewable energy sources, as fuel for zero-emission transport (especially in heavy-duty transportation and in the maritime sector), be mixed into the natural gas grid for distribution and storage, be used in reduction processes in the industry (e.g. steel industry) and be used for converting renewable energy into various energy carriers (power-to-x), such as synthetic methane, synthetic liquid fuels, ammonia, and methanol. Hydrogen's versatility has lately led to the installation of several large-scale electrolyser plants internationally, most of them in Europe. Electrolyser manufacturers plan to introduce 2–6 MW commercial electrolysers and even up to 100 MW electrolysers being capable of producing 40–50 tons hydrogen each day.

The European Union (EU) states that achieving the required energy transition will need hydrogen at large scale [1]. This is in line with the International Energy Agency (IEA) conclusions that this is the time to scale up these technologies and bring the costs down to allow hydrogen to become widely used and that is possible to take advantage of the currently increasing political and business momentum [2]. The European strategy includes explicit electrolyser capacity targets of 6 GW by 2024 and 40 GW by 2030, as well as production targets of 1 and 10 million tonnes of renewable hydrogen per year for these milestones years [3].

The production of green hydrogen from renewable energy can be realised through four existing water electrolysis technologies: polymer exchange membrane electrolysers (PEMEL), alkaline electrolysers (AEL), solid oxide electrolysers (SOEL) and anion exchange membrane electrolysers (AEMEL). The two latter are the least mature technologies, with very few demonstrated commercial plants so far. In comparison, AEL is the dominating technology dating back to the beginning of the 20th century. PEMEL on the other hand, is a less mature technology, with the first cells built in the 1960s but it has been gaining momentum in recent years. Both AEL and PEMEL electrolysis systems are currently being manufactured and deployed at multi-MW-scale.

The investment costs of these water electrolyser plants represent one key challenge for a renewable hydrogen-based energy system. Historic cost developments of electrolyser technologies has been the topic of several published works using different methods to further predict the cost development towards 2030 and beyond [4–11]. The data from these studies suggest a significant decline in the cost of electrolysers towards 2030 and the drivers for cost reduction are described as a combination of scale up, increased manufacturing volumes and technology improvements. However, most of these published studies are only analysing the expected cost development based on production volume or installation year, and do not consider the effects of the electrolyser plant size combined with the maturity of the technology or production processes.

The previously published studies have also to a large degree gathered cost data uncritically, using cost data from publications without any basis in techno-economic analyses in combination with more reliable data from detailed cost studies or quotes from suppliers of electrolyser systems. For example, Schoots et al. [4] analysed cost data as well as technology development goals in their study, even though such goals often are very ambitious. They did account for scale effects, but with a pre-selected scaling factor without any further discussion on the basis for the selected value for this factor. Saba et al. [6] provided a good overview and discussion on the available cost data as well as methods for estimating future cost developments, but did not take into account the varying production capacity of the electrolysers when discussing the cost developments towards 2030. Similarly, Glenk and Reichelstein [7] gathered cost data from the literature without evaluating the validity of the referenced values and only used the reference year as a variable for analysing future cost developments. The main weakness of the approach in these studies, beyond using cost values that are not founded in any detailed cost break-down analysis or based on real data from suppliers, is that historical data for the most part are based on smaller units in the kW range which cannot be directly compared nor extrapolated to future installations in the multi-MW range.

In this study, the available literature for current cost data and cost projections for both PEMEL and AEL technologies has been critically reviewed. The references used in the previous studies mentioned above were included in this review, as well as recent press releases from leading electrolyser manufacturers. Only data which either is based on i) detailed bottom-up cost estimates or ii) based on quotes/enquiries from electrolyser manufacturers has been included in the further analysis of cost evolution. In addition, cost values without reference to system size or estimate year or based on averages from expert statements from interviews were omitted. Moreover, effort is made to secure that the data used are referring to the same boundaries in terms of a clear definition of which components are included in the electrolyser plant data. In this study, the electrolyser plant contains the electrolyser stack, balance of plant (water purification, gas separators and driers, pumps, valves), as well as all required power electronics/rectifiers. Compressors, civil works and plant installation costs are excluded. A cost estimation model including both technology development and electrolyser plant size has been developed and used to estimate technology costs and learning rates for PEMEL and AEL towards 2030. In the following sections, the status for installations of electrolysers is described followed by a summary of the sources used to collect cost data and cost evaluations. The cost model is then presented with an evaluation of the model results and the use of the model to predict future electrolyser costs and to estimate learning rates for the different technologies. Finally, a discussion of the obtained results is provided.

Status on electrolyser installation capacity

An overview of installed capacity of electrolysers used in combination with intermittent renewable power is presented in Fig. 1. The figure is based on the recent IEA study The future
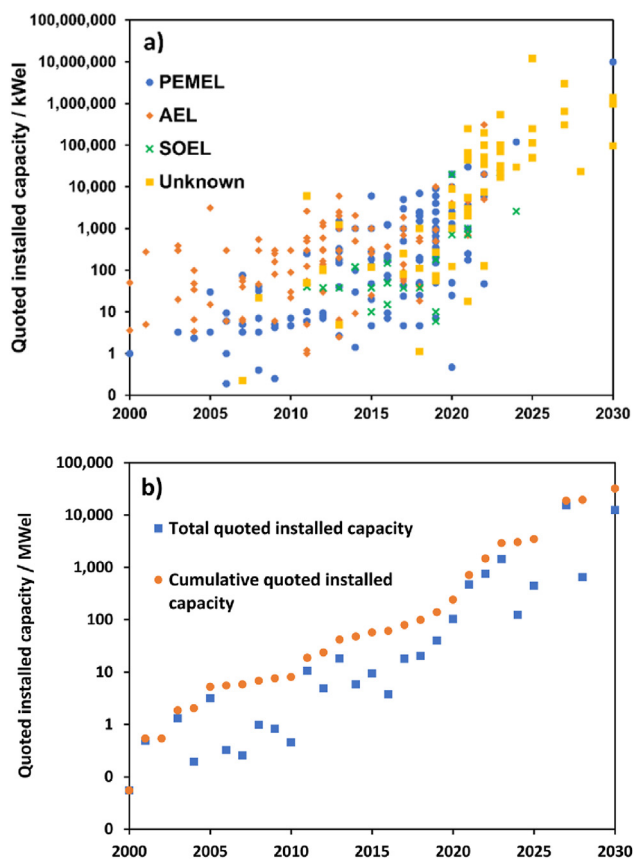
Fig. 1 − **Quoted installed capacity of flexible power-to-gas (P2G) and power-to-liquid (P2L) plants as function of year based on IEA hydrogen project database [12], a) divided for the electrolyser technologies, b) totals per year, all technologies combined, and cumulative capacities.**

of hydrogen [2] with a published dataset on worldwide hydrogen projects that have been commissioned since year 2000 [12]. This figure shows that the average size of these installations has been growing steadily during the last decade and during the last five years several plants larger than 1 MW have been realised with PEMEL catching up to AEL. For the period towards 2025−2030 several large-scale plants in the range up to 1 GW are either in a feasibility study stage or in planning phase. Most of these planned large-scale plants are in the IEA databased classified as "unknown" regarding choice of technology since a decision on type of technology has not yet been reached.

Currently, large-scale water electrolysis plants are being operated or commissioned for sizes up to 20 MW. For example, several multi-MW PEMEL electrolyser plants are planned through the European projects Haeolus [13] (Hydrogenics; 2.5 MW), H2Future [14] (6 MW), and REFHYNE [15] (ITM; 10 MW, 100 MW in phase 2). A 20 MW PEMEL electrolyser (Hydrogenics) has recently (January 2021) been commissioned in Canada [16]. In the period between 2020 and 2025, there are several planned projects awaiting final financing decisions in the range of 50 to more than 250 MW.

Large-scale AEL pilot plants were realised in the Audi e-gas power-to-gas plant in Werlte in 2013 (DE, 6.3 MW, McPhy [17]), the commercial George Olah Renewable Methanol Plant in Svartsengi in 2012 [18], and the E-ON demonstration plant in Falkenhagen in 2013 [19] (DE, 2 MW, Hydrogenics). The largest SOEL pilot plant to date is the 150-kW system of Sunfire in the GrinHy project in 2017 [20] (DE, Salzgitter).

Cost review and screening of data

Available literature and reports were reviewed for cost data and cost projections for PEMEL and AEL technologies. Selected values where either a bottom-up cost estimate has been performed or where the costs are based on quotes/enquiries from electrolyser manufacturers were included in the database. Cost values without reference to system size or estimate year or based on averages from expert statements from interviews were omitted. The electrolyser plant cost data selected for inclusion in this study contains the electrolyser stack, balance of plant (water purification, gas separators and driers, pumps, valves), as well as all required power electronics/rectifiers. Compressors, civil works and installation costs are excluded. In the section below, the included cost studies are briefly presented.

In 2001 Proton Energy System Inc. (Proton On-Site), now part of NEL ASA, demonstrated a functioning renewable hydrogen utility system with a cost reduction estimate of 50% over a ten year period based on technological improvements and limited mass production [21].

Cost data as function of hydrogen production capacity from ten electrolyser suppliers, nine AEL and one PEMEL, was presented in the work Market potential analysis for the introduction of hydrogen energy technology in stand-alone power systems of M. Zoulias from 2004 [22].

NEL ASA presented costs of large scale atmospheric and pressurized alkaline systems during their Q3 report in 2014. This presentation shows a significant reduction of electrolyser costs/MW when upscaling to sizes above 5 MW capacity [23]. In 2017, NEL ASA presented the CAPEX of a large scale, 400 MW alkaline plant [24]. In December 2020 it was announced that NEL ASA was awarded a 20 MW electrolyser contact with Everfuel A/S for green hydrogen production facility adjacent to the Frederica refinery in Denmark with the capacity to produce eight tons hydrogen per day from wind power, with a ten tonnes storage capacity [25]. The electrolyser will be delivered in 2021 and be fully operational in mid-2022. In the beginning of 2021 another press release came out from NEL ASA stating that they had been awarded a contract by Iberdrola for a 20 MW PEMEL solution for a green fertilizer project in Spain with planned delivery in 2021 [26].

In 2011, NOW published an electrolyser technology status report with a general review of PEMEL, AEL and SOE electrolysis as well as a bottom up estimation of current costs for larger scale units [27]. In 2014, a consortium of Fraunhofer ISE, DLR, Ludwig Bölkow Systemtechnik and KBB Underground Technologies published a government-supported study where one aim was to evaluate the technical and economic potential of alkaline and PEMEL technology with a view to its application on a large scale in the short term, as well as in the long term. To estimate the costs, a 5 MW and 100 MW system were designed for both technologies. The 5 MW plant presents the state of the art in 2016/2017, while the 100 MW plant is an

outlook for 2030. A detailed cost model of the investment (Capital Expenses = CAPEX) and running costs (Operational Expenses = OPEX) was presented. For the determination and estimation of the expected costs of the alkaline system, industrial offers were collected. For the 100 MW plant, the offer was supplemented by own estimates to take technical development until 2030 into account [28]. Nationale Organisation Wasserstoff (NOW) again published a study on the industrialisation of water electrolysers in Germany in 2018, giving bottom up cost estimates for PEM, alkaline and SOEC electrolysers towards 2050 [8].

The fuel cell and hydrogen joint undertaking (FCHJU) commissioned a study on electrolysis technology in Europe in 2014. This study gathered data from academic and industrial organizations and constructed trend lines that capture the expected developments for costs by experts and manufacturers from 2013 through 2030 [29]. The FCHJU updated this data for PEMEL and AEL systems for different systems sizes in 2017. This study also includes cost data on compressors, refuelling stations, operating costs as well as mobile and stationary storage systems for electrolysers [30].

Cost data for PEMEL were stated in the work of Strategic Analysis Inc. and NREL presented at the Electrocatalytic Hydrogen Production workshop in February 2014. In the work presented PEMEL electrolysis H2A case models were based on a generic system using input from several key industry collaborators with commercial experience with PEMEL electrolysis for making the key analysis modelling assumption and basis for assumption. They received information from four companies, and information regarding a current case, for year 2012, and a future case, for year 2025, was obtained [31].

In the report Analysis of Islanded Ammonia-based Energy Storage Systems by Bañares-Alcántara et al. [32] quotation from Proton OnSite for a PEMEL system delivering 0.9 ton H_2/day was stated to cost 2,750,000 \$.

In a study from 2014 performed by Felgenhauer and Hamacher state-of-the-art commercial electrolysers were analysed based on 16 quotes (11 AEL, 5 PEMEL) provided by nine companies (CETH2/Areva H2Gen, Hydrotechnik, Hydrogenics, ITM Power, McPhy Energy, NEL, Next Hydrogen, PERIC, Siemens) for commercial systems [33], all quotes provided in the first half of 2014.

In the AGM presentation of ITM power given in October 2018, an estimated trajectory of cost decline for the time period 2016 to 2024 was presented, with estimation of 1500 €/kW in the beginning of the period and 500 €/kW at the end [34].

An equation for PEMEL electrolyser plant cost was derived in the work of Oi et al. for systems with capacities in the range of 50−200 Nm^3 h^{-1}, with the hydrogen generation capacities and the rating current density as variables [35]. This was used to calculate the PEMEL electrolyser cost in the system range 50−200 Nm^3 h^{-1}.

The database for this study was formed on data points gathered from the references mentioned above, upon which the following analysis has been made. An excel file with the database is available in the Supporting Information.

The critically selected cost data (based on the criteria discussed above) for AEL and PEMEL in the period 2000−2030 are shown in Fig. 2 as a function of installation year. The cost
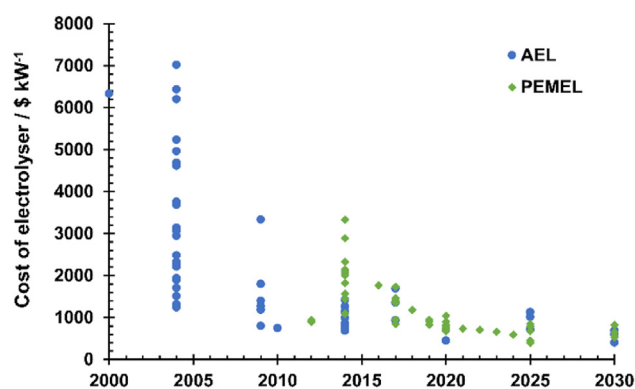
Fig. 2 − Literature data for electrolyser costs from 2000 until 2030, based on references [21−35].
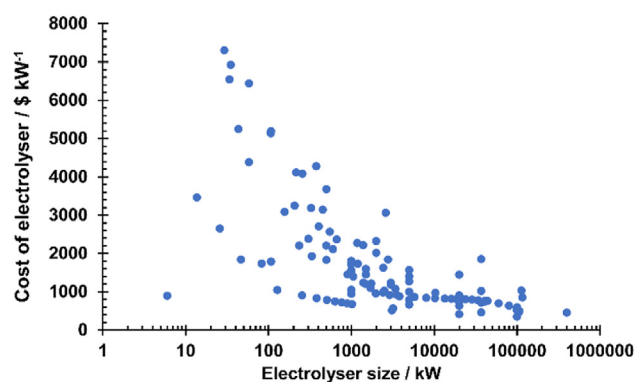
Fig. 3 − Literature data for electrolyser costs from 2000 until 2030, based on references [21−35].

information has been normalised to 2020 cost levels after correcting for inflation. Conversion from EUR to USD are based on the average exchange rates of the spesific year. The cost data has a significant variation within a specific installation year as well as trend towards lower costs as the installation year increases. In Fig. 3, the same data is plotted against the electrolyser size in kW. It is evident that there is a significant variation of the cost with the size of the electrolysers and that using the installation year as the only variable to estimate the future cost of electrolysers clearly is not sufficient.

Cost development evaluation

Cost model

To utilize the collected data for cost estimations for different plant capacities today and predictions for further cost reductions towards 2030, a modified power law was developed to describe the cost of electrolyser plants based on the plant capacity and a learning curves/technology development rate. This method is a further development of the cost estimation approach taken by Oi et al. [35] which is based on the power law for describing the cost as a function of plant capacity and rated current density.

In this study, we modified Oi's equation using production year instead of rated current density as a descriptor of

technology development and effects of increased manufacturing volumes (economy of scale). A pre-exponential constant, not dependent on the plant capacity, was introduced which represents a minimum cost which can be achieved. In this constant, improvements related to materials costs and stack costs at maximum stack size and high production levels are included.

The resulting equation, giving the cost of an electrolyser plant in $/kW, is shown below:

$$C = \left(k_0 + \frac{k}{Q}Q^\alpha\right)\left(\frac{V}{V_0}\right)^\beta \qquad (1)$$

where C is the electrolyser plant cost pr kW, k_0 and k are fitting constants, Q is the electrolyser plant capacity and V and V_0 are plant installation year and reference year, respectively. α and β are fitting constants and usually referred to as a scaling factor and learning factor, respectively.

Thereby, the revised equation (Eq. (1)) captures both cost reductions due to scale up of the best available technology for a given year, which at infinite scale would reduce to $(k_0)(V/V_0)^\beta$, as well as cost reductions by technology development and learning/manufacturing improvements, governed by the value of β. The assessment carried out in this study is purely a curve fitting exercise of available cost data and cost projections. Hence, the values of the fitting constants are not set through any technology development assumptions such as stack size, production levels or degree of automation.

The obtained projection parameters of performing the non-linear least squares curve fitting of the cost equation to the collected cost data for the electrolyser technologies and the resulting standard errors (SE) for the two fits are summarised in Table 1.

The resulting cost curves for AEL and PEMEL technologies for the years 2015 and 2030 are shown together with the collected cost data in Fig. 4 and Fig. 5, respectively.

Evaluation of model results

The comparison of AEL and PEMEL costs as a function of electrolyser plant size for the years 2020 and 2030 are shown in Fig. 6.

Effect of electrolyser plant size

The results from the model show that the capital costs for PEMEL decrease significantly until a plant size of around 1−2 MW is reached. This strong cost dependence in the low-capacity range is most probably attributed to peripheral costs, which are much less dependent on capacity than the
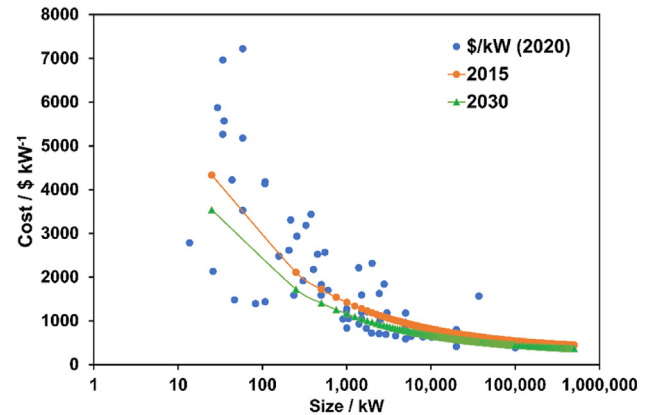

Fig. 4 − Cost of AEL from literature review (blue dots) as a function of electrolyser plant size and the prediction by the best fit of equation (1) for the years 2015 (orange dots) and 2030 (green triangles). (For interpretation of the references to color/colour in this figure legend, the reader is referred to the Web version of this article).

Fig. 5 − Cost of PEMEL from literature review (blue dots) as a function of electrolyser plant size and the prediction by the best fit of equation (1) for the years 2015 (orange dots) and 2030 (green triangles). (For interpretation of the references to color/colour in this figure legend, the reader is referred to the Web version of this article).
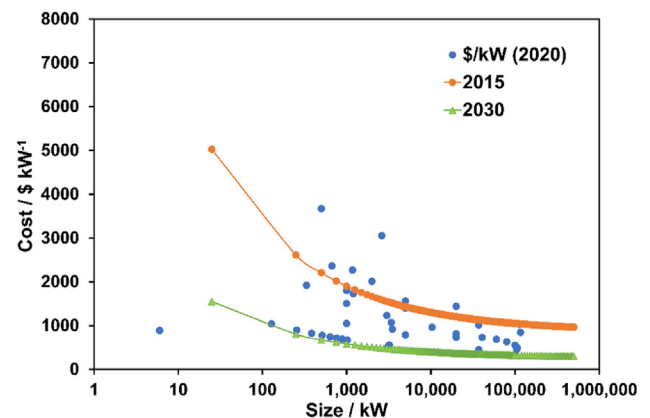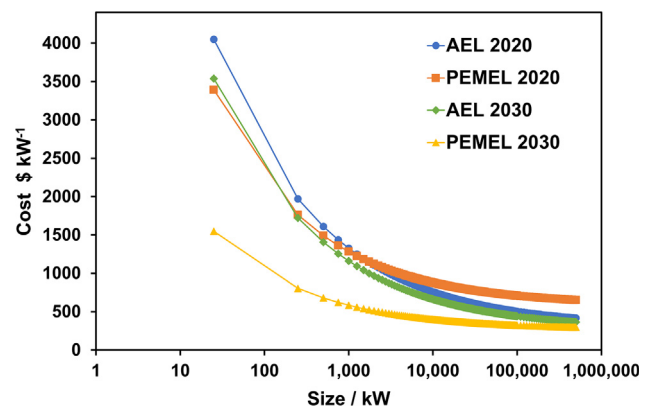

Fig. 6 − Cost prediction by the best fit of equation (1) for PEMEL and AEL compared for 2020 and 2030.

Table 1 − Projection parameters from the non-linear least square fitting for AEL and PEMEL.		
Parameter	AEL	PEMEL
α	0.649	0.622
β	−27.33	−158.9
k_0	301.04	585.85
k	11,603	9458.2
V_0	2020	2020
SE	547	510

main units such as electrolyser cell stacks. In addition, a significant cost reduction can also be expected when scaling up small stacks to a larger one, due to less materials usage per kW as well as reduction in assembly costs. This effect is, however, found to be marginal above the 1−2 MW stack size.

For alkaline electrolysers, the model predicts a more gradual decrease of cost as a function of plant size compared to PEMEL with a levelling off at plant sizes of 50−100 MW. The reason for this can be due to possible CAPEX gains from construction of alkaline stacks up to 10 MW in size, compared to PEMEL stacks in the range of 1−2 MW and more gradual gains in balance of plant components.

Effect of installation year/technology development

For PEMEL, the historical cost reduction has been high, and the model captures an expected continuation of rapid cost reduction due to technology development and increase in manufacturing volumes towards 2030, indicated by the high β-value of −159. For the alkaline electrolysis technology, the cost reductions over the past decades are moderate (β value of −27) and manufacturer cost data and expert estimations show good agreement. This can be explained with the higher maturity of the alkaline technology. As shown in Fig. 6, there is, however, still significant potential for cost reductions, both through technology development and scaling up the plants through improvements and automation in manufacturing and supply chain optimisation.

The high learning rate for PEMEL is probably somewhat overestimated in this model, and, hence, it is not recommended to use the model to predict costs beyond 2030. This is probably due to a combination of very high costs of PEMEL in the recent past combined with some optimistic estimations of future costs of this technology in the cost studies which the data is collected from. However, the trend predicted by the model, even with a lower learning rate, is showing a high probability that the gap in CAPEX between PEMEL and AEL will be much smaller towards 2030 than it is today.

Predicting the cost of future planned projects

The developed model can be used to predict the cost of electrolysers in future hydrogen projects towards 2030. As it is based on both plant capacity and installation year, it differentiates between smaller installations (e.g., at hydrogen refuelling stations) and larger hydrogen plants (such as green ammonia factories).

The model can also be used to predict the average learning rate of electrolyser installations. The concept of learning curves describes the empirical finding of decreasing costs at each doubling of cumulative production by a constant percentage, this learning rate parameter serves as a proxy for all aspects that contribute to observed changes in the cost of the technology [10]. We have applied our cost estimation model on the data on current and future planned electrolyser installations collected by the IEA [12], previously presented in Fig. 1. By taking the average cost of the electrolysers installed each year and combining this with the total cumulative capacity installed, we get a set of datapoints for electrolyser cost and cumulative production. In this analysis, we have calculated the cost of the future installations classified as
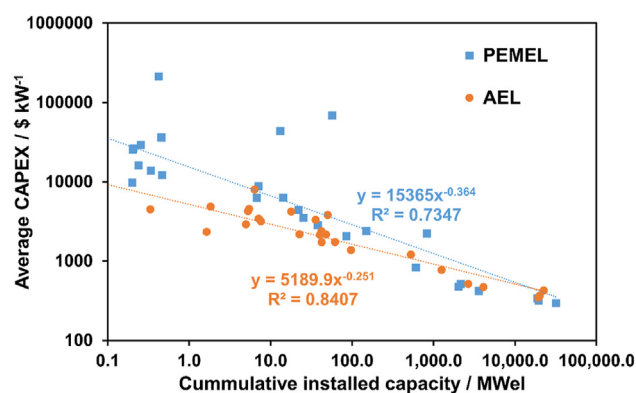

Fig. 7 − Calculated average electrolyser costs for PEMEL and AEL as a function of the cumulative installed capacity based on the current and planned installation of electrolysers from the IEA hydrogen project database [12] and the presented cost model.

"unknown" technology type in the IEA database for both the case of all of them being PEMEL or all of them being AEL. The resulting data is presented on a logarithmic scale in Fig. 7. Apart from some outliers in the PEMEL data, which are caused by the dataset only consisting of some very small PEMEL installations in certain years, the results are very well represented by linear learning curves both for PEMEL and AEL. The resulting learning rate is 36% for PEMEL and 25% for AEL, respectively.

Discussion

The calculated learning rates in Fig. 7 are significantly higher than previously reported learning rates for electrolysis technology. Böhm et al. estimated a learning rate for PEMEL and AEL in the range of 18% based on a method where a set of learning rates for different electrolyser components were estimated and used to calculate an overall learning rate [10]. Schoots et al. attempted to estimate the learning rate for electrolysis based cost data observed during the period from 1956 to 2007 which had high uncertainties in the data [4]. The cost data was also normalised to large scale plants with a set scaling effect of 0.9. The resulting learning rate was found to be $18 \pm 13\%$ with a poor fit $R^2 = 0.28$. Schmidt et al. used an expert elicitation study to estimate the cost electrolysis at a cumulative installed capacity of 1000 GWh and found a learning rate of $18\% \pm 6\%$ based on cost estimates in two different scenarios.

The previous studies with average learning rates at around 18% are mainly focussing on cost reduction through technology development and learning without accounting for the significant cost reductions which are available through a scale up of the electrolyser plants. As we have shown in Fig. 4, the cost of electrolyser systems is very dependent on the plant size up to levels of about 10 MW. Combining this information with the historical development of electrolyser plant size (Fig. 1), it is evident that the effect of plant size is an important parameter in estimating the learning rate of the technologies. On the other hand, as previously discussed, the future cost

reduction of PEMEL is probably somewhat overestimated in this model which will result in a higher learning rate. Based on these considerations, we believe that a realistic learning rate for both AEL and PEMEL is in the range of 25–30% and significantly higher than the previously reported learning rates in literature.

The cost estimation model developed in this study does not account for any possible material supply shortages and a corresponding increase in component cost, or limitations to the scale-up of the production volumes necessary to reach the political goals set forth for 2030 and beyond. As large-scale production of electrolysers with plant sizes of several hundreds of MW and total annual volumes in the range of several GW represents a dramatic increase from today's annual global production capacity, there is a significant probability that supply chain constraints leading to delays in deliveries and completion of plant installations might be faced soon. In addition, the industry might experience restricted availability of raw materials. The research and industry communities have pinpointed various materials that could limit or prevent the industrialisation of water electrolysis due to their criticality. In the IndWED report, titanium and the platinum group metals platinum and iridium were considered and evaluated [8]. These are all materials which critical components in the PEMEL technology are based on. The study found that the predicted demand for iridium can lead to bottlenecks in the future, assuming that the same amount of iridium metal as currently being employed per kW of PEMEL output is continued. Even assuming a 92% reduction in iridium loading, by 2050, 2.8% of the world market supply in 2016 would still be required - exclusively for electrolysis expansion in Germany alone. Accordingly, a significant reduction, if not substitution, must be achieved to produce the required amount of commercial scale PEMEL. For the other two raw materials, a reduction in the contribution per kW must be promoted as they are both considered to be in a critical supply situation and are responsible for a large share of the total costs of producing electrolysers.

Conclusion

In this work a critical screening of current cost data and cost projections for PEMEL and AEL was performed, including literature reviews, reports, and recent press releases from leading electrolyser manufacturers. The database upon which the analysis was carried out were entries either based on i) detailed bottom-up cost estimates or ii) based on quotes/enquiries from electrolyser manufacturers. A cost model for PEMEL and AEL including both the effect of plant size and technology improvements has been developed. The cost model predicts that the CAPEX gap between these technologies will be significantly reduced towards 2030 and that the CAPEX will decrease significantly with plant size until the 1–10 MW range. Beyond this, only marginal cost reductions can be expected with CAPEX values approaching 320–400 $/kW for large scale (greater than 100 MW) plants by 2030 with subsequent cost reductions possible. The model also predicts that PEMEL will be more cost efficient than AEL in the range up to 10 MW in 2030. Based on the cost model and announced installation plans for electrolysers towards 2030, learning rates for electrolysers were estimated to be in the range of 25–30% for both PEMEL and AEL, significantly higher than previous learning rates (about 18%) reported in the literature. The analysis performed shows the importance of including the electrolyser plant size in cost estimations and not only installation year as several other studies have done. The addition of plant size as an important factor for cost reduction, coupled with an expectation of significant growth in the average plant size installation in the next decade can explain the higher estimated learning rate.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.08.306.

REFERENCES

[1] Fuel Cells and Hydrogen 2 Joint Undertaking. Hydrogen roadmap Europe. A sustainable pathway for the European energy transition. https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf.

[2] Birol F. The future of hydrogen. Japan: IEA report for the G20; 2019. p. 203.

[3] International Renewable Energy Agency. Green hydrogen cost reduction: scaling up electrolysers to meet the 1. 5C Climate Goal 2020;106.

[4] Schoots K, Ferioli F, Kramer GJ, van der Zwaan BCC. Learning curves for hydrogen production technology: an assessment of observed cost reductions. Int J Hydrogen Energy 2008;33(11):2630–45. https://doi.org/10.1016/j.ijhydene.2008.03.011.

[5] Proost J. State-of-the art CAPEX data for water electrolysers, and their Impact on renewable hydrogen Price Settings. Int J

Hydrogen Energy 2019;44(9):4406–13. https://doi.org/10.1016/j.ijhydene.2018.07.164.

[6] Saba SM, Müller M, Robinius M, Stolten D. The investment costs of electrolysis – a comparison of cost studies from the past 30 years. Int J Hydrogen Energy 2018;43(3):1209–23. https://doi.org/10.1016/j.ijhydene.2017.11.115.

[7] Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. Nat Energy 2019;4(3):216–22. https://doi.org/10.1038/s41560-019-0326-1.

[8] Smolinka T, Wiebe Nikolai, Philip Sterchele, Palzer Andreas, Lehner Franz, Jansen Malte, Kiemel Steffen, Miehe Robert, Wahren Sylvia, Zimmermann Fabian. Studie IndWEDe Industrialisierung der Wasser-elektrolyse in -Deutschland: -Chancen und -Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und -Wärme. Berlin: Nationale Organisation Wasserstoff und Brenstoffzellentechnologie; 2018.

[9] Böhm H, Zauner Andreas, Rosenfeld Daniel C, Tichler Robert. Projecting cost development for future large-scale power-to-gas Implementations by scaling effects. Appl Energy 2020;13. https://doi.org/10.1016/j.apenergy.2020.114780.

[10] Böhm H, Goers Sebastian, Zauner Andreas. Estimating future costs of power-to-gas - a component-based approach for technological learning. Int J Hydrogen Energy 2019;17. https://doi.org/10.1016/j.ijhydene.2019.09.230.

[11] Schmidt O, Gambhir A, Staffell I, Hawkes A, Nelson J, Few S. Future cost and performance of water electrolysis: an expert elicitation study. Int J Hydrogen Energy 2017;42(52):30470–92. https://doi.org/10.1016/j.ijhydene.2017.10.045.

[12] IEA, Paris. Hydrogen Projects Database https://www.iea.org/reports/hydrogen-projects-database (accessed Mar 28, 2021).

[13] Haeolus project site http://www.haeolus.eu/(accessed Nov 23, 2019).

[14] H2FUTURE project site https://www.h2future-project.eu/ (accessed Nov 23, 2019).

[15] REFHYNE project site https://refhyne.eu/(accessed Nov 23, 2019).

[16] Air liquide to build 20 MW PEM electrolyser with Hydrogenics tech. Fuel Cell Bull 2019;2019(3):9. https://doi.org/10.1016/S1464-2859(19)30108-7.

[17] Power-to-Gas : McPhy energy awarded a maintenance contract for Audi power-to-gas plant in Werlte (Germany). May 21, 2015.

[18] Marlin DS, Sarron E, Sigurbjörnsson Ó. Process advantages of direct CO2 to methanol Synthesis. Front Chem 2018;6:446. https://doi.org/10.3389/fchem.2018.00446.

[19] Germany Trade and Invest GmbH. Green hydrogen & power to gas. Demonstrational Projects in Germany; 2012.

[20] Schaper R. Green Industrial Hydrogen via Reversible High-Temperature Electrolysis. GrInHy; 2016.

[21] Friedland R, John Speranza A. Proceedings of the 2001 U.S. DOE hydrogen Program review, hydrogen production through electrolysis; NREL/CP-610-30535. US Department of Energy; 2001. p. 382–92.

[22] Zoulias M, Gløckner R, Lymberopoulos N, Vosseler I, Tsoutsos T, Mydske HJ, Brodin M, Taylor P. Market potential analysis for the introduction of hydrogen energy technology in stand-alone power systems. 2004.

[23] Nel ASA. Nel ASA Q3 2014 Interim report. 2014.

[24] Jon André Løkke. Nel ASA Q3 2017. 2017.

[25] Nel ASA. Awarded Everfuel contract for fredercia hydorgen project. 2020. https://Mb.Cision.Com/Main/115/3263090/1355252.Pdf.

[26] Nel ASA. Awarded Iberdrola contract for 20 MW green fertilizer project in Spain. 2021. https://Nelhydrogen.Com/Press-Release/Awarded-Iberdrola-Contract-for-20-Mw-Green-Fertilizer-Project-in-Spain/.

[27] Smolinka T, Günther M, Garche J. Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff Aus Regenerativen Energien : NOW-studie : Kurzfassung Des Abschlussberichts. Fraunhofer ISE; 2011.

[28] Smolinka T, Bünger U, Friedrich A. Studie über die Planung einer Demonstrationsanlage zur Wasserstoff-Kraftstoffgewinnung durch Elektrolyse mit Zwischenspeicherung in Salzkavernen unter Druck; DLR, Fraunhofer ISE, LB Systemtechnic. KBB underground technologies; 2014.

[29] Chan A, Hart D, Lehner F, Madden B, Standen E, Luca Bertuccioli. Study on development of water electrolysis in the EU. 2014. p. 159.

[30] Chardonnet C, De Vos L, Genoese F, Roig G, Bart F, De Lacroix T, Ha T, Van Genabet B. Study on Early business cases for H2 in energy storage and more Broadly power to H2 applications. Tractebel and Hinicio; 2017.

[31] Colella WG, James BD, Moton JM, Saur Genevieve, Todd Ramsden. Techno-economic analysis of PEM electrolysis for hydrogen production. 2014.

[32] Bañares-Alcántara R, Dericks III G, Fiaschetti M, Grünewald P, Masa Lopez J, Tsang E, Yang A, Ye L, Zhao S. Analysis of Islanded ammonia-based energy storage systems. University of Oxford; 2015.

[33] Felgenhauer M, Hamacher T. State-of-the-Art of commercial Electrolyzers and on-site hydrogen generation for logistic vehicles in South Carolina. Int J Hydrogen Energy 2015;40(5):2084–90. https://doi.org/10.1016/j.ijhydene.2014.12.043.

[34] Cooley DG. AGM presentation October 2018 | London. 2018.

[35] Oi T, Wada K. Feasibility study on hydrogen refueling Infrastructure for fuel cell vehicles using the off-Peak power in Japan. Int J Hydrogen Energy 2004;29(4):347–54. https://doi.org/10.1016/S0360-3199(03)00152-6.