Racing for Green Hydrogen Economics with Polymer Electrolyte Water Electrolysis – How to Be Achieved

Svenja Stiber, Aldo Gago*, and K. Andreas Friedrich

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For renewable hydrogen production, polymer electrolyte membrane water electrolysis is the most promising technology. However, the technology is not yet competitive with conventional hydrogen production in terms of cost. The impact of cost reduction options on CAPEX and OPEX is investigated. Depending on the hours of operation, the main cost factor is the production and manufacturing of components or the price of electricity. Clearly a tremendous need to implement low-cost electrolysis cells on a large scale to bring green hydrogen production costs to a level 1–3 € kg⁻¹ hydrogen.

Keywords: Cost reduction, Electrolysis, Green Hydrogen, PEM Electrolysis

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1 Introduction

The energy sector is undergoing a profound transformation. The European Union’s hydrogen strategy once again underlines the need to significantly reduce carbon emissions by 2030 and relies on hydrogen. The decarbonization of various sectors such as industry or transport is difficult. Therefore, hydrogen must be used as a central energy carrier here in particular to achieve the climate targets. In this context, the production of hydrogen from renewable resources (green hydrogen) plays a decisive role, as the worldwide demand for hydrogen was about 94 million tons in 2021 [1]. When the target of installing 2·40 GW of electrolyser capacity by 2030 was set [2], the industry responded by expanding production and setting up gigafactories.

Despite the sharp rise in energy prices, e.g., due to the war in Ukraine, the production of green hydrogen is not globally competitive with conventional hydrogen production processes that use fossil fuels. It is estimated that from 2030 onwards [3], hydrogen from renewable energy sources will become more cost effective and therefore competitive. In this context, proton exchange membrane (PEM) electrolysis represents a technology for carbon neutral production of hydrogen if renewable electricity is used. In PEM electrolysis, water is split into hydrogen and oxygen when electricity is applied. By converting the energy to a chemical carrier, energy in the form of hydrogen becomes storable or can be used directly for chemical processes. A significant portion of the hydrogen costs is determined by the underlying electricity prices. This differs greatly from country to country for electricity from renewable energies. It can be said that hydrogen will be produced most economically where renewable energies are available in almost unlimited quantities and can therefore be produced at low cost. If electrolyzers reach operating hours below 3000–4000 h, the plant costs dominate more [4]. The challenge of reducing the still high capital expenditure (CAPEX) for the PEM electrolysis stack continues to be an important part of the research.

To realize the plant sizes of several hundred kW to MW demanded by the market, individual cells are connected in series and so-called stacks are built. The interconnectors, namely the BPP and PTLs, which are responsible among other things for the uniform current distribution and media routing, are commercially manufactured from titanium. In addition, precious metals are required as catalysts and protective coatings, which also increases costs. With the upscaling of PEM water electrolysis (PEMWE) plants, among other things, the automation of the processes as well as the higher yield can reduce the overall costs. Thus, the cost differential shifts to material costs, which can thus become the dominant factor. These are directly dependent on the

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amount of material used. Assuming the compact cell design mentioned above, the stack mass fractions are only 5% of the total system [5], according to a case study for a 1 MW plant, whose calculation showed that titanium accounts for the largest mass fraction of the PEMWE stack at more than 500 kg. Not only the cost of the high-purity feedstock, but also the difficulty of processing titanium itself contribute to the high cost shares. This clearly shows that costs will have to be reduced significantly in the future. Recent studies already show a potential for overall savings of 55% of stack costs, while bipolar plates (BPP) and porous transport layer (PTL) costs can be reduced by 74% [6]. In its 2020 cost analysis, the International Renewable Energy Agency highlights the savings potential for green hydrogen production and identifies medium potential for coating materials (Ir, Pt) and BPP and the highest potential for BoP components (power supply, pumps, H2 processing, cooling), manufacturing, membrane and PTLs [4]. They saw a major challenge in the production of Ti-free PTLs as well as precious metal-free protective coatings for these structures. Furthermore, their realization was rated with a very large benefit in terms of cost reduction and thus for the competitiveness of green hydrogen compared to fossil fuels.

Nevertheless, the aforementioned measures only have an influence on the investment costs of a plant; the operating costs are not considered. In principle, both CAPEX and OPEX are cost drivers for PEMWE, but their impact varies depending on region, country, electrolysis technology or mode of operation [7].

Cost reductions can be achieved on the one hand by saving or substituting materials, e.g., by using thinner BPP, lower catalyst loads or coatings free of precious metals, but also by optimized production processes and automation. In addition, efficiency improvements through economies of scale also have a significant impact on component cost shares [8, 9]. In 2017, future costs for PEMWE were estimated at 397–955 €/kW [10].

Since the future price development of CAPEX for PEM electrolysis is strongly related to the upscaling of the technology, different approaches were pursued to reduce them. Upscaling the technology as reported by Mayyas et al. [8] as well as the continuous development of the technology lead to the expectation of decreasing costs. This development could be observed in the past for PV technology, for example. Corresponding price development predictions were made here by determining so-called learning curves depending on the learning rate [11].

2 Costs for Hydrogen Electrolysis

2.1 Cost Development of PEMWE

The cost analysis for electrolysers is comparatively difficult for various reasons. On the one hand, the technology is still at an early stage of commercialization, so the necessary data is not available. In addition, the country in which production takes place and, finally, the scaling of production play a significant role in the price. Looking at the CAPEX development of PEMWE over the last years shown in Fig. 1, there is a cost reduction of 50% according to the estimate of BloombergNEF [12].

An electrolysis system consists of several components in addition to the stack. The balance of plant refers to the ancillary components and includes the power conditioning with transformer and rectifier for the DC supply, water treatment and hydrogen processing. Several studies on the cost distribution of the PEMWE system and stack are available. Thereby, the stack costs are in the range of about 30–60% proportionally to the system [4, 17–19].

Economies of scale in terms of plant size and production must be considered, as they have a significant influence on electrolyzer costs. More efficient use of materials, but also energy, for example through material development or automation, must be targeted. Finally, design optimization also plays a significant role in reducing the cost of the technology. Since upscaling of PEM electrolysis technology is an important part of achieving the planned electrolyzer capacity in Europe, the study by Mayyas et al. provides an interesting basis for discussion on this [8]. The authors performed a bottom-up cost analysis for PEM electrolysis, focusing on manufacturing costs under the influence of increasing production rates. Fig. 2 shows the resulting system and stack cost distribution for a MW-scale plant, respectively.

Figure 1. PEMWE cost development within the last ten years based on literature values [4, 13–16].
2.2 Future CAPEX of Hydrogen Electrolysis

The assessment of economics of hydrogen are undergoing a rapid change due to new hydrogen production technology development as well as enhancement of established technology. This and the scale-up of manufacturing of PEM electrolyzers will raise the expectation of further price reduction of the technology. Such trend is already known from other technologies such as solar PV panels or wind [20] and can be described by a learning curve. This approach has been also applied to fuel cell systems [21–23]. This empirical tool determines the price for a product from the historical price development, which experience has shown to fall by a certain percentage with increasing installed capacity. This approach is due to Wright’s Law [24] and can be represented as follows:

\[ C_P = C_R(1 - LR) \left(\frac{\ln X - \ln X_0}{\ln 2}\right) \]  

(1)

With the product price \( C_P \) at a given time with a cumulative production \( X \), the initial product price \( C_R \) at a cumulative production \( X_0 \) and the learning rate \( LR \).

Furthermore, this approach was also investigated for electrolysis, where the manufacturing process is classified as both modular and standardizable. For simple repeatable processes, learning curves are classified in the range of 18–22\% [25] where published empirical values for PEM electrolysis fit well with 13–18\% [4, 9, 10, 17, 26, 27]. In determining these experience curves, the underlying assumptions such as reference prices for electrolysis or assumed growth in the market are important [18, 26].

2.3 Basis for Cost Calculation

As discussed earlier, the operating time of the PEM electrolysis determines whether CAPEX or OPEX are dominant. According to the stack cost share shown in Fig. 2, the CCM alone accounts for 15\%. Therefore, the PTL and BPP follow with 9\% and the bipolar plates with 7\% as the largest stack price drivers. To further advance the goal of widespread deployment of PEM electrolysis thanks to lower costs, two possible approaches to this were pursued in earlier work. On the one hand, standard materials were substituted by lower-cost materials in DLR Articles I [28] as well as II [29], and on the other hand, operation under extreme conditions was investigated by increasing efficiency in Article III [30].

Articles I and II deal with the replacement of Ti with low-cost materials such as stainless steel protected from corrosion by non-precious metal coatings for the BPPs and PTLs. The previous developments by Gago et al. [31] and Lettenmeier et al. [32, 33] have shown so far that it is possible to use stainless steel as the base material for BPP fabrication. To prove the material durability a 14 000 h PEMWE test was performed by Stiber et al. [28] Besides the flat stainless-steel anode BPPs with dense Nb and Nb/Ti coatings applied by vacuum plasma spraying (VPS) and physical vapour deposition (PVD), a baseline material from Nel Hydrogen was tested comparatively while on the cathode side uncoated stainless steel BPPs also without flow-field structure were used. All cells showed comparable performance at 1.9 V at 1 A cm\(^{-2}\), which can also be expressed as a cell efficiency of nearly 78\% while the cell degradation rate was only 5.5 \( \mu V \) h\(^{-1}\) over the entire operating period. The post-test analysis demonstrated that the applied non-precious metal coatings provided complete protection against corrosion in the aggressive PEMWE environment over such a long period. If a value of 2.2 V is assumed as the end-of-life cell voltage, the stack could be operated for approx. 57 000 h and thus represent a stack lifetime relevant for industry and market requirements. However, from a cost perspective, the pure Nb coating would be preferable, as it can be produced in only one process step. This long-term test showed that a coating of the stainless steel BPP is not necessary on the cathode side and that this also contributes to cost reduction. These investigations are described in detail in DLR Article I.

A far more difficult challenge is to manufacture PTLs from stainless steel for use in PEMWE. There have been attempts in the literature, but so far no one has been able to achieve comparable performance to the state of art titanium PTL. Article II describes the approach of applying a developed coating of titanium and niobium to commercially available stainless steel multi-layered meshes. Preliminary physical testing of the material with regard to its quality and suitability for PEMWE use was promising, so that the samples were also electrochemically characterized and investigated. Furthermore, an AST of more than 1000 h was conducted with the PEMWE cell for durability test. Post-test physical analyses revealed full protection of the stainless steel PTL against corrosion by Nb/Ti coating. The results showed that the Nb/Ti coating on stainless steel PTL
reduced the cell overpotential by more than 300 mV at 2 A cm⁻², resulting in an efficiency increase of 12 %. As the EIS measurements confirmed, these positive effects were more evident at current densities above 0.25 A cm⁻² due to the following:

(i) a reduction in the ohmic resistance, which is caused by gas formation at the interface with the anode,

(ii) an improved utilization of the anode catalyst resulting in enhanced OER kinetics,

(iii) a reduction in mass transport losses.

To further understand the observed phenomena, pore network modelling showed that the advantage of the Nb/Ti coating was explicitly due to the preferred transport of water and gas to and from the active surfaces of the anode. Moreover, to reduce the cost of green hydrogen, future PEMWE will have to operate at much higher current densities than 2 A cm⁻², e.g., 4 A cm⁻² as nominal load and 6 A cm⁻² as overload, with efficiency above 70 %. Accordingly, the PEMWE cell was tested with coated stainless steel PTL and was able to achieve an unprecedented 77 % efficiency at 4 A cm⁻² and 80 °C. This performance of the PEMWE cell with stainless steel components is comparable to the highest performances reported so far by renowned research and development institutes in the field of electrolysis.

Article III addresses the second approach to reduce cost by optimized Ti-based PTLs with which higher cell efficiency can be achieved by operating them under extreme conditions (current density, temperature, pressure) and thus increasing the H₂ production rate. Therefore, a macro-porous sintered structure of Ti was deposited on a Ti expanded metal by diffusion bonding. This Ti-based PTL exhibits improved properties and is optimized in terms of its pore characteristics, allowing operation up to 6 A cm⁻², 90 °C and 90 bar H₂ outlet pressure. Investigations via pore network modeling have shown that the cell performance achieved could be attributed to the high permeability for both liquid and gas phases, allowing effective two-phase transport to be realized at these high current densities. Thus, a performance of 2.53 V at a maximum current density of 6 A cm⁻² and 2.19 V at a current density of 4 A cm⁻² could be achieved, respectively. Thinking about new standard operating conditions, the nominal current density can be set at 4 A cm⁻², at which an efficiency increase of almost 25 % could be achieved compared to the reference material in the tests performed.

The materials for the particular components used are summarized in Tab. 1, while the specific manufacturing processes for the components are described in detail in the respective publications, so that only the advantages over conventional structures are discussed here.

Starting from titanium-based components, the respective cost reductions are considered for the material developments. In Article I, the bipolar plate (BPP) can be cost-optimized by eliminating a flow-field structure compared to conventional BPP and by eliminating one processing step, namely the stamping of this channel structure, and the coating itself is made of the lower-cost base metals Ti or Nb. In Article II, the costs optimized by Article I are further reduced by using stainless steel as the base material for the porous transport layer (PTL) as well as the coating of base metal and the scaling effect. Article III also uses the low-cost stainless steel BPP already described for Articles I and II. The titanium-based PTL developed here does not require any further coating, eliminating this step in the manufacturing process.

For the cost calculation, the averaged values of the International Renewable Energy Agency study in terms of CAPEX with 1050 € kW⁻¹ is used. According to the stack specifications for a 1 MW electrolyzer by Smolinka et al. the number of cells per stack as well as the active cell area were assumed to be 265 and 1000 cm², respectively [15]. Coating costs were calculated by Gago et al. in a previous publication for BPPs of 1000 cm² [31]. To extrapolate the PEMWE costs by scaling to 1 GW, the learning rates for the respective components were used according to Böhm et al. [17]. For the CCM, this was further specified in the study and the learning rates for membrane and catalysts were broken down to 18 % and 8 %, respectively, which were assumed to be 11 % on average for this work, since the costs for the CCM are considered as a holistic component here. The learning rate for the BPP was assumed to be 10 %; for all other components, an average learning rate of 15 % was assumed [7].

To determine the annual OPEX depending on operating hours as well as specific electricity costs, the hydrogen production rate for a reference stack and the stacks corresponding to the articles on which this work is based were calculated as follows:

\[ f_{H_i} = \eta_F \frac{n_{Cell} a_{Cell}}{zF} \frac{22.41}{1000} \frac{3600}{j} \]  

where \( \eta_F \) is the Faraday efficiency, \( n_{Cell} \) the number of cells assembled to the stack, \( j \) the current density and \( a_{Cell} \) the active cell area.

Since the reduction of green hydrogen production costs is considered a key factor for further commercialization and upscaling of the technology, these are calculated as a function of operating hours for the stack configurations and

<table>
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<th>Parameter</th>
<th>Article I</th>
<th>Article II</th>
<th>Article III</th>
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<tbody>
<tr>
<td>BPP</td>
<td>Nb-coated stainless steel</td>
<td>Ti-coated stainless steel</td>
<td>Ti-coated stainless steel</td>
</tr>
<tr>
<td>PTL</td>
<td>Nb/Ti-coated stainless steel</td>
<td>Porous sintered layer on Ti-mesh</td>
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Table 1. Cell components developed within the scope of the present work that contribute to cost reduction in the respective stack configurations.
plant sizes. The hydrogen production costs $C_{H_2}$ can be presented as follows:

$$C_{H_2} = \frac{\text{LHV}}{\eta_{ges}} \left( \frac{i(1+i/100)^n}{(1+i/100)^n - 1} + \frac{C_{M/O}}{t_0} + P_E \right)$$

with the lower heating value of hydrogen $\text{LHV}$, nominal system efficiency $\eta_{ges}$, rate of interest $i$, depreciation period $n$, maintenance and operating cost $C_{M/O}$, specific investment costs $C_{CAPEX}$, annual full load hours $t_0$ and specific electricity price $P_E$.

Tab. 2 summarizes the assumptions made for the calculations, while the blue $C_{CAPEX}$ values represent the calculated costs for a 1 MW electrolyzer with an Article II or III stack configuration. Since a coated stainless steel bipolar plate is also the basis for Articles II and III, no separate costing was done for Article I, which would only look at BPP. Nevertheless, to determine the cost savings of using stainless steel for the bipolar plates, the component costs were determined using titanium as the base material.

The stack configurations from Articles II and III were used to calculate the hydrogen production costs. Comparing the performance of the cells at the same operating conditions and the same membrane (Nafion115), the PTL from Article III confirms a performance advantage of 3% when operating at high current density of 4 A cm$^{-2}$ compared to the PTL from Article II. As a further development step towards the next generation of PEM electrolyzers, the stainless steel based PTL from Article II was characterized at 80°C and with a CCM based on a thin Nafion212 membrane. This shows a further 9% increase in efficiency at 4 A cm$^{-2}$, which was investigated as the future nominal operating point. Accordingly, the performances of these two stack configurations served as the basis of the overall efficiency analysis of the PEMWE system used in the calculation of the hydrogen production costs. The data were compared at a standard operating current density of 2 A cm$^{-2}$ or operation at high current densities of 4 A cm$^{-2}$ as shown in Fig. 3 and presented as data $\eta$ and $j$, respectively.

### 3 Hydrogen Production Costs Depending on CAPEX and the Operating Mode

If the cost reduction potential from the component developments of Article I and II, i.e., the substitution of titanium by stainless steel for the BPP and PTL, is also considered like an upscaling from MW- to GW-scale, there are overall savings of more than 80%. For comparability of the

<table>
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<th>Parameter</th>
<th>2020</th>
<th>Article II</th>
<th>Article III</th>
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<tr>
<td>Rated stack power [MW] [15]</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Cell area [cm$^2$] [15]</td>
<td>1000</td>
<td>1000</td>
<td>1012</td>
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<tr>
<td>Cells per stack [15]</td>
<td>265</td>
<td>265</td>
<td>265</td>
</tr>
<tr>
<td>Current density [A cm$^{-2}$]</td>
<td>2 2 4 4</td>
<td>2 2 4 4</td>
<td>2 2 4 4</td>
</tr>
<tr>
<td>Cell voltage [V]</td>
<td>1.90 1.70 1.90 1.85 2.20</td>
<td>1.90 1.70 1.90 1.85 2.20</td>
<td>1.90 1.70 1.90 1.85 2.20</td>
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<tr>
<td>Faraday efficiency [%]</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>CAPEX [€ kW$^{-1}$] [4]</td>
<td>1050</td>
<td>1001</td>
<td>1012</td>
</tr>
<tr>
<td>Coating Costs VPS (PTL, BPP) [€ kW$^{-1}$]</td>
<td>0.83</td>
<td>0.83</td>
<td>0.83</td>
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<tr>
<td>Based on [31]</td>
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<tr>
<td>LR for BoP [%]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>LR for PTL [%]</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>LR for BPP [%]</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>LR for CCM [%]</td>
<td>(avg.) 11</td>
<td>(avg.) 11</td>
<td>(avg.) 11</td>
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<tr>
<td>LR for Frames [%]</td>
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<td>15</td>
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<tr>
<td>LR for Assembly [%]</td>
<td>8</td>
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<tr>
<td>LR for BoS [%]</td>
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<td>Rate of interest [%] [34]</td>
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<tr>
<td>Depreciation period [a]</td>
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<td>20</td>
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<tr>
<td>Maintenance and operating cost [% CAPEX a$^{-1}$] [34]</td>
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<td>3.3</td>
<td>3.3</td>
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<tr>
<td>Specific electricity price [€ kWh$^{-1}$]</td>
<td>0.06</td>
<td>0.06</td>
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Figure 3. Performance comparison of PTLs developed in Articles II and III. For comparability of the PTL developments, both components were tested at 90°C and a Nafion115-based CCM was used.
reduction potentials, coated titanium components were assumed as the basis in each case. For the comparison of the stainless steel based BPP from Article I, the cost distribution of the component according to Mayyas et al. [8] was calculated back to titanium as the base material. Fig. 4a and 4b show that around 40% of the BPP and PTL costs are attributable to the material, while the remainder is accounted for by energy, manufacturing, waste and equipment costs. Although material substitution reduces material costs, the remaining costs for manufacturing remain the same and thus increase proportionally to the component to almost 90% for the MW range.

Economies of scale, depreciation of equipment for manufacturing, and more efficient processes can reduce these costs by more than 90% and 60% for the manufacture of BPP and PTL, respectively, when increasing annual production rates to the GW range, resulting in a price of 7.64 and 7.94 € kW⁻¹, respectively. It becomes clear that in the GW-scale, material costs are the predominant factor on total component costs, which is in line with the findings of Mayyas et al. [8]. Accordingly, the relevance of the lower material costs of stainless steel compared with titanium is particularly evident from the GW scale upward.

Using the example of the stack configuration examined in Article II based on a stack made almost entirely of stainless steel, Fig. 5 shows the cost development of the stack components as a function of the annual production rate. The assumed learning rates allow costs to be saved in all areas, but of course considering the material developments carried out in this work, especially in the area of BPP and PTL. As shown in Fig. 6, their shares in the stack can thus be reduced to 2 and 3%, respectively. The CCM continues to account for the largest share of costs in the stack, at 15%. Since this was not the focus of the work, this component was considered with a relatively conservative learning rate, since otherwise a further subdivision into membrane and the respective catalyst layers would have been necessary. Predictions regarding future development progress are difficult, but currently there are already catalysts with reduced PGM loadings, especially on the cathode side. In the future, the aim will be to reduce these further, especially on the anode side, or even to develop PGM-free catalysts and thus further reduce the costs of PEM electrolysis technology. Summarizing the developments in material substitution and considering the stack cost distribution of a stack based on stainless steel components, the cost shares of the system shift further to the detriment of the BoP at almost 70% due to the cost reduction in the stack components as shown in Fig. 6.

Considering the second approach to cost reduction from Article III and the 25% increase in efficiency achieved there, this has a direct impact on operating costs, which can be reduced accordingly. Conversely, if the measured cell performance is compared with the current standard of approx. 2 V at 2 A cm⁻² twice as much hydrogen can be produced at almost the same voltage. The operating temperatures of the state-of-art (SoA), however, are in the range of 60–80 °C. For illustration, the hydrogen production costs were calculated as a function of the operating hours and shown in Fig. 7.

As the number of operating hours increases, the differences between the scenarios considered diminish. Electrolysers are currently operated at 2 A cm⁻² by default, which will be considered comparatively for the components developed in Articles II and III. Since this implies an operating point with voltage efficiencies higher than 80% for the
new components, this is defined as an efficiency-oriented operating point. Operation at high current densities of 4 A cm\(^{-2}\) is therefore defined as a current density oriented operating point. Compared to the 2020 reference scenario, the studied stacks from Articles II and III seem to differ only marginally in their CAPEX in component costs and, accordingly, in total plant costs, with about 5 and 4 %, respectively. Nevertheless, this has an impact on the hydrogen production costs at low operating hours. The 1 % CAPEX difference can be calculated in 2 € per kg hydrogen difference at 1000 h operation. The more operating hours, the more the hydrogen production costs become OPEX dominated [15]. Already from 6000 operating hours one comes close to the costs of fossil produced hydrogen or from 7000 h hydrogen can be produced competitively. Assuming a maximum operating time of 8000 h, the costs for hydrogen are 2.63 and 2.37 € kg\(^{-1}\) for the stack configurations with titanium- and stainless steel-based PTL, respectively. Calculating the price difference to SoA, 0.26 and 0.52 € kg\(^{-1}\) can be saved by using the PTLs developed in Article III and II, respectively. For a hydrogen demand of 90 TWh in 2030 [35], the example of the stack configuration with titanium based PTL from Article III can already save around 700 million Euro.

In summary, there is an urgent need to reduce the cost of large PEMWE cells. By developing a non-precious metal coating of Nb/Ti and applying it to the lowest cost structure that can be used as a PTL in PEMWE, namely a stainless-steel mesh, in combination with a stainless steel based BPP, an unprecedented cost reduction can be achieved. The presented results suggest that a promising option has been presented here to replace Ti as the base material for fabricating expensive porous structures for PTLs; low-cost stainless-steel mesh can be used instead. In addition, stainless steel meshes with different aperture sizes allow the use of flat plates as BPPs, which can also be fabricated from stainless steel, without a flow field. Thus, the cost of a PEMWE cell could be drastically reduced as it is almost entirely made of stainless steel, which can potentially establish this technology as a competitive solution for renewable green hydrogen production. While the PTL cost can be reduced by 88 % to about 8 € kW\(^{-1}\) for the coated stainless-steel component, the BPP cost also decreased by about 90 %. Compared to the literature [8], this corresponds to a reduction of PTL costs in the GW range by another 68 % and is below the medium-term estimated reduction potential for the component.

**Figure 6.** Updated Cost breakdown of PEM electrolyzer made almost entirely from stainless steel components.

**Figure 7.** Hydrogen production cost of PEM electrolyzer stacks using the PTLs developed within Articles II and III compared to a SoA reference stack in 2020 based on an electricity price of 0.06 € kWh\(^{-1}\).

4 Conclusion

Thanks to intensive research and development work to optimize electrolyzer technology, the share of production costs that limits the introduction of green hydrogen is decreasing. In addition to these, however, the electricity costs for operating the electrolyzers represent a significant cost factor. Although these have decreased in the past, mainly due to declining electricity costs for renewable energy, green hydrogen at medium operating hours is currently still about twice as expensive as hydrogen produced from fossil fuels. This makes it clear that electricity costs must also be developed at lower prices to make green hydrogen compet-
itive. For various reasons, however, there is currently no relief in sight on the electricity market. On the one hand, the constantly growing demand for energy and also the demand from the various sectors, such as individual households, but also from industry for green electricity is immense and growing. The energy transition itself brings costs – among others, the expansion of new renewable energy plants, the infrastructure development for the distribution of generated electricity and also the development of storage facilities. Renewable energy technologies must compete with the high efficiencies of highly controllable coal-fired power plants. Although the Ukraine conflict seems to provide further arguments for the energy transition and to give a boost to research and development topics in this regard, their expansion is inhibited due to rising prices for materials and energy. This makes it clearer that market deployment requires incentive systems, which can be in the form of subsidies or credits.

From the cost calculation carried out, it became apparent that a significant cost factor lies in the production and manufacturing costs of the components, which are strongly dependent on the installed electrolysis capacity. Therefore, manufacturers must specialize as suppliers for the production of electrolyser components in order to ensure cost-effective production and thus keep component costs low. In this respect, the optimizations achieved in DLR Articles I and II are an essential key to realizing the introduction of cost-efficient components even faster. This is due to the use of more readily available, machinable material, stainless steel, which is already common and well-known in the industry. This can sometimes increase the pool of suppliers and involve companies specializing not only in the machining and processing of titanium in this restructuring.

It is known that the longer electrolysis systems are operated, the more total costs are dominated by their operation, i.e., OPEX [15]. If materials can be produced at low cost, the efficiency improvement approach remains to reduce the hydrogen production cost. The efficiencies achieved in Article III can reduce the second significant variable in hydrogen production costs, which is electricity consumption or cost.

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### Symbols used
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<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>Specific investment cost [€ kW⁻¹]</td>
</tr>
<tr>
<td>CM/O</td>
<td>Cost for maintenance and operation [€ kW⁻¹]</td>
</tr>
</tbody>
</table>

### Abbreviations
- BoP: balance of plant
- BPP: bipolar plates
- CAPEX: capital expenditures
- CCM: catalyst coated membrane
- H₂: hydrogen
- Ir: iridium
- OER: oxygen evolution reaction
- OPEX: operational expenditures
- PEM: proton exchange membrane
- PEMWE: proton exchange membrane water electrolysis
- PGM: platinum group metal
- Pt: platinum
- PTL: porous transport layer
- PVD: physical vapour deposition
- SoA: state of art
- Ti: titanium
- VPS: vacuum plasma spraying

### References


