Study IndWEDe – Brief Overview

Industrialisation of water electrolysis in Germany: Opportunities and challenges for sustainable hydrogen for transport, electricity and heat

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Industrialisation of water electrolysis in Germany: Opportunities and challenges for sustainable hydrogen for transport, electricity and heat

COMMISSIONED BY:

Federal Ministry of Transport and Digital Infrastructure (BMVI),
Invalidenstraße 44, 10115 Berlin

REPRESENTED BY:

Project Management Jülich - Fuel Cell and Hydrogen (ESN 5)
Forschungszentrum Jülich GmbH, Zimmerstraße 26–27, 10969 Berlin

COORDINATED BY:

National Organisation Hydrogen and Fuel Cell Technology – NOW GmbH,
Fasanenstraße 5, 10623 Berlin

AUTHORS

Tom Smolinka, Nikolai Wiebe, Philip Sterchele, Andreas Palzer
Fraunhofer Institute for Solar Energy Systems ISE/Freiburg – Germany

Franz Lehner, Malte Jansen
E4tech Sàrl/Lausanne – Switzerland

Steffen Kiemel, Robert Miehe, Sylvia Wahren, Fabian Zimmermann
Fraunhofer Institute for Manufacturing Engineering and Automation IPA/
Stuttgart – Germany

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LIST OF ABBREVIATIONS

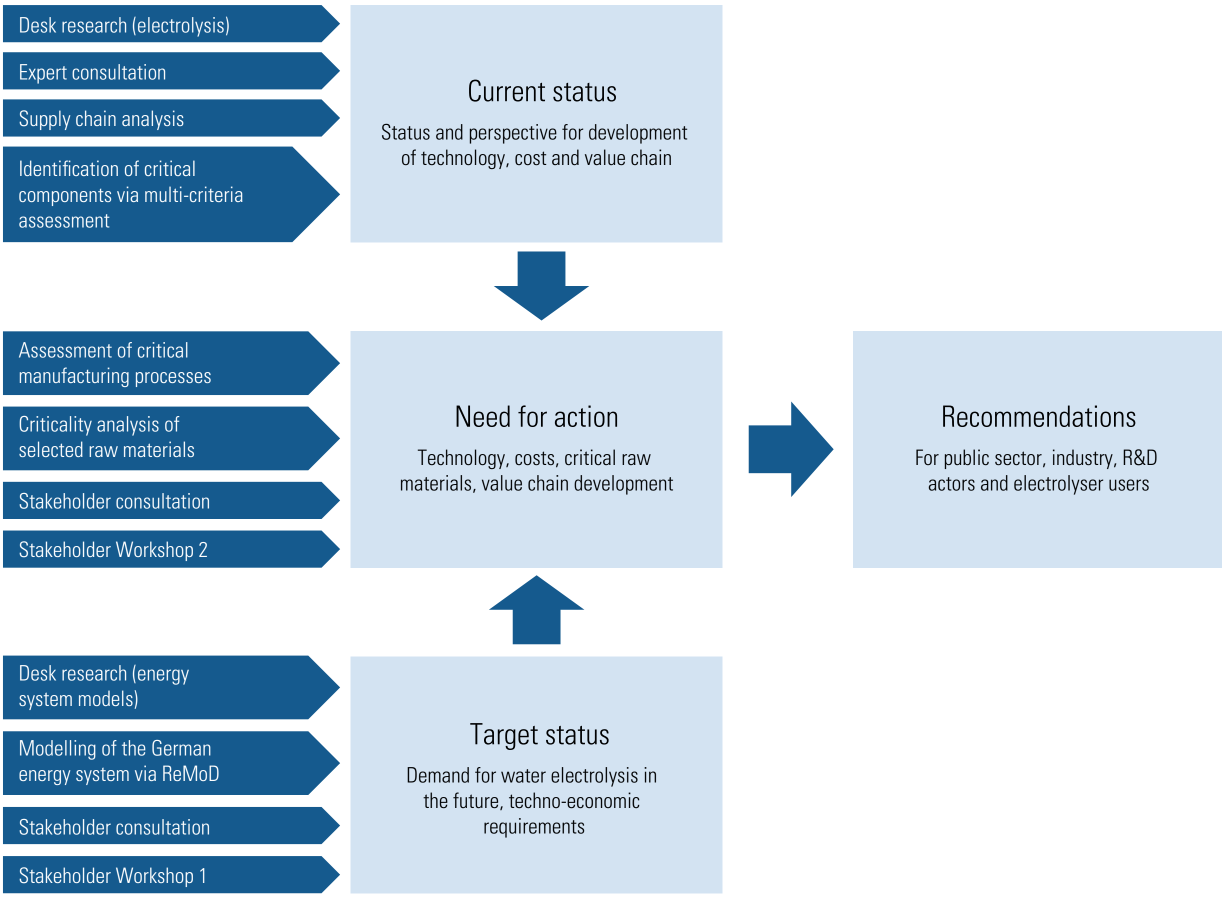
AEL	Alkaline electrolysis
BOP	Balance of plant
BPP	Bipolar plate
CAPEX	Capital expenditure
CCM	Catalyst coated membrane
CCS	Carbon capture and storage
EEA	Electrolyte electrode assembly
EEG	Erneuerbare-Energien-Gesetz (engl.: Renewable Energy Law)
EOL-RIR	End of life recycling input rate
H_2-GT	Hydrogen gas turbines
HHI	Herfindahl Hirschmann index
HT	High-temperature
HTEL	High-temperature electrolysis
IEK2050	Study "Legal framework conditions for an integrated energy concept 2050 and the integration of renewable fuels" (working title)
KPI	Key performance indicator
LHV	Lower heating value
M/O	Maintenance and operation costs, in this study, electricity cost is not included in M/O costs
MEA	Membrane electrode assembly
NIP2	Second National Innovation Program for Hydrogen and Fuel Cell Technology in Germany
OPEX	Operational expenditure
PEM	Polymer electrolyte membrane/proton exchange membrane (used interchangeably)
PEMEL	Polymer electrolyte membrane electrolysis
PTL	Porous transport layer
PV	Photovoltaics
PVD	Physical vapour deposition
R&D	Research and development
RCS	Regulations, codes and standards
RE	Renewable energies
RED2	Second EU Renewable Energy Directive
REMod-D	Renewable energy system model Germany
S	Scenario
SME	Small and medium-sized enterprise
SOFC	Solid oxide fuel cell
WGI	Worldwide governance indicators

1 Context and scope of the study

The continuous expansion of renewable energies, the intensification of global efforts to drastically reduce greenhouse gas emissions and the declared goal of limiting global warming to well below 2 °C are steadily increasing the importance of hydrogen as a chemical energy source. Water electrolysis is the central conversion step for the coupling of renewable energies (RE) with hydrogen and any other derivatives. A considerable expansion of electrolysis capacities is, therefore, expected in the coming decades. Numerous studies predict installed capacity in the high, double-digit gigawatt range for Germany alone by 2050. However, today, electrolysers are manufactured to order with very little automation and high labour content, so the question arises as to how and under what conditions production capacities can meet future demands.

For this reason, the Federal Ministry of Transport and Digital Infrastructure in Germany has commissioned this study to examine the technical, manufacturing and economic potential of electrolysis technologies for scaling up and thereby achieving the ambitious expansion targets. In addition, the scope of the study is to develop a roadmap for the necessary activities in the National Innovation

Figure 1-1: Methodological approach of the study



Program for Hydrogen and Fuel Cell Technology (NIP2) to establish a competitive electrolysis industry in Germany.

This study examined the challenges in setting up a gigawatt electrolysis industry in Germany, especially with regard to critical components of electrolysis systems, their manufacturing processes, necessary supply chains and investment requirements. Furthermore, the most important barriers were evaluated and a demand forecast for installed electrolysis capacity up to 2050 was drawn up. Based on these results, and with the involvement of stakeholders from the electrolysis industry, as well as current and potential future electrolyser users, actor specific needs for action and corresponding recommendations were derived. Figure 1-1 summarises the structure and approach chosen to achieve the study objectives.

The project consortium included the Fraunhofer Institute for Solar Energy Systems ISE, the Fraunhofer Institute for Manufacturing Engineering and Automation IPA and the international consulting firm E4tech. The study was coordinated by the National Organisation Hydrogen and Fuel Cell Technology (NOW GmbH) and overseen by Projektträger Jülich (PtJ) on behalf of the Federal Ministry of Transport and Digital Infrastructure (BMVI).

2 Status and development potential of water electrolysis

To capture the current status and development potential of water electrolysis technology, a literature review, structured interviews with experts and an extensive industry survey were conducted. The three technologies in scope were:

- Polymer electrolyte membrane electrolysis (PEMEL)
- Alkaline electrolysis (AEL)
- High-temperature electrolysis (HTEL)

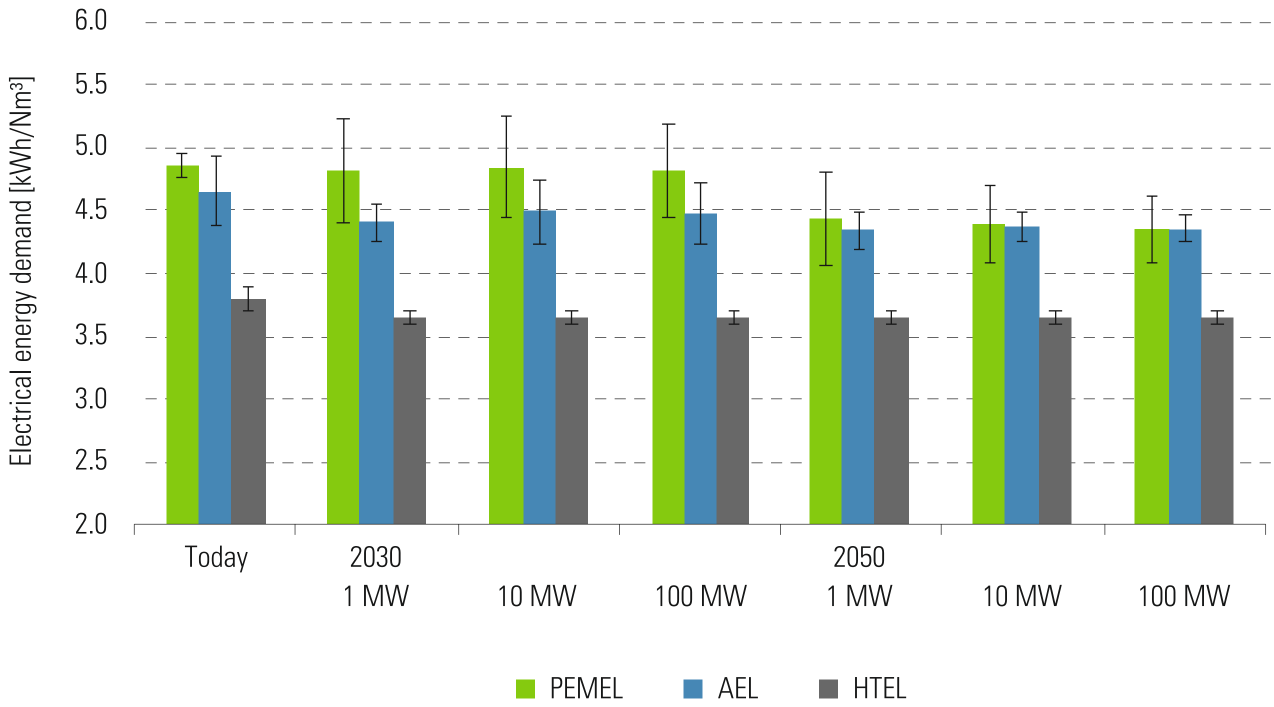
The expectations of industry and academic actors for the future technology development potential towards 2030, and where possible to 2050, was solicited by way of interviews and a survey. As part of the industry survey, techno-economic key performance indicators (KPIs) were collected and the current actor landscape for each of the technologies was captured. For the current status (2017), these parameters were requested regardless of system size, whereas for projections out to 2030 and 2050, the system size (1, 10 and 100 MW) was always specified.

Selected results of the KPI survey are presented below. For further results, please refer to the full report [23]. Given the respondents all work in the field of improving the technology, the survey results may be slightly on the optimistic side. If the authors of this study found clear discrepancy between the prevailing opinion in the literature and the survey results, this was noted in the commentary of the results. The depicted numerical values only reflect the responses from the questionnaires and not the authors' opinion.

Technical performance parameters

The system output pressure range of commercial low temperature systems (PEMEL, AEL) today ranges from atmospheric to approximately 30 bar. In the future, higher pressure ranges of up to 90 bar are expected for both technologies. To achieve this, some of the respondents assumed an additional mechanical compressor for some AEL systems. For larger system sizes, respondents report lower operating pressure, which may be explained by typically lower pressures required in large-scale industrial hydrogen use cases. Pressurised high-temperature stacks (HTEL) are currently only being tested in the laboratory, but may be available for commercial systems in the future. In systems that are currently available an additional mechanical compressor is required to raise the output pressure.

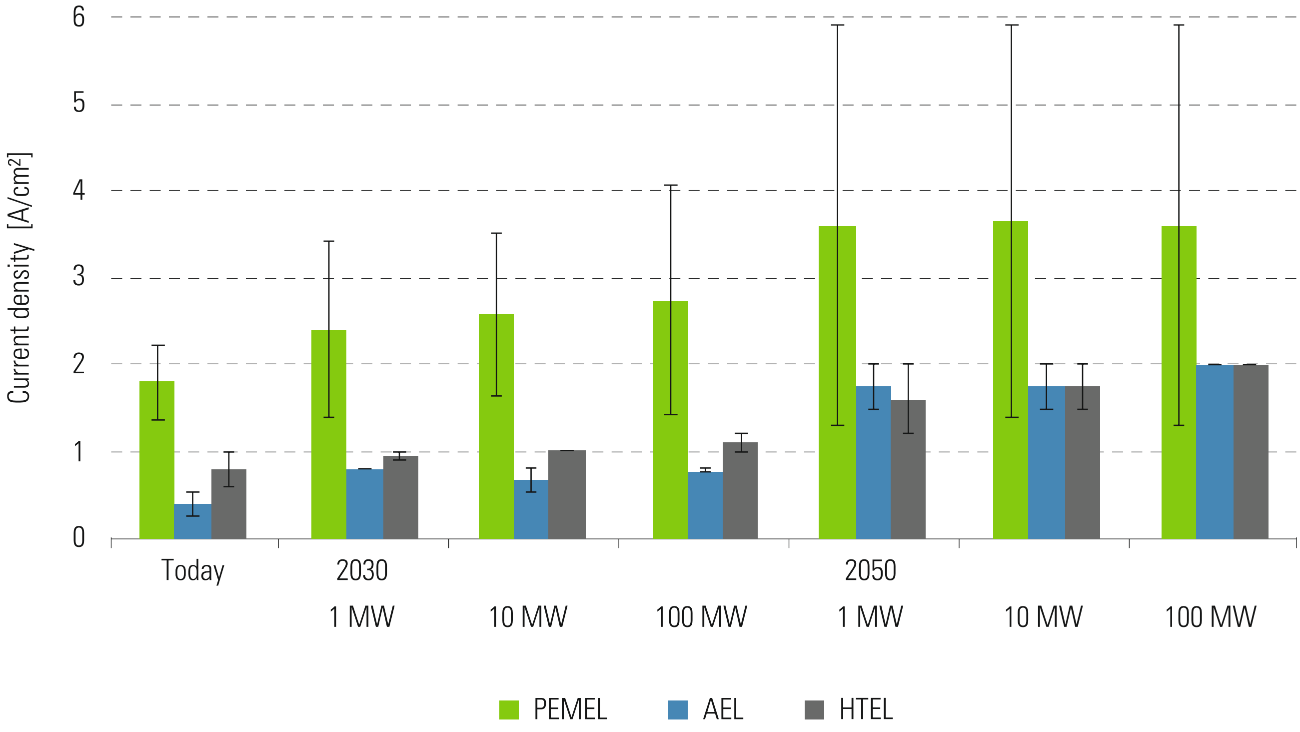
Figure 2-1: Development of the electrical energy consumption of hydrogen production for all three technologies according to the stakeholder survey



Comparison of the current electrical energy consumption in Figure 2-1 shows slightly lower energy consumption for alkaline electrolysis than for polymer electrolyte membrane (PEM) electrolysis. In the next growth period to 2030, this trend is seen to increase before levelling out to approximately 4.4 kWh/Nm^3 in 2050. This can be explained by an economic "catch-up" of PEM electrolysis compared to alkaline electrolysis, that developers expect as soon as system scale and production volumes of PEMEL grow substantially from the current low levels. With high-temperature (HT) electrolysis, the currently reported specific electricity input (excluding energy for steam generation) is around 3.8 kWh/Nm^3 and will only improve slightly to around 3.6 kWh/Nm^3 in the future. It should be noted that the values in Figure 2-1 apply to the system level, i. e. for some respondents this includes power requirements of low-pressure compression upstream of the gas treatment.

In the category of stack size and performance, questions about current density, active cell area, cell temperature and cell degradation were asked in the survey. The parameters active cell area and current density provide particularly useful indication of the future development potential of each technology. This is because both parameters have a direct effect on the scalability of individual stacks and cost reduction potential, e. g. through higher hydrogen production for the same total cell area. As shown in Figure 2-2, PEM electrolysis operates at much higher current densities compared to the other two technologies. This is likely to remain the case into the future, despite considerable growth potential for the current density of alkaline electrolysis.

Figure 2-2: Projection of the current density of AEL, PEMEL and HTEL cells according to the stakeholder survey



Regarding the active cell area (detailed results can be found in the full report) the survey confirms the general development trends. Overall, future cell areas are expected to be:

- well below 10 m² for alkaline electrolysis,
- less than 1 m² for PEM electrolysis, and
- less than 0.1 m² for high-temperature electrolysis.

The difference in cell size of one order of magnitude between the three technologies, combined with the differences in current densities (see Figure 2-2), imply entirely different cell and stack designs and hence different manufacturing processes and associated challenges.

Also not shown here is the future development of cell operating temperatures (detailed results can be found in the full report). The responses are broadly in line with literature, as far as PEM and high-temperature electrolysis is concerned (< 100 °C for PEM electrolysis and < 800 °C for HT electrolysis) [22]. Interestingly, some actors in alkaline electrolysis expect that temperatures can be increased to over 200 °C in the long term.

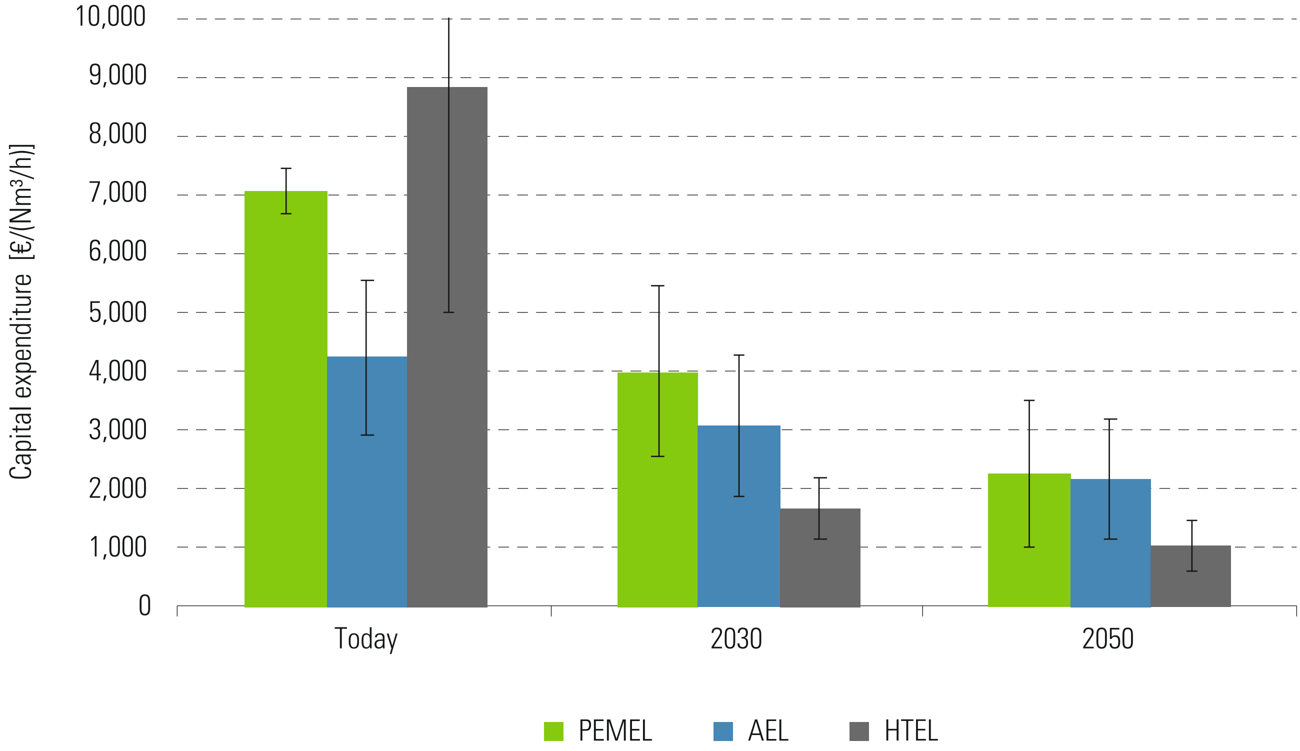
When forecasting stack life, respondents expect significantly improved service lifes in the future, even if the forecasts differ quite strongly from each other. Considerable potential for improvement of HTEL, in particular, is expected and operating times of over 80,000 hours are considered to be possible. HTEL may benefit from the progress already made in high-temperature solid oxide fuel cells (SOFC), but the ultimate lifetime of HTEL systems will likely depend on the operational profile in specific applications, and that may be dictated by the needs of the future energy system. In the longer term, operating hours of approximately 125,000 hours are considered feasible for PEM electrolysis. However, the values for 2050 cannot be confirmed by literature and are an indication that there is, in principle, considerable potential for improvement. The survey respondents indicated a rather conservative life span for alkaline electrolysis. However, the authors expect that the life span of alkaline electrolysis will be at least equivalent to PEM electrolysis in the future. The service life of the systems for all technologies is stated to be 20 to 30 years in the medium term and in some cases up to 40 years for alkaline electrolysis in the long term.

Economic performance parameters

In addition to the electricity costs for operating an electrolyser, the investment costs (capital expenditure – CAPEX) are of vital importance for future economic viability, see Figure 2-3. Due to a lack of system size-specific responses in the survey, the mean values for all system size classes (1, 10, and 100 MW) are shown. Overall, the picture from the survey is largely in line with the estimates from literature regarding expected cost developments in AEL and PEMEL technologies [15, 20, 21]:

- Alkaline electrolysis is already available at comparatively low cost and is particularly suitable for larger systems of 10 MW or higher. In the long term, comparably small cost reductions are expected due to limited economies of scale in AEL technology. From the authors' point of view, the survey results for the long-term CAPEX development can be considered as too conservative.
- For PEM electrolysis, the commercialisation of large systems is still in its infancy, so it is conceivable that there is still potential for substantial cost reduction. In the medium term, production costs are expected to be comparable to those of alkaline electrolysis. In the long term, PEM technology even holds potential to be lower cost than alkaline electrolysis.
- High-temperature electrolysis is considered a potentially disruptive technology, which offers significant scope for cost reduction. However, as HTEL technology is still in an early phase of commercialisation, data and cost estimates are based only on a small number of responses to the survey. Thus, HTEL has the largest uncertainty associated with the future development compared to the other two technologies. From the authors' point of view, it is debateable whether HTEL could be of significantly lower cost than AEL and PEMEL; considering that a large part of future system cost is likely to be attributable to peripheral components and power supply. Hence, system cost would be broadly independent of the technology choice.

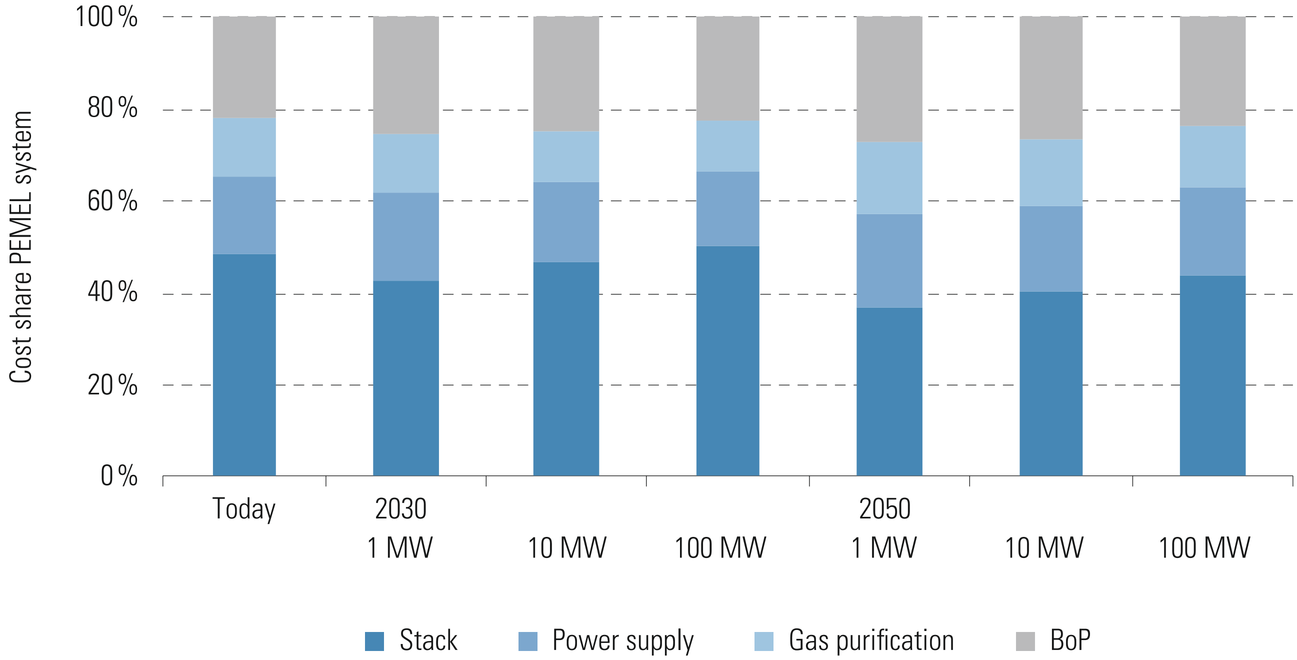
Figure 2-3: Projection of investment costs (CAPEX) of AEL, PEMEL and HTEL according to the stakeholder survey



Besides the system CAPEX data, the survey also tried to gain insight into the cost share of major components in the system and stack. Figure 2-4 shows the results for PEM electrolysis. Different survey participants will have assumed different stack designs and system configurations, and hence the answers are not fully consistent, but basic trends found in literature [4] are confirmed. Cell components (and hence stack cost) will likely fall in costs, as higher production volumes allow for optimised manufacturing processes. At the same time, the relative share in system cost for power supply components will likely be growing as other components, such as stack costs, fall. Given that transformers and rectifiers are produced at scale today for other industries, growing demands from the electrolysis sector will have little effect on their cost. However, since future deployment is likely to be dominated by larger plants of the 10 MW and 100 MW class, these larger systems will benefit from optimised and centralised balance of plant (BOP) components (gas and water treatment, cooling, etc.), as well as from more cost-effective, larger transformers and rectifiers. On the contrary, stack costs are less dependent on system scale, since they are intrinsically modular and larger systems are built by increasing the number of stacks (“numbering up”). For this reason, the relative share of stack costs, compared to the other components, will likely increase with the size of the system.

These trends also apply to AEL, although there is a less pronounced shift in the cost share. Since the technology is already mature, future cost reductions tend to be more uniform across the different components.

Figure 2-4: Proportion of key components of PEM electrolysis of the total system costs, according to survey returns



Due to the limited number of responses for high-temperature electrolysis, a robust evaluation of the cost share was not possible. The current opinion of the players in this technology is broadly that stack costs and power supply each account for about 30 % of system costs. Gas cleaning and other peripheral components, including heat exchanger and heating elements, contribute to the remaining 40 %. No significant shift in the cost share for larger systems is expected. This underlines the modular construction approach based on the "numbering up" concept, which is likely to be pursued in the long term as well, e. g. by building 100 MW systems using fleets of many small modules or subsystems.

Overall status of the water electrolysis industry

The increased interest in water electrolysis has led to a dynamic development of the electrolysis industry over only a few years. Based on the expert interviews conducted, the following statements can be made about the global industry:

- The turnover of water electrolyser system manufacturers is estimated at 100 to 150 million € per year.
- The annual capacity sold varies year-on-year due to individual large-scale projects. The total sold globally in 2016 is considered to be less than 100 MW, although the market has been growing since then.
- It is estimated that around 1,000 employees work directly for system providers. In addition, there are employees working for suppliers who are usually not solely attributable to the water electrolysis industry.
- According to manufacturers, worldwide water electrolysis production capacities totalling approximately 2 GW per year, could be built in the short term (by 2020),

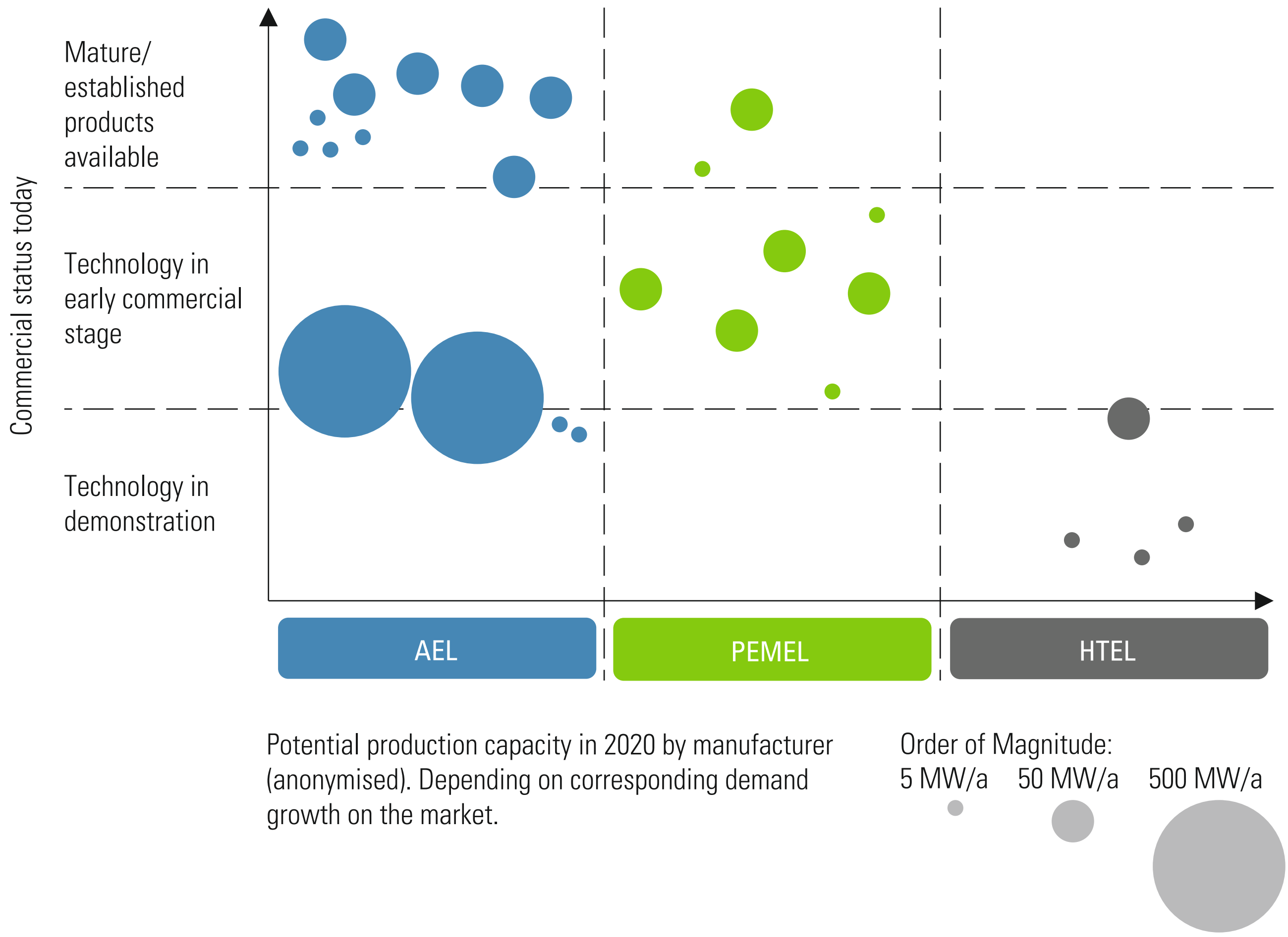
see Figure 2-5. About one third of these are attributed to European manufacturers. This short-term potential is dominated by companies from the chlor-alkali industry, who already have corresponding supply chains.

Structure of the industry and working methods

Since the market for large systems in the megawatt range is currently very limited, these are exclusively built specific to customer requirements. To go from commission to delivery of systems in the multi-megawatt range typically takes around one year. However, most manufacturers work with largely (in-house) standardised product platforms that rely on stacks with identical design. Smaller stacks in the sub-megawatt range are also kept in stock, which, for example, are used to supply existing industrial customers with replacement components quickly.

Most electrolyser manufacturers currently carry out the system integration in a largely manual and workshop-type production. However, some players are already using series production approaches, in which the product (often beginning production as an empty container on wheels) moves from station to station in the production line. Several manufacturers work with pre-assembled peripheral components, others are planning this for the future. Important future developments in system integration, which are not automated to date, will likely be manual mounting and assembly steps.

Figure 2-5: Development status of various electrolysis technologies and characterisation of the main suppliers per technology (anonymised)



Stack assembly, with its large number of identical parts stacked on top of each other, is the most suitable process for partial automation. However, so far none of the manufacturers interviewed have reached the threshold of production volumes above which the investment in partial automation of stack assembly would be economically viable. By contrast, for some stack component suppliers, production is already semi-automated.

Production depth and supply chain structure

The discrepancies between the current production (approximately 100 MW/a) and the existing and short-term production capacities (approximately 2,000 MW/a within a lead time of two to three years) result from the fact that many companies have major components manufactured externally (or could do so if needed) and these suppliers can react quickly to an increase in demand. However, this differs between the individual electrolysis technologies. With respect to the current industrial structure, there are very few limitations to the procurement of components for AEL technology. By contrast, for PEM electrolysis, know-how tends to be limited to only a few players. The small number of stablished system suppliers tend to carry out many production steps for stack components themselves (e. g. in-house catalyst coating of the membrane). This is also owed to the small number of suppliers worldwide that offer key stack components, such as membranes or membrane electrode assemblies (MEAs). For HTEL technology, there exists a variety of suppliers who normally supply components for high-temperature SOFCs. However, HTEL systems are still produced in such small quantities that an established supply chain does not yet exist. Across the three technologies, it was reported that the power supply (transformers and rectifiers) is the system component with the longest lead times (up to one year for multi-megawatt systems).

Future growth and further industrialisation

Overall, companies and their production capacities are growing in line with market developments. As such, an expansion of production is only possible for the players whose order books are filled accordingly. Most system providers are medium-sized companies whose resources for production expansions and expensive further developments are limited. Their business planning is, therefore, primarily tailored to the existing demand at present. Thus, to enable a scale-up of the industry, a high degree of planning security is required for them to invest. To reach such conditions, clear political and regulatory frameworks are needed. It is worth pointing out that the electrolysis industry lacks enterprises with deep enough pockets who can lead the way. This is in contrast to some automotive and oil majors who have strategically invested in advancing the fuel cell mobility sector to strengthen their own long term position.

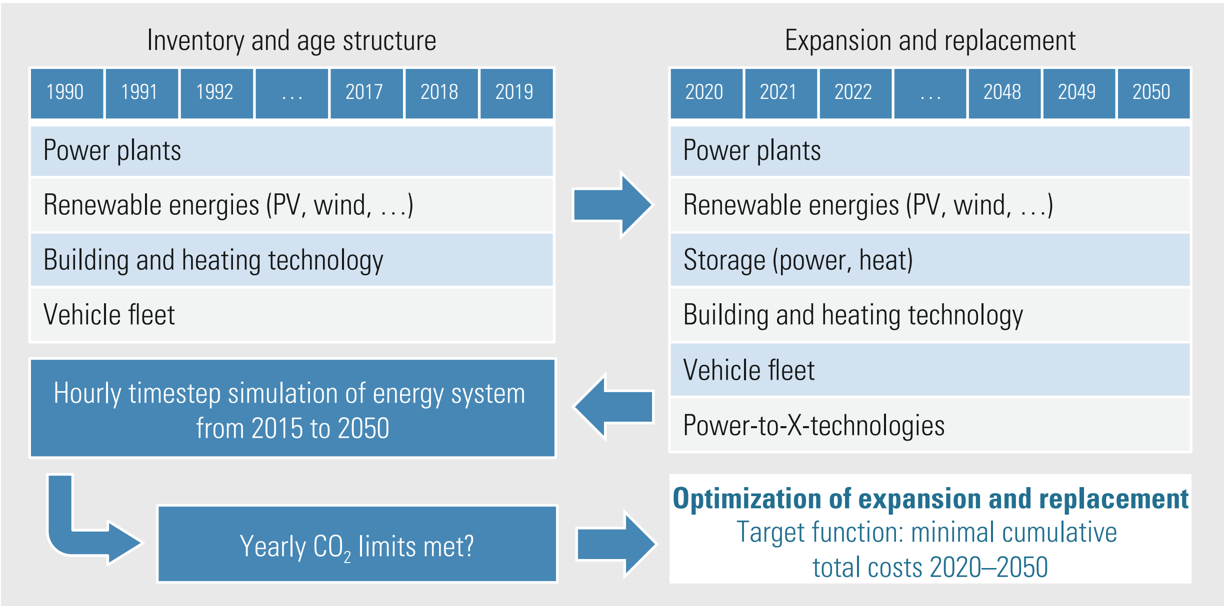
3 Development of electrolysis demand based on energy system modelling

Introduction to the simulation tool REMod-D

The quantification of the future hydrogen demand by sector was carried out with the tool REMod-D – Renewable Energy System Model Germany [8, 19] developed at Fraunhofer ISE. With its freely selectable scenarios, this tool was specially developed to analyse cost-optimised pathways for the transformation of the energy system in Germany towards 2050. The target function of the optimiser is to achieve minimum cumulative total costs for the period chosen (in this study from 2020 to 2050). The tool simulates all relevant producers, converters and consumers in such a way that the energy balances for the entire system and each subsystem are fulfilled at optimal cost in every hour of each year, see Figure 3-1. The maximum permitted upper limit of CO_2 emissions according to the German government's climate protection plan [1] must not be exceeded in any year.

The tool is based on detailed researched data sets containing current and future parameters for all technologies in the sectors under consideration (power generation, heat, transport and industry). Examples of these parameters include acquisition costs, efficiency, service life and maintenance, as well as refurbishment costs.

Figure 3-1: Schematic model structure of REMod-D



Considered scenarios

Table 3-1 summarises all six of the scenarios considered in this study. Unless specified otherwise, all boundary conditions and reference parameters are identical with those compiled by the advisory board of the IEK2050 study [17]. Based on this data, the influence of the CO_2 reduction targets for 2050 (–85 % vs. –95 %) on the future hydrogen demand and thus the required installed electrolysis capacity is investigated in the two start scenarios, S0-85 and S0-95. In scenario S0-95, the import of hydrogen from abroad is also possible.

Table 3-1: Scenario overview

Scenario	Description	Technology Development	Cost	CO_2 reduction by 2050	Model version
S0-85	Start scenario without H_2 import	Advisory board IEK2050	Advisory board IEK2050	85 %	Basis
S0-95	Start scenario with H_2 import	Advisory board IEK2050	Advisory board IEK2050	95 %	Basis
S1	'HTEL-only' scenario	Central trend	Central trend	85 %	Waste heat
S2	Conservative 'AEL & PEMEL only' scenario	Conservative trend	Conservative trend	85 %	Basis
S3	Reference scenario (AEL/PEMEL/HTEL)	Central trend	Central trend	85 %	Basis
S4	Reference scenario (AEL/PEMEL/HTEL) with ramping	Central trend	Central trend	85 %	Ramping

In the other scenarios S1, S2, S3 and S4, the reference parameter set is supplemented by a more detailed analysis of the three electrolysis technologies. This is based on research and surveys on technical and economic KPIs, as summarised in Section 2 and covered in detail in the full report. In these four scenarios, both different operating behaviour, as well as different projections of cost and technology development, are considered:

- Scenario S1 represents a '100 % high-temperature electrolysis only' pathway, taking into account the waste heat potential (> 200 °C) available in Germany for generating the water vapour required. The central development pathway for the technology and cost is based on the mean values of the KPI survey as summarised in Section 2. Given the low electrical energy required in HT electrolysis, and the substantial cost reduction potential indicated in the survey, overall this scenario illustrates a very progressive technology development.
- In contrast, scenario S2 represents a conservative test of technology development: HT electrolysis will not reach maturity, while low temperature electrolysis technologies such as alkaline and PEM electrolysis only show moderate further development by using the mean values of the KPI survey results minus the standard deviation (1 x sigma).
- The scenario S3 assumes a central, most plausible development pathway of all three technologies according to the mean values from the KPI survey (see

Section 2), whereby a ratio of installed electrolysis capacity of 40 % AEL to 40 % PEMEL to 20 % HTEL is assumed by 2050. The weighted parameters used in the model for the years 2017, 2030 and 2050 are shown in Table 3-2.

- Scenario S4 is related to scenario S3, but as part of a model extension, here a dynamic start-up and shutdown behaviour of the technologies included in the model is taken into account. This is combined with adapted parameters such as efficiency during start-up of power plants.

Table 3-2: Parameters of the central scenario S3

Parameter	Unit	2017	2030	2050
Efficiency	[$\%_{(LHV)}$]	64.3	65.5	72.2
CAPEX	[€/kW]	776	613	495
M/O	[% CAPEX/a]	3.5	3.3	3.9
Lifetime	[a]	26.8	25.3	28.1

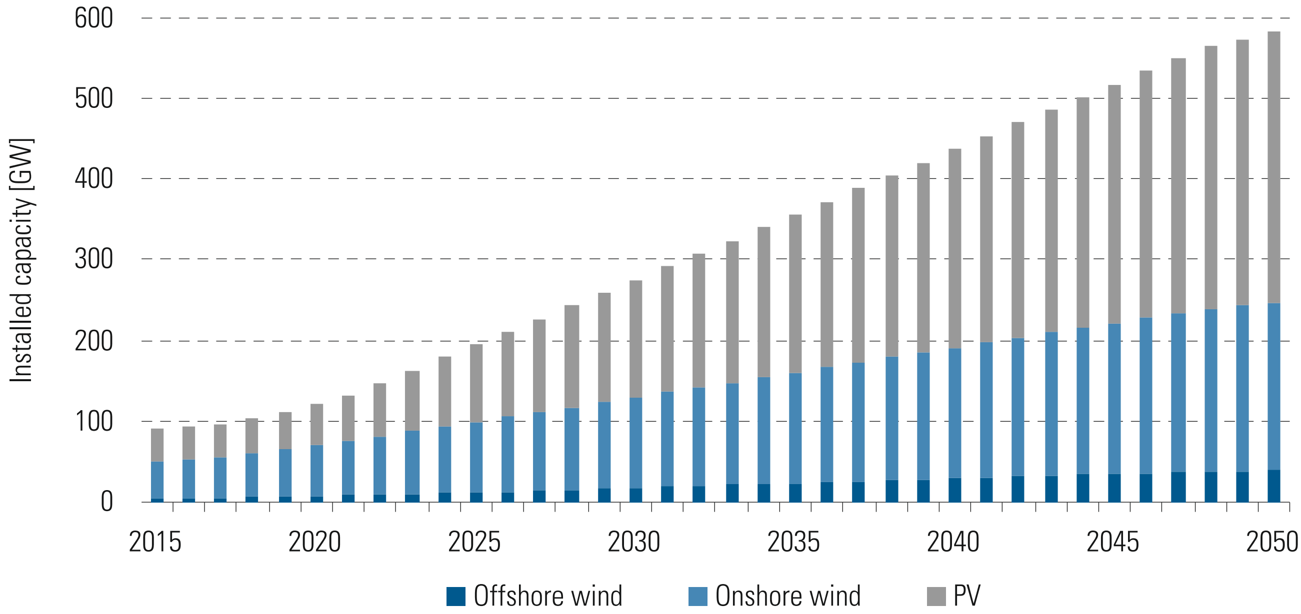
Selected scenario results for hydrogen and electrolysis demand

Key results of the six scenarios are presented in this section. For clarity, selected results of the central scenario S3 are presented first. It should be noted that this study refers to the calorific lower heating value (LHV) of hydrogen throughout.

With the requirement of decreasing CO_2 emissions, the power plant fleet in Germany will be successively converted by 2050. This will be done, among other things, by decommissioning almost all coal-fired power plants and building up additional power generation capacity by way of flexible hydrogen and methane gas turbines. However, the increasing electrification of the entire energy system is mainly made possible by the expansion of fluctuating renewable energies such as photovoltaics (PV) and wind, see Figure 3-2. The current cumulative installed capacity of almost 100 GW shows an increase by a factor of five to six across all scenarios. Of the ca. 600 GW installed capacity in 2050, the ratio of PV to wind (onshore) to wind (offshore) is 9 to 5 to 1.

Coupled with the significant expansion of renewable energies from 2020, hydrogen will also establish itself as an energy carrier with significant additions to electrolysis plants from the 2020s, see Figure 3-3. Hydrogen production by electrolysis plays a dominant role in all scenarios compared with other hydrogen production processes, such as production from biomass. From an installed capacity of approximately 1 GW in 2022, the electrolysis requirement in the central scenario S3 will increase to approximately 200 GW by 2050.

Figure 3-2: Development of fluctuating renewable energies in scenario S3



The most important results for the years 2020, 2030 and 2050 are summarised in numbers in Table 3-3. The year 2017 is used as the reference year for calculating the average deployment rates.

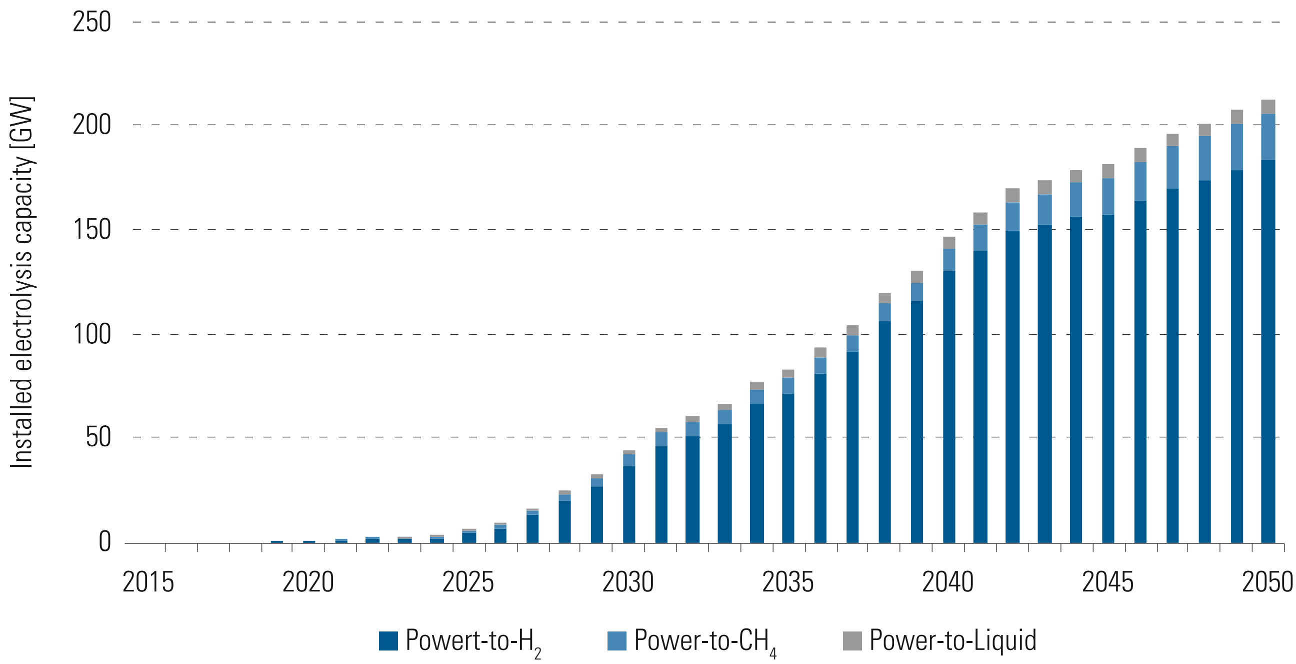
Table 3-3: Summary of results for S3 (range across all six scenarios in parentheses)

Parameter	Unit	2020	2030	2050
Hydrogen demand	[TWh]	0	78 (74 – 138)	294 (261 – 705)
Installed electrolysis capacity	[GW]	0.32 (0 – 1)	44 (7 – 71)	213 (137 – 275)
Avg. deployment rate (relative to 2017)	[GW/a]	0.1 (0.0 – 0.2)	3.4 (0.5 – 5.4)	6.4 (4.2 – 8.3)
Storage capacity	[TWh]	0.8 (0.0 – 1.4)	19 (9 – 33)	96 (59 – 139)

Comparison of all scenarios shows a range from 137 to 275 GW in 2050 for the total installed electrolysis capacity (Table 3-3). Scenario S0-95 yields the lowest deployment of electrolysis in Germany, since the option of H_2 imports from abroad is enabled. It should be noted that import of hydrogen was not allowed in the other five scenarios. This means that the several hundred TWh of hydrogen required to achieve Germany's CO_2 reduction targets must be generated entirely by electrolysers available in Germany. This is in line with the objective of the study to investigate the need for industrialisation of water electrolysis in Germany under the maximum deployment required. Ultimately, the scenarios should not be regarded as predictions of the future deployment in Germany. This will depend on the transformation pathways chosen, as well as market designs and regulatory frameworks, which are for the time being, still unclear. Reference is made here to the IEK2050 study for further discussion [17].

In scenario S3, 6.4 gigawatt electrolysis capacity needs to be added per year on average between 2017 and the year 2050. Across all scenarios, this range is roughly 4 to 8 gigawatts per year, as shown in Table 3-3. Further analysis of the required electrolyser components and critical manufacturing processes were based on the annual additions required in the central scenario S3.

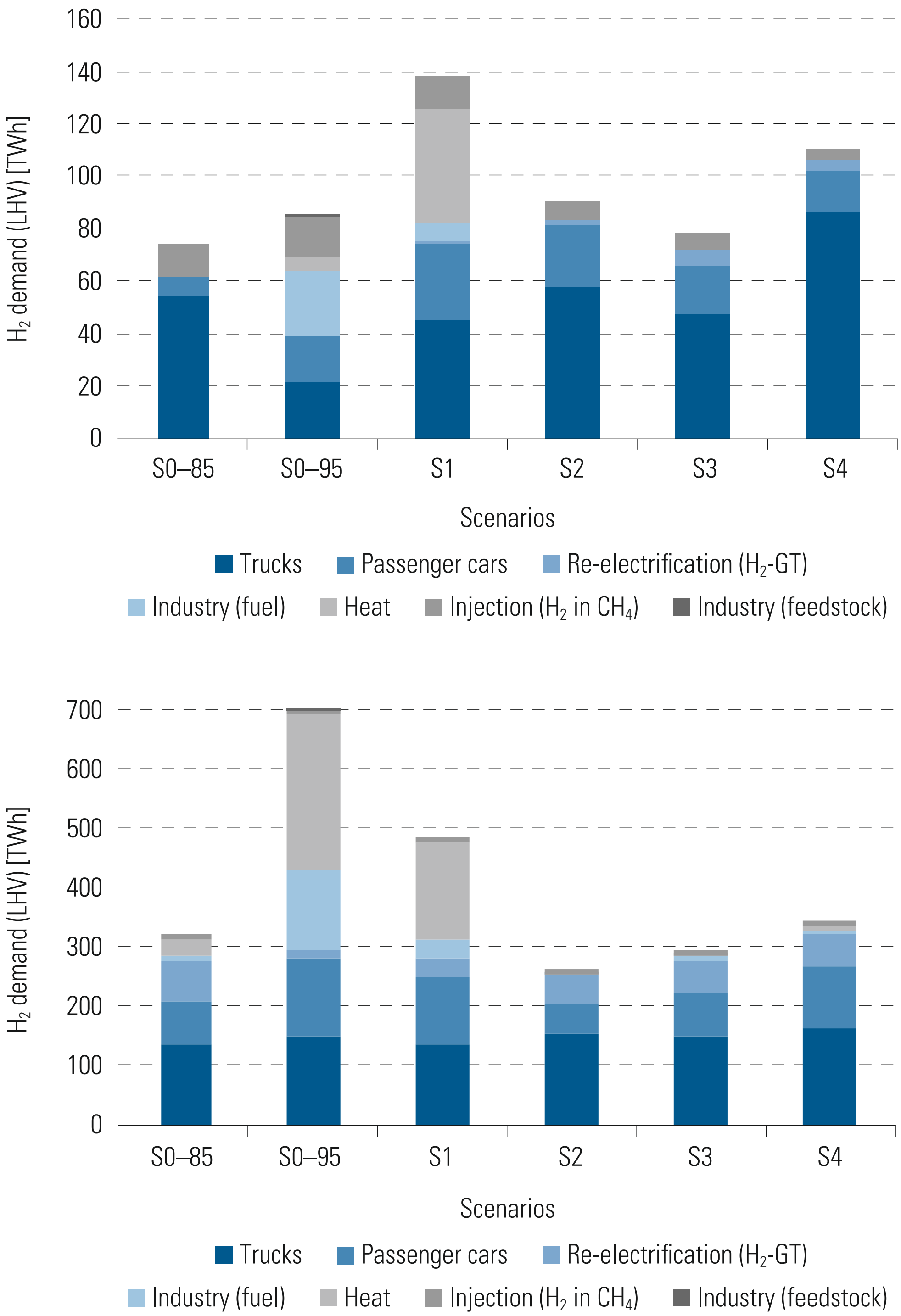
Figure 3-3: Development of installed electrolysis capacity in scenario S3



To investigate the sector specific hydrogen demand, the scenario results by sector for the years 2030 and 2050 are compared. As can be seen in Figure 3-3 a majority of the installed electrolysis capacity is required to meet direct hydrogen demand. Under the conditions of the model, the use of hydrogen for power-to-liquid and power-to-CH_4 routes plays only a minor role.

Figure 3-4 shows, by scenario, how the hydrogen produced for direct use (power-to-H_2) is distributed among the individual sectors in 2030 and 2050. Towards 2050 the H_2 demand across all scenarios is around 300 to 700 TWh of hydrogen (LHV basis).

Figure 3-4: Sectoral distribution of direct hydrogen demand in 2030 (top) and 2050 (bottom), i. e. without hydrogen demand for power-to-CH_4 and power-to-liquid.



Analysis of the demand distribution for the different sectors shows that towards 2030 hydrogen is predominantly required in the transport sector, whereas by 2050 other sectors are also gaining in importance. As the electrification of drive trains within the transport sector progresses, the demand for hydrogen comes initially mainly from heavy duty applications. However, by 2050 hydrogen will also gain in importance for passenger cars, both in relative and absolute terms. This trend is particularly evident in scenario S0-95, where high CO_2 reduction targets and the low-cost availability of hydrogen from imports are seen as drivers. Scenario S1 also shows this trend, in which the low electrical input per kg of hydrogen (due to 100 % HTEL) results in the availability of low-cost hydrogen. On the other hand, demand from heavy goods vehicles (trucks) remains dominant, especially in the medium term, when considering the dynamics in the energy system (S4) and in the long term, when accounting for conservative technology development (S2). It should be noted here that the fuel supply for aviation and shipping is pre-set in the model to liquid fuels, and so pure hydrogen is not used for these applications in any of the scenarios studied.

Demand for H_2 feed-in into the gas grid declines from 2030 to 2050 while re-electrification in hydrogen gas turbines (H_2-GT) increases. Hydrogen as a fuel in industry and hydrogen in the heating sector could already play a major role in 2030, provided electrolysis efficiencies are high (S1) or if imports of low cost hydrogen are allowed (S0-95). In the heating sector, hydrogen will gain in importance by 2050, especially when high CO_2 reduction targets are in place (S0-95).

While some of the electrolysis technologies (AEL, PEMEL, and HTEL) have certain advantages in specific applications, the competition on the market is expected to be driven mainly by overall cost. This is in line with the feedback from electrolyser users who generally do not have a preference for a specific technology in individual applications.

4 Development of electrolysis demand in literature and from a user perspective

In the reviewed literature on energy system analysis, broad consensus can be found regarding the key role that water electrolysis will play in achieving Germany's ambitious climate targets. However, the range, cf. Figure 4-1, of the future demand for installed electrolysis capacities (expressed in gigawatts of electrical load) differs widely between different studies [2, 7–14, 18, 24–27]. The assumptions made in the studies with respect to the following boundary conditions are particularly pivotal:

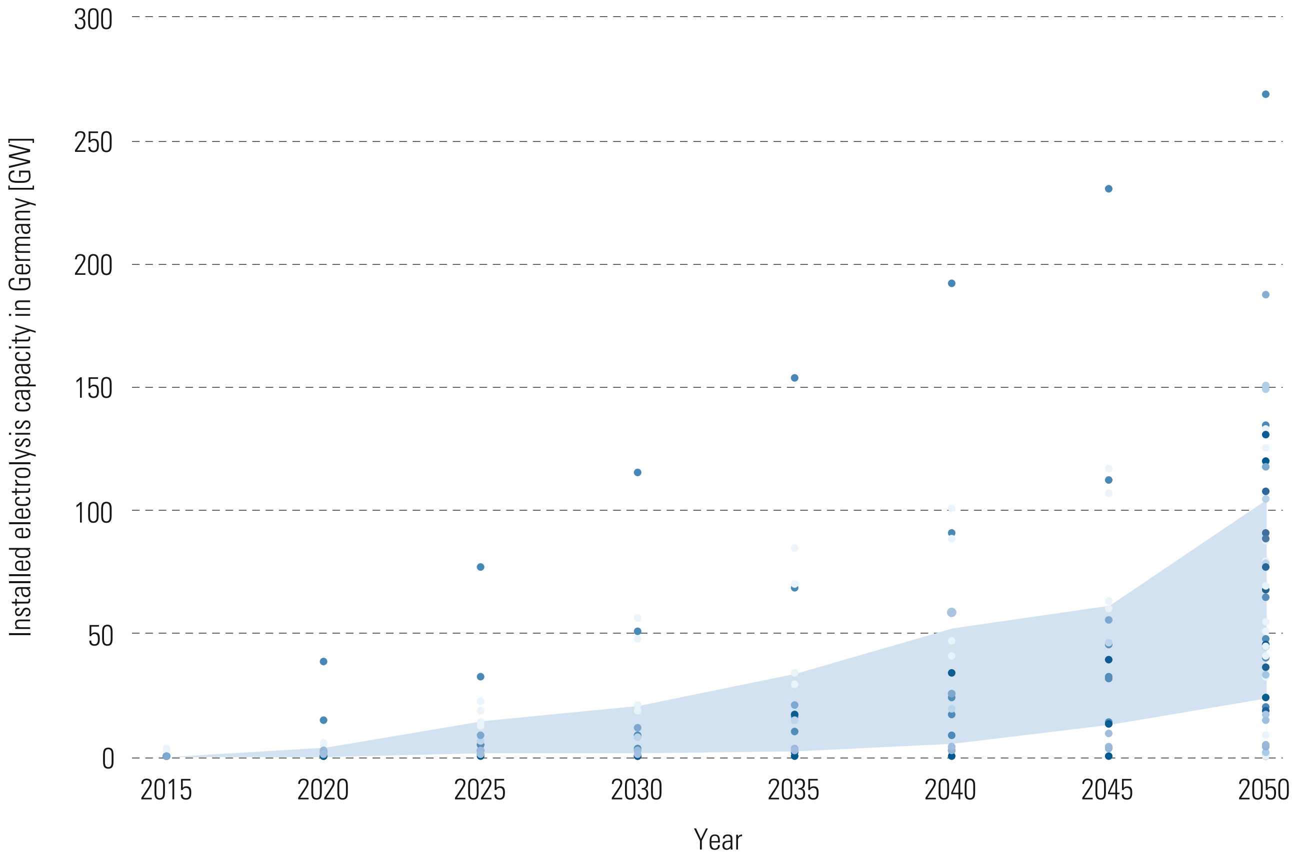
- Extent of electricity balancing with neighbouring countries for seasonal balancing,
- Possibility and extent of imports of renewable fuels,
- Development of battery electric mobility,
- Speed of expansion of wind power and photovoltaics,
- Possibility and extent of using carbon capture and storage (CCS) technology.

Under the chosen framework conditions, the results given by the model in the present study, with a deployment range of 137 to 275 GW electrolysis capacities in Germany by 2050 (see Section 3), appear plausible in comparison to other studies. Although the reviewed literature contains results with significantly lower long-term demand for electrolysis capacity in Germany, this is typically only the case when large quantities of imported, renewable fuels are used to achieve Germany's climate targets. However, the production of these fuels based on photovoltaic and wind energy abroad ultimately generates a comparable demand for installed electrolysis capacity, it is just that they are not located in Germany. In view of the necessary upscaling of manufacturing in the (international) electrolysis industry, the location of the installed electrolyser capacity is only of secondary importance.

The modelling results and the literature overview were complemented by detailed expert interviews with stakeholders from the user side in order to better assess the expected market ramp-up in the coming years. Representatives from the following industries were surveyed:

- Utilities (electricity and gas),
- Industrial gas companies,
- Hydrogen refuelling infrastructure providers,
- Initiatives in the field of industrial hydrogen use,
- Associations in the field of sector coupling and gas grids.

Figure 4-1: Installed electrolysis capacity (or equivalent) in Germany based on reviewed literature [2, 7–14, 18, 24–27]. The area between the 25 and 75 % quantile is highlighted.



The key statements and assessments that were obtained from the interviews can be summarised as follows:

- Water electrolysis technology is ready for broader market roll out.
- Users have no preference for certain electrolysis technologies. Possible market activation measures should be open to all types of technology.
- The cost of electricity, and in particular levies, charges and taxes as part of the electricity prices are regarded as the main obstacle to viable business cases and the uptake of water electrolysis.
- Direct coupling of water electrolysers to wind and PV plants should not be made a requirement to meet renewable hydrogen standards. Instead certificates of origin for renewable electricity sourced through the grid should also be permitted.
- The use of renewable hydrogen in the gas grid could play an important role in the decarbonisation of the heating sector in the long term.

Both the expected development of demand for renewable hydrogen in the next few years as well as the emergence of early markets are viewed quite differently by the different actors surveyed. Some see fuel cell mobility as the first larger market, others believe that the production of synthetic fuels will provide the initial push to larger electrolysis deployment. Finally, several interviewees expect that the substitution of conventional hydrogen in the chemical industry and refineries will provide early business cases for large electrolysers.

Provided that the second Renewable Energy Directive (RED2) sets attractive regulatory conditions from 2021, the use of green hydrogen in refineries could indeed boost the industrialisation of water electrolysis.

The modelling results in the present study imply a rapid expansion of hydrogen mobility in the coming years. This is mainly driven by compliance with the climate protection targets already in the 2020s and yields an installed electrolysis capacity of approximately 6 GW installed by the mid-2020s (according to scenario S3). Most of the stakeholders interviewed consider this unlikely, as drastic regulatory and political measures would be needed to jump start an extensive roll out fuel cell mobility immediately.

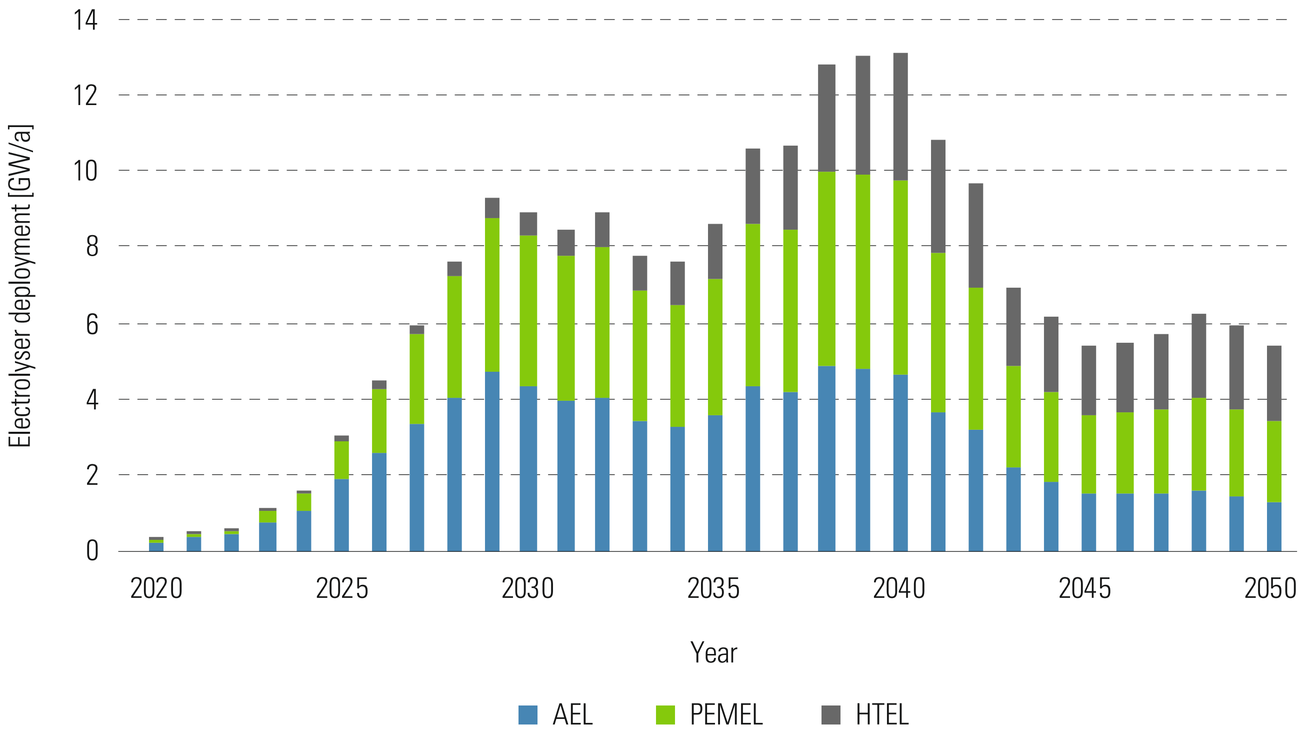
However, in the period to 2030, there is a consensus regarding the need for an annual electrolysis capacity increase in Germany of several gigawatts (this could also be added abroad, provided renewable fuels are imported to Germany). There is also consensus that significant quantities of green hydrogen (or its derivatives such as e-fuels) are needed to achieve Germany's climate targets, particularly in the transport sector.

5 Development of component demand and manufacturing processes

Future component demand

All three electrolysis technologies investigated (AEL, PEMEL, HTEL) are expected to eventually compete for market share. However, as the current state of development of each technology differs (as shown in Section 2), a plausible market share trajectory has been established, based on the assumption that in 2050 the installed capacity will consist of 40 % alkaline, 40 % PEM and 20 % HT electrolysis systems. This, of course, does not represent a market forecast, but merely serves as an indication to estimate the future component requirements of the individual technologies. The combination of the assumed market share development and the central scenario S3 of the energy system model yields a demand in GW per year for each technology, see Figure 5-1. This was then converted into individual component demands (e. g., membrane area, number of stacks, amount of bipolar plates). The detailed assumptions for this conversion can be found in the full report [23].

Figure 5-1: Average electrolysis deployment in GW in scenario S3 broken down by technology (annual values represented as a three year average to smooth the curve).



Evaluation of manufacturing processes of critical components

Considering the expected sharp expansion of electrolysis capacity, and consequently the increasing component demands in the coming years, manufacturing processes were investigated in view of critical steps and in view of their economic scalability. In order to identify and narrow down suitable production processes, a multi-criteria assessment was conducted to evaluate the criticality of manufacturing processes and their suitability for scale-up. The criteria were discussed in a workshop with a panel of experts and scored on a binary scale. The overall score of a component gives information about its criticality (a high score implies high criticality). For all three electrolysis technologies it was found that most of the critical components belong to the electrolysis stack (see Table 5-1). The findings have been presented and approved in the stakeholder workshops as part of the study.

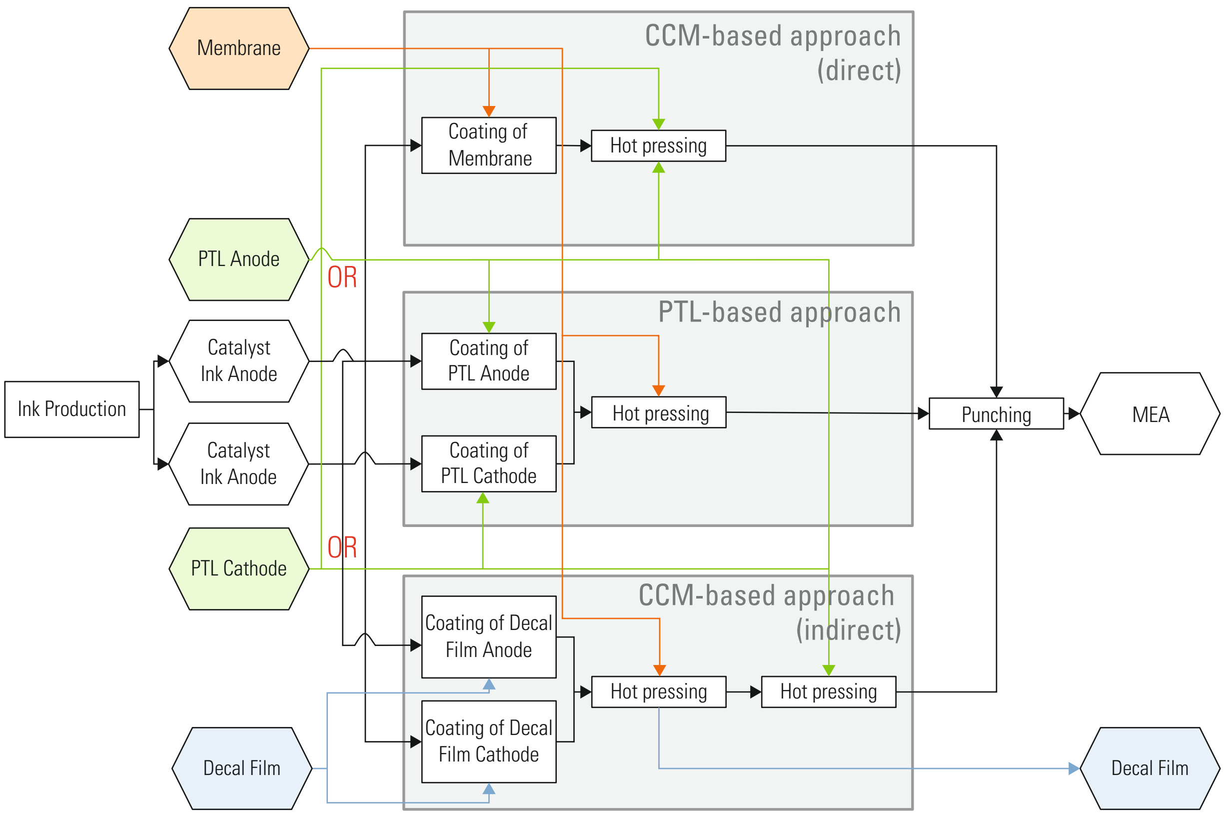
Table 5-1: Results of the multi-criteria assessment to identify critical components, in view of their manufacturing processes. The higher the score, the more critical the component considered.

Technology	Component	Score
AEL	Diaphragm	6
	Anode	4
	Cathode	4
	Power electronics	5
PEMEL	Stack	7
	Membrane electrode assembly (MEA)	10
	Porous transport layer (PTL) anode-side	8
	Bipolar plate	8
	Coating material for bipolar plate (BPP)	7
	Membrane	8
HTEL	Stack	9
	Electrolyte electrode assembly (EEA)	9
	Interconnect	10
	Electrolyte	9
	Anode	9
	Cathode	9
	Thermal and fluid management	9

Subsequently, a comprehensive review of potential manufacturing processes for components identified as critical was conducted. Suitable and scalable processes were selected and analysed in more detail to identify potential bottlenecks in the future supply chain for water electrolysers.

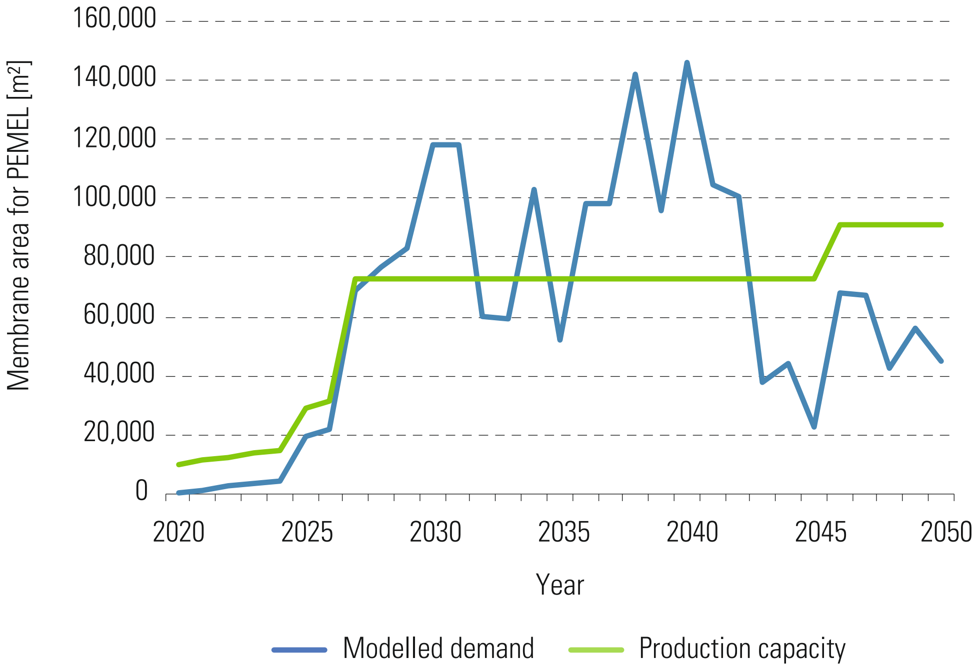
As an example, the described approach is outlined below for the MEA of a PEM electrolyser. The most common process paths for producing MEAs are shown in Figure 5-2. Based on discussions with manufacturers, the indirect catalyst coated membrane (CCM)-based approach is currently the preferred method of MEA production. This is due to the easily adjustable process parameters and consistent quality of the final product. Although the direct CCM-based approach eliminates the need for a decal film, which allows for cost savings, it has quality issues and procedural difficulties that currently inhibit the utilisation of this process for large-scale production. In both approaches, the catalyst ink can be applied by using continuous screen printing, doctor blade or slotted nozzle methods [5].

Figure 5-2: Schematic depiction of the most common manufacturing processes for membrane electrode assemblies of PEM electrolysis



To assess the scalability and to roughly estimate the necessary amount of investments, the capacity of an exemplary manufacturing machine was set in relation to the predicted future demand of MEAs, see Figure 5-3. In order to derive a sensible increase in production capacity, the annual component demands (blue line) that result from the model were smoothed (green line) by minimising over- and undercapacities whilst still covering the cumulative demands.

Figure 5-3: Membrane demand and production capacity for membrane electrode assemblies in PEM electrolysis



In analogy to the approach presented here for membrane electrode assemblies, the production processes for other critical components are evaluated and discussed in the full report.

Analysis of the modelled demands generally shows that all components currently defined as critical can already be produced on a commercial scale using state-of-the-art manufacturing technologies. Since the required machinery for the considered components is used in other industrial production processes, large-scale production plants for these components either already exist, or can be added relatively quickly.

Although a vast increase in installed electrolysis capacity is predicted in Germany by 2050, the component demands do not represent a major challenge with regard to production technology. Table 5-2 illustrates the capacities of the manufacturing equipment that are capable of producing the demand of critical components in 2030 and 2050. This highlights that the investments in manufacturing capacity required to cover future component demands are relatively low. The supply chain is thus able to react quickly and flexibly to changes in demand, especially if a demand growth over several years is predictable. This is in agreement with feedback from the industry; many of the suppliers surveyed felt that they are already well prepared for an increase in production. In addition to the above, both synergies and economies of scale are also to be expected for the manufacture of electrolyser components. For example the similarity in design and materials used in various components of electrolysers and fuel cells (especially in high-temperature technology) means that the same production infrastructure can be shared for different products and the utilisation of manufacturing equipment can be increased.

Table 5-2: Overview of critical component demands and suitable production processes as well as their typical production capacity

Technology	Component	Demand 2030 [m²/a]	Demand 2050 [m²/a]	Production method (commercial scale)	Capacity per production line [m²/a]
AEL	Diaphragm	310,000	310,000	Tape casting	>1,000,000
	Electrodes	520,000	520,000	Expanded metal cutting	79,200
PEMEL	MEA	73,000	92,000	Indirect CCM approach	<3,000,000
	BPP	73,000	92,000	Hydroforming & physical vapour deposition (PVD)	300,000
	PTL Anode	63,000	63,000	Expanded metal cutting/ resistance welding processes	79,200/3,300
HTEL	Stack	1,900,000 [cells/a]	6,000,000 [cells/a]	Manual assembly	100,000 [cells/ employee/a]
	Interconnect	81,000	235,000	Hydroforming	300,000
	EEA	81,000	235,000	Sintering/tape casting	>1,000,000

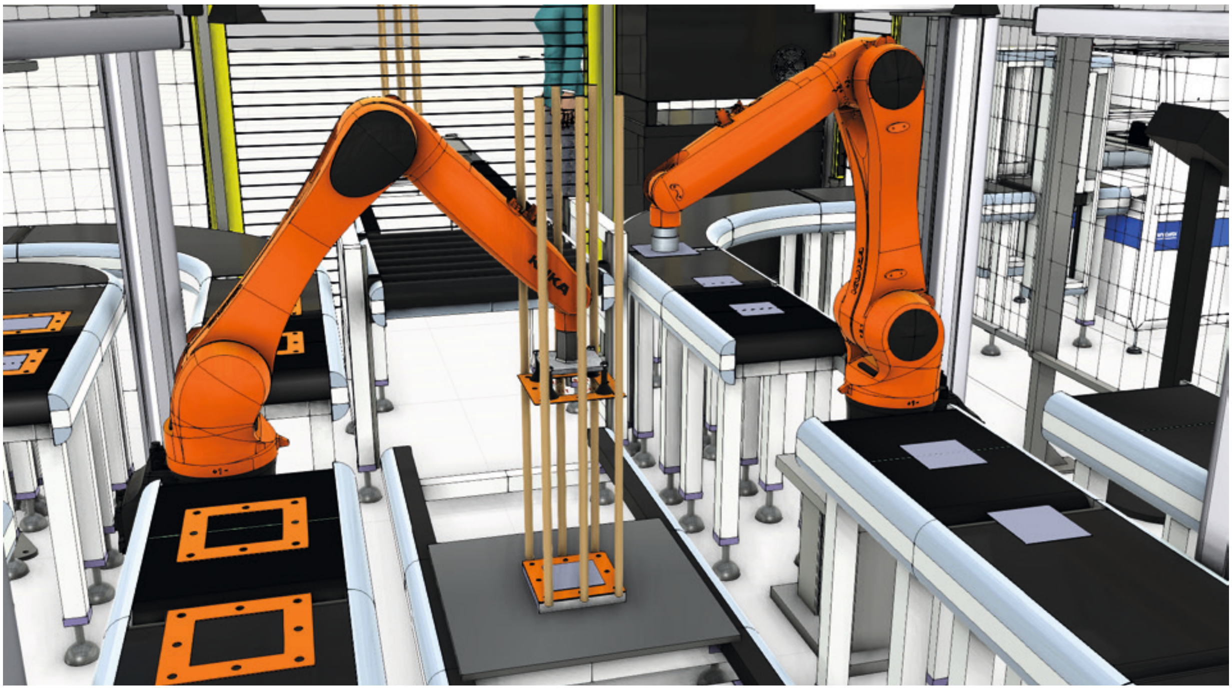
Automation of stack production

As shown above, suitable manufacturing methods are generally available for all components classified as critical. To further probe the future industrialisation of water electrolysis, the automation of stack assembly, and its economic viability, was investigated.

A concept for automated cell deposition for high-temperature stacks with a rough profitability estimation was developed. The profitability of implementing automated processes is generally highly dependent on the number of repeating steps. The stack fabrication of high-temperature electrolysis is thus particularly well suited for automation due to the small cell areas (in contrast to AEL and PEMEL, see Section 3), which means that the number of cells per output of hydrogen is highest in this technology. High-temperature stacks are currently being assembled manually, with the individual cell layers being deposited by hand on the end plates. The considerable expenditure of time and costs associated with this suggests that automation could be a better solution at increased production volumes.

To provide a comprehensive overview, two common automation concepts (parallel vs. serial assembly) were applied to the process of stack assembly and were compared against each other. In doing so, the parallel assembly has been identified as

Figure 5-4: Stacking of components in an automated parallel assembly line of high-temperature stacks



the preferable option, due to higher flexibility, lower cost and higher system availability. The deposition of the seven components per HT-cell then takes place directly on the lower end plate of the stack using two six-axis robots as shown in Figure 5-4.

Comparison of the annual costs (CAPEX and operational expenditure (OPEX)) of the manual versus the automated assembly of high-temperature stacks shows a cost benefit for the automated solution. This is especially noticeable during the significant increase in demand from the mid-2030s until the end of the scope of this study in 2050. During this time span, the costs diverge widely until, by 2050, the annual costs of the automated solution are expected to be around half of the costs of the manual assembly. To handle the maximum expected number of cells per year, seven of the illustrated robots would be required. It should be mentioned that in general conservative cost estimates have been chosen and therefore automation solutions are likely to be favoured even earlier. A more detailed analysis of automation concepts would be recommended, but it can be assumed that individual manufacturers are already examining the cost-effectiveness of automation concepts internally.

Raw material criticality

While manufacturing processes are not seen as critical, the availability and cost of certain materials is often mentioned by stakeholders as potentially problematic in view of large scale industrialisation of water electrolysis. Besides titanium and the rare earth metal scandium, the elements platinum and iridium, both platinum group metals, are also seen as critical.

To address these concerns, an overview was compiled as part of this study, which includes generally accepted indicators for assessing material criticality, as well as a comparison of the annual production rates of the aforementioned raw materials. Future material demands for electrolysis were compared using two scenarios. One scenario was a conservative scenario, in which the material input per kilowatt remains constant at today's levels until the year 2050. The other was an innovative scenario in which the specific material demand is drastically reduced through technology development to levels considered feasible in the research and development (R&D) community. A detailed description of the methodology and the discussion can be found in the full report.

As a result of this analysis, iridium (PEMEL) and scandium (HTEL) are identified as particularly critical (see Table 5-3). However, it should be noted that the electrolyte currently used in most high-temperature electrolysis EEAs does not generally use scandium as a dopant. Despite the critical supply situation, scandium can only be regarded as critical for the industrialisation of water electrolysis if manufacturers increasingly focus on scandium doping in the future. However, there is not currently an indication that such a development will take place.

Iridium, on the other hand, is considered an important catalyst for PEM electrolysis that is difficult to substitute. A complete substitution of the material which is used as the anode-side catalyst is currently not conceivable. In the conservative scenario more than a quarter of the current world-wide production rate of iridium is needed to meet the demand for PEM electrolysis in 2030 in Germany alone. Drastic reduction of iridium loading, which is assumed in the innovative scenario, can reduce this demand to around 5 % of the current annual production rate. The political situation in iridium-mining countries (parameter HHI-WGI in Table 5-3), as well as the by-production and the associated dependence on the primary mining of the main metals (Companionality in Table 5-3), aggravate the general supply risk of iridium (see Supply Risk in Table 5-3) [3, 16, 28]. Within the EU, iridium is already being recycled to some degree (see EOL-RIR in Table 5-3) [3]. In general, the recycling of platinum-group metals is a well-established process and promises recycling rates of up to 95 % [6]. Processes that aim to recover precious metals from fuel cells already exist and can be applied to extract materials from the cells of PEM electrolysers, owing to their similar construction and materials. That being said, from a materials point of view, an increase in efforts to recover precious metals is indispensable for supporting the ramp-up of PEMEL. Due to the small PEMEL capacity currently in service, secondary sources from recycled end-of-life electrolysis stacks will only be available in the longer term to help to alleviate the supply situation.

Table 5-3: Summary of the parameters for raw material criticality

	Iridium	Platinum	Scandium-oxide (Sc_2O_3)	Titanium
Supply Risk	2.8	2.1	2.9	0.3
HHI-WGI	3.4	2.5	3.0	0.4
Companionality [%]	100	16.1	–	0
EOL-RIR [%]	14	11	0	19
Annual production (year) [kg]	7,100 (2016)	190,000 (2013)	10,000 (2013)	290,000,000 (2016)
Demand conservative 2030 [kg]	~2,100	~1,050	~8,000	~1,310,000
Demand conservative 2050 [kg]	~2,650	~1,300	~25,500	~1,640,000
Demand innovative 2030 [kg]	~360	~180	~1,500	~207,000
Demand innovative 2050 [kg]	~200	~150	~2,900	~130,000

High Criticality Medium Criticality Uncritical

In general, a reduction of the amount of material used per kilowatt of installed capacity is welcome for all of the raw materials considered in this analysis and thus relevant efforts should be supported and encouraged. In addition to the critical supply situation, these materials contribute to the overall cost of electrolysers. Without efforts to reduce the amount of material used, the relative share of critical material costs in the overall costs will rise as soon as savings in other areas (e. g. automation of production of stacks) are realised.

6 Key conclusions

The overarching question of this study is how to ensure that water electrolysis will be available in Germany as an industrialised technology at the required scale, so it can act as a link between renewable electricity and other energy carriers and raw materials. Nine central conclusions can be derived from the study results.

1. The electrolysis sector must develop into a gigawatt industry.
Germany's climate protection targets require electrolysis capacity in the three-digit gigawatt range in the long term. This is irrespective of whether this capacity is installed in Germany or whether renewable fuels are produced abroad and imported. Based on a global electrolysis market of approximately 100 MW/a in 2016, substantial growth is needed to reach approximately 1 to 5 GW per year by 2030, to meet the demand from Germany alone. Figure 6-1 shows a plausible trajectory of market development to 2030.

2. The market ramp-up is more important than research funding.
Today, alkaline and PEM electrolysis are mature technologies. Economies of scale and volume production are the main lever to achieve the expected cost reduction. The industry itself will drive future cost and performance development and optimise manufacturing processes as soon as the market size allows for it. R&D and demonstration projects can usefully support the market ramp-up, but are not able to trigger it.

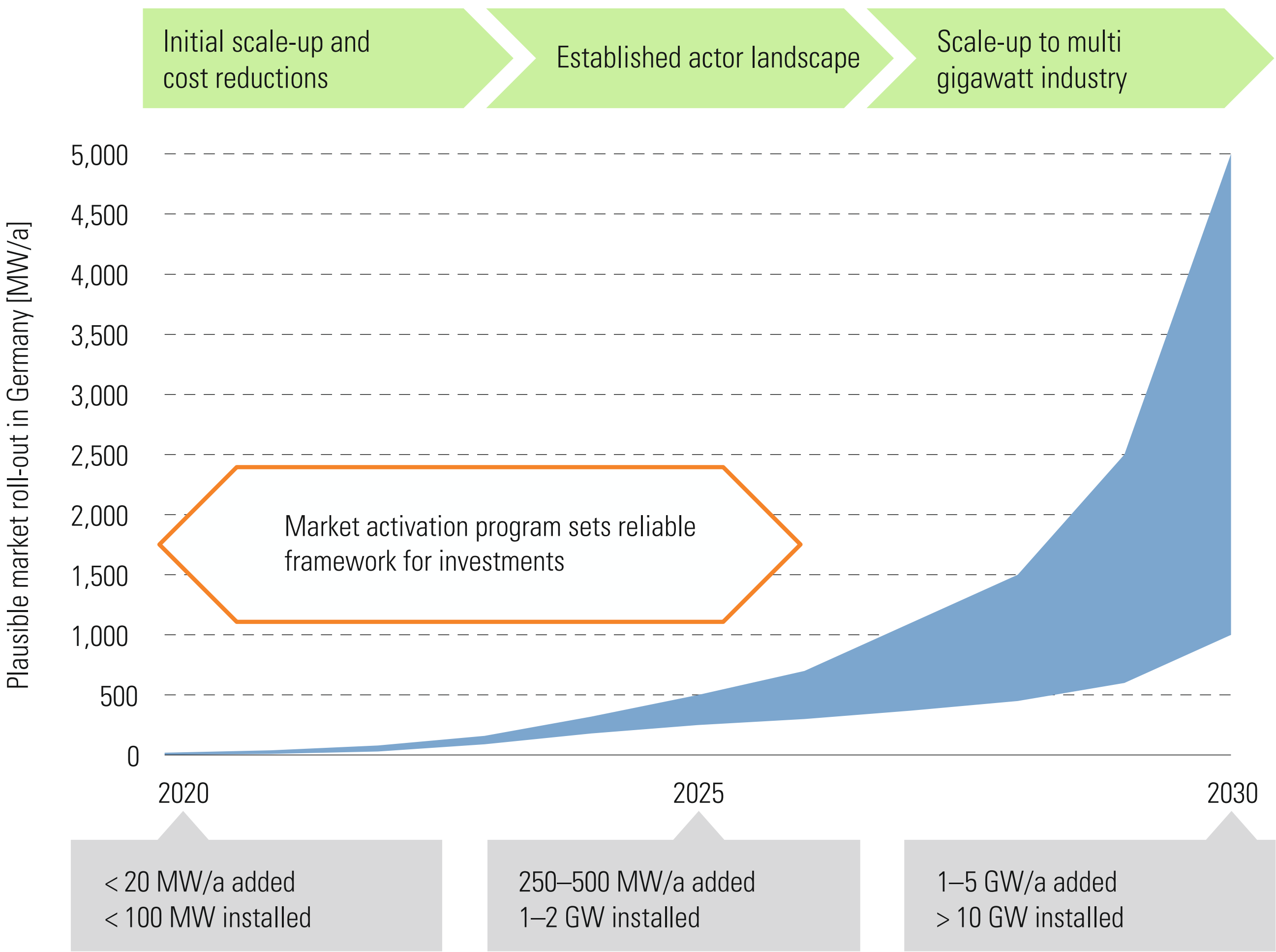
3. A stable sales level of 20 to 50 MW per year and per manufacturer is necessary for industrialisation.
Based on the industry survey, a minimum production volume of about 20 to 50 MW electrolysis capacity per year and manufacturer is required before industrialised production processes become viable and before a more robust supply chain will develop. To trigger investments in the sector, such market volume and stable framework conditions must be foreseeable for several years.

4. Suitable manufacturing processes for industrialisation are largely available.
Today, due to the low demand, electrolyser companies use little automation and typically manufacture products to order. Suitable processes for higher production volumes are already known from other applications and industries and could also be used in the electrolysis industry in the future to reduce manufacturing costs. Overall, there is no need to develop fundamentally new production processes.

5. Greater demand is needed to increase competition and diversity along the supply chain.

In the existing supply chain for water electrolysis, some components and materials can only be sourced from a single supplier. However, this is not due to protection of intellectual property, but can be attributed to a lack of competition in the currently small market. Future market growth is expected to ensure a sufficiently dynamic competition and strengthening of the supply chain.

Figure 6-1: Plausible market ramp-up until 2030



6. The industrialisation of water electrolysis will not be limited to Germany, but will take place in an international context.

Germany has a comparatively well-developed actor landscape, both among system manufacturers and along the supply chains. However, the German actor landscape and the market should not be viewed or analysed in isolation; despite its current small size, the industry is very international. Therefore, the assumption in this study was that exports and imports to and from Germany will roughly be equal, which was considered plausible by the actors.

7. Clear regulatory framework conditions are necessary, in particular with regard to how electricity for water electrolysis is priced.

In order to ensure the initial growth of the industry and achieve a critical mass, a clear regulatory framework is required. In particular, it is the fees, levies and taxes on electricity which are the biggest barrier to viable business cases for water electrolysis in Germany, and hence adjustments are needed here.

8. For PEM electrolysis to reach multi-gigawatt scale, iridium loadings need to be reduced.

In view of several gigawatts of electrolysis additions per year from 2030 onwards, iridium, used as a catalyst in PEM electrolysers, has to be considered as a critical material. The iridium loadings [g/kW] must be significantly reduced to prevent supply risks and cost hikes for PEM electrolysis in the future.

9. Promoting public awareness remains important.

The stakeholders consulted as part of the study emphasised that promoting public awareness of hydrogen as an energy carrier remains important. As an example, model regions could help to increase acceptance and awareness of hydrogen.

7 Recommendations for action

Based on the findings and conclusions of the study, concrete recommendations for action are derived. These are structured by the groups of actors they are addressed to.

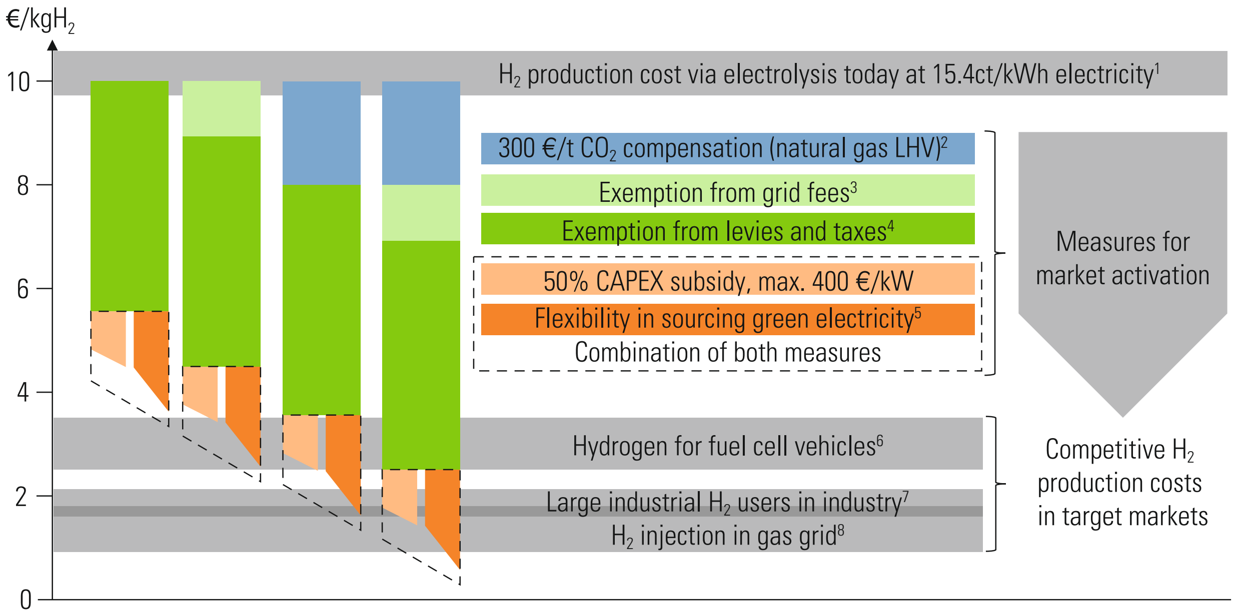
Recommendations for action by the public sector

The central postulation of this study is to set up a market activation programme for water electrolysis with the goal to help create a market of 250 to 500 MW per year by 2025 in Germany and reach cumulative installed capacity of 1 to 2 GW. This will be needed to ensure that a production capacity of several GW per year from 2030 onwards can be reached. To trigger investments, such a programme must establish transparent framework conditions and certainty for market participants. Of particular importance are measures that, on the one hand, reduce the specific hydrogen production costs in [€/kg] and on the other hand create added value for renewable hydrogen on the market. Figure 7-1 shows a selection of individual measures that are discussed among different stakeholders. In combination these could lead to competitive hydrogen production costs in some applications. The underlying assumptions can be found in Appendix A.1. The graphic representation aims to underpin the following key messages:

- Under the prevailing market conditions in Germany, hydrogen from water electrolysis can be produced at a cost of 10 €/kg assuming an operational profile linked to wind and photovoltaics that would yield 2,000 to 3,000 full load hours, with no exemptions from levies and taxes on the electricity price.
- Through direct comparison to fossil fuel prices at the pump of a refuelling station, fuel cell mobility can be viable with higher hydrogen production costs than, for example, industrial hydrogen. Nonetheless, even with a reimbursement of 300 €/t CO_2 savings for green hydrogen, there is still not enough added value to achieve competitive costs for fuel cell mobility, unless other measures are taken as well.
- The main lever for reducing hydrogen production costs lies in the exemption of fees, levies or taxes on the electricity consumption in electrolyser plants. From an energy system perspective, such exemptions will be required to make renewable electricity available to other sectors. Water electrolysis is not an end-consumer of electricity, but rather acts as a link between renewable electricity and renewable fuels.
- In addition, CAPEX subsidies for electrolysers could provide an incentive for investment. However, over the lifetime of a plant, the effect of upfront subsidies is less significant than the increase of full-load hours of electrolyser operation. If direct coupling of the electrolyser operation to the generation profiles of wind

and PV is not mandated during a transitional period, much higher full load hours than the 2,000–3,000 hours per year are possible. This could be enabled through sourcing of green electricity on the market with certificates of origin.

Figure 7-1: Combinations of selected measures for market activation with the aim of reducing hydrogen production costs (footnotes can be found in Appendix A.2)



A market activation programme should also be supported by various accompanying measures:

- Standardisation of approval procedures,
- Consistent methodology for the certification of green hydrogen,
- Standardised test procedures for electrolysis technology,
- R&D funding to support development of technology and production processes,
- Public relations and international cooperation.

Recommendations for action by the electrolysis industry

In view of sharply growing markets, the electrolysis industry can take measures to prepare for further industrialisation and market ramp-up:

- Development of (in-line) quality assurance in production processes,
- Development of concepts for upscaling production (e. g. automation of individual production steps),
- Standardisation of components and definition of component requirements,
- Certification of suppliers as part of quality assurance,
- Participation in standardisation committees such as the regulations, codes and standards (RCS) platform in the NIP,
- Taking measures against the impending shortage of skilled workers,

- Initiating product developments and certifications at supply chain companies,
- Exploit existing support mechanisms for financing of small and medium-sized enterprises (SMEs),
- Benefit from cooperation with research institutions.

Recommendations for action by research institutes

The active cooperation of R&D institutions with industry is an important contribution to the industrialisation of electrolysis technology. Research institutes can further expand and intensify their work on key topics, such as:

- Increasing current densities at cell level for all technologies,
- Reduction of precious metal loading in PEM electrolysis,
- Increasing lifetime of high-temperature electrolysis,
- In addition, further R&D topics can be taken up to support the market launch, including:
  - Coating processes,
  - Material compatibility,
  - Certification of materials,
  - Efficiency of power supply in partial load,
  - Components and processes in gas analysis, drying and compression,
  - Pressure resistance of components.

Recommendations for action by (potential) electrolyser users

Current and future operators of electrolysis plants and hydrogen users, are important pioneers in the ramp-up of the electrolysis industry, as they help to bring new electrolyser plants and projects into the field. These actors include electricity and gas utilities, municipal transport companies and industrial hydrogen users. They are already participating in demonstration projects and could assist in the development of model regions in the future. They can also develop new business models in line with changing market conditions, e. g. for wind and PV plants that reach the end of the 20 year feed-in tariff scheme in Germany (EEG). Gas utilities could offer the supply of green (natural) gas to early adopters among their clients, and future business models for new or existing actors could also be developed within the RED2 framework (e. g. green hydrogen in refineries).

8 Roadmap to industrialisation

The roadmap shown in Figure 8-1 graphically summarises the key measures, development needs and time dependencies. It is intended to serve as a guide for the various stakeholders involved in the industrialisation of water electrolysis.

If there are delays in individual measures, the overall process of industrialisation will probably also slow down, making it even more difficult to achieve the climate targets.

Market activation measures, see Section 7, are a central component of the roadmap. If the exemption from fees, levies or taxes on electricity sourcing cannot be implemented in the near future, other interim solutions would need to be created to reduce electricity costs for electrolysis operators.

By not strictly tying the electrolysis operation to wind and photovoltaic generation profiles during the initial market roll-out phase, but instead allowing green electricity to be drawn from the grid all year round, an effect equal or stronger than CAPEX subsidies can be achieved.

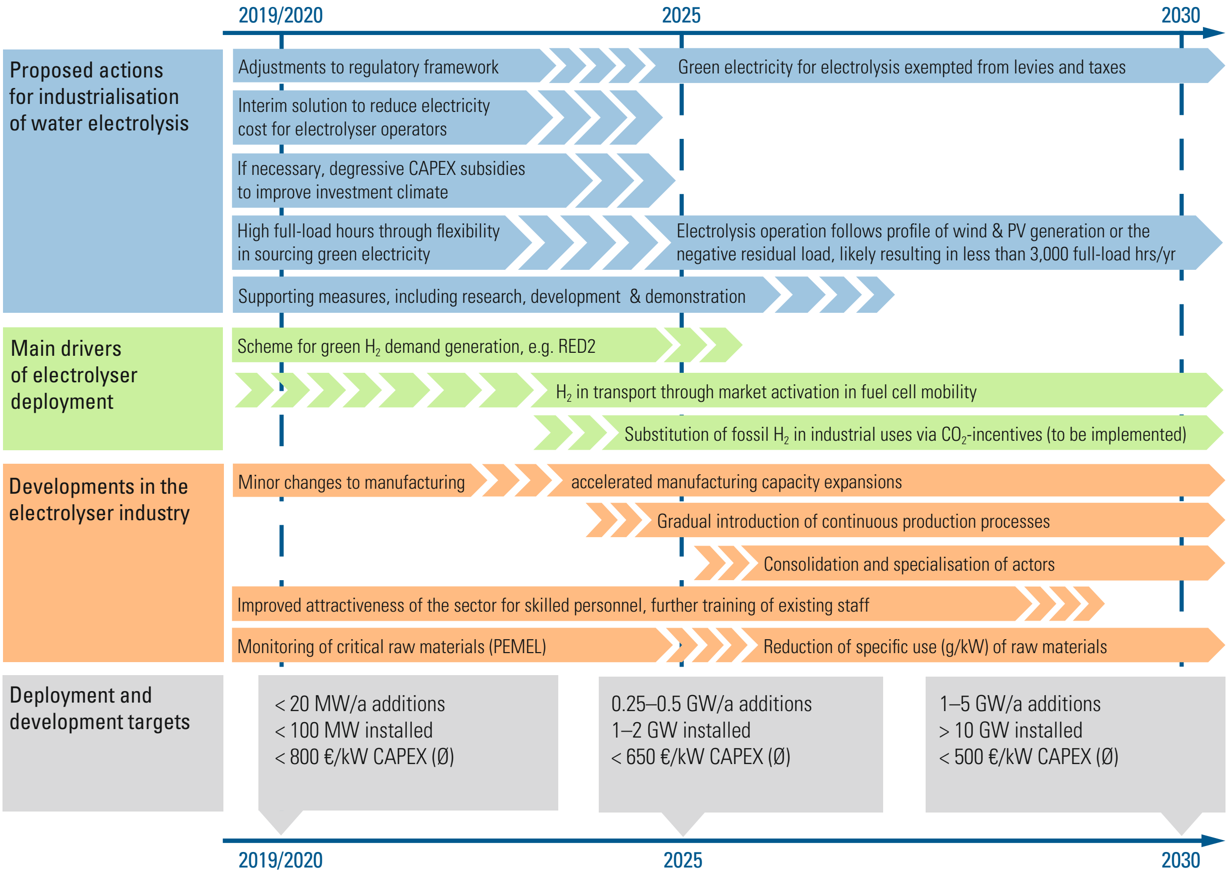
After a certain level of market scale is achieved, electricity sourcing regulations should be adjusted step-by-step to reflect the needs of the renewable energy market, i. e. electrolyser operation should be linked to the availability of wind and PV electricity or the negative residual load. This is necessary so that, in the medium and long term, water electrolysis uses additional renewable electricity instead of competing for the very limited dispatch of renewable generation capacities.

Once the market ramp-up has led to cost reductions among electrolysis suppliers, CAPEX subsidies would no longer be necessary, even if electrolysers are not operated all year round (with high full-load hours).

Since fuel cell mobility will not be able to generate significant hydrogen demand in the coming few years, additional demand for green hydrogen should be created in conventional large-scale applications (e. g. hydrogen in refineries).

For the current electrolysis industry, only minor adjustments are needed immediately, since the analysis has shown that the manufacturing capacity can be expanded quickly and more serial production processes can be introduced as soon as an increase in annual market volume is foreseeable. As part of the transition to a gigawatt industry, the sector, which is currently dominated by SMEs, will likely go through some consolidation and specialisation. Electrolyser companies will also have to compete with other industries to attract skilled workers for driving growth. For PEM electrolysis to be relevant in the multi-gigawatt production range, reductions in iridium loadings are required.

Figure 8-1: Roadmap for the industrialisation of water electrolysis in Germany



Appendix

A.1 Calculation of levelised cost of hydrogen

Formula for the calculation of hydrogen production costs:

$$WGK = \frac{LHV}{\eta_{ges}}\left(\left(\frac{i \cdot (1+i/100)^n}{(1+i/100)^n - 1} + M/O\right)\frac{CAPEX}{VLS} + P_E\right)$$

WGK	Levelised cost of hydrogen [€/kg]
VLS	Annual full load hours [h/a]
LHV	Lower heating value of hydrogen [kWh/kg]
ηges	Nominal system efficiency [%] (relative to the LHV)
i	Discount rate [%]
n	Amortisation period and system lifetime in years [a]
M/O	Maintenance and operating costs (incl. stack replacements, excl. electricity costs) [%CAPEX/a]
CAPEX	Specific investment costs of the electrolysis system [€/kW]
PE	Cumulated specific electricity price [€/kWh]

A.2 Assumptions for the calculation of hydrogen production costs

Nr.	Comment
1	KPIs of scenario S3 2017, range results from 2,000 to 3,000 full-load hours
2	Compensation payments for CO_2 savings (204 g CO_2-Äq/kWh LHV natural gas) Comparison based on substitution LHV of natural gas with hydrogen (33.3 kWh/kg LHV, assumption 100 % CO_2 free hydrogen)
3	2.06 ct/kWh electricity grid fees (Bundesnetzagentur/Bundeskartellamt (2016): "Monitoring-bericht 2016", industrial consumers with 24 GWh/a)
4	8.55 ct/kWh electricity levies and taxes ("BDEW Strompreisanalyse 2018", industrial consumers up to 20 GWh)
5	If electrolyser operations are not coupled to PV and wind generation profiles or to the negative residual load in the network, 8,000 full load hours (instead of assumed 2,000–3,000 hours) per year become possible, as long as (during a transition period) guarantees of origin can be provided from, e. g., hydro power plants.
6	Assumption: Competitive hydrogen prices at the pump 6 €/kg (Diesel passenger car 5 l/100 km at 1.20 €/l, fuel cell passenger car 1 kgH_2/100km), of which 3 €/kg deducted for distribution and station costs. Prerequisite: Roll-out of fuel cell vehicles and refuelling stations and continued tax exemption for hydrogen as a fuel.
7	Cost of steam methane reforming at 100 t/day hydrogen production based on FCHJU "Study on Development of Water Electrolysis in the EU" 2014.
8	Substitution of natural gas with hydrogen based on LHV, natural gas prices private customers in Germany (2016) 6.5 ct/kWh, large customers 3.4 ct/kWh (Eurostat), LHV hydrogen: 33.3 kWh/kg; Results in a value of hydrogen in gas grid between 1.13 and 2.16 €/kg.

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NOW GmbH
Nationale Organisation Wasserstoff-
und Brennstoffzellentechnologie
Fasanenstraße 5
10623 Berlin

+49 (0)30-311 61 16-00
kontakt@now-gmbh.de

CONTACT TO THE AUTHORS:
Tom Smolinka
Fraunhofer ISE
Heidenhofstraße 2
79110 Freiburg
+49 (0)761-4588 5212
tom.smolinka@ise.fraunhofer.de

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