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Present and future cost of alkaline and PEM electrolyser stacks

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HIGHLIGHTS

- We incorporate bottom-up with top-down costing approaches for stacks.
- Current stack cost range from 242 to 388 €/kW (AE) and 384–1071 €/kW (PEM).
- Stack costs may reduce to 52–79 €/kW (AE) and 63–234 €/kW (PEM) by 2030.
- Cost reductions are driven by higher current density (AE&PEM) and lower catalyst loading (PEM).
- Learning Investments of >73 bn € are needed to reduce system cost to 564 €/kW.

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ABSTRACT

We use complementary bottom-up and top-down approaches to assess the current cost of AE and PEM stacks and how the costs are expected to come down by 2030. The total AE and PEM stack cost reduce from a range of 242–388 €/kW and 384–1071 €/kW in 2020 to 52–79 €/kW and 63–234 €/kW in 2030 respectively. The main drivers of these cost reductions are an increased current density and a reduction and/or replacement of expensive materials with cheaper alternatives. To a lesser extent, manufacturing and labor costs reduction is expected due to mass manufacturing at a GW scale. The total cost decrease is less prominent for AE than PEM due to AE's maturity. The uncertainty range for PEM stacks is due to the low TRL associated with the advanced design PEM stack.

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Nomenclature

AE	Alkaline electrolysis
Al	Aluminum
ATR	Autothermal Reforming
BoP	Balance of Plant
BPP	Bipolar plate
Au	Gold
Ir	Iridium
LR	Learning Rate
MEA	Membrane Electrode Assembly
Ni	Nickel
Nb	Niobium
PV	Photovoltaic
Pt	Platinum
PGM	Platinum Group Metals
PSU	Polysulfon
PTFE	Polytetrafluoroethylene
PTL	Porous Transport Layer
PE	Power Electronics
PR	Progress Ratio
PEM	Proton Exchange Membrane
SS	Stainless steel
SMR	Steam Methane Reforming
Ti	Titanium
TRL	Technology Readiness Level

Introduction

With increasing intermittent renewable sources and limited electric storage capacity, hydrogen as an energy carrier will play an important role in tackling climate change [1]. Currently, 95% of EU hydrogen comes from Steam Methane Reforming (SMR) and to a lesser extent Autothermal Reforming (ATR), both highly carbon-intensive processes, while less than 1% comes from green hydrogen production methods (electrolysis) [2]. This can be attributed to the (historically) low gas prices compared to expensive renewable electricity and expensive materials (e.g. noble metals) used for electrolysis rendering green hydrogen expensive [3]. According to the EU Hydrogen Policy [4], the installed capacity of electrolysis needs to be ramped up from the MW scale to the GW scale with a goal to have 40 GW of installed electrolysis capacity in the EU by 2030. To achieve this, significant development is required to bring down the CAPEX and OPEX to deliver cost-competitive electrolysis in a GW scale. In this article, we focus on CAPEX reductions.

Research has been conducted on expected electrolyser system cost decline by 2030. Top-down analysis was conducted by Schmidt [5] using an expert elicitation process involving academic and industrial experts. Experience curve approach was used by Schoots [6–8], and [9]. A bottom-up approach was used by Mayyas [10] to estimate 200 kW and 1 MW proton exchange membrane (PEM) electrolyser cost as a function of increasing production volume. But the estimated share of manufacturing and labor cost accounts for ~1% of the total stack at a GW/year production which is not the case when compared to analogous manufacturing process like for the photovoltaic (PV) industry. The above mentioned sources use a single costing approach to estimate the cost decline of electrolyser systems. No bottom-up cost assessment has been done for alkaline electrolysers (AE) and future designs of AE and PEM. Even though electrolysers are important for the direction of the energy transition (because it determines in part the cost of hydrogen and hence whether this is an attractive option) there still lies a large uncertainty on the cost of electrolysers and its projected development.

It is important to note that CAPEX along with OPEX determines the true competitiveness of a technology. OPEX accounts for a major share of the hydrogen price (€/kgH_2) of which the cost of electricity can be considered to be the dominant parameter [11]. The OPEX of electrolysers is mainly dependent on the prices of renewable electricity which is outside the scope of this paper. Fig. 1 shows that the CAPEX of an electrolyser system can encompass the stacks, balance of plants (BOP), power electronics, civil, structural and architecture and utilities & process automation of which the stacks account for a small share of the CAPEX. But system components aside from the stacks, have less potential for cost reduction since they are more mature and often standardized and have been used in balancing other mature technologies such as Photovoltaics (PV). Therefore, it was decided to supplement our analysis with a bottom-up cost assessment of electrolyser stacks, since the stack has the most potential to learn (Fig. 1).

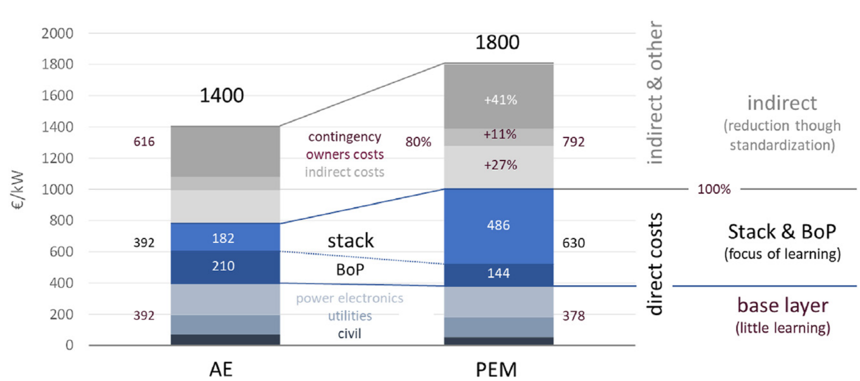

Fig. 1 – Breakdown of the cost for AE and PEM electrolyser systems based on ISPT estimates [12]

In our analysis, we employ and synthesize several costing approaches that complement one another in an attempt to estimate the current and expected CAPEX decline of both alkaline and PEM electrolyser stacks by 2030 for a 1 GW/year production capacity plant. In our work to provide a more realistic estimate of the current and future electrolyser costs, we conduct a bottom up cost assessment to calculate the material and manufacturing cost of current and future stacks. We do this by incorporating developments in future stack design and using cheaper alternate materials and reducing the use of expensive materials. To improve our bottom-up estimates we compare it to: 1) the cost breakdown of an analogous energy technology (in terms of manufacturing process), namely photovoltaics (PV); and 2) a top-down cost assessment based on annual financial statements reported by electrolyser manufacturers. The input data for our bottom-up costing approach was bolstered by our access to industry expertise, specifically from Nobian (HyCC), TNO, VDL and others who were part of a consortium for the ISPT Hydrohub GigaWatt scale electrolyser project under which this study was carried out.

Scope and methodology of stack cost modeling

Stack specifications and materials

Electrolyser stacks follow a modular design. A stack is made up a number of cells, each with a power rating (kW). These cumulative cells equal the total capacity of a stack. Each cell is made up a number of components which facilitate the functioning of a cell. Some cell components differ between electrolyser technologies.

Alkaline

The major components present within alkaline electrolyser cells are:

- A membrane for the transport of OH^- ions, separation of product gases and electrical insulation of electrodes
- Electrodes (cathode and anode) coated with non-noble metals to facilitate electrochemical reactions. The membrane and the electrodes together are termed as the Membrane Electrode Assembly (MEA)
- Seals and gaskets to prevent the escape of gasses
- A Zero-gap AE design consists of a wired mattress wedged between the bipolar plate and the electrodes to reduce the stress on the electrodes and membrane,
- Bipolar plates (BPP) to separate single cells in a stack, and provide electrical conduction between the cells

As mentioned earlier, a number of cells make up a stack and a stack is capped off with end plates. The end plates apply pressure on the cells to maintain the structure as well as prevent gases from escaping the cells and ensure a uniform compression over the whole cell area.

In our analysis to project the potential CAPEX decrease of electrolyser stacks by 2030, we established two stack designs for AE and PEM: A baseline design based on stacks currently available on the market (2020) and an advanced design which is expected to be on the market by 2030. These conceptual designs are used as a basis for costing. Fig. 2 illustrates the baseline and advanced design AE stacks.

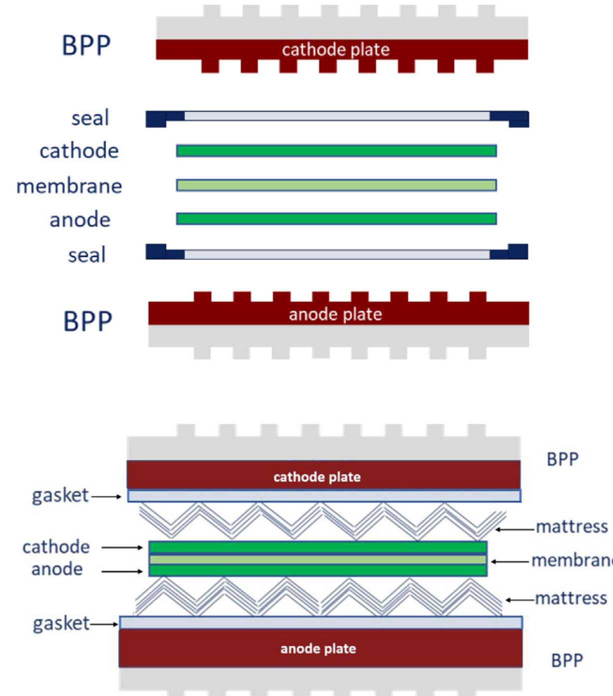

Fig. 2 – Baseline (top half) and advanced (bottom half) AE stack components.

The baseline design for AE is based on information provided in shareholder updates of NEL and the design used in “Norks Hydro alkaline electrolysis for small scale ammonia production” proposed by [13]. Other state-of-the-art stacks exists from Thyssenkrupp and AKC (ambient) and McPhy, PERIC, Suzhou-Jingli and Hydrogen-Pro (pressurized) which have different designs but all have the same main components: membrane, electrodes, bipolar plates, seals and gaskets. The AE baseline stack has a capacity of 2.2 MW and consists of 230 cells with an active surface area of 2.1 m^2 and runs at a current density of 0.245 A/cm^2.

The advanced design for AE is based on a zero-gap design. In this configuration the electrodes are pressed against the membrane to achieve a “zero gap” between the two electrodes and the membrane. This leads to significantly lower ohmic resistance and facilitates operation at a higher current density of 1.3 A/cm^2 as shown by [14]. The overarching design is modeled after a Hydrogenics (now Cummins) patent [15]. The design specifics were based on polarization curves and gas crossover models which were based on the work conducted by [16,17,18]. Further details on the implications of stack performance for the advanced AE stack design can be found in supplementary file *“Input data and Equations”*. Table 1 shows the stack specifications for the baseline and advanced design.

Component selection is based on a literature review on current and alternative materials used in electrolyser stacks and on expertise present in Nobian (HyCC). Alternative materials for the advanced design were selected to facilitate the

Table 1 – Stack specifications for baseline and advanced AE design.

	Baseline (2020)	Advanced (2030)
Stack Size	2.2 MW	20 MW
No of cells	230	335
Active surface area	2.1 m^2	2.6 m^2
Power density	0.5 W/cm^2	2.3 W/cm^2
Current density	0.245 A/cm^2	1.3 A/cm^2
Pressure	Ambient	5 bar
Temperature at Nominal load	80 °C	100 °C
Voltage	1.85 V	1.79 V

advanced design operating conditions and replace heavy materials used in current state of the art stacks.

Table 2 shows the materials selection for the baseline and advanced design for AE stacks. For AE we move from 500 μm to a thinner membrane of 220 μm to reduce ohmic resistivity. This results in a 40% reduction in ohmic resistance [19]. The Zirfon UTP 220 is a commercially available product of Agfa (Personal communication with Agfa, 2021). Since the advanced design is based on a zero-gap design, the baseline electrodes are replaced with wired meshes made of nickel with a wire diameter of 0.228 mm and an open area of 73% [20]. The specific open area was chosen to accommodate a 75 μm Raney nickel coating onto the mesh surface while still maintaining enough open area for the flow of gasses. To reduce the stress on the electrodes and membrane, a nickel wired mattress of 6–12 layers is placed between the bipolar plate and the electrodes [21]). In our analysis we chose the average of 9 layers. This also pushes the electrodes against the membrane thereby facilitating a zero-gap design. The carbon steel bipolar plate in both designs is coated with 200 μm of nickel [22].

PEM

PEM cells have similar components to alkaline cells with some differences:

- The membrane transports H^+ ions
- The membrane is coated with noble metals on either side to form the cathode and anode of the electrodes. Similar to AE, the electrodes along with the membrane is called the MEA.

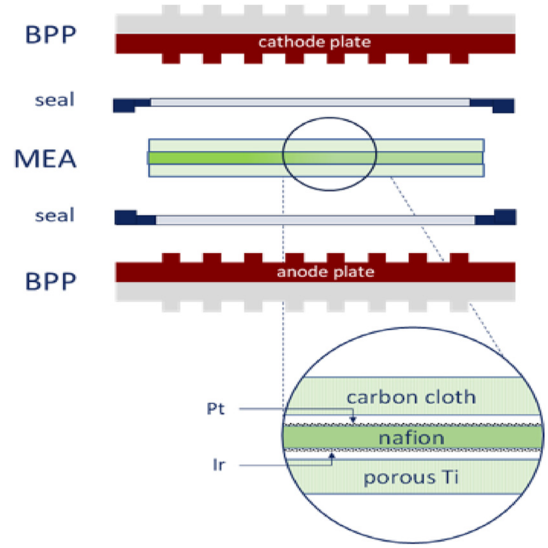

Fig. 3 – Baseline and advanced PEM stack components.

- PEM cells have an additional layer called the Porous transport layer (PTL) to aid in the diffusion of gasses between the bipolar plate and the MEA.
- The seals offer a similar function as in AE.
- The Bipolar plates separate single cells in a stack, distribute reacting agents within the electrolyser and provide electrical conduction between the cells.

The baseline and advanced PEM stacks have the same components. Differences lie in the materials used. Fig. 3 illustrates the baseline and advanced PEM stack components.

Our PEM analysis is based on the ITM design (Personal communication with ITM, 2020) while other designs exists (Siemens, Cummings, Giner ELX, H-TEC systems/MAN Energy solutions). The PEM baseline stack has a capacity of 0.67 MW, consists of 150 cells with an active surface area of 0.1 m^2 and runs at 2 A/cm^2.

The starting point for the advanced PEM design for 2030 is based on the targets of current density (3.5 A/cm^2) set by the [29]. To facilitate this high current density, expected improvements in cell design (e.g.: thinner membranes, lower PGM loadings, alternate cheaper materials) reported by IRENA's Green Hydrogen Cost Reduction report (2020) [30] were

Table 2 – Materials used in baseline and advanced design AE stack.

Components	Baseline (2020)	Advanced (2030)
Separator	Zirfon UTP 500 [23]	Zirfon UTP 220 [24]; *Agfa, 2021*
Cathode	Ni plated perforated Carbon Steel (156 μm) [25]	Ni Mesh Raney Ni Coating (75 μm) [24,20]
Anode	Ni plated perforated Carbon Steel (156 μm) [26]	Ni Mesh [24,20]
Mattress	Not applicable	Ni mattress [21]
Frames	Carbon steel (*NEL design*)	PSU + 30% Glass Fiber [15]
Gasket	Rubber [27]	PTFE [27]
Bipolar plate	Ni plated Carbon Steel (200 μm) [22]	Ni plated Carbon Steel (200 μm) [22]
End plates	Carbon Steel [28]	Carbon Steel [28]

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Table 3 – Stack specifications for baseline and advanced PEM design.

	Baseline (2020)	Advanced (2030)
Stack Size	0.67 MW	9.75 MW
No of cells	150	310
Active surface area	0.10 m^2	0.50 m^2
Power density	4.5 W/cm^2	6.3 W/cm^2
Current density	2 A/cm^2	3.5 A/cm^2
Pressure	20 bar	30 bar
Temperature at Nominal load	55 °C	70 °C
Voltage	2 V	1.8 V

incorporated into TNO's baseline design electrochemical model (Personal communication with Lycklama et al., 2022). The results from this model were then used as the basis for the performance for the advanced design. Further details on the implications of stack performance for the advanced PEM stack design can be found in supplementary file *"Input data and Equations"*. Table 3 summarizes the stack specification for the baseline and advanced design for PEM.

Component selection for the PEM stacks is based on a literature review on current and alternative materials used in electrolyser stacks and on expertise present in TNO. Alternative materials for the advanced design were selected to facilitate the advanced design operating conditions and reduce and/or replace expensive materials used in current state of the art stacks.

Similar to AE, we move to a thinner membrane for the PEM advanced design for 2030. The choice of a 80 μm Nafion membrane is based on the results of TNO's electrochemical model (Personal communication with Lycklama et al., 2022). Further reducing the thickness coupled with the lower loading may lead to an unacceptable increase in gas crossover. In the baseline design the major cost contributors to materials are the platinum group metals (PGM), gold (Au) and titanium (Ti) powder. Therefore, in the advanced PEM stack design these materials are assumed to be replaced by other materials or to be used less. The advanced design has a reduced loading of platinum and iridium by a factor 15 and 20, respectively. This proposed reduced loading is based on [29]. The titanium powder and gold is replaced by 316 L stainless steel (SS) powder and a niobium (Nb) coating of 20 μm since their electrochemical performance test demonstrate they have the potential to replace titanium based PTLs and the niobium shows excellent corrosion resistance in the acidic environment of the PTL anode [31]. The gold coating on the bipolar plate too is replaced with 20 μm of niobium which provides sufficient corrosion resistance and pressure-dependent contact resistance [32]. These materials are currently not seen in cells since they have a TRL of 3–7 but are expected to be commercially used by 2030 (Personal communication with TNO, 2021). Table 4 shows the material selection for the baseline and advanced PEM design.

Manufacturing process

A summary of the manufacturing process for AE and PEM stacks can be found in the appendix. For a more detailed description of the manufacturing process see supplementary document "*Manufacturing process for AE stack*" and "*Manufacturing process for PEM stack*".

For the alkaline advanced design, the electrodes and mattress have a mesh type structure and are therefore manufactured via weaving and welding. A bottom up assessment on the manufacturing cost for the advanced AE design was not performed due to the large uncertainties on manufacturing parameters especially regarding the process of weaving and welding which is required to manufacture three (anode, cathode and mattress) of the six components. Added to this there is a lack of knowledge on the preferred method to obtain a uniform deposition of Raney nickel onto a nickel mesh without drastically reducing the open space in the mesh.

Methodology

We categorized the cost of an electrolyser stack as follows (based also on [33,34,] and [10]):

1. Material cost
2. Direct manufacturing cost:
   a. Manufacturing labor cost
   b. Other manufacturing cost (capital and interest, building with interest, maintenance of equipment, energy cost)

Table 4 – Materials used in baseline and advanced design PEM stack.

Components		Baseline (2020)	Advanced (2030)
CCM	Membrane	Nafion 180 μm (Nafion 117) [10]	Nafion 80 μm (Personal communication with Lycklama et al., 2022)
	Coatings	Pt: 0.75 mg/cm^2 [10]	Pt: 0.05 mg/cm^2 [29]; (Personal communication with Lycklama et al., 2022)
		Ir: 2 mg/cm^2 [10]	Ir: 0.1 mg/cm^2 [29]; (Personal communication with Lycklama et al., 2022)
PTL	Anode	Sintered porous Ti [10])	Sintered porous 316 L Stainless steel [31]
		Au 100 nm [10]	Nb 20 μm [31]
	Cathode	Carbon cloth [10]	Carbon cloth [10]
Seals/Frames		PPS 40% Glass Fiber (*Mayyas* et al., *2019* [10])	PPS 40% Glass Fiber [10]
Bipolar Plate		316 L Stainless steel [10]	316 L Stainless steel [32]
		Au 100 nm [10]	Nb 20 μm [32]
End plate		A356 Al [10]	A356 Al [10]

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3. Overhead cost:
   a. R&D, prototype engineering
   b. Sales, general and administration (SG&A)

We employed two complementary approaches for costing: a bottom-up approach to calculate the material cost (including fluctuations in material prices) and direct manufacturing (manufacturing and labor) cost and a top-down cost assessment to validate the bottom up assessment of direct manufacturing cost and to evaluate the overhead cost. Finally we present the total stack cost which encompasses the sensitivities in material prices, the bottom-up and top-down costing approach for direct manufacturing and the overhead cost.

Bottom-up cost assessment

We developed a bottom-up cost model in which we estimated material and manufacturing costs for each cell component, for the assembly of cell components into cells, and for the assembly of cells and end-plates into stacks.

Material cost for raw materials were based on spot prices of raw materials plus a processing fee: 30% for platinum (Pt) and iridium (Ir) and 15% for nickel (Ni). The costs of nickel plated electrodes and bipolar plates in alkaline stacks were derived from a quotation (private communication VDL, 2021). Material prices for processed materials like PPS 40% glass fiber, titanium (Ti) powder and Zirfon were based on vendor prices.

Material price sensitivities were performed on materials that have a significant share in the stack cost and that show high volatility in price over the past decade. Material price sensitivities are based on 10-year historical price trend where the peak and trough are taken as a high and low price, respectively. For purchased commodities, the price decreases as a function of order quantity. Therefore, the low price estimate is based on the commodities' price at high order quantity. Material price sensitivities and sources are provided in the supplementary file *"Input data and Equations"*.

The lower platinum and iridium loading required for the advanced PEM design have a low TRL (3–7). Therefore an additional sensitivity was performed on technological uncertainty of the PEM advanced design where the baseline catalyst loading (0.75 mg/cm^2 Pt, 2 mg/cm^2 Ir) was assumed for the advanced design. We term this scenario as the conservative advanced design scenario. The advanced design with the lower loading is termed as the optimistic advanced design scenario.

Direct manufacturing cost for each cell component includes capital, building cost, operation & maintenance and the energy.

Labor cost for manufacturing was based on the line speed of the machinery, the number of laborers required to operate the machinery and the hourly labor rate.

Manufacturing processes and cost data were collected from literature [10,35] and expertise from the ISPT consortium. Capital expenditure for equipment and buildings was annualized using a capital recovery factor and building recovery factor which is based on the lifetime of a building. The maintenance cost is based on the product of the maintenance factor and the capital (including installation cost). The energy cost is based on the electricity price, rated power of the machine and the time required for a machine to manufacture the desired number of components for a GW electrolyser. The input assumptions, financial parameters and formulas used to calculate the manufacturing and labor cost are provided in the supplementary file *"Input data and Equations"*.

Top-down cost assessment

Bottom-up cost results were compared to cost data gathered from electrolyser manufacturers financial statements, PV manufacturers from literature and public statements for ITM's 1 GW factory. We compare electrolyser manufacturing cost to PV manufacturing due to the similarities in manufacturing process. Both are modular technologies that require equipment for stamping and coating.

For current electrolyser manufacturing, 2017–2020 financial statements of NEL, McPhy and ITM were investigated to derive a cost ratio of materials to labor to manufacturing costs. Combining this cost ratio with the bottom-up estimate for the material cost yields estimates for labor and manufacturing costs. This scenario is referred to in Section Direct Manufacturing Cost: Manufacturing and Labor as "Financial Reports" (Fig. 7). These results were compared to cost ratios derived from PV manufacturing at half a GW scale based on literature sources [36]; this scenario is referred to as "PV (4:2:1)" (materials: labor: manufacturing) in Section Direct Manufacturing Cost: Manufacturing and Labor.

To assess the cost structures for electrolyser manufacturers in 2030, data on ITM's 1 GW factory and PV manufacturing at a GW scale [37,38] were used. This approach is referred to as "Empirical assessment" (Fig. 7).

Overhead cost data were assessed and based on financial reports of electrolyser manufacturers for business in the infancy (2020) and from PV manufacturers for "running business".

For the baseline stacks, overhead cost were based on 2017–2020 annual financial reports of NEL, McPhy and ITM. They can be divided into four categories: R&D, Prototype Production and Engineering, Sales & Marketing and Administrative Expenses.

For the advanced stack design, we assumed that by 2030 electrolyser manufacturers will have a mature business. Therefore we assess financial statements of PV manufacturers (First solar, Canadian Solar [8] and Sun Power) that have achieved a GW per year production. In addition to PV manufacturers we also assess overhead cost for a mature manufacturing industry: reported in literature, bottom-up assessment by the ISPT consortium and estimates by expertise within the manufacturing industry. See supplementary file *"Input data and Equations"* and supplementary excel file "*PV cost estimates inferred from annual reports*" for further information on overhead cost.

Results and discussion of stack cost modeling

Bottom-up cost analysis: materials

Fig. 4 shows a breakdown of the baseline and advanced stack material cost for both AE & PEM. The baseline AE design has a material cost of 118 €/kW and the advanced design shows reduced cost of 30 €/kW. The PEM baseline design has a material cost of 190 €/kW and the advanced design shows a

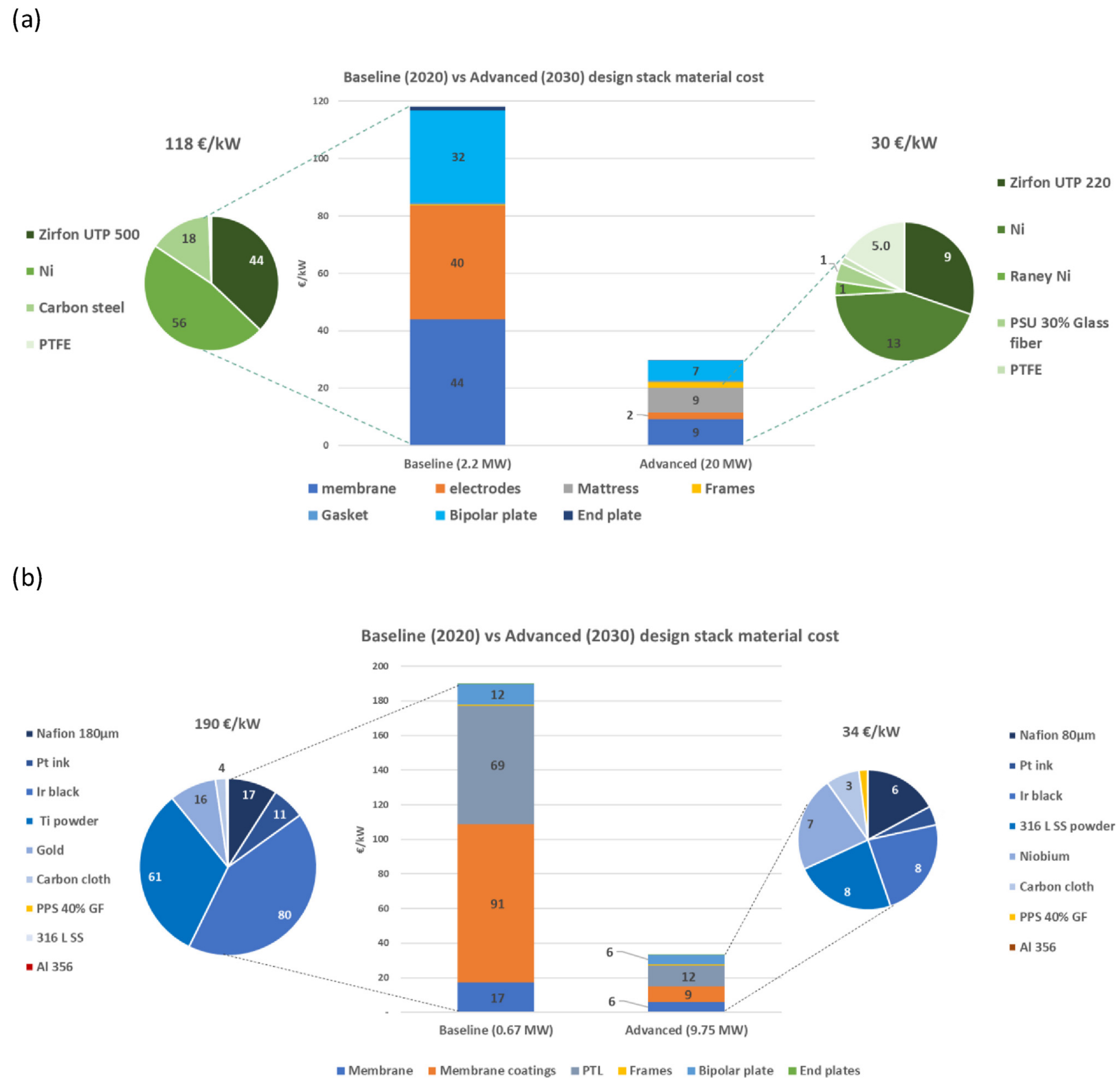


Fig. 4 – Baseline and advanced stack material cost for (a) AE & (b) PEM electrolyser. The bar graphs depict material cost per component and the pie chart shows a breakdown into materials.

reduced cost of 34 €/kW. Below we discuss the main material cost drivers per technology.

Alkaline

In the baseline design, the main cost contributors are the Zirfon UTP 500 membrane, the electrodes, and the bipolar plates. The Zirfon UTP 500 membrane costs 150 €/m^2 (Agfa, 2021). For the electrodes and the bipolar plate, the major cost contributors are the nickel coating with a share of 47% of the total material cost. The next major cost contributor is the carbon steel used as a base plate for the electrodes and the bipolar plate and for the frames and end plate. This cost is calculated from a carbon steel price of 0.4 €/kg [39] and a requirement of 0.04 kg/kW.

For the advanced design the factor 5.3 increase in current density is the major driving force in cost reduction. The major cost contributors in the advanced design are the Zirfon UTP 220 membrane, the nickel mattress, and the bipolar plate. The nickel mattress accounts for 27% of the material cost which can be attributed to a nickel price of 16 €/kg [40] and a requirement of 9 layers of mattress. The bipolar plate accounts for 25% of the material cost due to its thickness (5 mm) and requirement of nickel coating (200 μm). The share of electrodes in the material cost is significantly less when compared to the baseline design because the carbon steel and nickel coating is replaced with a single layer pure nickel wire mesh and a coating of 75 μm of Raney nickel on the cathode. Even though the price of Raney nickel is higher by a factor 3 than nickel, only 75 μm is coated on the wire mesh with an open area of 73%. Similar to the baseline design, nickel accounts for a major share (44%) of the material cost since 37.8 kg of nickel is required per cell.

The cost of the advanced AE design stack in €/m^2 is higher than the baseline AE design due to the additional nickel required for the nickel mattress. When taking the efficiency (€/kW) into account, a significant cost reduction of 75% is seen. The Raney nickel coating aids in increasing Hydrogen Evolution Reaction (HER) which in turn aids in increasing the current density [41]. But there is uncertainty around the required thickness of the Raney nickel coating to achieve improved performance. Raney nickel coating thicker than 75 μm could plug the open spaces of the wire mesh electrode chosen for the advanced AE design. Therefore there is a tradeoff between the wire diameter of the wire mesh electrodes and the Raney nickel coating thickness. Uncertainty also lies in the manufacturing process of Raney nickel. Process such as atmospheric plasma spraying [42] powder metallurgy and sintering [41] are used to synthesize Raney nickel but are in early stages of development. For example Raney nickel developed by sintering undergoes degradation caused by nickel – hydride formation due to volumetric expansion [41]. Therefore further research needs to be conducted on improving the manufacturing process method.

PEM

In the baseline design the main cost contributors are the membrane coatings and the PTL, specifically the PTL anode. The expensive membrane coating can be attributed to the expensive iridium (41.9 €/g) [43] coupled with a high loading of 2 mg/cm^2. The major cost contributor to the PTL is the expensive Ti powder (0.4 €/g) [10], [44] required to make the sintered porous anode. Gold is also a major cost contributor as it has a spot price of 49 €/g [45] and 100 nm of coating is required in both the PTL anode and the bipolar plate.

For the advanced design the cost reduction is related to the 1.75 factor increase in current density coupled with a reduction in PGM loading by a factor 15 and 20 for platinum and iridium respectively and using cheaper alternate materials like 316 L stainless steel powder [46] and niobium instead of the titanium powder and gold. Using thinner Nafion membrane (180 μm–80 μm) also contributes to cost reduction. We assume the price of a thinner Nafion membrane is linearly related to the reduction in thickness of the membrane. The supplementary file *"Input data and Equations"* shows the price reduction in Nafion membrane.

The PEM stack advanced design achieves a significant cost reduction of 82%. But the lower loading and the alternative materials are associated with low TRL thereby highlighting the uncertainty in achieving the advanced PEM stack design. Alternatives to the chosen materials for the advanced design exist such as non-fluorinated hydrocarbons to address the environmental impact of Nafion [5], Telluride and nanocatalysts of IrOx and IrRuOx instead of currently used iridium in the anode to facilitate running at higher current densities [47], carbon/polymer composites for bipolar plates due to their low fabrication cost, light weight and chemical stability [48]. These materials are currently in the experimental phase and may be commercially available in the long-term future.

Material cost sensitivity analysis

Based on material price volatility, the material cost for AE stack varies from 78 to 157 €/kW for the baseline design and 19–38 €/kW for the advanced design. For PEM stacks the material cost varies from 95 to 361 €/kW for the baseline design and 23–51 €/kW for the advanced design.

Alkaline

For the baseline and advanced design sensitivity analysis on material prices were performed on Zirfon, nickel, carbon steel and including Raney nickel prices for the advanced design (Fig. 5 a & b). A ±10% price sensitivity was performed for Zirfon due to lack of price fluctuation data availability. The nickel prices range from 7 to 27 €/kg with a spot price of 16 €/kg [40]. With a nickel content of 47%, the volatile nickel price is the major contributor to the fluctuating AE stack material cost.

Raney nickel only accounts for 3% of the advanced design stack cost due to the requirement of only 0.014 kg/kW. Yet, Raney nickel is an expensive material with a spot price of 52

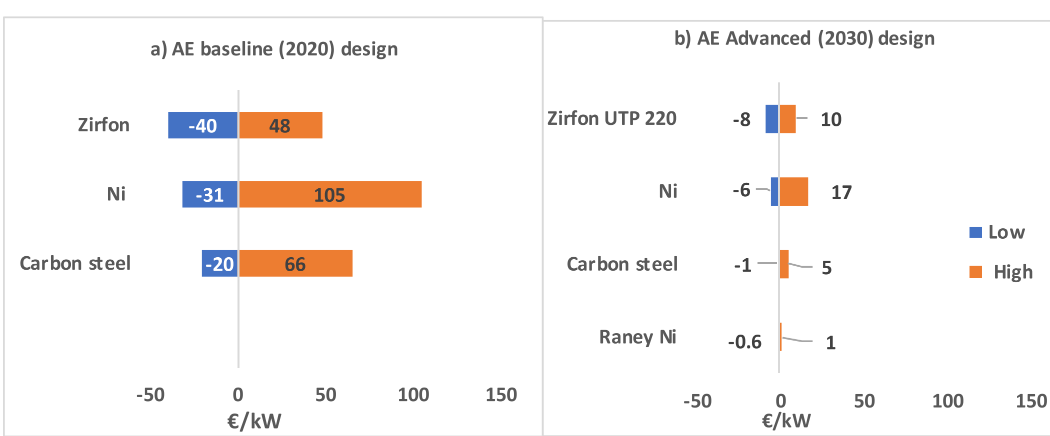


Fig. 5 – AE material cost sensitivities for: a) baseline (2020) and b) advanced design (2030). The low and high refer to the peak and trough of the ten year historical price trend of materials.

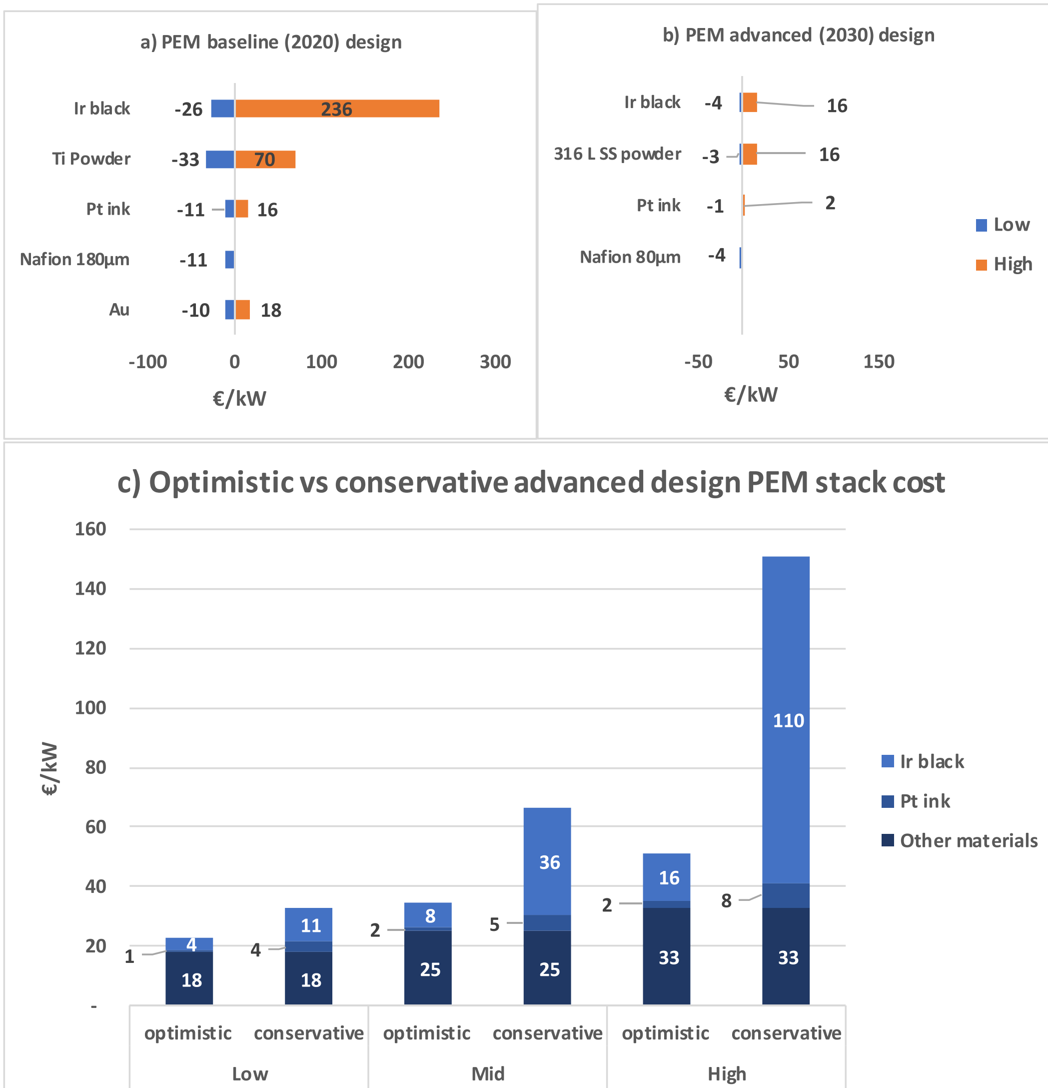


Fig. 6 – a) depicts material cost sensitivities for baseline (2020) and b) advanced (2030) PEM stack design. c) compares the material cost of the conservative advanced design PEM stack scenario (Pt: 0.75 mg/cm^2, Ir: 2 mg/cm^2) with the optimistic scenario (Pt: 0.05 mg/cm^2, Ir: 0.1 mg/cm^2).

€/kg [49], roughly three times the price of nickel, and fluctuates with nickel price. Therefore, price sensitivity was also performed for Raney nickel with the price ranging from 27 €/kg to 76 €/kg [49].

The next major contributor to the spread in material cost for AE baseline and advanced stacks are the carbon steel prices. They range from 0.4 €/kg to 1.62 €/kg [39] for carbon steel content of 0.04 kg/kW for the baseline design and 0.002 kg/kW for the advanced design. The reduction in carbon steel weight for the advanced design is attributed to replacing the electrodes and frames with pure nickel wire mesh and PSU 30% glass fiber respectively.

PEM

The major contributors to the material cost of PEM stacks for which sensitivities were performed are the coatings (platinum, iridium, gold and niobium), the metallic powders (titanium and 316L stainless steel) required for the PTL anode and the Nafion membrane (Fig. 6 a & b).

For the baseline design the main contributor to the fluctuation seen in the material cost is the volatility in iridium price. The low to high estimate ranges from 11 €/g to 155 €/g [43] with a mid-estimate at 42 €/g [43]. This high volatility in the iridium price can be linked to limited reserves of iridium coupled with being mined as a byproduct of platinum. The volatility is further exasperated with increase in demand and scale up of electrolysers and chlor-alkali industry [50]. The same driving forces are also the reason behind the volatility seen in platinum prices which ranges from 20 €/g to 52 €/g [51] with a mid-estimate of 29 €/g [51]. But the fluctuation in platinum price has a negligible effect on the stack material cost since only 0.18 g/kW of platinum is required. Only 6% wt of platinum is required to form the platinum ink [52]. The other components for the ink are detailed in the supplementary file *"Input data and Equations"*. The second major contributor is the titanium powder followed by the gold coating. These material prices do not exhibit much volatility but still have a major cost contribution due to them being expensive and requiring 0.15 kg/kW of titanium powder and 0.0003 kg/kW of gold.

As for the advanced design, the volatility in the iridium price dominates the variation seen in the low to high estimate of the optimistic advanced design material cost. The 316L stainless steel powder used in the PTL anode also contributes to an equal share (low: mid: high; 16%: 23%: 32%) in material cost along with iridium despite being cheaper than titanium powder used in the baseline design. In the baseline design the iridium has a much higher contribution to material cost than the titanium powder. This difference is due to the fact that the iridium loading has reduced by a factor 20 and the weight of the stainless steel powder has increased by a factor 35 which can be attributed to the increase in thickness of the PTL anode from 1.5 mm to 3 mm. Niobium used in coating the PTL anode and the bipolar plate is the third major cost contributor but sensitivity was not performed due the fact that niobium has shown barely any volatility in the past decade [53].

The Nafion membranes constitutes 9% and 17% of the baseline and advanced design stack material cost. The Nafion membrane price drops as a function of order quantity. So for the advanced design the Nafion price drops to the cost associated with highest order quantity. Likewise, the Nafion membrane price is not expected to increase and therefore for the high estimate (Fig. 6 a&b), the price values used in the mid estimate were chosen.

Fig. 6 c also shows the sensitivity performed on the technological uncertainty for the advanced PEM design (conservative scenario). Using the baseline platinum and iridium loading of 0.75 mg/cm^2 and 2 mg/cm^2 and incorporating material price sensitivities, the advanced design PEM stack cost ranges from 32 €/kW to 151 €/kW. Similar to optimistic advanced design scenario (platinum and iridium loading or 0.05 mg/cm^2 and 0.1 mg/cm^2), the major driving force in material cost fluctuations is the iridium content and price.

For PEM (baseline and advanced), the electrodes and the PTL layer account for a major share in the stack cost. This is due to the requirement of expensive platinum group metals for the electrodes and titanium powder and gold (baseline) and niobium (advanced) for the PTL anode layer. The cost of the PEM stacks are highly sensitive to the price fluctuation seen in iridium (11 €/g to 155 €/g). This is also true for the advanced design optimistic scenario despite the factor 20 reduction in iridium loading. Therefore it is imperative that the advanced design PEM stacks reduce the iridium loading and not fall back on the baseline loading (conservative scenario).

Direct manufacturing cost: manufacturing and labor

The direct cost (materials, labor and manufacturing) for AE stack ranges from 192 to 205 €/kW for the baseline design and 49–66 €/kW for the advanced design. For PEM stacks this cost ranges from 308 to 332 €/kW for the baseline design and 56–70 €/kW for the advanced design. Below we elaborate on the spread of direct stack cost.

Fig. 7 shows the direct cost for AE and PEM stacks for the baseline and advanced designs. Results from the bottom-up model show that labor and manufacturing cost account for ~5% of the stack cost. This share is highly underestimated when compared to the cost ratios (materials: labor: manufacturing) seen in PV manufacturing, electrolyser manufacturer financial reports and the empirical assessment. Potential reasons for this discrepancy are an underestimation of the investment costs per machine, the number of machines required and machine hours, the number of laborers and labor hours involved per production line. These input data (supplementary file *"Input data and Equations"*) result in a requirement of only 1 production line per machine to meet a GW/year production of stacks. Assuming a maximum machine operating hours of 1600 h/year, the machine utilization rate amounts to 5%–10% and therefore highly underutilized. Average machine utilization rate seen in manufacturing industry is around 75%–80% (personal communication with VDL, 2021).

The exercise conducted on deriving cost ratios for the analogous technology of PV was done for comparative purposes to provide an estimate of the expected direct stack cost for electrolysers [36]. investigated the change in direct cost by scaling a PV installation from 10 MW to 500 MW which resulted in a cost ratio of 4:2:1 (materials: labor: manufacturing). Using this cost ratio and the mid estimate for material cost, the AE and PEM stack direct cost results in 205 €/kW and 332 €/kW for the baseline design and 52 €/kW and 60 €/kW for the advanced design.

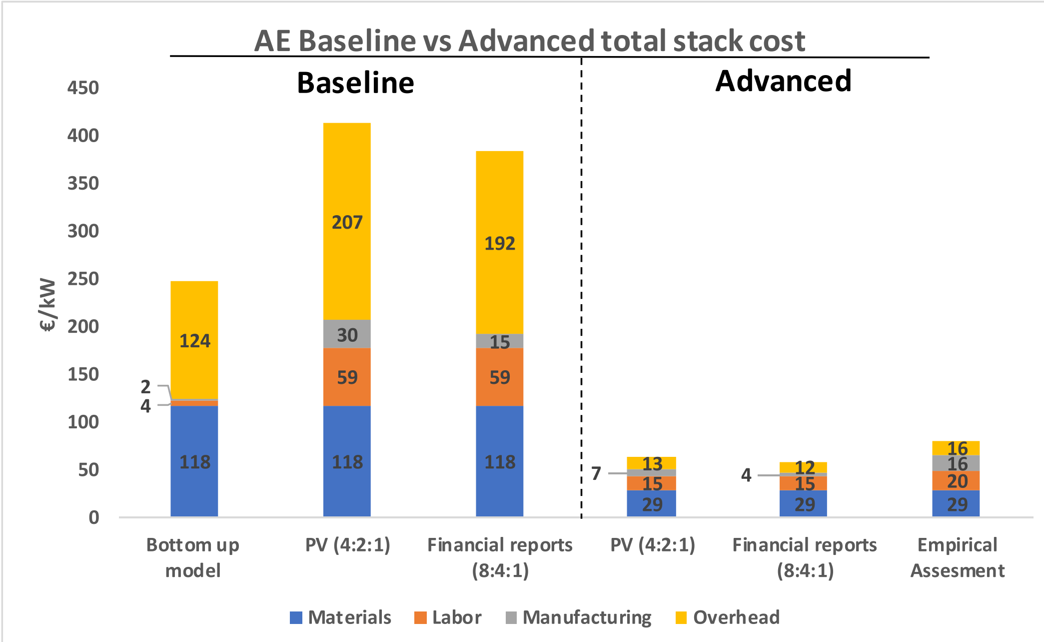
To estimate the direct stack cost for electrolysers we investigated the annual financial statements of 3 electrolyser manufacturers namely NEL (2017–2020) [54], McPhy (2018–2020) [55] and ITM (2017–2020) [56] for the baseline design. NEL, McPhy and ITM are major players in the electrolyser market with NEL having a dedicated production of AE electrolysers and ITM producing PEM electrolysers. McPhy produces both AE and PEM electrolysers.

Based on the financial statements, we derive a cost ratio of materials: labor: manufacturing of 8:4:1. This results in a direct stack cost of 191 €/kW and 308 €/kW for the AE and PEM baseline design and 49 €/kW and 55 €/kW for the advanced design.

For the advanced design we investigated ITM's public statement of a 1 GW factory in Sheffield, U.K. We also investigated the reported decrease in CAPEX/GW of PV cells as a function of time (2012–2020) in the U.S and China thus incorporating the expected direct cost for a GW factory in 2030 [37,38].

In the U.S the CAPEX for a PV module can be as low as $120 million for a 1 GW/year production line while in China the CAPEX dropped from €130 million in 2012 to €34 million in 2020 [37,38].

ITM's GW factory boasts a £172 million fundraise (the share of CAPEX is unknown) constituting 185 staff and a production facility of 12,499 m^2. Therefore, for the empirical assessment we derive a CAPEX on equipment to be in the order of €100 million which falls within the above-mentioned range (£172 million: ITM, $120 million: U.S, €34 million: China). Using the common industry practice of 10 €/hr for 100,000 € worth of equipment (personal communication with VDL, 2021) and machine operating hours of 1600 h/year, the equipment



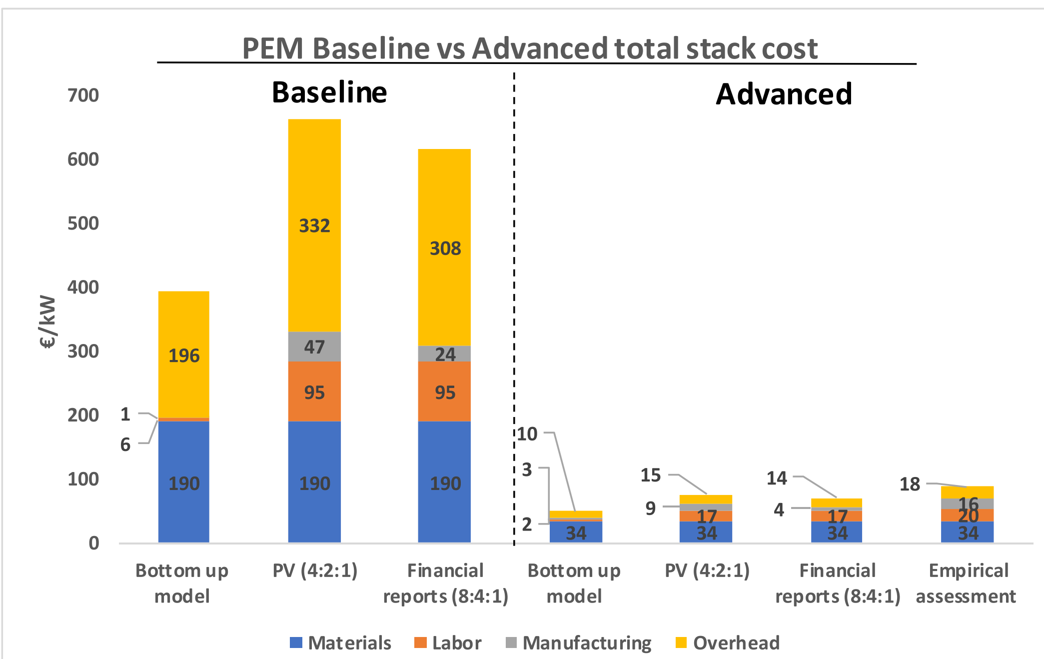


Fig. 7 – Baseline and advanced stack direct cost including overhead: AE (top panel) and PEM (bottom panel). Note: we do not depict the "Bottom-up model" for the advanced AE design due to lack of data availability on the manufacturing process. See section 2.2 (Manufacturing Process) for more details.

CAPEX for a GW/year electrolyser production facility is estimated to be 16 €/kW. ITM's GW facility reports 185 staff. Based on mature manufacturing industries, employees in production account for 2/3 of the work force. In our analysis we estimate 120 staff are involved in production and engineering (direct manufacturing). With an annual work rate of 1600 h/year and an hourly salary of 100 €/hour, the labor cost amounts to 20 €/kW. Therefore, for the empirical assessment the labor and manufacturing cost are estimated to be 20 €/kW and 16 €/kW. Unlike the other estimates based on cost ratios (PV manufacturing and financial statements of electrolyser manufacturers), the empirical assessment has a fixed labor and manufacturing cost. The empirical assessment results in a direct stack cost of 66 €/kW and 70 €/kW for AE and PEM advanced design. This falls within the range of direct stack cost based on cost ratios seen in PV industry (4:2:1) and electrolyser manufacturers annual financial statements (8:4:1): 49–66 €/kW for AE and 56–70 €/kW for PEM.

Therefore, based on the top-down analysis of PV manufacturing, electrolyser manufacturers annual financial statements and the empirical assessment, the direct stack cost for AE falls within the range of 192–205 €/kW for the baseline design and 49–66 €/kW for the advanced design. For PEM the direct stack cost ranges from 308 to 332 €/kW for the baseline design and 56–70 €/kW. The top-down assessment of manufacturing and labor cost asserts that the share of material accounts for 43%–62% of the direct stack cost and not 95% based on the bottom-up model.

Indirect manufacturing cost: overhead cost

To assess the total cost of electrolysers, the indirect cost needs to be accounted for. Indirect cost relates to the overhead cost incurred by a manufacturing company. It encompasses investment in R&D, prototype & engineering, sales & marketing and administration as seen in the cost breakdown for [56] financial statement (Supplementary file *"Input data and Equations"*).

Accounting for the overhead in the direct stack cost, the total stack cost for the baseline design ranges from 377 to 406 €/kW for AE and 616–663 €/kW for PEM. For the advanced design, AE stacks cost ranges from 60 to 82 €/kW and the PEM from 70 to 88 €/kW. Below we elaborate on the total stack cost ranges calculated for the AE and PEM baseline and advanced design.

As stated in Section 2, the baseline design assumes stacks being manufactured in 2020. Therefore, to estimate the overhead cost for baseline design stack, cost structures reported in 2017–2020 financial statements of electrolyser manufacturers (NEL, ITM and McPhy) were assessed. The overhead cost accounts for ~50% of the total stack cost or 100% of the direct stack cost (Supplementary file *"Input data and Equations"*). This high overhead cost can be attributed to businesses in the start-up phase where significant investment is made in prototype production, engineering and in administration. The cost breakdowns derived from these financial statements also show a negative profit margin which is common in businesses in the startup phase as they are forced to sell electrolysers at below the cost price to stay competitive. These electrolyser manufacturers keep their business afloat as they are offered government grants and investment from shareholders banking on the success in the future.

The advanced design assumes state of the art stacks manufactured in 2030 where electrolyser manufacturers are expected to progress from a business in the startup phase to a "running" business. Thus, the overhead cost is expected to decrease with a decline in R&D investment in Prototype Production and Engineering. Added to this, the share of administrative expenses decreases with increasing production. The overhead cost was estimated to be 20% of the total cost based on the annual financial statements of 3 PV manufacturers (Canadian solar [57,58], First solar [59] and Sunpower [60]), Harvard Business Review of U.S and Japanese manufacturing industry [61] and ISPT's bottom up assessment of a running business in the Netherlands. The direct and indirect stack cost for the AE advanced design ranges from 60 to 82 €/kW and 70–88 €/kW for the PEM advanced design. From Fig. 7 we can see that for the baseline and advanced design, materials still

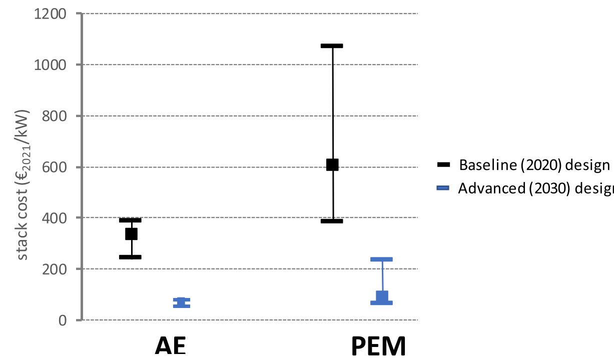


Fig. 8 – The left half depicts the total cos including material and manufacturing cost sensitivities for the AE stacks. The right half depicts the total cost for PEM stacks. The dots represent the total stack cost incorporating the mid estimate for material cost.

dominate the direct stack cost. The other cost components: labor, manufacturing and overhead drop as a result of scale up. This has a significant effect on overhead costs which can be associated with the decline in R&D investment and share of administrative expenses as the business reaches maturity and becomes more streamlined.

Total stack cost

Fig. 8 (left half) shows the range of total stack cost for baseline and advanced AE stack design and the right half for baseline and advanced PEM stack design. The total stack cost encompasses the direct cost (material, labor and manufacturing) and indirect cost (overhead). The material cost sensitivities (mid, low and high cost estimates) are also incorporated into the total stack cost ranges.

Baseline design: The total stack cost ranges from 242 to 388 €/kW for AE. For PEM baseline design the stack cost ranges from 384 to 1071 €/kW. Regarding labor, manufacturing and overhead, results from the annual financial statement were incorporated into the total stack cost. The cost ratios based on PV scale up estimates were used only for comparison with the underestimated bottom-up results and validating the cost ratios seen in electrolyser manufacturers financial statement and the empirical assessment. Therefore, for the baseline design only the results from the financial statements were used.

Advanced design: The total stack cost ranges from 52 to 79 €/kW for AE stacks and 63–234 €/kW for PEM stacks. The AE stack cost range is narrow due to the low fluctuations seen in nickel price which is the dominant material. The PEM stack has a wider cost range due to: 1) the extreme fluctuation seen in iridium price and 2) incorporating the material cost sensitivities for the conservative scenario, thus accounting for the low TRL associated with the advanced design material choices. This wide range indicates the uncertainty with the cost of the advanced design PEM stack and can be interpreted that the lower catalyst loading coupled with the thinner membrane and alternative materials might not be available for commercial production by 2030.

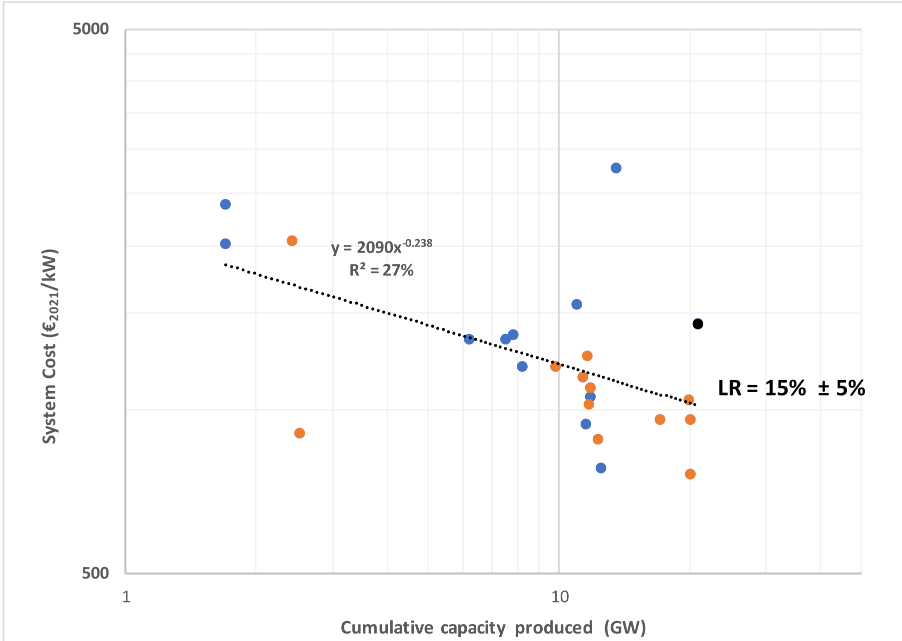


Fig. 9 – Global experience curve for AE system 1956 to 2020. The blue data points represent data from [6]; the orange data points represent data from [8] and the back dot represent ISPT's estimate [12]. The dashed grey line represents the cost curve of the combined learning rate of 15% ± 5%. Cumulative capacity encompasses alkaline, PEM electrolysers and chlor-alkali production. Note: the y-axis states system cost but there is uncertainty associated with what system components are included in the original data points: Only direct cost such as BoP and Power Electronics or including other direct costs like civil, structural and architectural. It is also uncertain if the original data points represent prices or costs.

Comparison of stack cost developments with electrolyser system cost developments

To get an overview of the historic developments and the cost reduction trend seen in electrolysers over time, an experience curve approach was undertaken by [8]. Fig. 9 shows a global experience curve for alkaline electrolyser (AE) systems from 1956 to 2020. The CAPEX data include data from [8] and coupled with data from [6]. The solid black data point represents ISPT's estimate for total system cost for alkaline electrolyser systems [12]. Based on the spread of data in Fig. 9, we found that the experience curve analysis generates a learning rate (LR) of 15% ± 5%. For every doubling of cumulative capacity the price of the technology drops by 15% ± 5%.

The focus of our analysis is to estimate current and future stack cost. Most literature source usually report system costs. Therefore in order to compare our results with literature we estimate the system cost by incorporating our range of stack cost with the ISPT cost estimate for other system components (includes Power electronics; BoP; civil, structural & architectural; utilities & process automation; indirect and owners cost and contingencies). This results in a system cost of 372–564 €/kW for AE and 359–1300 €/kW for PEM. We also compare the stack and system cost estimates with our top-down estimate (AE learning curve, Fig. 9). Table 5 summarizes and compares the different estimates.

IEA (2021) [64] estimates around 91 GW of installed capacity by 2030. This results in a global cumulative installed capacity of 112 GW (current cumulative capacity including chlor-alkali is 21 GW). Projecting the AE system cost (Fig. 9) to 2030, using the

Table 5 – Comparison of 2030 stack and system cost estimates with estimates in literature. *based on 19% of system value; **based on 14% of system [12].

	System				Stack			
	PEM (€/kW)		AE (€/kW)		PEM (€/kW)		AE (€/kW)	
	Low	High	Low	High	Low	High	Low	High
Bottom-up results	359*	1300*	372**	564**	63	234	52	79
AE LR estimate			524	1166			73**	163**
[62]	1404		972		267*		136**	
[63] LR	701		932		336		447	
[5]	593	1330	368	840	113*	253*	52**	118**

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learning rates of 15% ± 5% and accounting for the share of AE stack cost according to the ISPT advanced design estimate (14% of direct cost) results in a total stack cost that ranges between 73 and 163 €/kW. This range is higher than our estimate for the advanced design. This difference in stack cost estimates can be attributed to the factor 5.3 increase in current density (assumed in the bottom-up analysis). Since learning curves are usually based on price data it can be assumed that the projections using learning rates include a certain profit margin.

The 2030 electrolyser stack costs based on system cost projections by [62] and using the ISPT stack cost share (AE: 14%, PEM: 19% of system cost) are higher than our stack cost projections. The authors use electrolyser price data between 2003 and 2016 and perform a univariate regression to project the 2030 system cost. They report an annual price decline of ~4.77% for PEM and ~2.96% for AE thus explaining their higher estimates.

Using learning rates [63]; projects the 2030 stack cost to 336 €/kW for PEM and 447 €/kW for AE. They use a disaggregated approach to determine the learning rate of each component within a stack. The stack cost values for PEM and AE are higher than our bottom-up estimate probably due to the differences in presumed capacities for the year 2030. They also project the stack cost to have a much higher share (48%) than the ISPT assumption of 14% (AE) and 19% (PEM) of system cost. It is also important to note that scaling effects are not only attributed to technological learning but also unit scale up. For electrolyser systems, scaling has more of an effect on the BoP and PE than the stack itself [63].

Aside from learning rates we also compare our results to the expected CAPEX decline in electrolyser systems by 2030 based on expert elicitation conducted by [5]. We compare our results to the expected CAPEX decline provided for a 10 MW system based on a RD&D (Research and development with production scale up) scenario with three levels of investment: 1x, 2x and 10x. We estimated the stack cost from [5] based on the ISPT estimate of the stack cost share (AE: 14%, PEM: 19% of system cost). The resulting stack cost for the three levels of investment (1x, 2x and 10x) ranges between 52 and 118 €/kW for AE and 113–253 €/kW for PEM. Our estimate for advanced AE stacks falls within the aforementioned range and complies with the experts assumption that major CAPEX decrease in AE is expected due to production scale up (GW scale) coupled with larger stack (2.2 MW–20 MW) sizes and moving to higher current densities (0.2 A/cm^2 to 1.3 A/cm^2). The CAPEX estimate for 2030 PEM stacks from [5] is higher than our estimate (63–234 €/kW) mostly attributing to our assumption of reduced PGM loading by 95% while experts from [5] assume a 50% reduction in loading.

On a system level, our cost estimate for systems falls within the cost ranges estimated through learning rates (our LR estimate for AE and [63] estimate for PEM) and the expert elicitation method used by [5]. Our system cost estimate is closer to the upper ranges of the top-down cost estimates.

To achieve cost reductions by 2030, investments are required. Using the generated learning rate of 15% ± 5% and an initial cost of 1012 €/kW at an installed capacity of 21 GW as the starting point, we could calculate the forward buydown cost for alkaline electrolyser systems (Fig. 10). The forward buydown costs (F) are the learning investments required before the technology reaches competitiveness. Thus, we integrate the difference between electrolyser costs and a competitive price

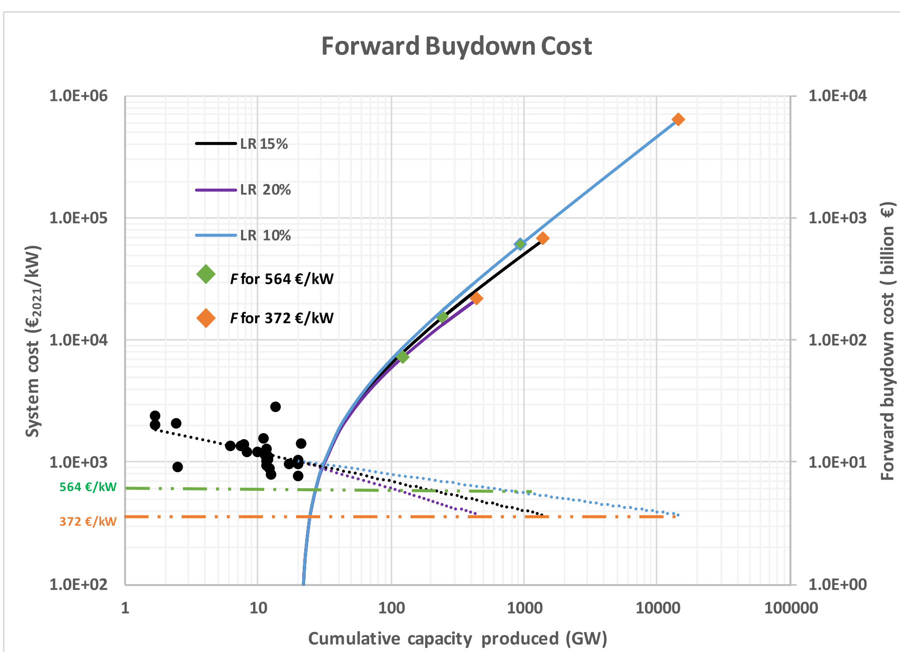

Fig. 10 – Required cumulative capacity productions of AE systems to bring down the cost to 564 €/kW and 372 €/kW at learning rates (LR) of 15 ± 5%. The dashed lines represent the experience curves with rates (LR) of 15% (black), 20% (purple) and 10% (blue). The solid black, purple and blue lines represent the forward buydown cost at a LR of 15%, 20% and 10% respectively. The green and orange data points on the solid lines indicate the required forward buydown cost to achieve system cost of 564 €/kW and 372 €/kW respectively.

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over time until this competitive price has been obtained. The experience curve and forward buydown cost formula can be found in the supplementary file "*Input data and Equations*".

For electrolysers to achieve a CAPEX decline to a CAPEX range of 372–564 €/kW (estimated system cost based on calculated stack cost and ISPT share of stack cost) at a LR of 15%, a range of 0.25 TW (564 €/kW) to 1.5 TW (372 €/kW) of global cumulative installed electrolyser capacity is required. The IEA Net Zero Scenario projects 0.7 TW of installed capacity by 2030 [65] which fall within the aforementioned range. This would imply a range of 3.6–6.2 doublings of global installed electrolyser capacity, and the installed capacity would then produce 21 to 124 million tons of H_2 annually (based on a system efficiency of 69% and a full load hours of 4000 h/year). This implies that AE systems can reach competitive price levels by 2030 when compared to IEA's estimate of 100 million tons of H_2 demand for industry by 2030. But there exists a high uncertainty range (LR 10%–20%) on the required global cumulative capacity additions to achieve cost parity with alternative methods of hydrogen production. This could result in a mismatch between supply and the IEA estimated demand of 100 million tons of H_2 by 2030. To achieve this cost decline (372–564 €/kW), electrolyser manufacturers and public investment will have to incur a forward buydown cost in the range of 73 and 6400 billion € (20%–10% LR) as seen in Fig. 10. This is in line with [66] projection of annual investment in excess of 100 billion € for the coming decade. This is within the same order of magnitude when compared to the PV industry where the expected forward buydown cost from 2002 till breakeven was estimated to be 64 billion € (based on LR of 20%, cost of PV 6 €/W_p and assumed breakeven cost at 1 €/W_p) [67]. In reality, PV reached grid parity by 2014 [68,69] at a price of 0.8 €/W_p [70] and a cumulative installed capacity of 177 GW [71]. The total global investment was around 140 billion € with a realized learning investment in the range of 86–114 billion € (based on a learning rate range of 22.8% [72] - 21.5% [73]). The expected global cumulative installed electrolysis capacity of 112 GW is much lower than the range of 0.25–1.5 TW (Fig. 10). This highlights the importance of incurring a high buydown cost along with scaling up. On the other hand, if natural gas prices were to remain at the average 2022 levels, the break-even point may be reached much earlier.

Conclusion

In this paper we have estimated the cost of electrolyser mass-production in 2020 and how such costs are expected to come down in the 10 years to 2030.

The total AE stack cost (materials, labor, manufacturing and overhead) reduces from a range of 242–388 €/kW in the baseline design to 52–79 €/kW in the advanced design. For both the baseline and advanced design, the most dominant contribution to the direct cost is coming from the material cost. The stack components that contribute most to the material cost are the membrane, bipolar plate and the electrodes for the baseline design. For the advanced design these are the membrane, bipolar plate and the mattress. The most important driver of cost reduction anticipated in the advanced design is moving to higher current density (factor 5.3 increase). As a result, less materials are required. The associated material cost reduction outweighs the cost of having to include a 9-layer nickel mattress.

The total PEM stack cost reduces from a range of 384–1071 €/kW in the baseline design to 63–234 €/kW in the advanced design. Similar to AE, the most dominant contribution to the direct cost is coming from the material cost for both the baseline and advanced design. In both designs the stack components which contribute most to the material cost are the membrane coatings and the PTL anode. Moving to a higher current density (factor 1.75 increase) is one of the main reasons for the expected cost reduction for the advanced PEM design as less materials are required. Additional main drivers in cost reduction are lowering the platinum and iridium content by a factor 15 and 20 compared to the baseline design, respectively; and replacing expensive titanium powder and gold coating in the PTL anode a with cheaper 316 L stainless steel powder and niobium coating, respectively.

Next to cost decline for materials, there is a smaller cost reduction expected for manufacturing and labor cost for both AE and PEM stacks, due to mass manufacturing. Overhead cost are also expected to decline as a business reaches maturity.

Employing an experience curve analysis we found that for each doubling of global cumulative electrolyser system capacity, costs decline 15% ± 5%. Extrapolating this trend forward, we found that (globally) a cumulative learning investment in the range of 73 and 6400 billion € is required to bring electrolyser system cost down to 372–564 €/kW, which is a prerequisite so that green hydrogen becomes competitive with blue and grey hydrogen.

When making a choice between AE and PEM electrolysers different considerations need to be accounted for. Based on CAPEX for stacks, the total cost decrease is less prominent for AE than PEM since AE is a more mature technology, thereby starting from a lower base and leaving less room for improvement. The advanced AE and PEM stacks come out at comparable prices, but the range of uncertainty is larger for advanced PEM stacks than for advanced AE stacks, because the uncertainty in the achievability of the advanced PEM design is larger than the advanced AE design. This is due to low TRL (3–7) and, in addition, there is high volatility in the price of iridium required in the PEM stack. Other considerations that need to be accounted for are size, power density, pre compression capability, flexibility of the stacks in relation to ramping and use of critical raw materials. AE stacks are much larger than PEM stacks (2.6 m^2 vs 0.5 m^2) which could lead to logistical issues in terms of space and transportation to the electrolyser site. PEM stacks can operate at the higher power density (6.3 W/cm^2 vs 2.3 W/cm^2) and pressure (30 bar vs 5 bar). This aids in efficiency and pre compression by reducing the electricity required and cost for post compression. Furthermore PEM electrolysers respond better to ramping rates [74]. Unlike AE stacks, PEM stacks use critical raw materials. Global annual production of platinum and iridium for the electrochemical industry in 2018 amounted to 135 ton/year and 8.5 ton/year respectively [3]. Assuming the projected installed capacity of 91 GW by 2030 [64] to be met by PEM electrolysers, the current global iridium production will not be able to meet the demand based on current iridium loading required for PEM electrolysers.

Therefore it is imperative to reduce the iridium loading by a minimum of factor 5 in case a factor 20 reduction (as assumed for the advanced PEM design) cannot be achieved by 2030. Therefore significant R&D needs to go into reducing the iridium loading by 2030 while maintaining optimal stack performance. Since materials dominate the stack costs, research needs to be conducted into the future production rates and cost development of noble and non-noble metals and the materials required for the membranes. Market dynamics of these materials will play an important role is determining the CAPEX of electrolyser stacks.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Subramani Krishnan reports financial support was provided by Institute of Sustainable Process Technology.

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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.2023.05.031.

REFERENCES

[1] Hydrogen Council. Hydrogen scaling up: a sustainable pathway for the global energy transition. 2017. https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf.
[2] European Union. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. Brussels: A hydrogen strategy for a climate-neutral Europe; 2020a. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN.
[3] European Commission. Study on the EU's list of critical raw materials – final report 2020.
[4] Erbach G, Jensen L. EU hydrogen policy: hydrogen as an energy carrier for a climate-neutral economy 2021.
[5] 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 2017b;42(52):30470–92.
[6] 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.
[7] Schmidt O, Hawkes A, Gambhir A, Staffell I. The future cost of electrical energy storage based on experience rates. Nat Energy 2017a;2(8):1–8.
[8] Krishnan S, Fairlie M, Andres P, de Groot T, Kramer GJ. Power to gas (H2): alkaline electrolysis. In: *Technological learning in the transition to a low-carbon energy system*. 1st ed. Academic Press; 2020. p. 165–87.
[9] Böhm H, Goers S, Zauner A. Estimating future costs of power-to-gas–a component-based approach for technological learning. Int J Hydrogen Energy 2019;44(59):30789–805.
[10] Mayyas AT, Ruth MF, Pivovar BS, Bender G, Wipke KB. Manufacturing cost analysis for proton exchange membrane water electrolyzers. Golden, CO (United States): National Renewable Energy Lab. (NREL); 2019 (No. NREL/TP-6A20-72740).
[11] 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.
[12] ISPT, Institute for Sustainable Process Technology: Hydrohub GigaWatt scale electrolyser. https://ispt.eu/projects/hydrohub-gigawatt/.
[13] Grundt T, Christiansen K. Hydrogen by water electrolysis as basis for small scale ammonia production. A comparison with hydrocarbon based technologies. Int J Hydrogen Energy 1982;7(3):247–57.
[14] De Groot MT, Kraakman J, Barros RLG. Optimal operating parameters for advanced alkaline water electrolysis. Int J Hydrogen Energy 2022;47(82):34773–83.
[15] High Pressure Electrolyzer Module. Patent No: 6554978 B1, Hydrogenics (now Cummings). 2003.
[16] Fischer U, Voigt A, Tannert D, Krautz HJ. Pressure and temperature influence on alkaline electrolysis performance. In: Proceedings of 5th European PEFC and H_2 forum, luzern, schweiz, june/july 2015. European Fuel Cell Forum AG; 2015.
[17] Haug P, Kreitz B, Koj M, Turek T. Process modelling of an alkaline water electrolyzer. Int J Hydrogen Energy 2017;42(24):15689–707.
[18] Trinke P, Haug P, Brauns J, Bensmann B, Hanke-Rauschenbach R, Turek T. Hydrogen crossover in PEM and alkaline water electrolysis: mechanisms, direct comparison and mitigation strategies. J Electrochem Soc 2018;165(7):F502.
[19] Loos S. Active anodes for alkaline water electrolysis. Advanced alkaline electrolysis, 3rd Ind. Work 2020.
[20] Heanjia Super Metals. https://nickel-wiremesh.com/material/nickel-wire-mesh/; 2021.
[21] Mattress for Electrochemical Cells. Patent: EP 0 726 971 B1. Dow Chemical Company; 1998.
[22] Hachiya T, Sasaki T, Tsuchida K, Houda H. Ruthenium oxide cathodes for chlor-alkali electrolysis. ECS Trans 2009;16(39):31.
[23] Brauns J, Schönebeck J, Kraglund MR, Aili D, Hnát J, Žitka J, Turek T. Evaluation of diaphragms and membranes as separators for alkaline water electrolysis. J Electrochem Soc 2021;168(1):14510.
[24] Phillips R, Dunnill CW. Zero gap alkaline electrolysis cell design for renewable energy storage as hydrogen gas. RSC Adv 2016;6(102):100643–51.
[25] Method for Preparing Active Cathodes for Electrochemical Processes. Patent. Norsk Hydro; 1979. p. 1 548–147.
[26] Method for Preparing Active Anodes for Electrochemical Processes, particularly for manufacture of hydrogen. Patent: 1 565 040. Norsk Hydro; 1980.
[27] Diaphragm element for an electrolytc filter press assembly. Patent: 5919344. Norks Hydro ASA; 1999.

[28] Tilak BV, Lu PWT, Colman JE, Srinivasan S. Electrolytic production of hydrogen. In: Comprehensive treatise of electrochemistry. Boston, MA: Springer; 1981. p. 1–104.
[29] Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU). Multi-annual work program. 2018.
[30] IRENA. Green hydrogen cost reduction: scaling up electrolysers to meet the 1.5°C climate goal. Abu Dhabi: International Renewable Energy Agency; 2020.
[31] Daudt N, Hackemüller FJ, Bram M. Porous transport layers Made of niobium/steel Composites for water electrolysis. Werkstoffsynthese und Herstellungsverfahren. No. FZJ-2020-03926 4848310. 2020.
[32] Kim Y-S, Lee I-S, Choi J-Y, Jun S, Kim D, Cha B-C, Kim D-W. Corrosion behavior of niobium-coated 316L stainless steels as metal bipolar plates for polymer electrolyte membrane fuel cells. Materials. 2021. https://doi.org/10.3390/ma14174972.
[33] Nold S, Voigt N, Friedrich L, Weber D, Hädrich I, Mittag M, Preu R. Cost modeling of silicon solar cell production innovation along the PV value chain. Proceedings of the 27th European photovoltaic solar energy Conference and exhibition 2012, September:1084–90.
[34] Woodhouse MA, Smith B, Ramdas A, Margolis RM. Crystalline silicon photovoltaic module manufacturing costs and sustainable pricing: 1H 2018 Benchmark and Cost Reduction Road Map (No. NREL/TP-6A20-72134). Golden, CO (United States): National Renewable Energy Lab.(NREL); 2019. https://doi.org/10.2172/1495719.
[35] Mayyas A, Mann M. Emerging manufacturing technologies for fuel cells and electrolyzers. Procedia Manuf 2019;33:508–15.
[36] Smestad G. Renewable energy, sources for fuels and electricity. In: Johansson Thomas, Kelly Henry, Amulya Reddy, editors. Robert williams, executive editor laurie burnham. Washington, DC: Island Press; 1996. p. 1142. 1993) ISBN 1-55963-139-2 (Cloth), ISBN 1-55963-138-4 (pbk.).
[37] Chen Y, Altermatt PP, Chen D, Zhang X, Xu G, Yang Y, Verlinden PJ. From laboratory to production: learning models of efficiency and manufacturing cost of industrial crystalline silicon and thin-film photovoltaic technologies. IEEE J Photovoltaics 2018;8(6):1531–8.
[38] Haegel NM, Atwater H, Barnes T, Breyer C, Burrell A, Chiang YM, Bett AW. Terawatt-scale photovoltaics: transform global energy. Science 2019;364(6443):836–8.
[39] Agmetalminer.com. Carbon steel prices. 2021. https://agmetalminer.com/metal-prices/carbon-steel/.
[40] Markets Business Insider. Nickel price. 2021, August. https://markets.businessinsider.com/commodities/nickel-price.
[41] Muller CI. *Raney-Ni electrodes for the alkaline electrolysis of water* [Conference presentation]. In: 1st International Conference of Electrolysis (ICE). Copenhagen.; 2017, June 12-15.
[42] Chade D, Berlouis L, Infield D, Cruden A, Nielsen PT, Mathiesen T. Evaluation of Raney nickel electrodes prepared by atmospheric plasma spraying for alkaline water electrolysers. Int J Hydrogen Energy 2013;38(34):14380–90.
[43] Umicore. Iridium price. August, 2021. https://pmm.umicore.com/en/prices/iridium/.
[44] Chengdu Huarui Industrial. (August, 2021) Titanium powder price:. https://www.alibaba.com/product-detail/Powder-Titanium-Price-3d-Printing Metal_60184770372.html?spm=a2700.7724857.normal_offer.d_title.38488b1arcGN0X&s=p.
[45] Bullionvault. (August, 2021a). Gold price. https://www.bullionvault.com/gold-price-chart.do
[46] Chengdu Huarui Industrial Co. Ltd. 316 L stainless steel powder price. August, 2021. https://www.alibaba.com/product-detail/SS-316-316l-MIM-Stainless-Steel_62401200333.html?spm=a2700.7724857.normal_offer.d_title.1bfc66b6UP4C96.
[47] Siracusano S, Van Dijk N, Payne-Johnson E, Baglio V, Aricò AS. Nanosized IrOx and IrRuOx electrocatalysts for the O2 evolution reaction in PEM water electrolysers. Appl Catal B Environ 2015;164:488–95.
[48] Gautam KR, Banerjee S, K Kar K. Bipolar plate materials for proton exchange membrane fuel cell application. Recent Pat Mater Sci 2015;8(1):15–45.
[49] Chengdu Nuclear 857 New Materials. Raney nickel price. August, 2021. https://www.alibaba.com/product-detail/factory-outlet-raney nickel_60773368086.html?spm=a2700.7724857.normal_offer.d_image.f61147b9rTt8dB.
[50] Minke C, Suermann M, Bensmann B, Hanke-Rauschenbach R. Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis? Int J Hydrogen Energy 2021;46(46):23581–90.
[51] Bullionvault. Platinum price. https://www.bullionvault.com/platinum-price-chart.do. August, 2021b.
[52] Battelle Memorial Institute. Manufacturing cost analysis of PEM fuel cell systems for 5- and 10-kw backup power applications/DOE contract No. DE-EE0005250. 2016. https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_cost_analysis_pem_fc_5-10kw_backup_power_0.pdf.
[53] Metalary.com. Niobium price. August, 2021. https://www.metalary.com/niobium-price/.
[54] NEL Annual Financial Report. (2020). 1392136.pdf (cision.com).
[55] Mcphy Annual Financial Report. https://cellar-c2.services.clever-cloud.com/com-mcphy/uploads/2021/05/21.05.10.URD_2020_McPhy_V210430_Vclean_EN_FINAL.pdf; 2020.
[56] ITM Annual Financial Report. https://www.itm-power.com/images/ITM_Power_Annual_Report_2020_-_281020_-_final_v3.pdf; 2020.
[57] Canadian solar Annual Financial Report (2006). [canadiansolar.com)].
[58] Canadian solar Annual Financial Report. http://investors.canadiansolar.com/static-files/be40be13-7efb-4753-ad56-53aae8282efe#page5; 2020.
[59] First Solar Annual Financial Report (2020), page 72. https://s2.q4cdn.com/646275317/files/doc_financials/2020/ar/First-Solar-2020-Annual-Report.pdf.
[60] Sunpower Annual Financial Report, (2020), page 84. https://investors.sunpower.com/static-files/a8bf03f5-b29d-4c95-b5aa-f8fd0b12227c.
[61] Miller JG, Vollmann TE. The hidden factory. Harv Bus Rev 1985;63(5):142–50.
[62] Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. Nat Energy 2019;4(3):216–22.
[63] Böhm H, Zauner A, Rosenfeld DC, Tichler R. Projecting cost development for future large-scale power-to-gas implementations by scaling effects. Appl Energy 2020;264:114780.
[64] IEA. Hydrogen. Paris: IEA; 2021. https://www.iea.org/reports/hydrogen.
[65] IEA. Electrolysers. Paris: IEA; 2022. https://www.iea.org/reports/electrolysers.
[66] IRENA. Making the breakthrough: green hydrogen policies and technology costs. Abu Dhabi: International Renewable Energy Agency; 2021.
[67] Van der Zwaan B, Rabl A. The learning potential of photovoltaics: implications for energy policy. Energy Pol 2004;32(13):1545–54.
[68] Finance, B. N. E. (2015). Rebound in Clean Energy Investment in 2014 beats expectations.Retrieved November, 11, 2015.
[69] Shah V, Booream-Phelps J. Deutsche Bank markets research, crossing the chasm. 2015.
[70] Jäger-Waldau A. PV status report 2019. Luxembourg: Publications Office of the European Union; 2019. p. 7–94.
[71] Nowak S. Trends 2018 in photovoltaic applications. Sweden: IEA International Energy Agency; 2018.

[72] ITRPV. International technology roadmap for photovoltaics. 9th ed. Frankfurt, Germany: VDMA photovoltaic equipment; 2018. http://www.pvmen.com/upload/attachment/201803/20/053037/ITRPV%20Ninth%20Edition%202018_1.pdf.

[73] Metz A, Fischer M, Trube J. International technology roadmap for photovoltaics (ITRPV): crystalline silicon technology-current status and outlook. Proceedings of the PV manufacturing in Europe conference, Brussels, Belgium 2017, May:18–9.

[74] Smolinka T, Ojong ET, Garche J. Hydrogen production from renewable energies—electrolyzer technologies. In: Electrochemical energy storage for renewable sources and grid balancing. Elsevier; 2015. p. 103–28.

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