Global Energy Perspectives

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Part 1: Basic elements for avoiding greenhouse gases and generating climate-neutral energy (technical toolbox)

Chapter 2-4

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2.4. Hydrogen production

The production and subsequent use of climate-friendly hydrogen (low-carbon H_2) will play a major role in the desired decarbonisation/lowering of emissions. Alternatives to the production of low-carbon H_2 include the use of electrolysers powered by renewable energy (water electrolysis), which is favoured by politicians, as well as methane pyrolysis and the production of low-carbon synthesis gas through simultaneous capture and storage of the carbon dioxide produced and captured in parallel (CCS: Carbon Capture and Storage).

In the broadest sense, a synthesis gas is a gas mixture that is used as an educt for a synthesis. For example, a mixture of nitrogen and hydrogen is the synthesis gas for ammonia synthesis ($2\ NH_3 \Leftrightarrow N_2 + 3\ H_2$). In most cases, the production of synthesis gases is based on natural gas, coal and petroleum (crude oil distillates) or biomass as feedstock. The synthesis gases produced by the processes of steam reforming, partial oxidation and, rarely, converter plasma are gas mixtures that mainly contain carbon monoxide (CO) and hydrogen (H_2) along with varying amounts of other gases. These synthesis gases are used, for example, for the synthesis of methanol or the synthesis of fuels via the Fischer-Tropsch process.

Traditionally, hydrogen is also produced from synthesis gas. The catalytic water gas shift reaction (also known as shift, $CO + H_2O \Leftrightarrow CO_2 + H_2$, see below) is a method of minimising the CO content in a synthesis gas and simultaneously increasing the H_2 content.

In all production processes, before the synthesis gas can be fed into a catalytic reactor system, it has to undergo complex purification and treatment (e.g. water removal and drying, separation of sulphur compounds, CO_2 separation).

To produce "blue" or better "low-carbon H_2", it is necessary to sequester the relatively pure CO_2 obtained in this way (see chapter 2.8).

2.4.1 Steam reforming of natural gas

Traditionally, hydrogen production is based on steam reforming of natural gas. Thanks to optimised technologies, economies of scale make single-line plants with a maximum capacity of 200,000 Nm³/h hydrogen relatively cost-effective, although a further increase in plant capacity becomes uneconomical due to the then excessive complexity of the steam reformer (a "numbering-up" may then be necessary, i.e. two or more plants are operated in parallel). Greenhouse gas emissions occur at two points in these plants (see Figure 70): Both during steam reforming in the flue gas and in the process itself. CO_2 capture in the process is a normal and necessary step in the production of hydrogen. However, if higher CO_2 recovery rates are required for the production of low-carbon H_2, the CO_2 contained in the flue gas must also be removed. Since the flue gas is produced at atmospheric pressure, contaminated and with low CO_2 concentrations, this requires complex and expensive flue gas scrubbing (see chapter 2.3). CO_2 recovery rates of up to 97 % can be achieved in this way.

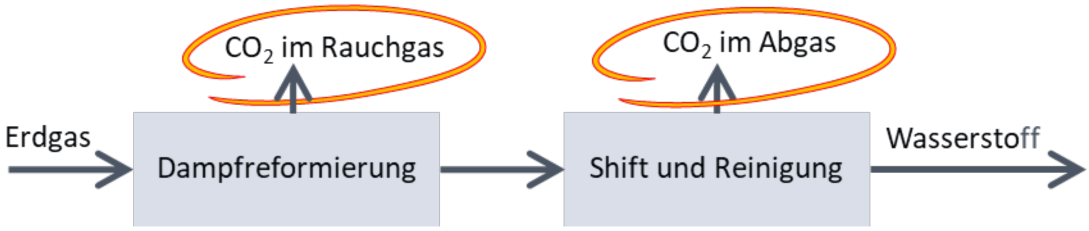

Figure 70: Emission sources for CO_2 during the production of hydrogen by steam reforming

Source: Author

2.4.2 Partial oxidation /autothermal reforming of natural gas

If large hydrogen capacities of more than 200,000 Nm³/h up to a maximum of 800,000 Nm³/h of hydrogen are required, this can be produced relatively cost-effectively ("economy of scale" effect) by partial oxidation. Greenhouse gas emissions are produced in the process itself in these plants (see Figure 71) and in additional furnaces, which are usually operated with natural gas or also with waste gases containing hydrocarbons. CO_2 capture in the process is a normal and necessary step in the production of hydrogen.

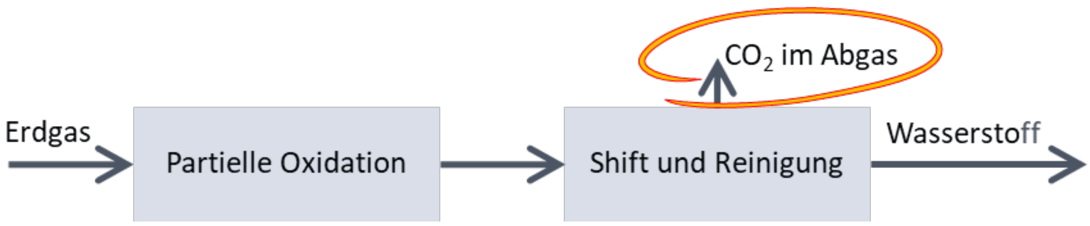

Figure 71: Emission sources for CO_2 during the production of hydrogen by partial oxidation;

Source: Author

If higher CO_2 recovery rates are required for the production of low-carbon H_2, the separation of the CO_2 can be further optimised in the process itself and the furnaces can be operated in a climate-neutral manner. In contrast to the above-mentioned production of low-carbon - by steam reforming, this does not require complex and expensive flue gas scrubbing. Higher CO_2 recovery rates are achieved through intelligent modifications of the process itself. Figure 72 shows an example of the patented AdWinHydrogen® technology from GasConTec.[175]

[175] Cf. GasConTec, n.d.

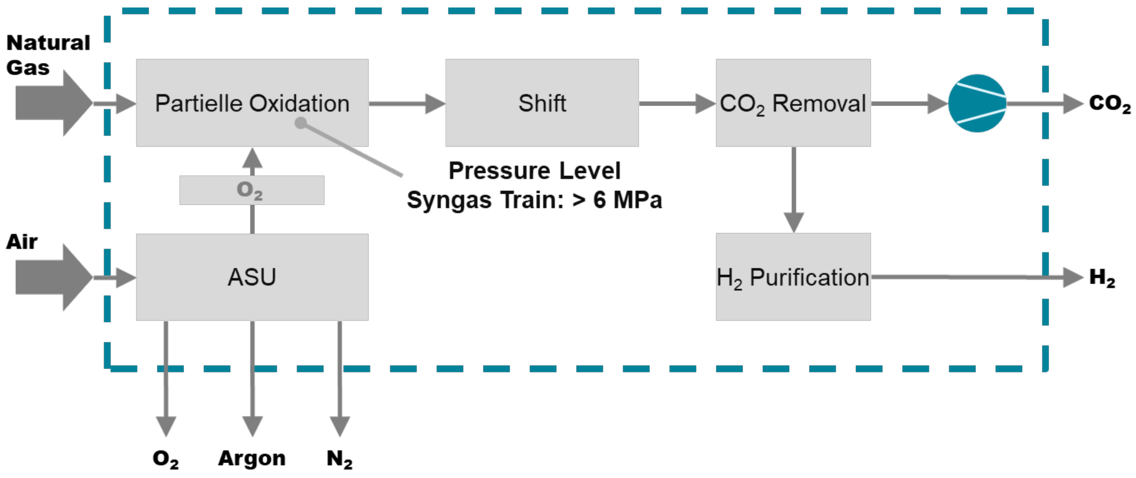

Figure 72: Hydrogen production by partial oxidation ;

Source: Author

Large quantities of largely pure, climate-friendly low-carbon H_2 can thus be produced cost-effectively. With possible CO_2 recovery rates of up to 99 %, this low-carbon H_2 has a smaller CO_2 footprint than "green" H_2 .

2.4.3 Electrolysis

2.4.3.1. Core statements

- Low-temperature technology processes (AEL and PEMEL) are technologically ready for market ramp-up; high-temperature electrolysis (HTEL) and anion-exchange membrane electrolysis (AEMEL) are at the research stage and are to be brought to market maturity in future
- The international expansion of electrolysis capacity is on the **upswing** - as of November 2021, the largest share of global electrolysis projects in the megawatt range has been announced in Europe (261 projects), followed by Asia and especially China (121 projects, half of them in China), North America (67 projects), Oceania (43 projects), Latin America (10 projects) and the Middle East and Africa (20 projects) - resulting in a (current) expansion corridor of **93 GW of** installed electrolysis capacity by 2030.
    - German hydrogen production will probably not be able to meet future domestic demand, imports as well as the use of hydrogen based on methane in combination with CO_2 capture will be necessary
- High investment costs, high electricity prices, lack of production capacities and production technologies for standard modules of electrolysers, lack of subsidies and regulations (e.g. a global CO_2 price) as well as high transport costs for hydrogen (see chapter

2.2.3) are (still) obstacles for the market ramp-up of hydrogen production based on electrolysis, which is necessary to meet the future demand for cheap hydrogen with low CO .2

- Furthermore, a shortage of raw materials, **especially iridium,** could hinder the market ramp-up of **PEM electrolysis unless** further technological advances are made
- In addition to hydrogen from renewable energy sources, hydrogen production based on methane with CCUS or methane pyrolysis should therefore be included and promoted, according to leading experts.

2.4.3.2 Introduction to the topic

Water) electrolysis as an electrochemical process can be used to produce hydrogen based on renewable electricity. In an electrolyser, water molecules (H_2O) are split into hydrogen (H_2) and oxygen (O_2) using electrical energy (electricity). In simplified terms, electrolysis converts electrical energy into chemical energy (H_2). The process of electrolysis follows the following scheme: The electrolyser contains two electrodes (negatively charged=cathode; positively charged=anode) that are suspended in water. An electrical voltage is applied between the two electrodes so that current flows. The electrical conductivity of the water is increased by adding certain acids or bases (electrolytes). The water then splits into hydrogen and oxygen at the two electrodes (hydrogen is formed at the cathode and oxygen at the anode). To prevent the electrodes from ageing too quickly in the acidic solution and electrode material from being transferred into the solution, they are usually made of (semi-)precious metals or non-ferrous metals (e.g. nickel, gold, platinum or iridium) or graphite. The hydrogen produced in this way is "low in CO_2" if the electrical energy used comes from renewable power sources (e.g. electricity from solar cells), thus reducing the so-called "CO_2 footprint".

2.4.3.3 Relevance of the topic to the overall context

The specialist literature reports unanimously that the national as well as international demand for hydrogen will increase strongly in the coming years if, for example, the goals of the Paris Climate Agreement or the German government are to be achieved. In the current sustainability index, McKinsey cumulates the future total hydrogen demand for Germany in 2050 at more than 12.6 million Metric Tons (MT) compared to the 55 TWh, i.e. about 1,226 t today.[176]

[176] Cf. McKinsey & Company, (2021).

Worldwide, today's consumption is about 90 t, by 2030 it will be 140 t and by 2050 it will probably be more than 660 t.[177 178.]

Figure 73 shows the Hydrogen Council's projected demand for hydrogen in 2030 and 2050. It shows that China is expected to be the largest domestic market for hydrogen by 2050 (200 t), followed by Europe (95 t) and North America (95 t). "Rest of World" includes the regions of Southeast Asia, Oceania, Middle East and Latin America (235 t in total).[177]

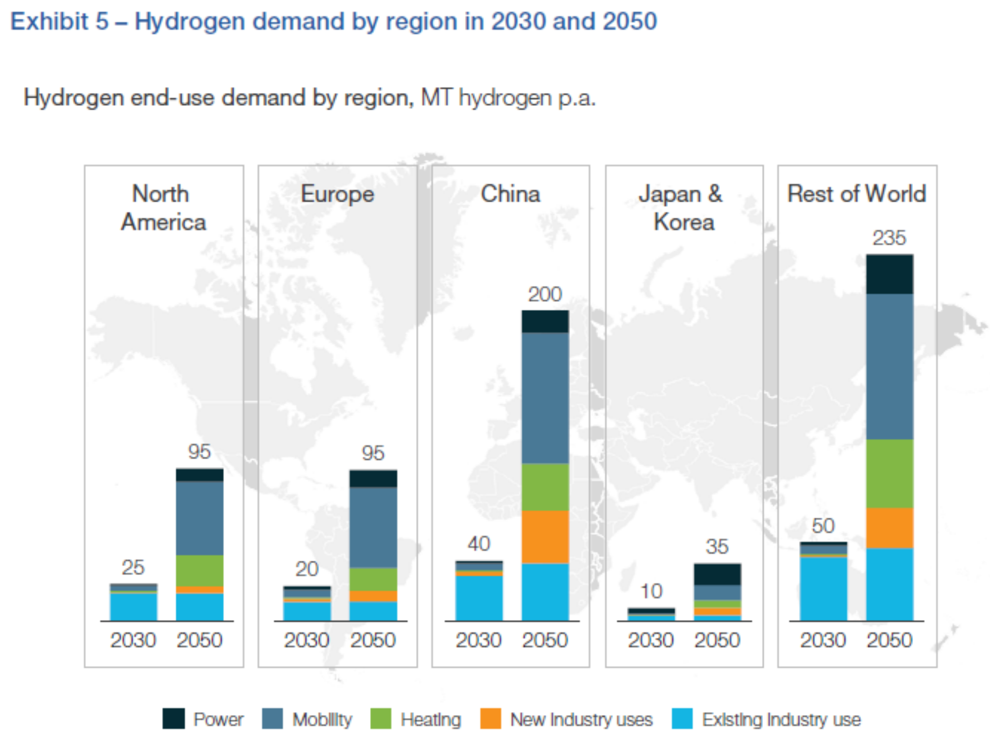

Figure 73: Projected hydrogen demand by region in 2030 and 2050.

Source: Hydrogen Council/McKinsey & Company, 2021 .

Currently, hydrogen is only produced to a small extent with low CO_2,[179] but predominantly via steam reforming with natural gas or methane (grey hydrogen). Hydrogen produced in this way causes **900 t of** CO_2 emissions per year worldwide with **90 t of grey hydrogen produced (as of 2020)**.

If hydrogen were to be produced largely in this way in the future, individual industries could reduce their CO_2 emissions by using grey hydrogen instead of coal in production, for example.

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[177] Cf. Hydrogen Council/McKinsey & Company, (2021).
[178] Forecasts of global hydrogen demand in the future depend on the assumptions in which sectors hydrogen will prevail against competition from other CO_2 poor energy sources. The forecast quoted here refers to the calculations of the Hydrogen Council & McKinsey, who assume that hydrogen with low CO_2 emissions will be used primarily in industries that cannot be electrified or cannot be electrified economically.
[179] In this context, "low CO_2 " means that the hydrogen produced in this way has the smallest possible CO_2 emissions footprint.

However, *climate neutrality* would not be achieved if this production chain were established. One way in which the production of hydrogen from methane can also be achieved with low CO_2 emissions is the use of so-called Carbon Capture and Usage/Storage (CCUS) processes at the point source (often referred to as "blue hydrogen") or methane pyrolysis (often referred to as "turquoise hydrogen"), which are discussed in more detail elsewhere (see Table 7) and will be important for the ramp-up of a hydrogen economy (see Chapter 2.4.3.6.).

Nevertheless, on the way to limiting global warming, which globally requires the increased use of low-CO_2 H_2, electrolysis plays an **essential role**. This is because in the long term, this process can establish de-fossilised hydrogen production, which can be made sustainable through the use of renewable electricity.

2.4.3.4 The most important key figures at a glance

Table 7: Electrolysis key figures at a glance

Currently installed electrolysis capacity worldwide	approx. 0.2 GW (200 MW)[180] - 0.363 GW (363 MW) [181]
For a "break-even" with grey hydrogen (cost 2 USD/kg) in production costs required installed electrolysis capacity (in optimal regions!), assumptions: System investment costs (CAPEX) fall to USD 200-250/kW output "Levelised cost of energy (LCOE) decrease to USD 13-37 MW/h Load factors increase so that more hydrogen (H_2) can be produced per plant.	65 GW [182]
Attention: Production costs do not correspond to the actual market price (factors such as high demand with low supply and additional transport costs can additionally drive up the market price).	
Extent of announced projects of installed electrolysis capacity worldwide until 2030 (mainly located in Europe and Oceania)	93 GW (as of November 2021)[183]

[180] Cf. Aurora Energy Research, 2021a.
[181] Cf. IEA, 2021a.
[182] Cf. Hydrogen Council/McKinsey & Company, 2021a.
[183] Cf. Hydrogen Council/McKinsey & Company, (2021).

Total volume of announced projects for the expansion of installed electrolysis capacity worldwide (time period uncertain)	342.9 GW; 200.7 GW of which in Europe (as of November 2021)[184]
Installed electrolysis capacity required by 2050 (according to McKinsey and Hydrogen Council), assumption: Use of low-CO_2 H_2 has the potential to avoid emissions of 7 Gt CO_2 This requires 660 t CO_2 -low hydrogen Low-CO_2 H_2 thus contributes to 22 % of global final energy demand in 2050	3 - 4 TW (3000 - 4000 GW) to produce 400 - 500 million metric tons (MT or t) of hydrogen by electrolysis If 660 t were produced exclusively via the electrolysis process with electricity from renewables, approx. 5.5 TW of installed capacity would be required (which is probably not achievable). In addition, 260 - 160 t are therefore needed in the form of hydrogen based on natural gas (often: "blue/turquoise" hydrogen).
Installed electrolysis capacity required by 2030 (according to McKinsey and Hydrogen Council), assumptions: By 2050, approx. 400 - 500 t of renewable hydrogen per year will be needed (660 t CO_2 -low H_2 in total). By 2030, it should therefore be possible to produce 75 t CO_2 -low H_2 per year in order to strengthen the hydrogen economy. 20 - 30 t renewable 45 - 55 t based on fossil fuels + CCUS	200 - 250 GW and growth rate of 45 GW per year[183] If 75 t were produced exclusively via the electrolysis process, approx. 600 GW of installed capacity would be required - i.e. just under 3 times this amount).
(Current) annual cumulative production capacity of electrolysis plants announced by manufacturers	> 3 GW (as of February 2021)[185] This figure could rise as demand for electrolyser capacity increases
Cost of market ramp-up (based on Hydrogen Council & McKinsey assumption that 200 - 250 GW of installed electrolysis capacity needs to be achieved by 2030 to meet 2050 targets).	700 USD billion by 2030[186] Investment gap: 540 USD billion (investment volume of projects announced so far = 160 USD billion)

[184] Cf. Aurora Energy Research, 2021b.
[185] Cf. Hydrogen Council/McKinsey & Company, 2021a.
[186] Cf. Hydrogen Council/McKinsey & Company, 2021b.

Potential development of hydrogen based on regeneratively generated electricity through electrolysis outside Europe	109,000 TWh - reduced to 69,000 TWh due to uncertain investment conditions [187] Equivalent to about 14 TW (14,000 GW) of installed electrolysis capacity at an average utilisation of 5000 hours per year. Thus, about 1.5 Gt of hydrogen could be produced per year (based on assumption: 33.33 kWh/kg H_2).[188]

2.4.3.5 The different electrolysis technologies

In electrolysis, a distinction is currently made between four main technologies: Alkali Electrolysis (AEL), Proton Exchange Membrane Electrolysis (PEMEL), High Temperature Electrolysis (HTEL) and Anion Exchange Membrane Electrolysis (AEMEL). These are briefly described below.

Alkali electrolysis (AEL)

The longest commercially used electrolysis technology is alkaline electrolysis (AEL). In this process, two metallic electrodes (usually made of nickel) are immersed in an alkaline aqueous solution, the so-called electrolyte, which is electrically conductive. When a DC voltage is applied, electrolytic water splitting begins, and hydrogen and hydroxide ions are produced as reaction products at the cathode (negatively charged). The half-cells in which the electrodes are suspended are also separated by a permeable membrane (diaphragm), which is only permeable to hydroxide ions (OH^-). The hydroxide ions migrate through the membrane to the anode, where they react to form water and oxygen. The membrane prevents the mixing of the resulting product gases (hydrogen and oxygen) in the electrolysis cell and the formation of an explosive gas (oxyhydrogen). The hydrogen and oxygen bubbles are transported through the electrolyte circuit to the separators, where they are separated from the caustic potash solution.[189]

- <u>Technological maturity:</u> Mature

[187] Cf. Pfennig et al., (2021).
[188] Cf. DWV, (2021).
[189] Cf. VBI, (2019).

- The largest operating alkali electrolysis plant: Industrial Cachimayo, Peru (25 MW, draws electricity from the general power grid) [190]

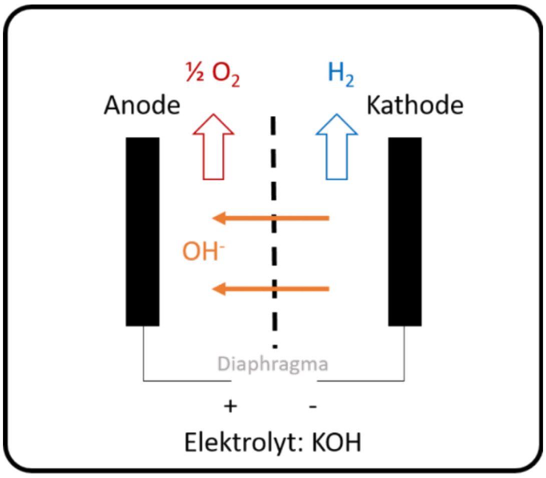


Figure 74: Schematic of alkaline electrolysis.

Source: FfE, 2019 .

PEM electrolysis (PEMEL)

Proton Exchange Membrane Electrolysis (PEMEL), which has been increasingly used and further developed in recent years, does not use a liquid electrolyte, in contrast to alkaline electrolysis, but uses a proton-conductive, gas-tight membrane, which also represents the electrolyte. The electrodes with the catalyst particles are attached directly to the membrane and form the membrane-electrode unit. Furthermore, the PEMEL works differently from the AEL in an acidic environment, since the proton conductivity is achieved by mixing ionomer into the electrode layer.[191] Therefore, the use of precious metals is necessary for the electrodes to prevent corrosion. On the cathode side, a porous electrode made of platinum supported on carbon is used, and on the anode side, metallic or oxide precious metals such as iridium are used. Water is then added to the anode side and an external voltage is applied to the electrodes in accordance with the basic principle of electrolysis. Oxygen, free electrons and positively charged H+ ions are now produced at the anode. The H+ ions then migrate through the gas-tight membrane from the anode chamber to the cathode chamber, where they combine with the electrons present to form hydrogen.

[190] Cf. IEA, 2021a.
[191] higher proportion of hydrogen ions - the more hydrogen ions a solution contains, the more acidic it is - pH <7.

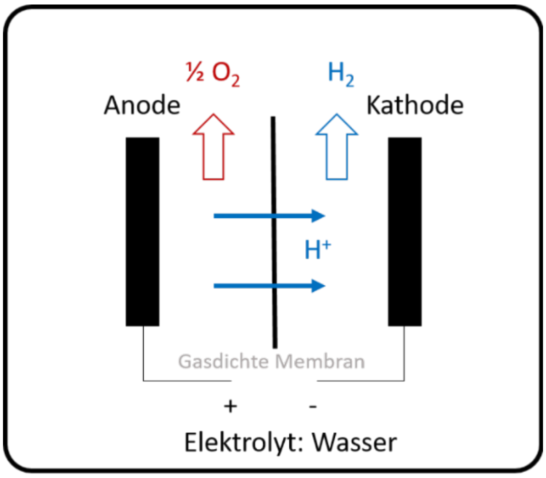


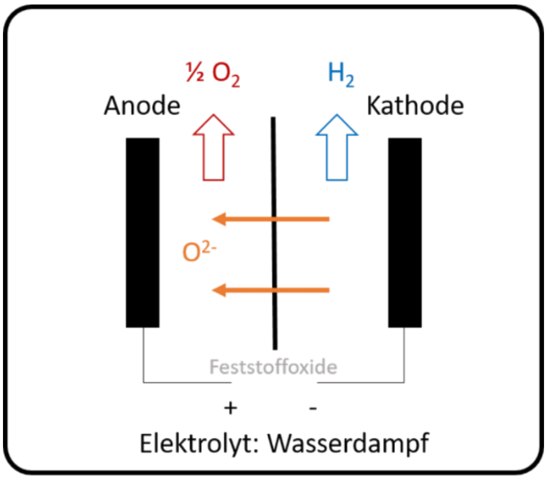
Figure 75: Schematic of PEM electrolysis.

Source: FfE, 2019 .

- Technological maturity: Mature
- The largest operating PEM electrolysis plant: Air Liquide Becancour (20 MW, draws electricity from a connected hydropower plant).[192]

High temperature electrolysis (HTEL)

High-temperature electrolysis (HTEL) has now made the step from the research stage to the first demonstration plants. The technology, also called steam electrolysis, uses a ceramic solid electrolyte (solid oxide) to separate the half-cells, which becomes conductive to oxygen ions at very high temperatures (> 800 degrees). Oxygen ions thus diffuse from the cathode chamber to the anode chamber. With HTEL, part of the energy required for water splitting can be supplied by thermal energy instead of electrical energy. Thus, valuable renewable electricity could be saved.



[192] Cf. IEA, 2021a.

Figure 76: Schematic of the HTEL.

Source: FfE, 2019 .

- Technological maturity: advanced stage of research
- Largest operating HTEL electrolysis plant: Hydrogen Lab Leuna (1MW) (pilot phase)

Outlook: The AEM Electrolysis (AEMEL)

The AEM electrolysis technology, which is being pioneeringly promoted by the German clean-tech company Enapter, combines the advantages of the AEL and the PEMEL: The construction of the AEM cell is the same as that of a PEM cell, because here, too, the electrodes lie directly on a membrane made of ion-conducting polymer. Thus, the AEMEL can be operated under pressure and with high electrical power. Unlike the PEMEL, however, the AEMEL does not operate in an acidic environment but, like the AEL, in an alkaline environment. Therefore, less rare and also cheaper non-precious materials such as nickel can be used for this technology. As with the AEL, water splitting takes place on the cathode side. Due to these combining properties (precious metal-free and relatively inexpensive; compact design; high energy efficiency), great hopes are pinned on the further development of this technology. However, in order to be able to implement projects in the megawatt range with AEM, further research is needed, especially in membrane technology. According to experts, such AEM electrolysers could still be ten years away from realisation. Currently, systems can be realised on a kilowatt scale.

- Technological maturity: early stage of research

Advantages and disadvantages of the electrolysis technologies

These descriptions already indicate that each electrolysis technology has its own advantages and disadvantages, which also has an impact on the costs of the plants concerned. Due to the technological maturity of the market, AEM is excluded from the following observations.

Investment and operating costs

The greatest advantage of alkaline electrolysis is the comparatively low investment costs (CAPEX), which can be explained by the market maturity and the lower material costs. Since this technology has been known since the 19th century and electrolysers have already been built on a larger capacity scale, economies of scale and modularisation have already reduced the costs of plant construction accordingly. Due to this circumstance, future cost reductions of this technology with further scaling will probably be less drastic than for PEM electrolysis, for example. The fact that the electrodes are made of nickel also has the advantage that considerably more expensive precious metals such as platinum or iridium, which are used in PEM electrolysis plants, can be *dispensed with*.

Anlage	Einheit	2020	2030	2040	2050	Variation untere Bandbreite	Variation obere Bandbreite
AEL	EUR_{2016} /kW_el	878	717	594	512	0,90	1,10
Stack AEL	EUR_{2016} /kW_el	439	358	297	256	0,72	1,32
PEMEL	EUR_{2016} /kW_el	1.610	1.216	952	793	0,90	1,10
Stack PEMEL	EUR_{2016} /kW_el	805	608	476	396	0,72	1,32
HTEL (SOEC)	EUR_{2016} /kW_el	1.999	1.477	1.123	905	0,90	1,10
Stack HTEL	EUR_{2016} /kW_el	1.000	739	561	453	0,72	1,32

Figure 77: Assumptions on the investment costs of the electrolysis plants (AEL, PEMEL, HTEL).

Source: Prognos, 2020

Figure 77 shows, according to research and calculations by Prognos, the CAPEX of an alkaline electrolysis plant was 879 EUR/kW (or 439 EUR/kW stack costs) in 2020, [193][194] [195] [196] and could decrease even further by 2030 (716 EUR/kW or 358 EUR/kW).

The situation is different for PEM electrolysis; here the commercialisation of large systems in the megawatt range is still in its infancy, which means that economies of scale have not yet been realised.[197] According to Prognos, the CAPEX of PEM would therefore be 1610 EUR/kW (or 805 EUR stack costs) in 2020. However, the specialist literature still sees considerable potential for cost reductions here in the future (see Figure 77). According to this, the CAPEX of PEM plants could fall to 793 EUR/KW by 2050 (or 396 EUR/kW stack costs).

At this point, it should be mentioned that the projected CAPEX differ considerably depending on the source and the **Prognos** figures should be considered **rather conservative. For** example, Hydrogen Council & McKinsey calculate that investment costs at the system level of

[193] The so-called "stack" forms the core of the electrolyser, which consists of electrolysis cells connected in series (the more stacks, the more power the electrolysis system has).
[194] In addition to the costs for the stack of an electrolysis plant, there are investment costs for other components such as power supply, gas purification and plant peripherals (BoP), which were evaluated here with a factor of 2 of the stack costs.
[195] Cf. Kreidelmeyer et al., (2020).
[196] Prognos calculates the cost reduction potentials of the individual technologies taking into account the factors of economies of scale, higher production volumes, supply chain development, increased degree of automation in the manufacturing process and further technological innovations.
[197] Cf. Smolinka et al., (2018).

200 - 250 USD/kW (i.e. 176 - 221 EUR/kW) could be achieved by 2030, but do not name the technology used.[198] Due to the market maturity, it can be assumed that AEL is meant. Furthermore, an industry expert interviewed by Global Energy Solutions sees the progression as follows: "For the costs of electrolysers, a target corridor of 150-320 EUR/kW is aimed at in the EU for 2030."[199] This, however, is to be considered ambitious. In China, on the other hand, extremely favourable prices are already being achieved for electrolysis systems, the source adds: "The costs of (alkali) electrolysers in China [today already] amount to **only 260 – 300 USD/kW** [230 - 265 EUR/kW]. These are explicitly not only stack costs, but for the complete system consisting of electrolyser, transformer, rectifier cabinet, control cabinet, alkaline solution, tank and auxiliary equipment frame. When exporting e.g. to Europe, the electrolysers become more expensive according to the codes & standards applicable in the respective region to be supplied."[200]

In the long term, Smolinka et al. find that the CAPEX of PEM electrolysis could be lower than that of alkali electrolysis in the future: The electrolysis cells of a PEM plant are built much more compactly than those of the AEL (3 m^2 /cell AEL vs. < 1 m^2 /cell PEM). On the one hand, this is due to the fact that PEM electrolysis plants are essentially identical in construction, whereas AEL electrolysis plants can vary in construction, which leads to specific material use and thus higher costs. Secondly, the current density at which the membrane of the PEM can be operated is higher (< 1 A/cm^2 AEL vs. 2 A/cm^2). Thus, in practice, significantly more cell area is required for the same amount of hydrogen with the AEL than with the PEM. In addition, the system technology is less complex due to the use of a solid electrolyte, among other things.[201] Above all, the simpler system management and the absence of a liquid electrolyte also mean lower maintenance costs and mean that the OPEX of the PEM plants can also be more favourable than with the AEL. Nevertheless, one disadvantage of PEM electrolysis is the dependence on expensive and rare precious metals such as iridium. This aspect in particular can stand in the way of scaling up decisively, which is taken up again in chapter 2.2.2.7.

The total costs (CAPEX+OPEX) of an HTEL plant are difficult to estimate at the present time, as there are no complete systems ready for the market yet. According to Prognos, CAPEX will therefore be highest in 2020, as expected, at 1,999 EUR/kW electrolysis capacity.

However, the participants interviewed in a study conducted by NOW-GmbH (NOW) from industry and business attribute potentially disruptive properties to this technology, which could

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198 Cf. Hydrogen Council/McKinsey & Company, 2021a.
199 Expert 1, (2021).
200 Expert 1, (2021).
201 Cf. Smolinka et al., (2018).

drive up demand, especially due to the favourable characteristics of the use of waste heat for industry.[202]

Here, too, system costs will still fall, although (probably) not to the level of AEL and PEM by 2030 (**2030: 1477 EUR/kW; 2050: 905 EUR/kW system costs**).

Efficiencies

Despite future potential cost reductions in the CAPEX of hydrogen electrolysis plants due to economies of scale, it must be taken into account that as the load factor of an electrolysis plant increases, the electricity purchase costs account for the largest share of the production costs for hydrogen based on renewable electricity. The more hours an electrolysis plant is operated per year (load factor), the more hydrogen is produced and the CAPEX, i.e. the initial costs for installing the plant, are spread over more units of hydrogen. The cost reduction potential for electricity based on renewable energy sources in Germany remains questionable and the authors of NOW even see the burden of electricity costs as the main obstacle to the market ramp-up of hydrogen electrolysis in *this country*.[203] Internationally, however, significantly lower prices for renewable electricity could be realised in the sun deserts of the world (approx. 1.5 - 2 ct/kWh), which could have a positive effect on the production costs of hydrogen produced in this way. The factors to be considered in this regard are considered further in chapter 2.4.3.7. An important aspect in this respect is the efficiency of the respective water electrolysis technology, i.e. the ratio of (electrical) energy to be expended to the available (chemical) energy (hydrogen) produced after electrolysis. The lower the efficiency, the higher the power loss and the greater the disproportion between input and output, which in simple terms means high electricity costs for a given amount of hydrogen produced by electrolysis.

In comparison, alkaline electrolysis systems have the lowest average efficiency (based on the calorific value,[204] **68%**).[205] For one kilogram of hydrogen with the AEL, **57.9 kWh of electricity** are therefore required. This is higher for PEM electrolysis (71 % - 55.5 kWh of electricity are

[202] Cf. Smolinka et al., (2018).
[203] Cf. Smolinka et al., (2018).
[204] The calculated efficiency depends on how one evaluates the energy content of the hydrogen. This is because the efficiency is the ratio between the **energy used** and the **usable energy**, i.e. the calorific value or heating value of the product. The calorific value of hydrogen is 39.4 kWh/kg, while the calorific value is "only" 33.3 kWh/kg. This discrepancy is due to the fact that the calorific value includes the additional heat that is released during the condensation of the water vapour due to the combustion of the hydrogen.
[205] The stated efficiencies refer to the overall system and not to the efficiency of the stack. This means that the additional energy consumption of the auxiliary units such as compression, cooling, purification and control of the system was taken into account. The efficiency of the stack is therefore higher than that of the overall system.

needed for one kilogram of H_2) and highest for high-temperature electrolysis with 73 % (53.97 kWh electricity/kg H_2), since this technology can also use process waste heat from industry. Projected to 2050 and assuming further technological progress, the Institute assumes that the efficiency of the technologies can be increased even further (71 %, 75 %, 79 %). In the future, it will thus be possible to produce **1kg of H_2** from **50 kWh of electricity** (at an efficiency of 79 % in 2050, see Figure 78). [206]

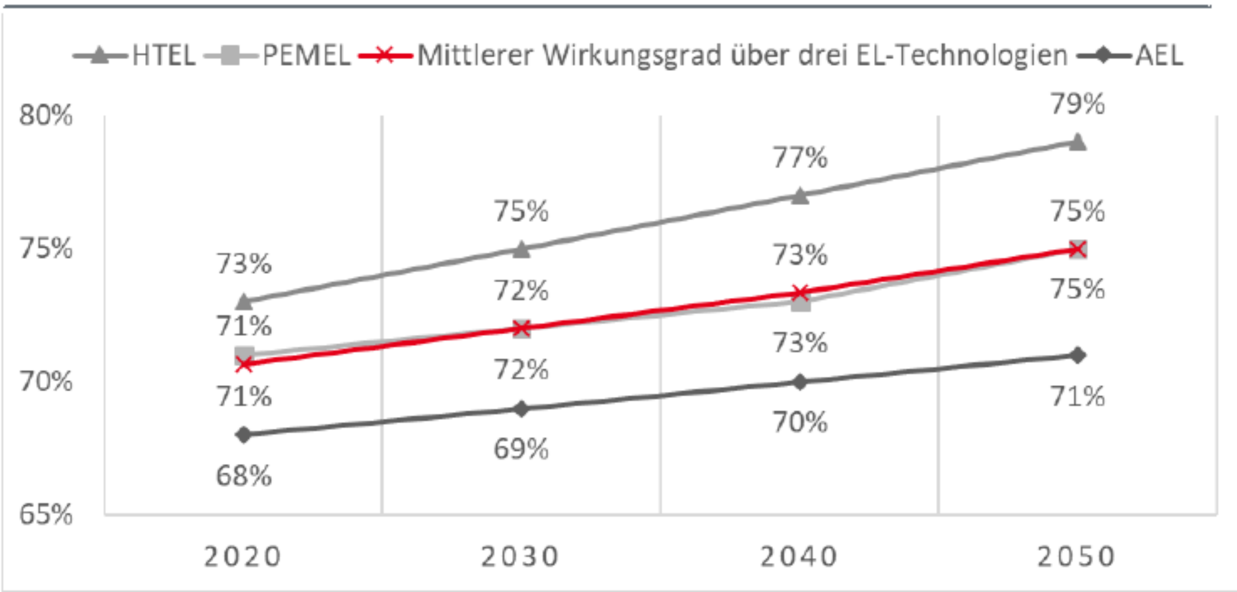

Figure 78: Forecast of the development of electrolysis efficiencies (calorific value-related).

Source: Prognos, 2019

In view of this, it can be assumed that the electricity procurement costs of the PEMEL and HTEL will be lower than those of the AEL, as mentioned above. If it is possible to reduce the CAPEX of PEMEL and HTEL to the level of AEL (e.g. through economies of scale and the use of cheaper production materials), these two technologies could be the cheaper electrolysis systems overall in the future due to the higher efficiencies and the lower OPEX described above.

Further efficiency advantages of PEM and HTEL compared to AEL

In addition to the better efficiencies, PEM and HTEL electrolysis technologies currently have further efficiency advantages over AEL.

The mean values for the start-up time from cold standby to nominal operation are lowest for PEM electrolysis (well below 50 minutes, above 50 minutes for AEL and more than 600

[206] The stated efficiencies refer to nominal load operation, under partial load the efficiencies may deviate.

minutes for HTEL). This time is important because in an energy market based more and more on renewable energy in the future, power availability may vary or be volatile. PEM electrolysers, which can react better to this variation and ramp up quickly as soon as renewable energy is available, have an advantage here. Also, the minimum partial load is less than 5 %, which means that the systems can better handle varying amounts of electricity. However, it should be noted that industry insiders, interviewed by NOW, predict that the standby times of the AEL and HTEL will continue to decrease. In the future, it will be possible to achieve start-up times of less than 50 minutes with all system technologies, with the PEMEL continuing to ramp up the fastest (see Figure 79). [207]

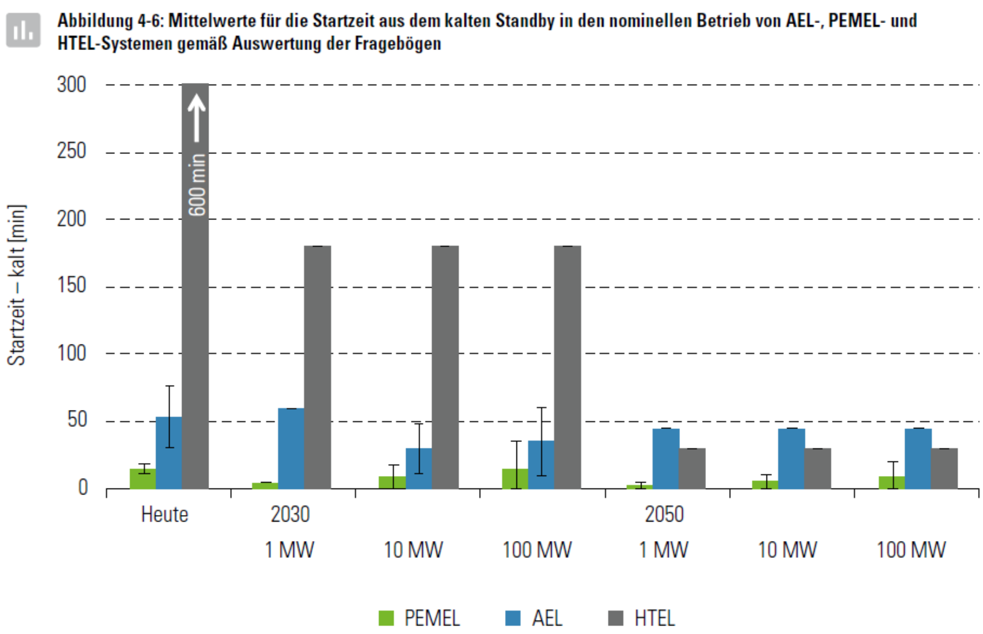

Figure 79: Predicted start-up times from cold standby to nominal operation of AEL, PEMEL and HTEL systems. Source: Smolinka et al. 2018

The properties of high-temperature electrolysis could, as indicated above, be of particular importance for industrial companies when it comes to energy efficiency. Since part of the electrical energy required for electrolysis can be substituted by thermal energy in this technology, waste heat from industrial processes could be used to heat the plants. This saves (renewable) electricity, increases the efficiency of the HTEL and thus lowers the production costs for hydrogen based on renewable electricity (given a sufficient utilisation factor).

In summary, it can be said that the different electrolysis technologies have different advantages and disadvantages. AEL is currently the most cost-effective and established electrolysis technology on the market and has already been realised on a large scale and at low material costs.

[207] In partial load operation, the standby times may differ from those specified here.

However, its efficiency is (still) lower than that of PEM and HTEL and the plants are less compact in design. The PEM, on the other hand, is highly flexible due to its compact design and low standby times but requires rare precious metals for the manufacturing process. HTEL, lastly, already has the highest efficiency among the electrolysis technologies through the use of waste heat, but still requires very high stand-by times and is generally not yet considered a market-ready technology (for a list of the individual aspects of the electrolysis technologies see Table 8).

Realistically, there will probably not be a monoculture of electrolysis technologies on the market in the future, but rather the appropriate systems will be applied depending on the context and area of application.

Table 8: Overview of the different electrolysis technologies.

	AEL	**PEMEL**	**HTEL**
Electrolyte	Basic liquid electrolyte	Polymer solid electrolyte	Solid oxide
Typical temperature level (°C)	60 - 90	50 - 80	700 - 900
Typical pressure level (bar)[208]	10 - 30	20 - 50	1 - 15
Advantage	High degree of establishment/lowest CAPEX cheapest materials	High flexibility (partial and overload capable) Compact design	High efficiencies possible when integrating process heat
Disadvantage	Lowest efficiency Less compact	Rare precious metals (iridium, platinum) needed	Little experience High operating temperatures (700-900 °C)

2.4.3.6 Market ramp-up of hydrogen electrolysis

Despite technological progress, it should not be forgotten that the production process of water electrolysis plants is still almost entirely a manual operation due to the low demand for hydrogen produced in this way.[209] To put this in perspective: in 2019, the Europe-wide capacity of installed hydrogen electrolysers amounted to approximately **92 MW (0.092 GW)**, producing

[208] The higher the pressure at which the plants can be operated, the less energy is required for the subsequent compression of the hydrogen produced. The potential elimination of compressors has advantages on OPEX (less maintenance and servicing costs) as well as CAPEX (less investment costs for additional compressors).
[209] Cf. Smolinka et al., (2018).

about **41 t of electrolytic hydrogen per day and** thus covering about **0.14 % of** hydrogen production.[210] This represents an increase of 33 % compared to the previous year (68 MW to 92 MW).[211] Most installations are in Germany (28), followed by the United Kingdom (13) and France (9). Germany produces the most hydrogen via electrolysis with 17 t per day, followed by Finland with 4 t and Switzerland with 3 t.[212]

On a global scale, consultancies such as AURORA estimate the installed capacity of hydrogen electrolysis systems to be about twice that in Europe, i.e. about 0.2 GW (200 MW). [213]

From the IEA's current database of worldwide electrolysis projects, the cumulative installed and operational electrolysis capacity is 0.363 GW (363 MW).[214] So if we assume that the global production capacity of electrolysis hydrogen is about twice as high as in Europe, i.e. 82 t per day, and compare this figure with the amount of hydrogen produced daily by steam reforming, which in 2019 was about 69 t per year, i.e. about 189,041.1 t per day, it becomes clear[215,] how infinitesimally small the share of electrolysis hydrogen in the global market still is. The literature therefore agrees that in order to increase the supply of low-CO_2 hydrogen, the electrolysis industry must develop into a globally networked gigawatt industry. To achieve this goal, however, it is necessary to further develop the aforementioned manufactory operation with single-digit gigawatt production capacity through series production of standard modules that can then be integrated in terms of process technology. According to the expert we interviewed, who has contacts with manufacturers of electrolysis plants, the plants plan to be able to produce up to 20 GW per year globally as early as 2025 and up to 100 GW and more per year in 2030, depending on market requirements. An important player in the production of electrolysers will be China, where the production of PEMs is currently being massively subsidised by the government.[216] As described above, lower production costs for electrolysis systems are already being achieved there, which could fall even further in the future and provide strong competition for European and American manufacturers. According to the expert interviewed, 10 GW of electrolysis capacity could be produced there alone in 2025. [217]

In their November 2021 study, the Hydrogen Council and McKinsey calculate the global hydrogen demand to set the course for reducing global CO_2 emissions to net-zero by 2050. By 2030, 75 t of "clean hydrogen", i.e. hydrogen with low CO_2 emissions, will be needed per

[210] Cf. Fuel Cells and Hydrogen Observatory, (2021).
[211] Cf. Fuel Cells and Hydrogen Observatory, (2021).
[212] Cf. Fuel Cells and Hydrogen Observatory, (2021).
[213] Cf. Aurora Energy Research, 2021a.
[214] Cf. IEA, 2021a.
[215] Cf. Hohmann, (2021).
[216] Cf. Bork, (2021).
[217] Cf. Expert 1, (2021).

year.[218] By 2050, 660 t (22 % of the global final energy demand). Accordingly, the use of low-CO_2 H_2 in CO_2 -emission-intensive industries has the potential to **prevent the emission of 7 GT CO_2** in 2050. To achieve this goal, **200-250 GW of installed electrolysis capacity is** needed by 2030, plus an annual manufacturing capacity of 45 GW.[219] Thus, by 2050, 3 - 4 TW of installed electrolysis capacity should be achieved (producing approx. 400 - 550 t of hydrogen).[220] Along the entire value chain for low-CO_2 hydrogen, a further USD 540 billion will have to be invested in addition to the already announced USD 160 billion (a total of USD 700 billion).[221] Two observations are important at this point:

1. Hydrogen Council and McKinsey predict that low-CO_2 hydrogen will play a complementary role in global energy supply, alongside other technologies such as renewable electricity, biofuels, energy efficiency innovations, and will become especially prevalent in industries that require high-energy-density energy sources and cannot be directly electrified - such as steel, shipping, aviation, or long-distance transport (see Figure 80).

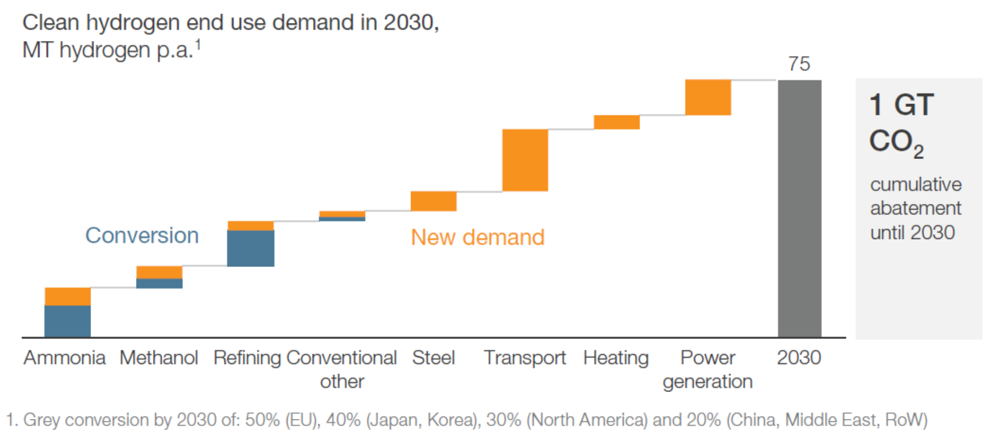

Figure 80: Projected demand for low-CO_2 hydrogen by 2030 by sector.

Source: Hydrogen Council & McKinsey, 2021

2. Hydrogen Council and McKinsey assign an important role for the ramp-up of a global hydrogen economy to the production of low-CO_2 hydrogen, i.e. hydrogen produced on the basis of fossil energy sources with the help of CCUS technology or methane pyrolysis. This is mainly because the establishment of the electrolysis infrastructure, as highlighted here, is *still in its infancy*. In order to achieve a competitive supply of low-CO_2 hydrogen at a comparable market price to conventional hydrogen and thus increase demand, the authors of the Hydrogen Council and McKinsey, but also for example the International Energy Agency (IEA), see the upscaled production of **so-called blue and**

[218] Cf. Hydrogen Council/McKinsey & Company, (2021).
[219] According to expert reports, these production capacities are achievable (see info box on page 19).
[220] Cf. Hydrogen Council/McKinsey & Company, (2021).
[221] Cf. Hydrogen Council/McKinsey & Company, (2021).

turquoise hydrogen as a tool to be able to produce large quantities of low-CO_2 H_2 more quickly and at the same time to "relieve" the ramp-up of electrolysis hydrogen based on renewable electricity.[222] If the above-mentioned 75 t were to be produced exclusively via electrolysis by 2030, this would require an installed electrolysis capacity of approx. 600 GW by 2030 and 5.5 TW by 2050.

Achieving this expansion curve seems questionable in view of the current situation. Hydrogen Council and McKinsey therefore accumulate that of the 75 t, 45 - 55 t are produced on the basis of fossil energy sources in combination with CCUS. This requires an additional expansion of the CO_2 storage infrastructure of 350 - 450 t CO_2 per year. By 2050 and with the increasing ramp-up of "renewable hydrogen", the share of hydrogen based on natural gas in the total quantity of 660 t CO_2 -low H_2 decreases, but still amounts to 140 - 280 t, i.e. approx. 20 - 40 %.[223]

The table below shows different demand levels for hydrogen and the theoretically required installed electrolysis capacity for electrolysis hydrogen based on various recent studies on the subject. From this, it becomes particularly clear that forecasts of the required installed capacity of electrolysis plants depend on the proportion of the total global hydrogen demand that is to be accounted for exclusively by electrolysis hydrogen based on renewable energy sources.

Table 9: Overview of the different hydrogen demand scenarios from the literature.

Source	Date	2030	2040	2050
LBST/WorldEnergy Council	Sept. 2020			270 t 9000 TWh/a approx. 1.5-2 TW insta capacity
PwC study	23.4.2021	88 t approx. 500 - 600 GV installed capacity	137 t 4590 TWh/a approx. 1 TW in- stalled capacity	
PwC study	16.8.21			600 t approx. 4 TW installed pacity
IEA Global Hydro Review	2021	230 t (of which 70 % via ele trolysis or by CCUS) approx. 850 GW in- stalled capacity		500 t 3.6 TW installed capac
Frost & Sullivan	2021	168 t 5.7 t of which from ele trolysis with renewab electricity approx. 50 GW instal electrolysis capacity		

[222] Cf. IEA, 2021b.
[223] Cf. Hydrogen Council/McKinsey & Company, (2021).

Hydrogen Council McKinsey	11.2021	75 t 20-30 t of which with newable electricity approx. 200-250 GW stalled electrolysis ca pacity		660 t 400-500 t of which with renewable electricity approx. 3-4 TW installe capacity
IRENA	2021	154 t 350 GW		614 t 5 TW installed power

According to NOW, the future demand level for electrolysis capacity for *Germany alone* could be **137-275 GW of installed capacity** by 2050 if the German government's climate targets for CO_2 neutrality are to be achieved.[224] However, this is independent of whether hydrogen produced in this way can also be imported from abroad. This comes close to McKinsey's assumption that about 12.6 Mt of hydrogen could be needed in Germany by 2050.[225] If this were to be produced only from electrolysis, the demand would be about 83 GW of electrolysis capacity (assumed utilisation = 5,000 VLH). For comparison, the national hydrogen strategy currently envisages the expansion of electrolysis plants in the country of approx. 5 GW by 2030 and a further 5 GW by 2040.[226]

The authors of NOW-GmbH, but also Hydrogen Council and McKinsey and others, consider the low-temperature electrolysis technologies, i.e. AEL and PEM, to be mature for a market ramp-up and argue that further optimisations and cost reductions can be achieved through scaling (lowering CAPEX) as well as the expansion of renewable energies (to lower the electricity price from renewables).[227] This, they argue, is more important than further research funding, as only through market ramp-up can the potential of economies of scale and a reduction in electricity prices from renewables ultimately reduce the cost of electrolysis hydrogen. Only in the case of high-temperature electrolysis, which has not yet been implemented in a complete commercial system, would further research funding make sense in order to bring this technology to market maturity in the future. In principle, NOW emphasises establishing as many technologies as possible on the market, as this has a positive effect on competition and the most efficient technology prevails in the various sectors,[228] which corresponds to the assessment described above that the market for electrolysis plants will not correspond to a monoculture.

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224 Cf. Smolinka et al., (2018).
225 Cf. McKinsey & Company, (2021).
226 Cf. BMWi, (2020).
227 Cf. Smolinka et al., 2018; Hydrogen Council/McKinsey & Company, (2021).
228 Cf. Smolinka et al., (2018).

2.4.3.7 Limiting factors for the market ramp-up

Trade-offs

McKinsey and the Hydrogen Council estimated in a report at the beginning of 2021 that with a globally installed electrolysis capacity of 65 GW, the associated reduction in CAPEX in optimal regions could achieve production costs similar to those for grey hydrogen, which at natural gas prices of 2.69 ct/kWh **are** around **1-2 EUR/kg or 1000-2000 EUR/t** (see Figure 81).

However, this assumes that CAPEX will fall to 200-250 USD/kW by 2030 (compared to Prognos' figures, this seems optimistic), electricity costs for electrolysis will fall to 13-37 USD/MWh (Figure 82) shows the price level in selected OECD countries in 2020) and an optimal utilisation factor for the plants is achieved (> 50 %).

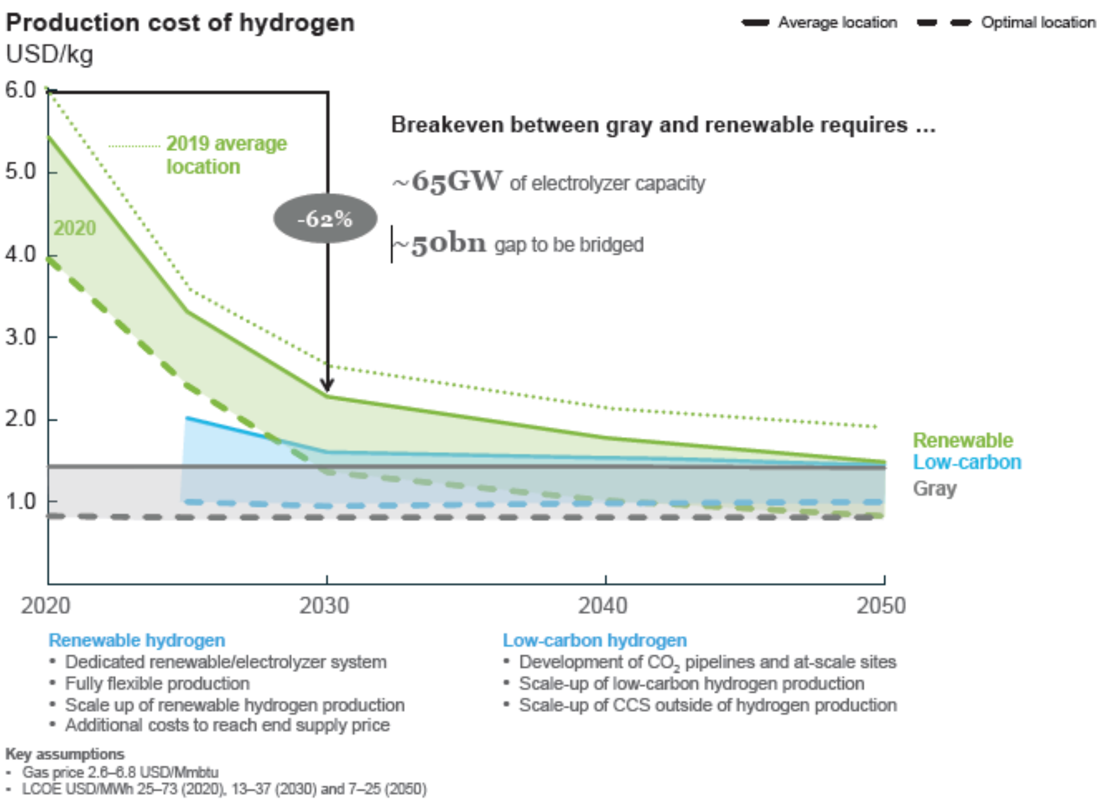

Figure 81: Hydrogen production costs by type of production.

Source: Hydrogen Council & McKinsey, 2021

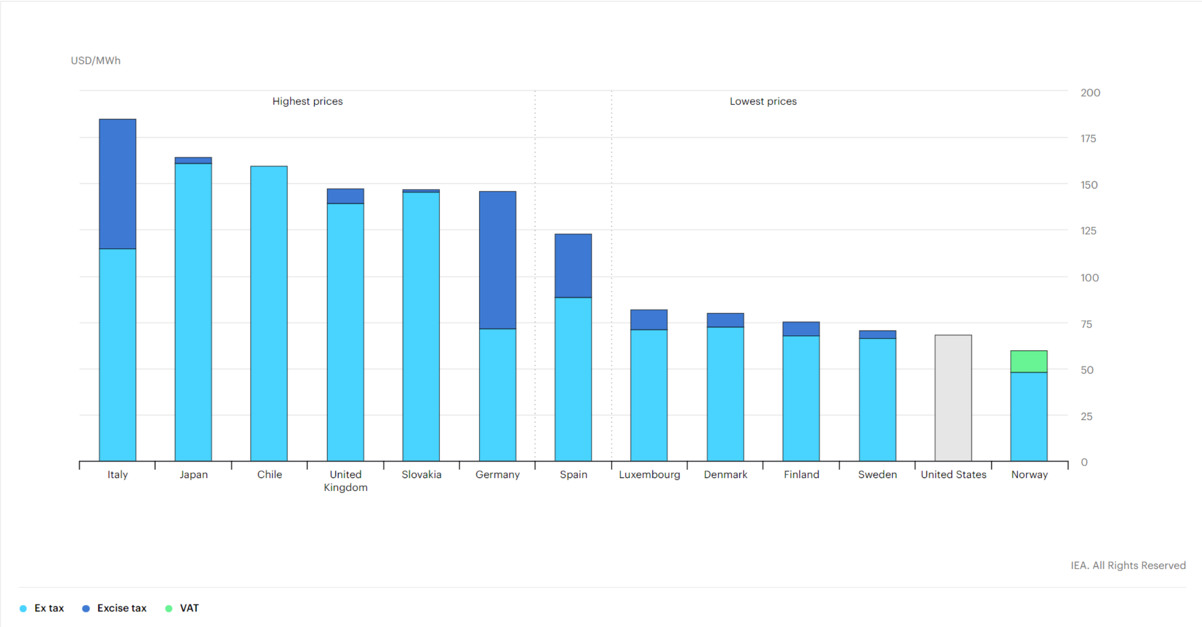

Figure 82: Industrial electricity costs in selected OECD countries 2019

Put simply, decisive factors that influence the production price of hydrogen through electrolysis are thus:

a) CAPEX,

b) OPEX,

c) the electricity and water costs and

d) the utilisation factor

If CAPEX and OPEX are low, electricity and water costs are low and the utilisation factor is high, then the production of CO_2 -low hydrogen, as the Figure 81 can achieve prices comparable to those for grey hydrogen. This results in the following *simplified* equation:

$$Levelised\ Cost\ of\ Hydrogen\ (LCOH) = \frac{CAPEX\ (\$)\ +\ O\&M(\$)\ +\ Inputs(\$)}{Hydrogen\ Output\ (kg)}$$

with

CAPEX (\$) = Investment costs in any currency

O&M (\$) = Operations & Maintenance

Inputs (\$) = Electricity + Water

Hydrogen Output (kg) = depending on load factor

LCOH in selected currency per kh-H_2

The upscaling of electrolysis systems primarily reduces the CAPEX of the plants. CAPEX reductions have the greatest impact on the production price of hydrogen when the utilisation or the full load hours of the system (hereafter load factor) are below 50 %, i.e. the plant produces approx. 4,380 h/a of hydrogen. This is shown by the following model calculations:

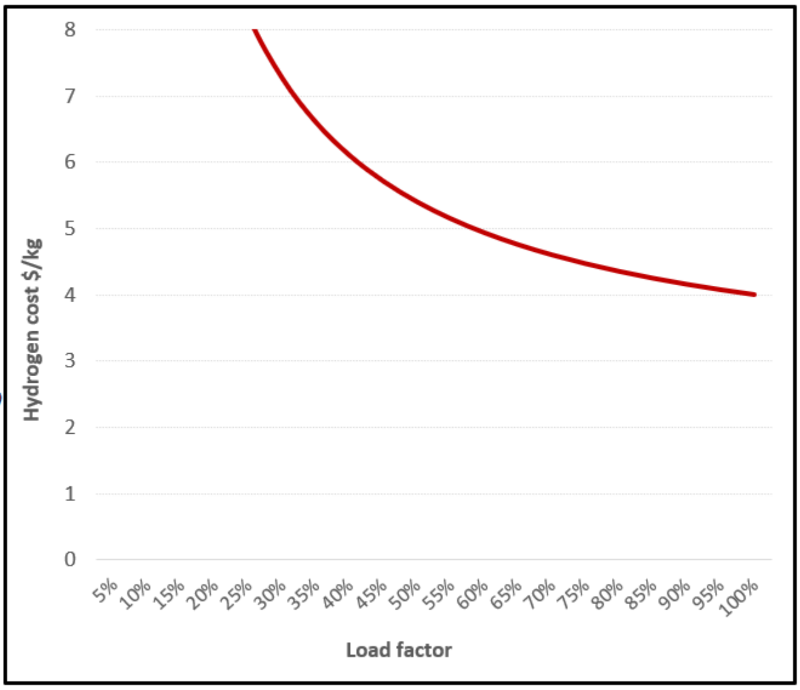

Figure 83: Model A. ; Source: World Hydrogen Leaders, 2021

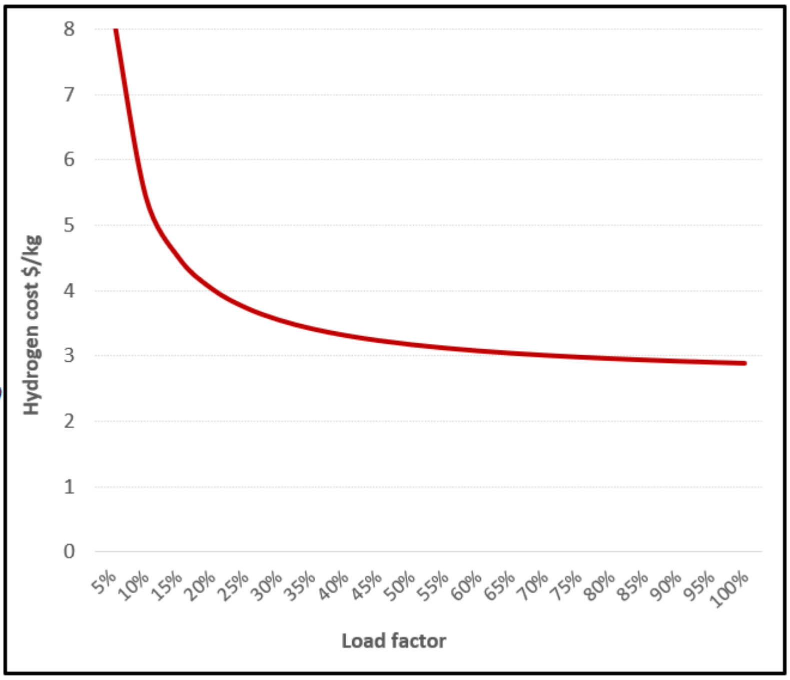

Figure 84: Model B. ; Source: World Hydrogen Leaders, 2021 .

In model A in Figure 83 the system costs as named by Prognos for the year 2020 for the AEL are 878 euros/kW (i.e. approx. USD 985). In model B Figure 84 they are USD 200/kW as calculated by McKinsey and Hydrogen Council for the year 2030. The electricity and water costs are the same in both models (50 USD/ MWh and 1 USD/m^3). It is assumed that at an efficiency of 68 %, 58 kWh electricity/kg hydrogen are required. The OPEX are 4 % of the CAPEX. At a capacity utilisation of 50 %, the production costs in model A are **5.41 USD/kg** H_2 and in model B 3.41 USD/kg H_2. Although a significant reduction in production costs can thus be achieved, it is not possible to achieve a price at the level of the *market price of* grey hydrogen (1-2 euros/kilogram or 1.12- 2.24 USD/kg).[229] This is also not possible if CAPEX is only 100 USD/kW (3.23 USD/kg at 50 % load factor) and the load factor remains the same. However, even if the systems were more heavily utilised, a pure reduction in CAPEX would not significantly reduce the production price any further. Both models show that the curve flattens out as the load factor increases. This can be explained by the fact that CAPEX are distributed over more and more units of hydrogen as production increases and thus account for a smaller share of the total production costs. In *fact, the* electricity procurement costs become more significant with increasing capacity utilisation, as shown in Figure 85 shows using the example of Germany.

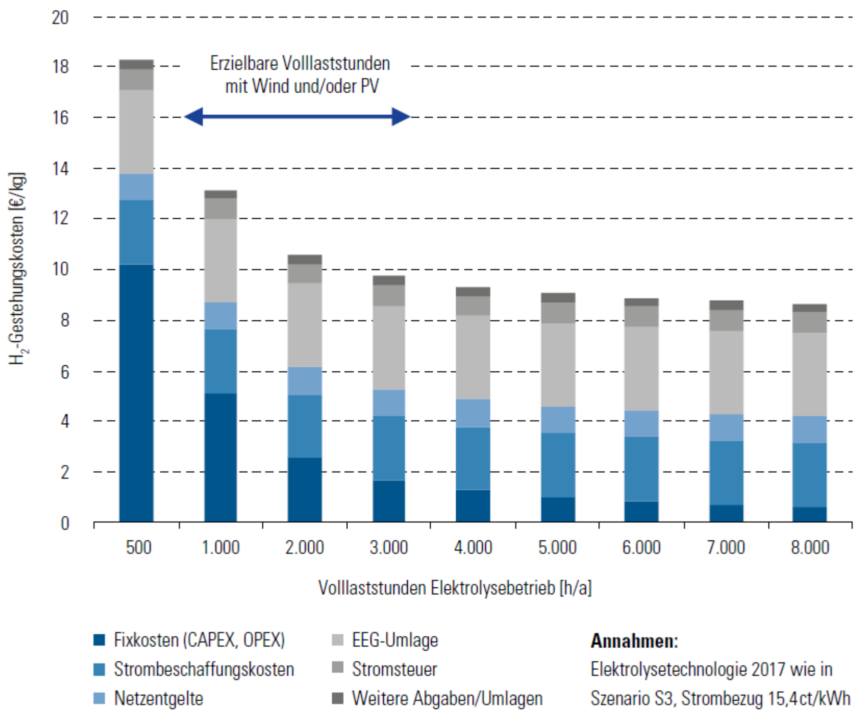

Figure 85: Composition of hydrogen production costs using Germany as an example.

Source: Smolinka et al., 2018 .

[229] It is important to distinguish between market price and production price. The market price is usually higher than the production price of hydrogen, as it reacts to the relationship between supply and demand and includes other costs such as transport costs.

In order to achieve a competitive production price for low-CO_2 hydrogen from electrolysis, the electricity procurement costs must be reduced in addition to the CAPEX and a sufficient load factor must be achieved at the same time.

Assuming a scenario in which electricity prices of around 20 USD/MWh (0.02 USD/kWh) can be realised in the world's sun deserts in 2030, CAPEX for electrolysers fall to 200 USD/kW (McKinsey & Hydrogen Council) and the efficiency of AEL systems rises to 69 % (Prognos), then according to the (simplified) model used here a hydrogen production price of 1.77 USD/kg at 50 % utilisation factor would result. A competitive price to grey hydrogen would be achieved.

In reality, however, there are *trade-offs that* (still) hinder the market ramp-up of low-CO_2 hydrogen through electrolysis. On the one hand, CAPEX for electrolysis plants will probably not fall as far by 2030 as assumed by McKinsey and the Hydrogen Council. According to Fraunhofer ISE and, as mentioned above, Prognos, plant costs of **approx. 500 - 700 USD/kW are** more realistic, which, however, increases the load factor required to achieve a competitive production price. On the other hand, electricity production costs from renewable energies for 0.02 USD/kWh and currently rising prices for PV modules and wind turbines are probably not feasible across the board for the time being, even in the sunny MENA regions, for the required load factor of at least 50 % or more, which is needed for the economic viability of electrolysis.[230]

Prognos shows that if, for example, an electrolysis plant in the sunny MENA region is operated only with a PV system, this results in LCOE of 3.9 cents/kWh, i.e. 39 EUR/MWh.[231] However, an electrolyser (without additional superstructure of the PV fields and battery storage) can only be operated for 3000 hours per year with the electricity directly from the PV system. With CAPEX currently at USD 985 and these electricity prices, the model results in a production price of approx. USD 9/kg with the specified load factor and approx. USD 5/kg if CAPEX drops to USD 500 according to Fraunhofer ISE.

In order to increase the load factor, a superstructure of the installed capacity of the PV plants with additional battery capacity for the operation of electrolysis plants in sunny regions is now possible in order to store the surplus energy and then use it, for example, at night. However, this places an additional burden on the electricity production costs and only appears to make sense if the load factor of the electrolysis plant can be increased to a sufficient percentage and the production price for the resulting hydrogen can be lowered in proportion. With such PV battery solutions, 5,000 hours of full load could be achieved at an electricity production cost of 5-6 cents/kWh (LCOH = approx. 4 USD/kg). [232], [233]

[230] Cf. Theurer, (2021).
[231] Cf. Kreidelmeyer et al., (2020).
[232] CAPEX= 500 USD/kW; efficiency = 69 %.
[233] Cf. Kreidelmeyer et al., (2020).

Furthermore, the additional feed-in of electricity via a wind turbine is conceivable. Such hybrid use could probably achieve more than 5,000 full-load hours, but the electricity production price is around 4-5 cents/kWh (LCOH = approx. 3.5 - 4 USD/kg) due to the additional costs. [234], [235]

Otherwise, the number of full-load hours can be increased by drawing additional electricity from the grid. However, this is usually priced significantly higher than the self-sufficiently produced electricity from the PV or wind system connected to the electrolysis system (electricity from renewable sources in particular).

In summary, for a successful market ramp-up of electrolysis, the various *bottlenecks* (above all CAPEX and electricity production costs) must be addressed *simultaneously.* Because the exclusive reduction of one of these factors does not lead to low-CO_2 hydrogen being able to assert itself on the market against conventional grey hydrogen. Only if low-CO_2 hydrogen can be produced at competitive prices compared to grey hydrogen will *business cases* arise and the market ramp-up accelerate. This requires appropriate government regulation and further investment in the expansion of electrolysis capacities and renewable energies.

Platinum and Iridium

The shortage of precious metals could hamper the ramp-up of PEM electrolysis. Although Smolinka et al. argue on the basis of their survey responses that the manufacturing processes for the mass production of electrolysers are available, they note a possible future shortage of iridium in particular for PEM electrolysis (which is currently the more compact and efficient system than AEL and can be better adjusted to the volatility of renewables).[236] See for more details chapter 2.13.2.

As mentioned, iridium (as well as platinum) is used as a catalyst in PEM electrolysis, as both precious metals are largely resistant to corrosion and at the same time have a sufficiently high electrochemical activity. Currently, the required loading is 0.667 g/kW, which could potentially be reduced to 0.05 g/kW by 2050 through further research. Deloitte Sustainability calculates in an innovative scenario, which foresees that the loading can be successively reduced from 2027 onwards, that the requirement will be at most 540 kg in 2027 and 200 kg from 2046 onwards, which corresponds to about 2.8 % of the annual iridium production in 2016.[237] It

[234] Cf. Kreidelmeyer et al., (2020).
[235] Another possible way to increase the full load hours of an electrolysis plant based on electricity from renewable energies is to use so-called hydropower. However, this is only possible at limited locations.
[236] Cf. Smolinka et al., (2018).
[237] Cf. Smolinka et al., (2018).

should be noted that this only applies to the demand for electrolysis capacity for the German market.

It is currently assumed that 600-700 kg/GW of installed electrolysis capacity will be needed, but in the future this figure is expected to drop to 200-250 kg/GW, or according to companies such as Heraeus, even to a fifth of the current demand.[238]

Natural iridium occurs very rarely in nature, and the annual production rate is 7-9 tons. Therefore, a *very high supply risk is* stated. Further research to reduce loading therefore remains essential, as well as the exploration of further possibilities for substitution and recycling, which is only carried out in small quantities today. Recycling, however, will not be sufficient to cover the demand for iridium in the years of market ramp-up.[239] A so-called circular economy is only possible as soon as enough electrolysers are available and returns accumulate (e.g. due to obsolete plants, etc.).

For platinum, a loading of 0.333 g / kW is currently assumed. Through innovations, the loading level could also be reduced here to approx. 0.0375 g / kW. In the case of this innovative scenario, the demand in 2046 could be approx. **150 kg** for the German market and electrolysis capacity to be installed, which seems low when one considers the annual production volume of **190 tons.** However, Smolinka et al. emphasise that total global demand already exceeds the supply of platinum, and any additional sales market could mean further shortages. Here too, therefore, a *high supply risk is* stated and the need for recycling is emphasised, **which are, however, more promising than for iridium,** since many industries use platinum and returns can be recycled. **Worldwide, for example, 125 t of platinum were already recycled in 2016**. [240]

Iridium in particular will therefore lead to bottlenecks in the future if the **raw material input per GW of** installed electrolysis capacity remains **unchanged** - even if iridium loading were to fall by 92 %, **2.8 % of the world market supply** would still be **needed in 2050 - exclusively for Germany.**[241] A strong reduction in loading or even substitution must be achieved so that PEM electrolysers can be established on the market on a gigawatt scale. Nevertheless, a scale-up of PEM electrolysers is possible to a certain extent. However, due to the problems described above, there will inevitably be upper limits to the installable capacity depending on the demand and availability of iridium.

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[238] Cf. Smolinka, (2021).
[239] Cf. Smolinka, (2021).
[240] Cf. Smolinka et al., (2018).
[241] Cf. Smolinka et al., (2018).

Water availability and seawater desalination

The production of one kilogram of hydrogen theoretically consumes 9 litres of water, i.e. 0.81 litres per Nm^3 of hydrogen. In practice, the water consumption is 5-10 % higher.[242] According to the current state of innovation, water of drinking water quality is needed for electrolysis, which is why locations on inland waterways are particularly suitable for electrolysis plants. However, local conditions must be taken into account when planning electrolysis projects, especially in countries where access to fresh water is scarce and needed to supply the local population.

Seawater desalination is increasingly used in regions suffering from drinking water shortages. In 2020, around 16,000 plants were in operation and the global volume of water produced in this way is around 95 million m^3 per day.[243] This process produced 142 million m^3 of concentrated brine per day in 2019, which contains additional chemicals and dissolved metals whose impact on the environment would be problematic without further treatment. In addition, desalination plants are now powered by electricity from fossil fuels, which emits CO_2 . The current cost of water from desalination plants is calculated at 1.5 EUR/t, excluding the cost of treating the resulting waste.

Since these produced water and waste quantities refer to the status quo, it must be assumed that electrolysis projects in water-scarce regions, where the required water is therefore forcibly obtained from desalination plants, will on the one hand increase the production costs for the hydrogen, since more plants must be built to produce it, and on the other hand could also encounter local challenges if the additional desalination capacity were actually needed for the local water supply.[244] The Fraunhofer Institute's PtX Atlas therefore only considers regions for the potential production of electrolysis hydrogen where there is certainly no water shortage. In addition, the CO_2 balance of the hydrogen produced in this way increases, since the desalination of the required water also emits CO_2 due to the electricity used. For these reasons, research is being conducted worldwide to develop an electrolysis technology that can produce hydrogen directly from seawater without having to rely on external water desalination plants. This requires, above all, suitable membranes, since the membranes used today in electrolysis technology cannot block the salt impurities in the water. However, research is still in the early stages.[245]

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242 Cf. VBI, (2019).
243 Cf. Kreidelmeyer et al., (2020).
244 Cf. Heinemann, (2021).
245 Cf. Tong et al., (2020).

2.4.3.8 Production sites for electrolysis

As already indicated, Germany's hydrogen demand, among others, will not be covered by domestic production through electrolysis. Even with the "conservative" estimates of the National Hydrogen Strategy (NWS), which assume 90-110 TWh demand by 2030, with simultaneous electrolysis expansion to 5 GW (14 TWh), the supply of 76 - 96 TWh hydrogen would not remain given. Therefore, German research institutes see a much higher demand with a view to the time span until 2050. In its current report, for example, Agora Energiewende cumulates a demand of **422 TWh** by 2045 and 500 TWh by 2050. [246]

The Fraunhofer Institute has taken this problem as an opportunity to create the "PTX Atlas", an overview of the worldwide potential for the production of electrolysis hydrogen **on the basis of renewable electricity**, which would then be available for export. In the long term, the institute calculates a total of **109,000 TWh of liquid hydrogen produced in this way**. However, since the Fraunhofer also takes into account concerns about investment security and infrastructure, the realistic expansion capacity is reduced to about **69,000 TWh of hydrogen.** According to the authors, the production volume of electrolysis hydrogen based on renewable electricity **could** thus exceed that of oil (53,610 TWh) and natural gas (45,380 TWh) in 2019.[247] At a capacity utilisation of 5,000 hours per year, this corresponds to about 14 TW of installed electrolysis capacity and a production volume of about 1.5 Gt of hydrogen per year. This exceeds the demand of 660 t calculated by the Hydrogen Council and McKinsey by more than 3 times, which also includes a share of so-called blue and turquoise hydrogen. As described, however, such a production volume exclusively via electrolysis by 2050 is unlikely from today's perspective. Rather, as the IEA and the Hydrogen Council have also pointed out, hydrogen based on methane in combination with CO capture$_2$ is also needed to ramp up a hydrogen economy and meet future demand.

In relation to Germany, according to the PTX Atlas, 778 TWh of hydrogen from electrolysis with renewable electricity would potentially be available via imports from non-European countries, which exceeds the above-mentioned "conservative" demand of 110 TWh according to the NWS many times over but could also cover the previously mentioned demand until 2050.[248]

However, the Fraunhofer Institute points out that when considering import potentials, the distance to the respective export country must definitely be taken into account. Long distances and the resulting increased transport costs could drive up the cost advantages of cheaper production and thus have a negative impact on the cost price. For example, the geographical

[246] Cf. White et al., (2021).
[247] Cf. Pfennig et al., (2021).
[248] Cf. Pfennig et al., (2021).

conditions for the production of electrolysis hydrogen with renewable electricity in Australia and South Africa are considered favourable. However, the high transport costs (potentially) cancel out this advantage. In Morocco, on the other hand, the production costs are higher due to somewhat worse geographical conditions, but the transport costs to Europe are also lower, which is why lower production costs could be realised there overall (approx. 190 EUR/MWh). In addition, hydrogen has to be liquefied for transport and evaporation losses on the way mean that hydrogen imports from far away countries do not seem to make much sense.

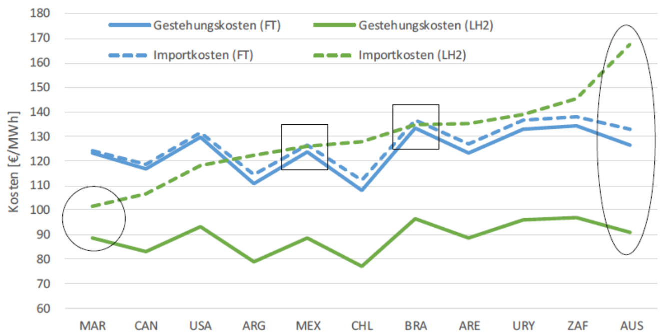
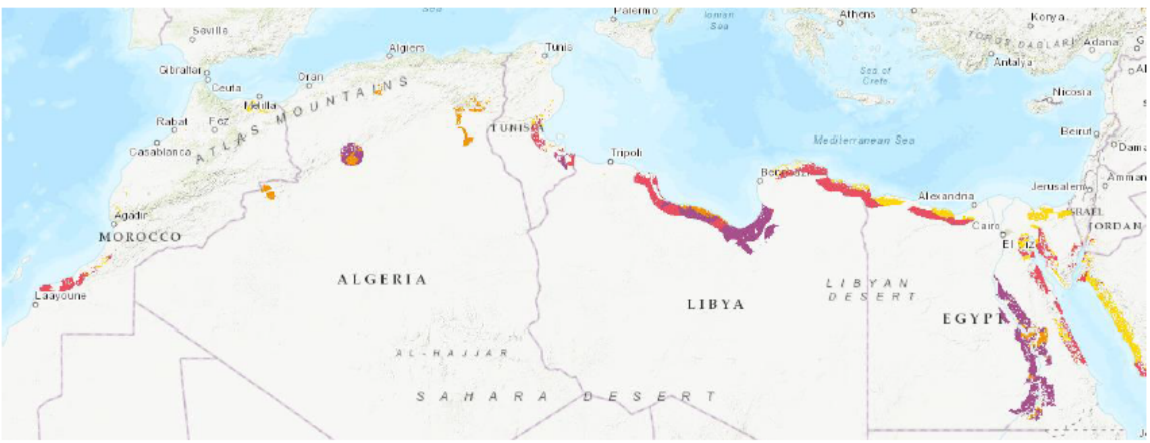


Figure 86: Hydrogen production costs vs. import costs by country.

Source: Pfennig et al., 2021

From North Africa, on the other hand, liquid hydrogen could be transported to Europe via gas pipelines after being produced locally. In addition to Morocco and Tunisia, countries with a higher production potential are Algeria, Libya and Egypt (production potential of a total of 8,638 TWh of hydrogen).[249] However, the socio-economic conditions there are estimated to be significantly worse (especially in Libya) than in Morocco and Tunisia, for example, which can "only" produce 814 TWh of hydrogen. [250]



[249] Cf. Pfennig et al., (2021).
[250] Cf. Pfennig et al., (2021).

Figure 87: Hydrogen development potential in North Africa.

Source: Pfennig et al., (2021).

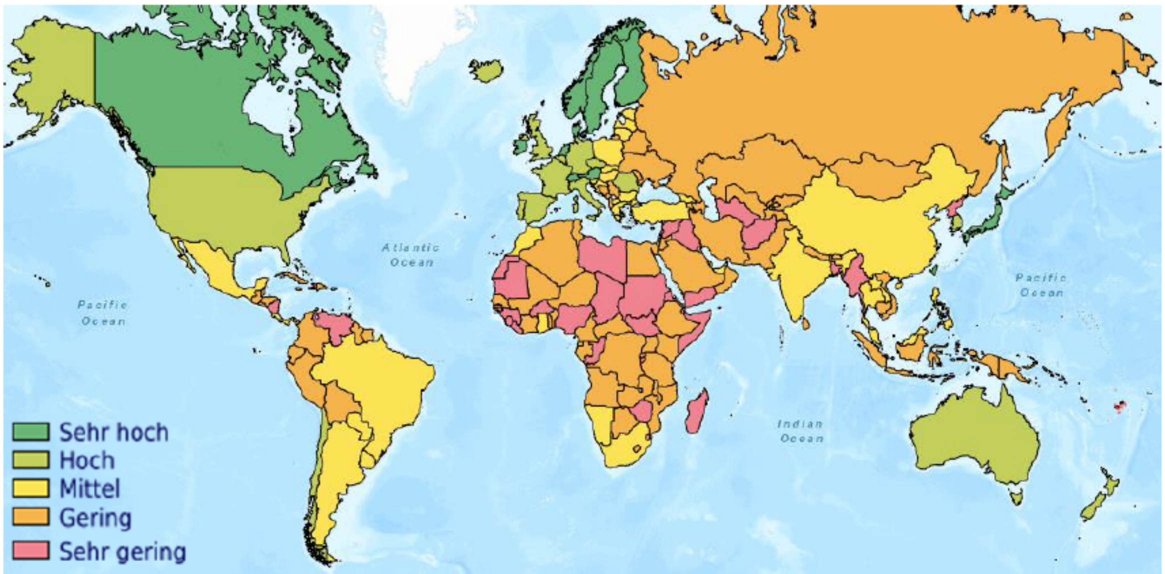


Figure 88: Hydrogen development potential worldwide.

Source: Pfennig et al., 2021

The same applies to Mauritania, from which imports could be made at a lower cost than in Chile, for example (82 EUR/MW), and which, as a "hybrid location", has higher generation capacities than pure wind power locations,[251] but which harbours uncertainties for potential investors due to socio-economic instability (see chart above).

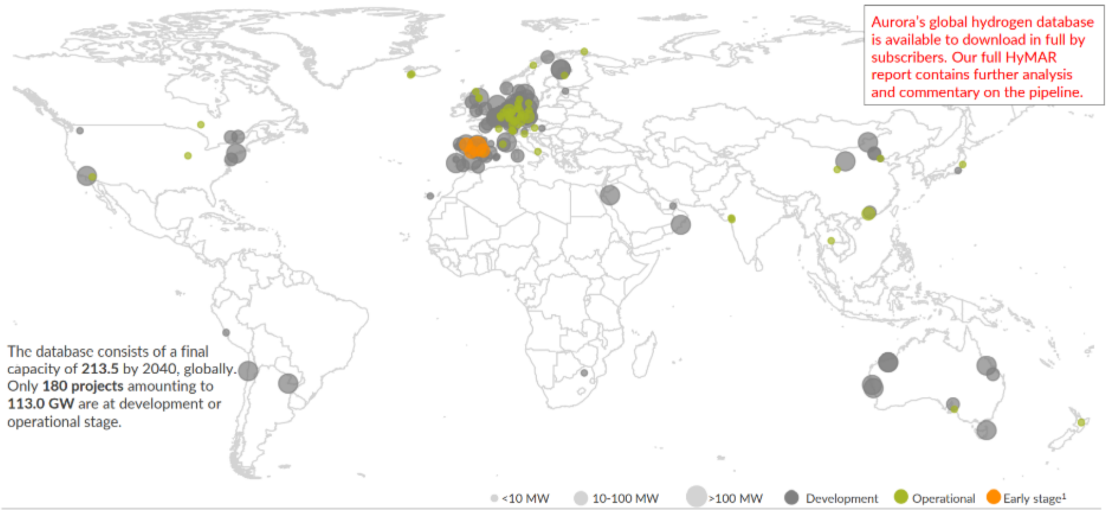


Figure 89: Electrolysis projects currently planned worldwide.

Source: Aurora Energy Research, 2021b.

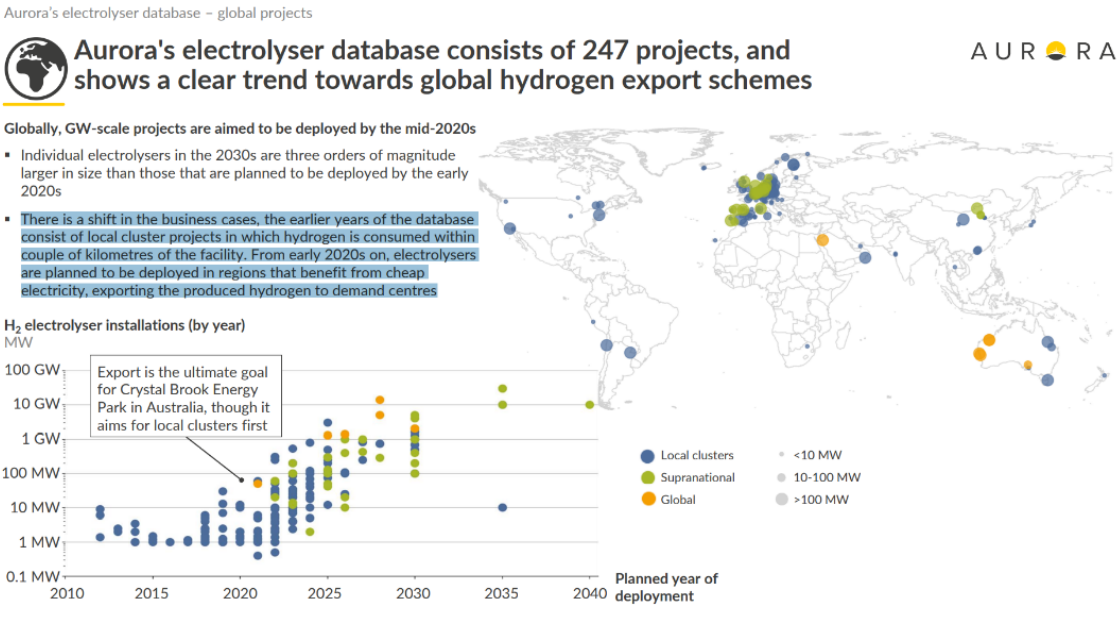


Figure 90: Purpose of use of the produced hydrogen by country.

Source: Aurora Energy Research, 2021 a.

[251] Cf. Pfennig et al., (2021). Fraunhofer IEE defines "hybrid sites" as sites where renewable electricity can be generated from wind power and photovoltaics. The generation potential at such sites is lower than at pure PV sites, but the costs are just as high, since cheap wind power is added to the electricity mix when it is available.

The fact that socio-economic factors seem to play a decisive role for investors is shown by an outlook by AURORA Research on the (currently) planned electrolyser expansion projects worldwide until 2040 (see below).

The majority of these are concentrated on the European continent (85 %). According to this data, only one project in South Africa is planned in Africa. However, cost-effective export to Europe remains questionable. In general, according to the consultancy firm, the trend is towards supranational and global export projects in the electrolysis sector - that is, the quantities of hydrogen produced are not only consumed in the immediate vicinity of the electrolysers, but are explicitly produced for global export (see below).

A key question that arises when exporting electrolysis hydrogen in summary is the possibility of reducing transport costs through new/adapted infrastructure. This question is addressed in chapter 2.5.

The table below lists some large-scale electrolysis projects:

Table 10: Major projects for electrolysis.

Manufacturer	**Electrolysis method**	**Power**	**Location**	**(Advance) Year completion**
NN	AEL	2 GW	Middle East	2023/24
Norsk	HTEL	220 MW	Norway	2026
Linde & ITM Power	PEM	24 MW	Leuna, Germany	2022
TKIS & Industry De Nora	AEL	20 MW	Germany	/
Air Liquide	PEM	20 MW	Quebec, Canada	2021
Shell & ITM Power	PEM	10 MW	Wesseling, Germany	July 2020
Asahi Kahei	AEL	10 MW	Fukushima, Japan	April 2020[252]

[252] All (known) electrolysis projects are listed in the database of the International Energy Agency, online at: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

2.4.3.9 Summary and possible significance for development cooperation

From the above explanations on the topic of electrolysis, the opportunities and problems of the ramp-up of electrolysis technologies worldwide become clear. On the one hand, AEL and PEM are technologically mature and numerous hydrogen projects are currently being initiated (between February and August 2021 alone, the number of announced projects increased by 100 %). On the other hand, there are numerous *bottlenecks to* overcome that stand in the way of the ramp-up: High investment costs, high electricity prices, too low utilisation factors when operating exclusively with renewable energies and still insufficient subsidies and government regulations, as well as - as already mentioned above - high transport costs for imports). Another problem has already been indicated in this context with essential importance for future projects in development cooperation: according to the PTX Atlas, countries on the African continent have great potential for producing hydrogen by means of electrolysis with renewable electricity. However, the socio-economic situation in terms of infrastructure and investment security discourages potential investors from the private sector from implementing electrolysis projects in countries such as Libya, Algeria, Mauritania or Egypt. At the same time, these countries often do not have the means to promote their own national hydrogen strategies, also because technologies such as PEM electrolysis are still associated with high costs. The opportunities for both low-income and high-income countries arising from a functioning global hydrogen economy are equally high. So-called "green clusters" in which electrolysis hydrogen is produced could lead to the promotion of sustainable industrial development through positive spill-over effects in regions that have been poorly developed so far.

In terms of SDGs 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation and Infrastructure), this technology transfer offers the opportunity for the production and distribution of alternatives to fossil fuels and needs to be accompanied by grants and loans for local infrastructure as well as policy incentives. These and other opportunities for international cooperation in the hydrogen economy, particularly with regard to the development of critical infrastructure, are discussed further in the following chapter.