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Life cycle environmental impacts and costs of water electrolysis technologies for green hydrogen production in the future

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Abstract

Background To limit climate change and reduce further harmful environmental impacts, the reduction and substitution of fossil energy carriers will be the main challenges of the next few decades. During the United Nations Climate Change Conference (COP28), the participants agreed on the beginning of the end of the fossil fuel era. Hydrogen, when produced from renewable energy, can be a substitute for fossil fuel carriers and enable the storage of renewable energy, which could lead to a post-fossil energy age. This paper outlines the environmental impacts and levelized costs of hydrogen production during the life cycle of water electrolysis technologies.

Results The environmental impacts and life cycle costs associated with hydrogen production will significantly decrease in the long term (until 2045). For the case of Germany, the worst-case climate change results for 2022 were 27.5 kg $CO_{2eq.}$/kg H_2. Considering technological improvements, electrolysis operation with wind power and a clean heat source, a reduction to 1.33 kg $CO_{2eq.}$/kg H_2 can be achieved by 2045 in the best case. The electricity demand of electrolysis technologies is the main contributor to environmental impacts and levelized costs in most of the considered cases.

Conclusions A unique combination of possible technological, environmental, and economic developments in the production of green hydrogen up to the year 2045 was presented.

Based on a comprehensive literature review, several research gaps, such as a combined comparison of all three technologies by LCA and LCC, were identified, and research questions were posed and answered. Consequently, prospective research should not be limited to one type of water electrolysis but should be carried out with an openness to all three technologies. Furthermore, it has been shown that data from the literature for the LCA and LCC of water electrolysis technologies differ considerably in some cases. Therefore, extensive research into material inventories for plant construction and into the energy and mass balances of plant operation are needed for a corresponding analysis to be conducted. Even for today's plants, the availability and transparency of the literature data remain low and must be expanded.

Keywords Life cycle assessment, Life cycle costing, Green hydrogen, Water electrolysis, Critical raw materials, Levelized costs, Climate change, Alkaline water electrolysis, Proton exchange membrane electrolysis, High-temperature solid oxide electrolysis

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Background

According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), the global temperature has increased by approximately 1.07 K since 1850 [1]. One main reason for this is the anthropogenic use of fossil fuel energy. Consequently, the reduction and substitution of fossil energy is a major challenge and is being addressed by current energy transformation approaches. A major outcome of the United Nations Climate Change Conference, COP28, was an agreement on the beginning of the end of the fossil fuel era. Hydrogen produced by water electrolysis technologies can substitute fossil energy carriers if renewable energy is used. Furthermore, hydrogen is promising for energy storage and a wide range of other applications [2, 3]. Thus, it has the potential to be a key enabler of the transition to a post-fossil fuel age [4].

The three most mature and predominant water electrolysis technologies are the subjects of this study. These include alkaline electrolysis cells (AECs), polymer electrolyte membrane electrolysis cells (PEMECs), and solid oxide electrolysis cells (SOECs). These characterizations mirror their fundamental cell concepts [3].

In this study, the environmental impacts and costs during the life cycle of these water electrolysis technologies are assessed by means of life cycle assessment (LCA) and life cycle costing (LCC). Knowledge of the key technological, economic, and environmental development potentials is of great importance for today's technology roll-out as well as the future development of the hydrogen economy. This section presents relevant literature and identified research gaps around these technologies. It is followed by a goal definition and formulation of the research questions pursued in this study. Subsequently, the technological principles and differences of these technologies are described.

Previous relevant studies and identified research gaps

The three water electrolysis technologies have several similarities, such as requiring water and electricity for operation and with hydrogen as the common output. However, they differ in their individual characteristics, making technology-specific assessments necessary.

A recent review by Wilkinson et al. [5] on LCAs for hydrogen production revealed that several publications consider only two different water electrolysis technologies. However, no study that included a comparison of all three technologies was identified. In addition, a review by Koj et al. [6] of 32 studies, including water electrolysis technologies and further power-to-X (PtX) technologies, illustrated the scarcity of electrolysis technology comparisons in LCAs.

Although not included in the review studies, some publications focusing on environmental assessments of all three electrolysis technologies have been published. Tenhumberg and Büker [7] conducted an environmental comparison of AECs, PEMECs, and SOECs. Their study was limited to considering the impact of climate change effects caused by these technologies and does not represent a complete assessment according to the ISO 14040 and 14044 standards for LCA [8, 9]. Consequently, this study should be seen as ta carbon footprint assessment rather than a LCA of these technologies. In addition to the carbon footprint, hydrogen production costs were also analyzed. Conditions between the years 2018 and 2030 were taken into account. The LCA presented by Zhao et al. [10] compared the manufacturing and construction processes of the three technologies without assessing their operating phases and analyzing the prospective conditions and costs. Two LCA articles authored by Gerloff considered all three electrolysis technologies [11, 12]. In the first of these [12], the main focus was on power-to-methane plants, but environmental results for electrolysis were identifiable as part of the overall results. Gerloff [11] compared the three electrolysis technologies using an environmental assessment study, which can be regarded as an LCA. In addition to the climate change impact category, up to seven other environmental impact categories were analyzed in one part of the analysis. In addition to conditions for the year 2019, future scenarios for 2030 and 2050 were considered. However, the only prospective variation that occurs concerns the composition of the national electricity mix. Variations in important technological parameters, such as electricity demand and the service life of the stacks, were not carried out. The study by Gerloff [11] does not include an LCC or any other form of economic analysis. Compared to the first article, the second included several identical approaches (e.g., assessments of the years 2019, 2030, and 2050 and the same impact categories) and assumptions regarding electrolysis (e.g., electricity demand). The most recent environmental assessment publication considering all three water electrolysis technologies was published by Zhang et al. [13]. The study could be considered an LCA and takes water electrolysis with onshore and offshore wind power into account. Changes in parameters over time, economic aspects, or hydrogen production using the electricity grid mix are not considered. Table A 1 in the Supplementary material summarizes several characteristics of these previous LCA studies compared to those of the present LCA study, indicating the novelty of the work. In addition to LCA studies, LCC and its interaction with LCA are of interest. The LCA review by Wilkinson et al. [5] also includes information on whether economic and/or technological aspects are considered alongside environmental ones. Overall, 15% of the studies considered economic aspects in addition to environmental ones, and 10% considered economic, technological, and environmental aspects in parallel. However, such combined analyses usually only focus on one electrolysis technology. In addition, prospective analyses that include both LCC and LCA results are extremely rare.

A closer look at studies that can be regarded as LCC studies of hydrogen production using water electrolysis in a review by Nicita et al. [14] demonstrated a clear emphasis on PEMEC electrolysis technology. SOEC was only considered in one LCC study, by Bekel and Pauliuk [15], who were aware of one publication comparing the LCC results of all three electrolysis technologies, which was published as part of the Center of Excellence "Virtual Institute – Power to Gas and Heat" project and that serves as the basis for this work [16].

Objectives and research questions

To address the existing research gaps, this study aims to investigate various technological, economic, and environmental aspects while taking into account advancements in hydrogen production from AECs, PEMECs, and SOECs through 2045. The study aims to point out the development of relevant influencing technological factors and their impact on environmental and economic results. Special attention is given to the following factors:

- *Different electricity sources (wind power vs. electricity mix).*
- *Development of the demand for electricity.*
- *Development of the demand for critical raw/construction materials.*
- *Development of lifetimes.*

Furthermore, this study seeks to answer several fundamental research questions to achieve its aims:

- *How do the electrolysis technologies differ from each other with respect to different environmental impact categories and compared to a reference technology?*
- *How do the life cycle costs differ when using different water electrolysis technologies?*
- *How do the results differ for the years 2022 and 2045?*
- *Do the environmental and economic results show a positive or opposite dependency compared to each other?*

To answer these research questions, technological, environmental, and economic sub-models were implemented and are presented in the "Methods" section.

Methods

Technology descriptions

Water splitting via water electrolysis is an electrochemical reaction. This requires an energy supply in the form of direct current [17] as well as heat [18]. The reaction occurs in electrolysis cells, with Eq. (1) describing it:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \;\; \Delta H_R^0 = +286\frac{kJ}{mol} \tag{1}$$

Despite the same overall reaction, the three electrolysis technologies differ, which can already be seen in the differences in the cell structure and partial reactions.

Schematic representations of the cell concepts on which the three electrolysis technologies are based, as well as partial reactions, can be found in Fig. 1.

AECs are characterized by two chambers separated by a diaphragm. These chambers contain a liquid electrolyte, a solution of water and potassium hydroxide

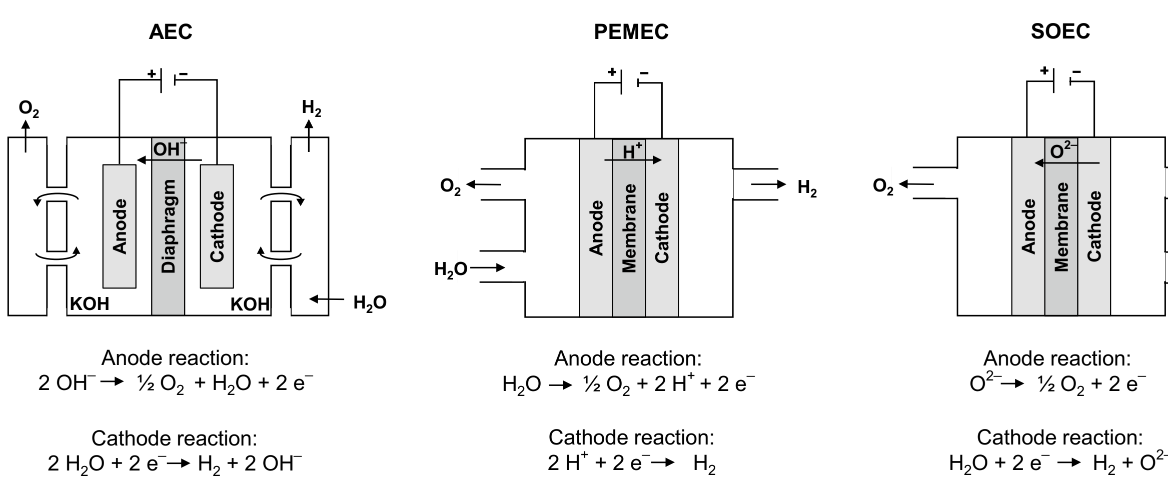

Fig. 1 AEC, PEMEC, and SOEC: schematic illustration of cell concepts and reactions; based on Steinmüller et al. and Liu et al. [3, 19]

(KOH). At the cathode, water splits into H_2 and OH^- ions [20]. To date, nickel and nickel alloys have been preferentially used as electrode materials [21]. Composite materials, such as Zirfon®, which consists of zirconium oxide and polysulfone, are currently mostly used in the diaphragms [22].

In a PEMEC, a proton-conducting polymer membrane, usually NAFION®, is used as the electrolyte [20]. In these cells, the water is split on the anode side. From there, the protons flow through the membrane. Hydrogen is then formed at the cathode. In this technology, the membrane is directly connected to the electrodes, as no liquid electrolyte is used [20]. In addition to the above-mentioned membrane material, the following materials are particularly relevant for PEMECs: platinum as the anode material and iridium or ruthenium as possible cathode materials [21].

The central element of the SOEC is a solid oxide layer, which acts as the electrolyte. At the anode, the water vapor used for this high-temperature technology is split into H_2 and O^{2-} ions. The O^{2-} ions can reach the anode via vacancy diffusion and react to form O_2 [20]. Typically, the electrolyte or solid oxide layer consists of zirconium oxide (ZrO_2) doped with yttrium oxide (Y_2O_3) [21]. Nickel is used as the catalyst [20].

The most advanced [23–27] and common [28] electrolysis system to date is AEC, which allows large plant capacities to be realized at the lowest investment costs to date for water electrolysis technologies [23–25, 27, 28]. It should be noted that minor impurities and an associated product purity of $\geq$ 99.5% may still be present before the final gas treatment [29].

As mentioned previously, several materials are required for the manufacturing and construction of electrolysis cell stacks. Regarding the life cycle inventories used for these cell stacks, which can be found in the "Methods" section, the following materials for electrolysis technologies are considered critical in the EU's list of critical raw materials [30]. For the construction of AEC stacks, graphite and nickel are typically used. Titanium and the platinum group metals (PGMs) iridium and platinum are typically used for the construction of PEMEC stacks. Small amounts of titanium can also be used for the construction of SOEC systems. Furthermore, cobalt, nickel, and the rare earth elements of lanthanum and yttrium are also used for SOEC construction. More detailed information regarding the assumed materials and their quantities can be found in the "Methods" section.

The main methodological aspects of LCA and LCC are first explained before the specific methodological selection for this study is presented.

Methodological approach

An LCA is characterized by standardization based on ISO standards 14040 and 14044 [8, 9]. An LCA examines environmental aspects and impacts throughout the life cycle, ranging from raw material extraction to disposal. Due to its comprehensive and multi-layered analysis capabilities, LCA was used in this study as the environmental assessment method.

The economic aspects of water electrolysis systems can be analyzed and compared using various methodological concepts. Techno-economic analysis is a very common approach for this, in which selected economic indicators are used on the basis of a technical analysis. LCC is an alternative to this. In methodological terms, LCC and LCA are similar and can be based mostly on the same data. This method takes into account the system boundaries, the functional unit (FU), and the phases of classic LCA. Due to its proximity to the LCA approach and the resulting data consistency, the LCC approach is used in this study.

Goal and scope of LCA and LCC

As described in detail in the "Background" chapter, this study aims to investigate various technological, economic, and environmental aspects as well as advancements in hydrogen production from AECs, PEMECs, and SOECs through 2045.

For the present LCA and LCC study, a mass-related FU was selected with "1 kg H_2". Furthermore, this specification is supplemented by specification of the physical property, in this case, the pressure, which is assumed to be 10 bar. The technologies examined for the production of hydrogen are thus directly comparable in terms of their environmental impacts and life cycle costs.

All three water electrolysis technologies, AEC, PEMEC, and SOEC, are analyzed. Germany was chosen as the geographical framework. In addition to its conditions in 2022, future developments, especially those involving technological improvements and a decarbonizing electricity grid mix, are also analyzed. As Germany is aiming for greenhouse gas-neutrality by 2045, this year is of particular interest and is analyzed in this paper. For both years, a time horizon of plant operation and accompanying hydrogen production over 20 years is considered.

Modeling approach, system boundary, software, and databases

An attributive cradle-to-gate LCA approach was chosen for this study. Cradle-to-gate assessments typically begin with the extraction of raw materials through the construction of plants, energy supply and conversion, and end with the provision of hydrogen (at the factory gate). A possible subsequent use of hydrogen, e.g., as fuel, lies outside these system boundaries. A schematic representation of the main system boundaries is presented in Fig. 2.

Furthermore, the recycling and end-of-life of electrolysis systems have not yet been standardized and, consequently, are not considered in the LCA section of this study. The openLCA software, version 1.10.3, was used. The LCA database ecoinvent (version 3.7.1) in the "cut-off by classification" system model was used to provide background data for the Life Cycle Inventory [31].

Information on the foreground data used for the LCA and LCC for AEC, PEMEC, and SOEC is discussed in the sections, "Common data for LCA and LCC", "Data for LCA", and "Data for LCC".

For the LCC analyses, an own Microsoft Excel tool, which includes numerous literature-based economic parameters of the technology options under consideration, was used. As a variant of LCC, environmental life cycle costing was chosen. The LCC Excel tool developed also contains key formulas for levelized costs of hydrogen (LCOH) calculations.

Environmental impacts (LCIA indicators)

The synthesis of existing LCIA methods in the European context in the form of the Environmental Footprint (EF) framework [32] in version 3.0 was used for this study. The mid-point impact indicator values selected were considered to be more scientifically robust than end-point indicators [33]. Table 1 contains a list of the environmental categories and indicators selected on this basis, as well as the associated units and abbreviations used. Major reasons for the selection are the classification as more robust (categories I and II) than other indicators (robustness category III) and their good comparability with other studies.

LCC indicators

The choice of indicators is also relevant for the LCC. For this study, therefore, particular attention was given to the selection of indicators within existing hydrogen-related publications. An earlier study [34] showed that previous LCC calculations of hydrogen production systems have most frequently used the following indicators: LCOH, capital expenditures/plant costs (CapEx), and plant operating expenditures (OpEx). LCOH concepts are fundamental approaches to techno-economic comparisons of competing technologies and/or production sites, as

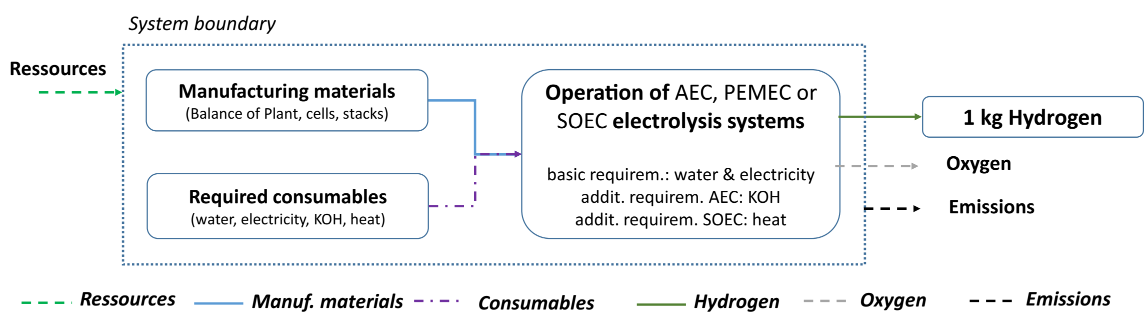

Fig. 2 System boundaries of cradle-to-gate hydrogen production; based on Koj et al. [16]

Table 1 Environmental indicators selected for the LCIA

EF impact category	Impact category indicator	Abbreviation	Unit
Climate change	Global warming potential (100 years)	GWP_{100}	kg CO_{2eq}
Ozone depletion	Ozone depletion potential	ODP	kg CFC11 eq
Particulate matter	Impact on human health	PM-ihh	Disease incidence
Ionizing radiation	Human exposure efficiency relative to U^{235}	IR-hee	kBq U-235 eq
Photochemical ozone formation	Tropospheric ozone concentration increase	POF-toci	kg NMVOC eq
Acidification (potential)	Accumulated exceedance	A-ae	mol H^+ eq
Eutrophication (potential), terrestrial	Accumulated exceedance	EP-ter-ae	mol N eq
Eutrophication (potential), freshwater	Fraction of nutrients reaching freshwater end compartment (P)	EP-fw-p	kg P eq
Eutrophication (potential), marine	Fraction of nutrients reaching marine end compartment (N)	EP-mar-n	kg N eq

well as for technology assessments in general [35, 36]. The LCOH reflect the total lifetime costs of the systems under consideration. Furthermore, according to Kuckshinrichs & Koj, the LCOH can be understood as a break-even value that indicates the price required as revenue over the lifetime of a technology to justify an investment [35]. The CapEx and OpEx indicators can be considered separately but are also components of production costs. As the LCOH are based on CapEx and OpEx and are more meaningful and relevant, OpEx and CapEx are not treated separately as part of the LCC calculations in this study. Based on its advantages and the establishment of its use, the LCOH indicator was preselected as the first indicator for LCC in this study. A more recent study by Ishimoto et al. [37] presents a literature review of LCC approaches on fuel cell and hydrogen systems. Regarding cost calculation methods and indicators, they found out the levelized cost method and the net present value (NPV) to be the most frequently applied. Although the levelized cost approach reveals specific economic results for a unit of a product (e.g., kg H_2), the NPV embodies the absolute economic results of a project. According to Rosłon et al. [38], NPV is the primarily used indicator for assessing the economic efficiency of projects. This economic metric can also be considered to support decision-making by comparing the economic attractiveness of different investment opportunities [39]. Thus, NPV was selected as the second economic indicator in this study because it is also a frequently used and established indicator and provides additional information on the profitability of hydrogen production opportunities.

In its simplest form, the LCOH indicator represents the following mathematical relationship: the sum of CapEx and OpEx is divided by the total energy yield of the plant under consideration over its lifetime and discounted to the reference year [40]. In addition, subcategories and further categories can be included in the calculation. Examples include decommissioning costs, taxes, or external costs [35]. As described by Kuckshinrichs & Koj [35], LCOH assessments can consider a private (or synonymously business) or social perspective. In this study, a private perspective is used. The difference between these two perspectives is not described in detail here but can be found in Kuckshinrichs & Koj [35]. Equation (2) takes different previously published LCOH formulations for this private perspective into account [30, 35, 41, 42]:

$$LCOH = \frac{I_0 + \sum_{t=1}^{n} \frac{WC_t + EC_t + HC_t + RC_t + AC_t + OFC_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{MHydrogen_t}{(1+i)^t}} \tag{2}$$

In Eq. (2), I_0 represents the sum of the initial investment costs (CapEx). The unit of the investment costs is $€_{2022}$. In addition, several fixed (operation-related) and variable (demand-related) cost components are taken into account. The variable costs, which are based on the amount of hydrogen produced, include the water costs per year (WC_t), the electricity costs per year (EC_t), and the heat costs per year (HC_t). Furthermore, the costs of the cell stack replacement (RC_t) are relevant. The fixed (operation-related) costs include administration costs (AC_t), and other fixed operating costs (OFC_t). All cost components are considered in real terms, meaning that inflation is not considered. The entire service life of the water electrolysis system is recorded with n, where t indicates the respective year under consideration. The variable i represents the interest rate used for discounting. $MHydrogen_t$ indicates the annual amount of hydrogen provided in kWh. As for the LCA, recycling and end-of-life of the systems are not considered for the LCC in this study. This approach is also common in many other studies for calculating LCOH. The unit for the variables WC_t, EC_t, HC_t, RC_t, AC_t, IC_t, and OFC_t is $€_{2022}$/year for annual production, whereas the unit for $MHydrogen_t$ is kWh/year (or MWh/year).

The two parameters I_0 and i are of particular interest, as value assumptions for these are particularly intensely debated in academia and beyond, e.g., the debate on the cost of capital [43–45]. Furthermore, these parameters are associated with uncertainties, as they can change over time and vary depending on location. Consequently, an established and multi-layered approach was chosen to determine future CapEx values. In addition, both latter parameters were subjected to a sensitivity analysis, which is presented in the "Results" section.

The second considered LCC indicator, NPV, takes into account the initial and potential later investments, the net demolition costs at the end of the lifetime as well as net cash flows (revenues minus expenditure) during the years considered in the planning horizon. There are several different formulas for NPV, which ultimately describe the same basic calculation approach. Equation (3) is based on similar equations that were published by Rosłon et al. and Schoenmaker & Schramade [38, 39]:

$$NPV = \sum_{t=0}^{n} \frac{NCF_n}{(1+i)^n} \tag{3}$$

where NCF_n stands for the net cash flow, considering the initial point of time ($t=0$) and year n at the end of the planning horizon. Again, the variable i represents the interest rate used for discounting.

Learning curve approach

To extrapolate the CapEx values to the year 2045, a learning curve approach was taken. The basic learning curve concept was developed by Wright and first published in 1936 [46]. The study analyzed the costs of technologies and their development over a selected period. In addition, these learning curves combine technological improvements in manufacturing processes over time with cost developments. Thus, for this study, learning curves were selected for a consistent assessment of prospective technological and LCC developments by describing the relationship between the increase in production or cumulative capacity of a good and the reduction of its costs [47]. Based on the different configurations of learning curves, Eq. (4) was chosen for this study:

$$C_t = C_0\left(\frac{X_t}{X_0}\right)^{-\beta} \tag{4}$$

where C_0 represents the costs at time t = 0. X_0 represents the cumulative capacities of technologies at time t = 0. X_t represents the cumulative capacities and C_t the costs at a prospective time t. The applied learning parameter is given by β and can be calculated with a logarithmic equation based on a learning rate. For example, an economic learning rate of 15% means that the costs decrease by 15% when the cumulative installed capacity doubles [48].

To calculate prospective CapEx values for water electrolysis technologies, it is important to know their identified learning rates. For electrolysis, different learning rates between 8% [49] and 18 ± 13% [50] were identified by literature review. Table A 2 in the Supplementary material lists values from the literature according to the level of learning rates. The highest learning rates were identified in the distant past of the last century, when only AEC technology was available and less mature. Consequently, newer values are lower and tend to be greater for PEMEC and SOEC than for the most mature AEC technology. To take the range of values and different developments into account and present more current conditions, three different learning rates for electrolysis systems were taken into account for our own calculations as part of this study: 7%, 10%, and 13%.

As previously noted, learning curve calculations also require values of production volumes (leading to cumulative installed capacities). Several projections of total water electrolysis capacities have been published to date. However, differentiation of capacities corresponding to different electrolysis technologies has been very rare. Publications by Boehm et al. [47, 51] are an exception in this regard. In the first of these [47], starting values and projections of the global cumulative electrolysis capacities up to the year 2050 were included. The entire globally assumed annual increase in electrolysis capacity was then multiplied by the share of the respective electrolysis technologies, as presented in Boehm et al. [51]. Based on the annual capacity expansion and initial values, the cumulative installed capacity could be calculated. Furthermore, Boehm et al. differentiated between variants of high- and low-capacity expansion. This differentiation of "high" and "low" developments of installed capacities from 2022 until 2045 was also considered in this study and is shown in Fig. 3.

Figure 3 shows that, based on the assumptions of Boehm et al., the highest absolute capacity increases are expected for PEMEC systems. Until 2045, higher capacities are expected for AECs than for SOECs. Nevertheless, stronger increases in SOEC capacities are assumed from 2035 in particular, which leads to a noticeable approximation of the results. Furthermore, the highest absolute increases are assumed for the distant future, particularly from 2040 onward. In contrast, the highest rates of capacity multiplication are already projected for the period between 2025 and 2030.

The chosen values for the cost components in this study are listed in the sub-section "Data for LCC".

Common data for LCA and LCC

For a fair comparison of technology options, it is important to use a data source that is as consistent as possible. One such common data source is seen in the “State-of-the-Art and Targets” of the U.S. Department of Energy (DOE), which have been published separately for the three technologies [52–54]. These documents contain data on the status (state-of-the-art) as of 2022, the targets for the year 2026, and the ultimate targets for several key performance indicators (KPIs). For this study, assumptions for electricity demand, lifetime, critical raw material content and capital cost are especially relevant. In addition, the heat demand can be derived from the SOEC data. Electricity and heat demand, as well as lifetime, are important for both the LCA and LCC. The material content is relevant for the LCA, and the capital cost is used for the LCC. In this study, it is assumed that the ultimate targets are applicable to the year 2045. No restriction on the US market is discernible regarding these technical targets. The information contained in the DOE documents is therefore considered to be globally applicable and usable for the German analysis framework.

In addition, important data relevant for LCA and LCC were supplemented by literature data on water and KOH demand, as well as our own assumptions on nominal load and full load hours (FLH). A nominal load is also assumed for 2045 to ensure objective comparability, as there are no economies of scale for the stacks due to their modular design. The operation with the electricity mix assumes of a very even operation over a long period of time. The FLH assumed for this purpose are therefore much higher than those assumed for connecting to

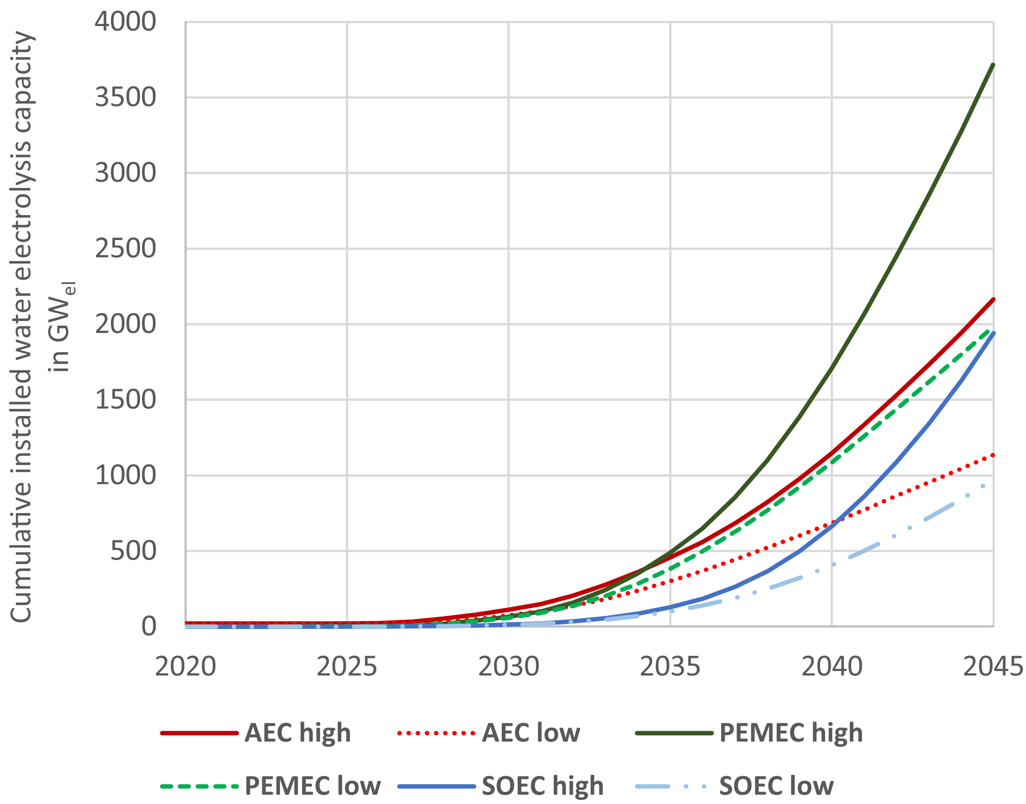

Fig. 3 Assumed cumulative installed capacities of AECs, PEMECs, and SOECs until the year 2045; based on [47, 48, 51]

Table 2 Common data assumptions for LCA and LCC

	Unit	2022			2045			Primary source
Type of electrolysis	**–**	**AEC**	**PEMEC**	**SOEC**	**AEC**	**PEMEC**	**SOEC**	
Nominal load	MW_{el}	1	1	1	1	1	1	Own assumpt.
Lifetime stack	h	60,000	40,000	20,000	80,000	80,000	80,000	[52–54]
FLH (Electricity mix (M)/Wind (W))	h/a	7,000; (M) 2,000 (W)	7,000 (M); 2,000 (W)	7,000 (M); 2,000 (W)	7,000 (M); 2,000 (W)	7,000 (M); 2,000 (W)	7,000 (M); 2,000 (W)	Own assumpt.
Electricty demand (system)	kWh/kg H_2	55	55	38	48	46	35	[52–54]
Heat demand (system)	kWh/kg H_2	-	-	9	-	-	7	[52–54]
Water demand	kg H_20/kg H_2	8.9	8.9	8.9	8.9	8.9	8.9	[55]
KOH demand	kg KOH/kg H_2	8.5 E-04	–	–	8.5 E-04	–	–	[16]

fluctuating electricity-generating wind turbines. Table 2 lists the common LCA and LCC data assumed in this study.

Data for LCA

When selecting Life Cycle Inventory (LCI) data for cells and cell stacks, it is important to ensure that transparent LCI models are used and that these also enable fair comparisons. For this reason, the following LCI models were selected for the stack, as these LCI models also consider stack components made of steel. The model from Lotrič et al. was used for the PEMEC, the inventory from Koj et al. was used for the AEC, and the LCI data published by Schreiber et al. were used for the SOEC [22, 56, 57].

The LCI model from Bareiß et al. [58] is otherwise frequently used for LCAs with PEMEC technology. However, this approach accounts for a very small amount of steel for screws and bolts. The Lotrič LCI model used in this work [56] is also characterized by more material information and a high degree of transparency compared to other known PEMEC LCI models, such as those developed by Bareiß et al. and Schmidt Rivera et al. [58, 59]. Based on the DOE's technical targets, however, it is apparent that the estimate of the required PGM quantity differs significantly from the state-of-the-art quantity determined by the DOE. Therefore, the value determined by the DOE is used in the PEMEC LCI model for 2022 in this study instead of the original value. In addition, the energy required for the manufacturing and construction of the three electrolysis technologies should be considered. This aspect and accompanying data are partially neglected in the previously mentioned LCI model publications. Consequently, this additional energy input is considered within the LCI models of this study on the basis of the consistent consideration of only one publication. For this purpose, data for all three electrolysis technologies on manufacturing and construction energy published by Gerloff [11] are taken into account. As these assumptions essentially rely on the manufacturing of small or micro plants, they were scaled up according to the scaling assumptions mentioned by Gerloff [11]. Although the PGM demand within the base Lotrič LCI model was modified as described above, the critical raw material intensity for the base models of AEC and SOEC were considered usable for 2022 for the sake of simplicity. With regard to the German electricity mix for 2022, statistical data [60] were used and combined into an electricity mix LCI model using own assumptions and available ecoinvent data sets. A study of several research institutes [61] was used for the electricity mix in 2045, and a model was also created, that took into account our own assumptions and ecoinvent data sets. The resulting LCI table of assumed German electricity mixes for 2022 and 2045 can be found in Table A 3. In addition, LCI data on the construction of the electrolyzers and their components can be found in Table A 4–Table A 9 in the Supplementary material.

With respect to future cell stacks, it can be assumed that the use of materials decreases over time because of advancing manufacturing and construction processes and improving material properties. This applies in particular to the use of raw materials that are considered to be potentially critical. The DOE's ultimate target is to reach an electrode PGM loading of 0.03 g/kW, whereas 0.8 g/W is regarded as state-of-the-art for PEMEC technology. This corresponds to a reduction in the specific material requirements of 96.25%. In the European context, there are also targets for KPIs for electrolysis technologies that are comparable to the DOE's technical targets, but do not reflect the status quo in 2022. These targets are published by the Clean Hydrogen Joint Undertaking (CHJU) or Clean Hydrogen Partnership [62]. The CHJU targets assume a reduction in the total specific demand for critical raw materials as catalysts for PEMEC electrolysis from 2.5 to 0.25 g/kW, i.e., by 90%, between 2020 and 2030. For AEC and the same decade, the CHJU targets assume a reduction in the total specific demand for critical raw materials from 0.6 g/kW in 2020 to 0 g/kW in 2030. No clear targets are specified for SOEC in the DOE and CHJU documents. Nevertheless, it can be assumed that the use of critical raw materials will also be significantly reduced for this technology in the future. Based on this, a simplifying and cross-technology assumption of a 96.25% reduction until 2045 compared to the original values (also for the AEC, although a reduction of 100% is mentioned above) is made in this work. With respect to the AEC, this is a fairly conservative estimate compared to the CHJU target values. Consequently, reductions in following critical raw materials were considered for the different electrolysis technologies: cobalt (SOEC), graphite (AEC), lanthanum (SOEC), nickel (AEC and SOEC), platinum (PEMEC), titanium (PEMEC and SOEC), and yttrium (SOEC).

All three electrolysis technologies were compared with an established reference technology, in this case, steam reforming with natural gas/methane (SMR). The applied LCI data for SMR were based on publications by Wulf [63, 64]. The authors describe that data can be considered for the years 2030 and 2032 for this reference technology. As no sources of SMR LCI literature could be identified extending further into the future, the model was used for both points in time in this study. The applied LCI model of the German electricity grid mix and the LCI data used for SMR can be found in Table A 10, Table A 11, and Table A 12 in the Supplementary material.

Data for LCC

The data needed for the LCC model in this study to calculate the LCOH were collected with the goal of being as consistent as possible and taking current conditions into account. Thus, most values were taken from the techno-economic publications by Boehm et al. [51]. Many of the values used to determine LCOH are expressed as a percentage of the CapEx. The CapEx, which develops over time, is therefore of particular importance. For this reason, the DOE publications already used for the consideration of other electrolysis data [52–54] are used as the starting points (values for 2022) and as a basis for the CapEx projections. The DOE values describe the uninstalled CapEx of entire electrolysis systems. The starting values were calculated using the average exchange rate between the Euro and US dollar for 2022 of 1.05 $/€ [65]. For the AEC, the starting value in 2022 was 476.19 €/kW$_{el}$; for the PEMEC, it was 952.38 €/kW$_{el}$; and for the SOEC, it was 2,380.95 €/kW$_{el}$. To obtain CapEx values for the year 2045, the already described learning curve approach is used. Considering the three electrolysis technologies, different learning rates (LR) (7%, 10%, and 13%), and two different capacity scenarios (low and high increase) are calculated. The CapEx development values of the AEC, PEMEC, and SOEC can be found in Fig. 4. The upper whiskers of the respective boxplots (maximum value) indicate starting values in the year 2022, as assumed by the DOE documents [52–54]. In contrast, the lower whisker limit (minimum value) represents the calculated CapEx values for 2045. The circles represent the CapEx results in 5-year increments. In addition, the centerline inside the box marks the median value. The x-marker within the boxplots in Fig. 4 represents the arithmetic mean of the data points.

For each electrolysis technology, the upper limits of the whisker's boxplots in Fig. 4 represent the starting values. The learning curve analysis in Fig. 4 exhibits significantly decreasing CapEx values for all three electrolysis technologies. As is illustrated, the CapEx of AEC systems can be reduced from 476 to 186 €/kW$_{el}$ in the

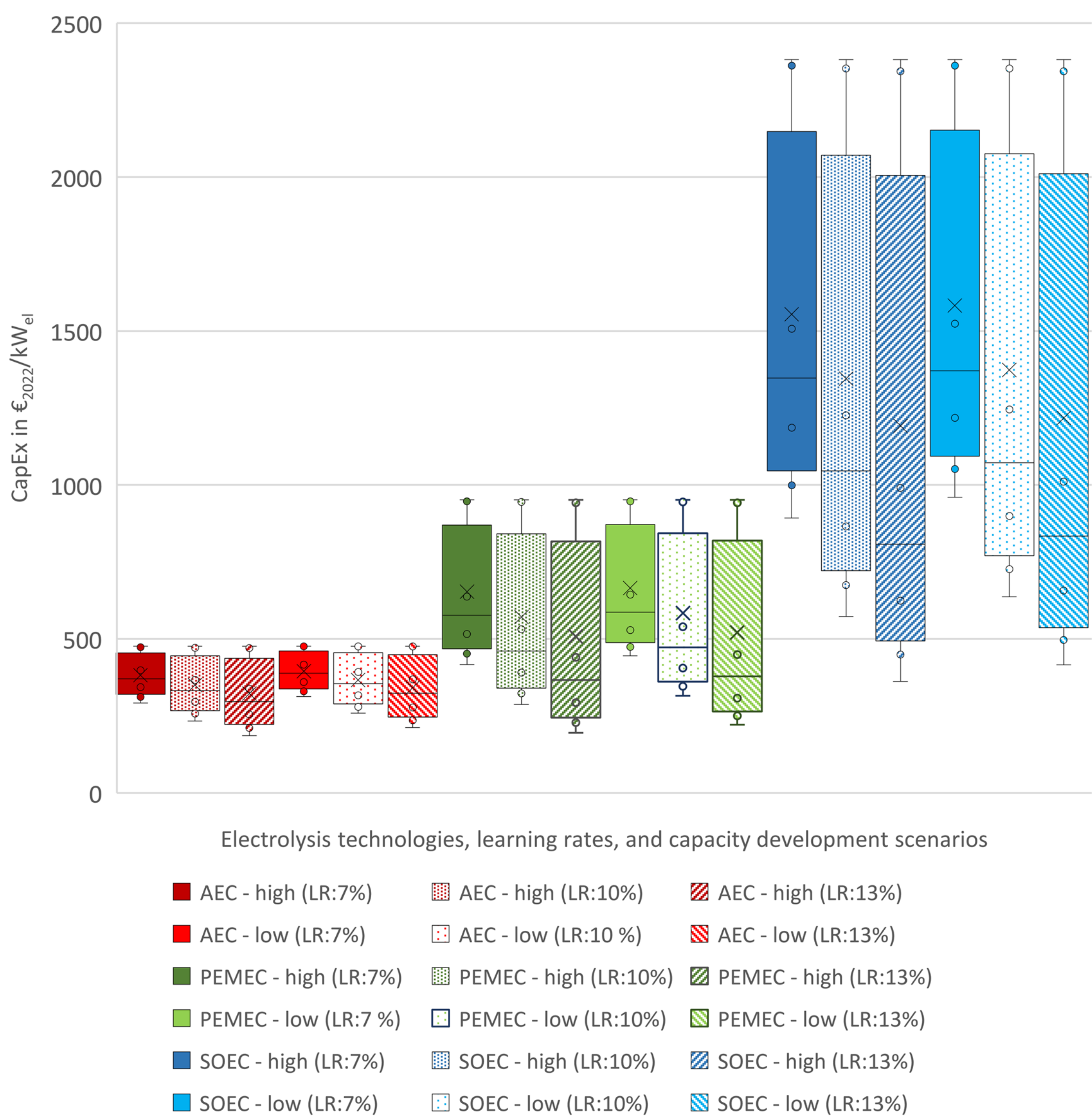

Fig. 4 CapEx of electrolysis technologies based on learning curve analysis taking into account different learning rates and capacity increases

best case and to 313 €/kW$_{el}$ in the worst case. The projected relative reductions ranged from 34 to 61%. For PEMEC systems, Fig. 4 reveals CapEx reductions from 952 to 195 €/kW$_{el}$ as the best case and to 446 €/kW$_{el}$ as the worst case. These decreases ranged from 53 to 80%. The CapEx of SOEC systems can be reduced from 2381 €/kW$_{el}$ to 363 €/kW$_{el}$ (best case) and 960 €/kW$_{el}$ (worst case). Furthermore, LR variations have significantly greater effects than different capacity scenarios. Higher CapEx starting values are given for PEMEC systems, but by 2045, this technology could reach the level of AEC systems in the best case.

For the LCC model in this study, the best case (BC) and worst case (WC) results obtained from the learning curve analysis for the year 2045 were considered as CapEx values for each technology.

To keep the LCOH calculations as consistent as possible, further relevant data were taken from the Supplementary material of a paper published by Boehm et al. [51]. The publication includes data from 2020 to 2050. As no exact figures were available for the years 2022 and 2045, values for 2020 and 2050 were taken from the publication. In particular, the assumptions regarding the costs of electricity and heat can be discussed critically, as the data published by Boehm et al. [51] could not take more recent developments regarding effects on energy markets into account. However, the development of these prices will remain subject to considerable uncertainty in the future. For this reason, these assumptions were initially used here as a consistent basic assumption, with the effects of other prices shown later in a sensitivity analysis. The final choice of assumptions with exclusive relevance for the LCC calculations can be found in Table 3.

Results

LCIA results

As part of the life cycle impact assessment, the absolute GWP$_{100}$ results of hydrogen production using electrolysis technologies were first compared with those of the reference technology. A subsequent contribution analysis revealed the different reasons for these results. The causes of the GWP$_{100}$ results of different cell stack variants were also determined. Finally, additional impact categories were investigated and compared with those of the reference technology.

Figure 5 first shows the absolute GWP$_{100}$ results for different electrolysis technologies, points in time and power supply variants in comparison to the reference technology, SMR.

Figure 5 clearly illustrates the great potential for reducing the GWP$_{100}$ of hydrogen production through operation with wind power compared to the use of grid electricity (electricity mix). Using wind power, reductions of almost 93% can be achieved for AEC and PEMEC systems, whereas a decrease of 81% is possible for an SOEC in 2022.

Electrolysis based on the German electricity mix in 2045, which is assumed to be fully renewable, still provokes significantly higher results in GWP$_{100}$ values than for wind power-supplied systems (35.7–41.2%), but the gap between the values is narrowing. Compared to SMR, the water electrolysis technologies can achieve up to 87.8% lower values for the GWP$_{100}$ indicator when using wind power. The results converge across the technologies over time. AEC and PEMEC are already at a highly comparable level, which is due to the identical electricity consumption assumptions. The different contributions to the overall environmental impacts of hydrogen production

Table 3 Data for LCC (LCOH) calculations for the years 2022 and 2045

	unit	2022			2045			Prim. source
Electrolysis technology	–	**AEC**	**PEMEC**	**SOEC**	**AEC**	**PEMEC**	**SOEC**	–
Spec. invest (CapEx)	€$_{2022}$/kW$_{el}$	476.19	952	2381	186.3 (BC); 313.2 (WC)	195.4 (BC); 445.52 (WC)	362.5 (BC); 959.9 (WC)	[52–54] and own calcul.
Stack share on CapEx	%	50	60	30	44	36	10	[51]
OpEx fixed	% of CapEx	4	4	4	2	2	2	[51]
Insurance costs	% of CapEx	0.5	0.5	0.5	0.5	0.5	0.5	[51]
Administration costs	% of CapEx	2	2	2	2	2	2	[51]
Electricity supply costs	€ct/kWh$_{el}$	3.5 (Mix)	3.5 (Mix)	3.5 (Mix)	4 (Wind); 8 (Mix)	4 (Wind); 8 (Mix)	4 (Wind); 8 (Mix)	[51]
Heat supply costs	€ct/kWh$_{th}$			5.5			5.5	[51]
Interest rate	%	4	4	4	4	4	4	[51]

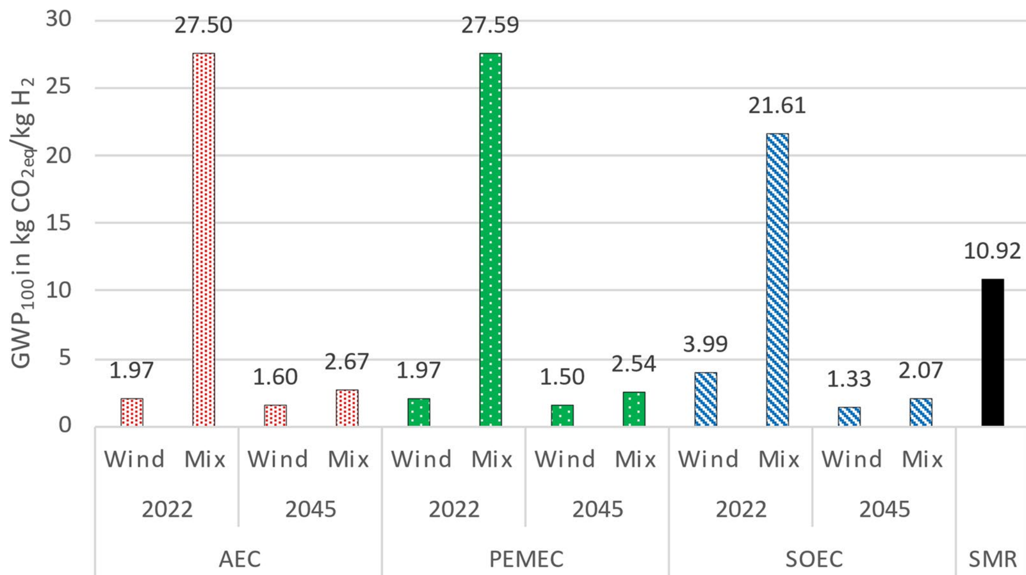

Fig. 5 GWP_{100} results for power supply variants (Wind, electricity mix (Mix)) of hydrogen production by AEC, PEMEC, and SOEC compared to SMR

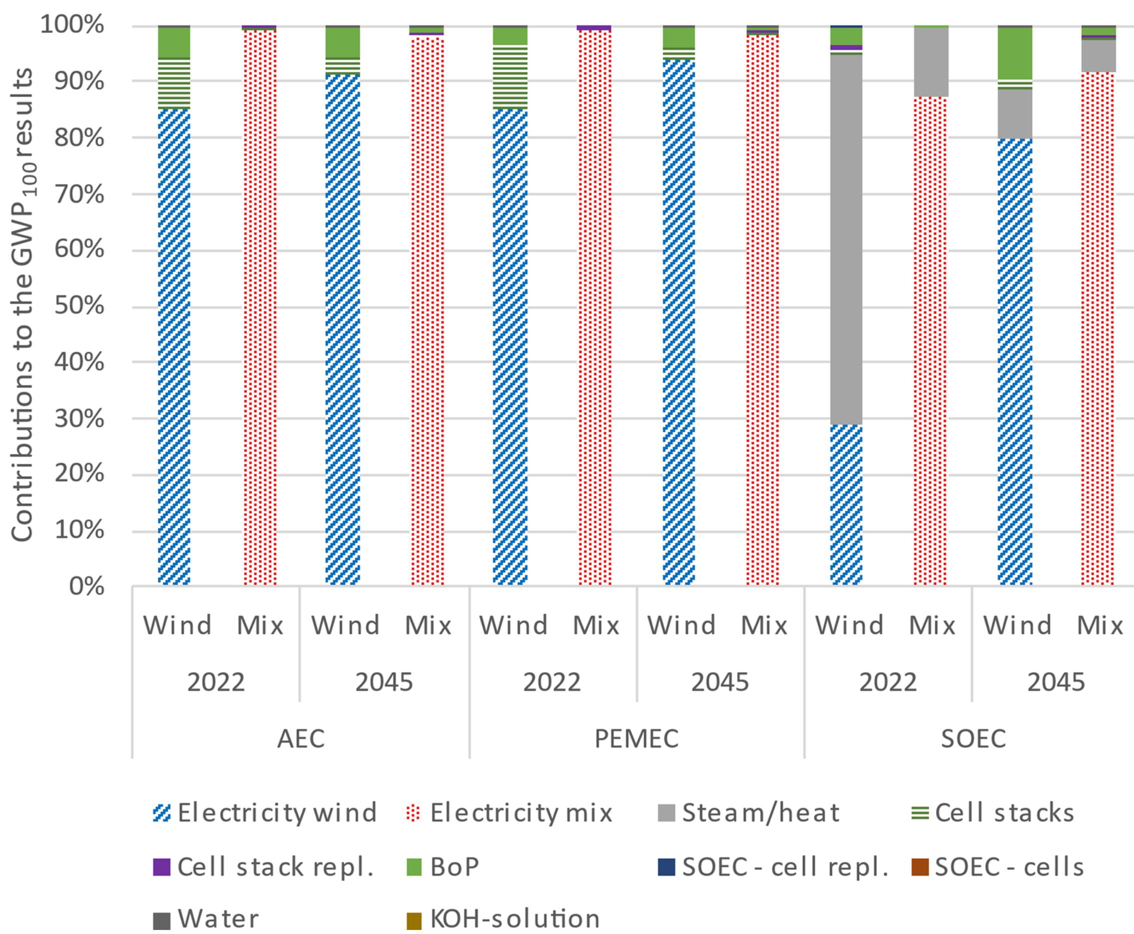

Fig. 6 Contribution analysis for AEC, PEMEC, and SOEC for the indicator GWP_{100}

are discussed in detail in the contribution analysis (Fig. 6). Figure 6 illustrates the relative contributions to the results of hydrogen production for the GWP_{100} indicator. The underlying data are presented in Table A 13 and Table A 14 (Supplementary material).

As can be seen in Fig. 6, the energy sources, electricity and, in the case of SOEC also steam/heat, are responsible for most of the GWP_{100} results. The contribution of the electricity supply to the environmental impacts is most pronounced in the case of electricity mix use. The contributions shown can be allocated to the life cycle phases of manufacturing and construction as well as operation. Plant operation predominates over manufacturing and construction across all technologies. Manufacturing and construction include the cells, cell stacks, and Balance of Plant (BoP) components. In addition, a replacement is considered if the number of hours of hydrogen production exceeds the service life. Within the considered time horizon of plant operation over 20 years after initial installation, AECs require two stack replacements, PEMECs three, and SOECs six. This is based on 2022 conditions and operating with the electricity mix. When operating with wind power under the assumptions made, only SOECs require one stack replacement. Due to increasing lifetimes, there is no need for stack replacement in the case of electrolysis with wind power. For electricity mix-based electrolysis, one stack replacement is required in 2045 for each technology. For SOEC, a combined view of the last two figures shows that the clear prospective reduction in GWP_{100} results is primarily due to the assumed more environmentally friendly heat supply.

Figure 7 shows the results of the GWP_{100} indicator for the different electrolysis technologies and for different years and underlying LCI stack manufacturing and construction models. The suffix "A" indicates the respective original LCI model. The suffix "B" describes the consideration of assumptions regarding manufacturing and construction energy from the paper by Gerloff [11] as used in this study and explained in the "Data for LCA" section. For each technology variant, the five materials (Top 5) with the highest influence on the GWP_{100} indicator were considered. The remainder (Rest) always includes all contributions that cannot be assigned to these respective Top 5. Some of the material designations are abbreviated and have not been mentioned previously. ABS is an acronym for acrylonitrile–butadiene–styrene, (P)TFE is the abbreviation of (poly)tetrafluoroethylene, and NMP stands for N-methyl-2-pyrrolidone.

Figure 7 illustrates that the results of the different LCI stack manufacturing and construction models are heterogeneous. The PEMEC electrolysis stacks, whose

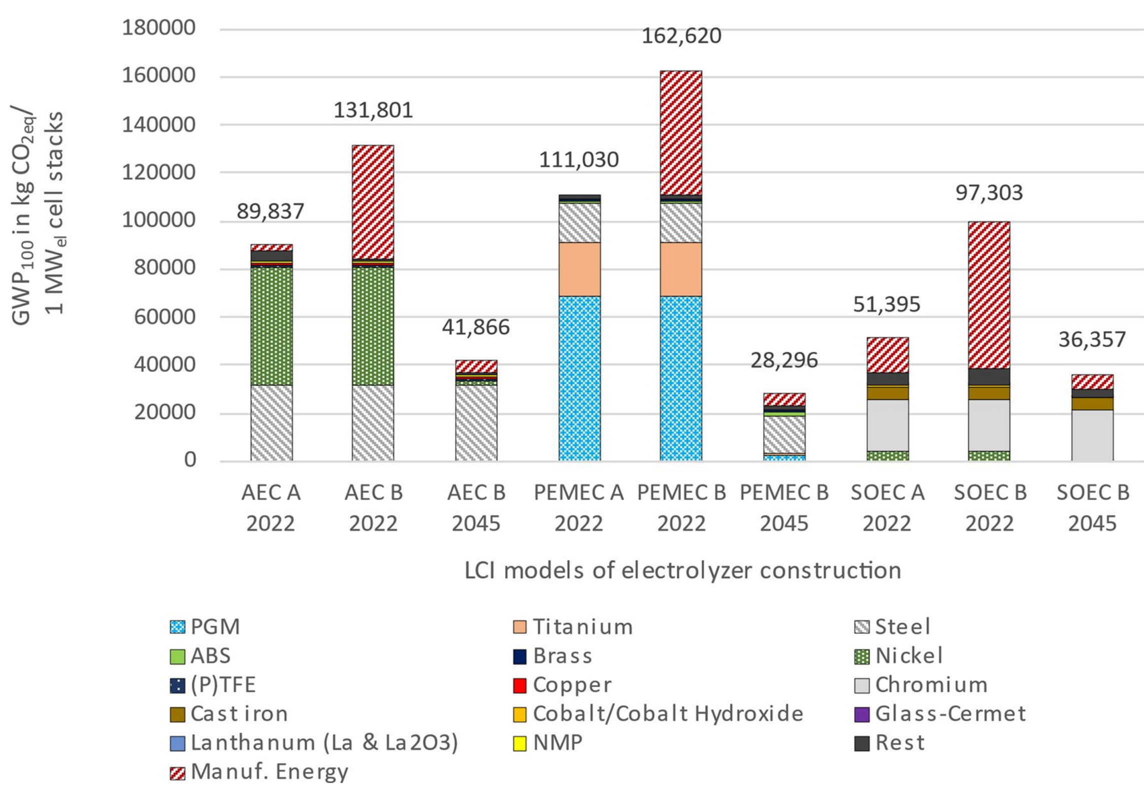

Fig. 7 GWP_{100} results for different LCI stack manufacturing and construction models

production in 2022 is still associated with the highest results, feature the lowest in 2045. For PEMEC, this is primarily due to the high contributions of the critical raw materials, PGMs and titanium, in 2022. This is because the mining and provision of platinum and iridium are particularly energy- and emissions-intensive. According to the International Renewable Energy Agency (IRENA), one kilogram of these materials, including their supply, contributes around 10,000 kg CO_{2eq} to climate change [66]. As a significant decrease in the specific use of these materials is expected and assumed in this study, the climate change results are also strongly declining. The AEC and SOEC also exhibit significant reductions in the GWP_{100} results for 2045 compared to those for 2022. However, their results are not determined to the same extent by critical raw materials. The contributions of manufacturing energy in the LCI models for 2022 differ significantly. This manufacturing energy assumption based on the publication by Gerloff [11] leads to significantly higher results than in the original models by Koj et al. for AEC, Lotrič et al. for PEMEC, and Schreiber et al. for SOEC [22, 56, 57]. While the calculated GWP_{100} results for the "B" LCI models are around 47% higher for AEC and PEMEC systems, the results for SOEC are even 89% higher than for model "A".

LCIA for additional impact categories and comparison with the reference technology

The environmental analyses in this study were not limited to the GWP_{100} indicator. Further indicators listed in the "Methods" chapter are included in the analysis and the electrolysis technologies were analyzed in comparison to each other and with SMR using spider diagrams. The presentation was based on a decadal logarithmic scale and the results are shown relative to the environmental impacts of SMR. The grey area (100% values) indicates the calculated environmental impacts of SMR for each impact category. For greater clarity and comprehensibility, the analyses for 2022 and 2045 are shown in separate diagrams. Figure 8 shows the results for 2022.

Figure 8 reveals that the advantages of certain technology variants determined for GWP_{100} do not apply equally to all additional environmental impacts considered. Furthermore, Fig. 8 illustrates clear differences between the technology variants that produce hydrogen with the German electricity mix in 2022 and those that also do so with wind power for the other impact categories. The variants using the electricity mix have a significantly higher environmental impact. In the most extreme case of the eutrophication potential of fresh water, the values for operation with the electricity mix are up to 115 times

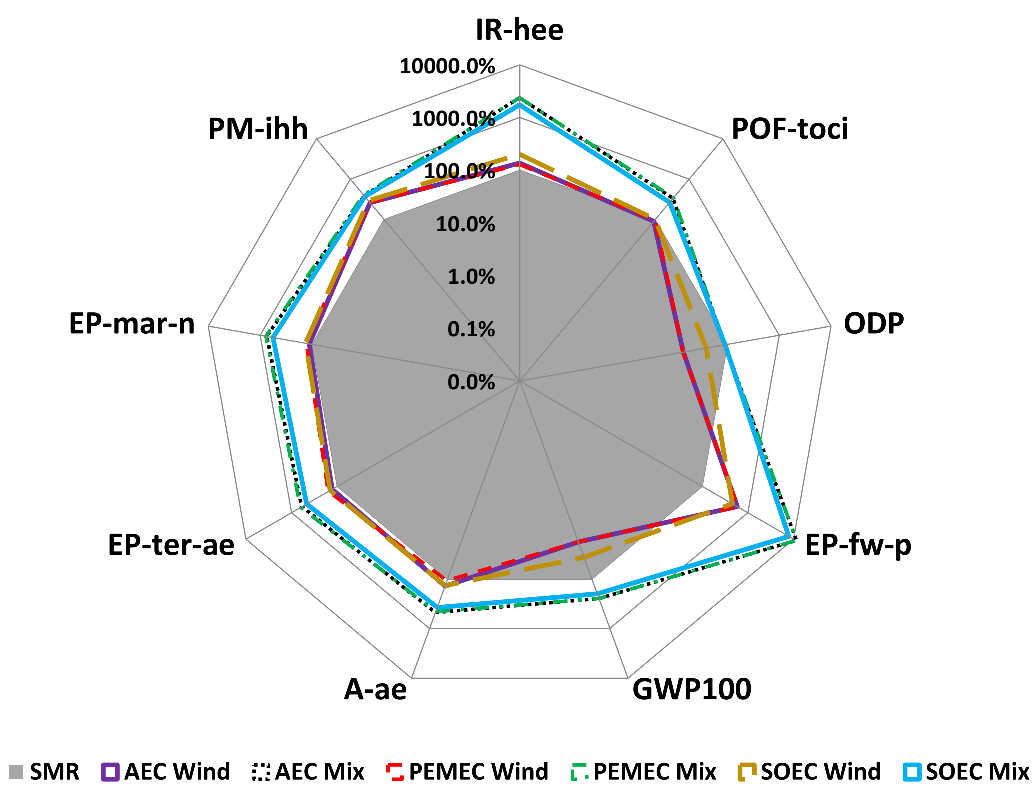

Fig. 8 Comparison of AEC, PEMEC, and SOEC with SMR for the year 2022 using several environmental indicators

higher compared to SMR. The main reason for this is coal-fired power generation as a component of grid electricity (electricity mix). Large amounts of the energy- and emissions-intense produced materials steel, aluminum, and copper are required for these types of power plants. These electricity mix contributions also have a high impact on several other environmental indicators.

In contrast, electrolysis using wind power already achieves significantly lower results in 2022 compared to SMR regarding the GWP_{100} and ODP indicators and comparable results with respect to the EP-mar-n, EP-ter-ae, A-ae, and POF-toci indicators. The ODP results of electrolysis technologies supplied by wind power are 61–86% lower, and the GWP_{100} results are 63–82% lower, than SMR. However, regarding EP-fw-p, IR, and PM, water electrolysis with wind power does not achieve the environmental performance of SMR. The main reason for this is the environmental impact caused by the upstream processes of the steel components required for the cell stacks.

The results of the electrolysis technologies compared to SMR for 2045 are presented in Fig. 9. As illustrated in Fig. 9 for 2045, the electricity mix variants are significantly more competitive in terms of their environmental performance compared to the reference technology (SMR). This is a result of the fully renewable electricity mix. Thus, the values clearly improve against 2022. Depending on the technology, the variants with wind power perform better than the reference technology for five or six indicators (POF-toci, ODP, GWP_{100}, A-ae, EP-ter-ae, and EP-mar-n). Advantages that are given for both the variants with wind and with the mix are shown for the indicators ODP, GWP_{100}, and POF-toci. Clear disadvantages with up to five times higher environmental impacts compared to the reference technology are only given for the EP-fw-p indicator. The other indicator for which significantly higher results are available for all electrolysis variants considered, at up to 160% higher, is PM-ihh. The use of steel for cell stacks and for constituents of the electricity provision is of great importance for these indicators, as high environmental impacts are associated with the energy- and consequently emissions-intensive upstream processes of steel.

LCC results for the indicators LCOH and NPV

Based on the assumptions and calculated CapEx values in the "Methods" chapter, the LCOH of the electrolysis technologies was calculated for 2022 and 2045. First, the LCOH resulting from operation with the electricity mix in 2022 is determined. Then, the costs of electrolysis

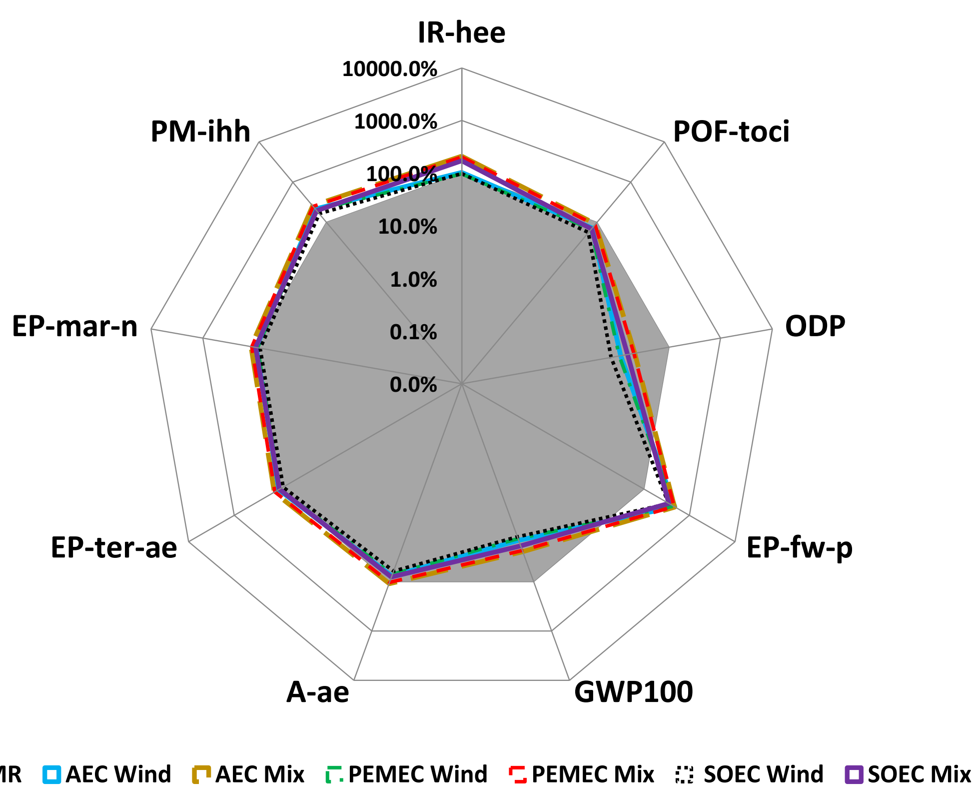

Fig. 9 Comparison of AEC, PEMEC, and SOEC with SMR for the year 2045 using several environmental indicators

operation with wind power in 2045 were analyzed. Extreme cases were thus taken into account. For 2045, the WC is given for the lowest learning rates and capacity increases within the assessed range. Contrary to this, the BC was given for the highest learning rates and capacity increases within the range. The resulting LCOH for water electrolysis technologies, given in $€_{2022}$/kg H_2, is illustrated in Fig. 10.

A wide range and significant influencing factors that change over time can be observed in Fig. 10. In 2022, there were still clear differences in the LCOH results for the three electrolysis technologies. The LCOH was the lowest for AEC systems. This is due to the higher CapEx and higher costs of replacing the stacks given for PEMEC and SOEC systems. With these two systems, more frequent stack replacements occur due to lower lifetime expectations and the high assumed operating times when utilizing the electricity mix. Analyses for 2045 show a strong convergence of the LCOH. The calculated range reaches 2.3–3.8 $€_{2022}$/kg H_2. A longer lifetime has a reducing effect on the LCOH as no replacement costs will occur. Reductions in LCOH will additionally be provoked by a prospective CapEx decrease. In contrast, the assumed electricity supply costs increase from 2022 to 2045, along with the accompanying specific cost contribution. This cost-increasing effect outweighs the cost-reducing ones (especially CapEx reductions) if the AEC systems are operated in 2045 and the WC. Consequently, the LCOH increases in this specifical case. For SOEC systems, there is additional cost reduction potential if waste heat from a neighboring plant can be used free of charge or at a low cost.

The following NPV calculation is intended to show the hydrogen prices at which the technology options are economically viable at different points in time. While NPV < 0 expresses economic losses over the period considered, variants with NPV > 0 indicate economic surpluses. A somewhat typical range of 2–5 €/kg H_2 is

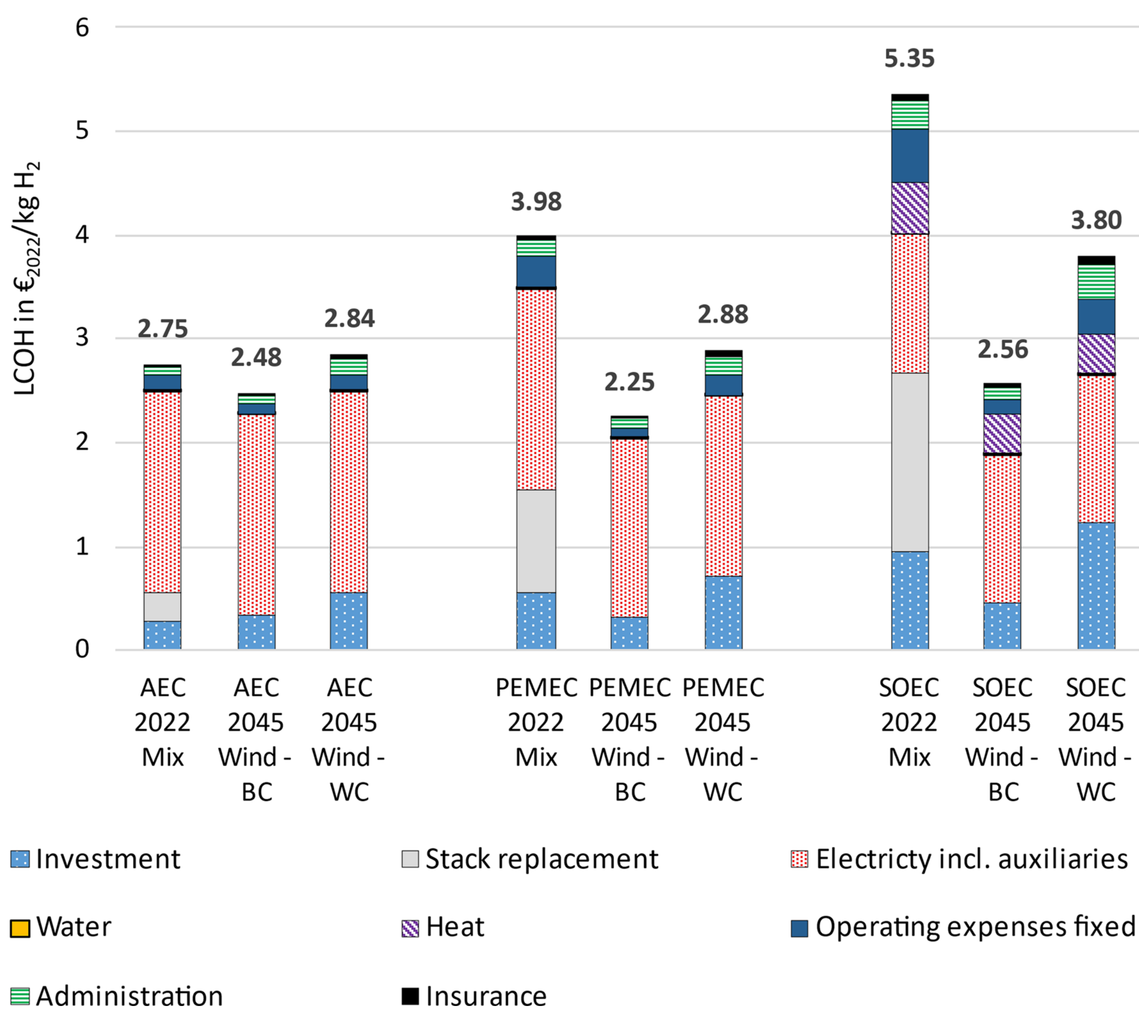

Fig. 10 LCOH results of AEC, PEMEC, and SOEC for the years 2022 and 2045

assumed for hydrogen price assumptions, as also considered by Abadie & Chamorro (Abadie & Chamorro, 2023). The results of the NPV calculations for all three electrolysis technologies for 2022 and a BC and WC in 2045 are shown in Fig. 11.

Figure 11 also shows that at a hydrogen price of 2 €/kg H_2, the initial investment and costs incurred would not be sufficiently covered by revenues in all cases. At a hydrogen price of 3 €/kg H_2, financial surpluses could be generated for all AEC system options considered. Due to decreasing CapEx values, PEMEC systems would be economically viable in 2045 for both variants at a hydrogen price of 3 €/kg H_2. In 2022, however, this would only have been possible for PEMEC systems at a hydrogen price of 4 €/kg H_2. The economic viability of the SOEC system at the hydrogen prices considered is even more difficult than for the alternative technologies, especially for 2022. Furthermore, in the WC scenario of 2045 there are disadvantages for SOEC systems and a price of 3 €/kg H_2 would not be sufficiently economically viable. On the other hand, in the BC scenario of 2045, SOEC systems are as economically viable as the alternative ones. The reason for these different results is that the underlying CapEx value in BC for the SOEC systems is much closer to the level of the alternative technologies than in WC.

Sensitivity analyses

The following section presents separate sensitivity analyses for LCA and LCC. Due to the outstanding importance of this indicator in LCA studies the LCA part of the sensitivity analyses start with and is limited to an assessment of the GWP_{100} results. The variations are compared with the results of the base case (Fig. 5). To ensure that analyses are similar and consistent, the same parameters are used wherever possible. Four parameters were considered in the LCA sensitivity analyses and are subsequently mentioned. In accordance with the results presented above, the parameter of electricity demand was of the highest importance. In addition, the variations in the parameters of FLHs, lifetime, and time horizon were also examined. In addition to the process data, these parameters are relevant and variable parameters within the underlying LCI models of this study. The FLH and time horizon were each included in the calculation of the amount of hydrogen produced. Consequently, these parameters lead to changes in the amount of cell stacks and cells considered for producing a fixed amount of hydrogen. Furthermore, variations in these parameters could potentially create the need for component replacements. The lifetime assumption, on the other hand, is not included in the balancing of the amount of hydrogen generated. This parameter only takes into account whether components must be replaced during the period under consideration. GWP_{100} sensitivity analyses for these four parameters are applied to one of the electrolysis technologies under consideration only. PEMEC was selected because it has become the electrolysis technology that has received the most attention in recent years. This can be seen in a data set of global hydrogen projects provided by the International Energy Agency (IEA) [67]. Within the current version of this data set, corrected in January 2024, more than 340 projects related to the PEMEC, and

	AEC 2022	AEC 2045 BC	AEC 2045 WC		PEMEC 2022	PEMEC 2045 BC	PEMEC 2045 WC		SOEC 2022	SOEC 2045 BC	SOEC 2045 WC
2 €/kg H2	-748,156	-261,178	-457,764		-2,426,4	-149,310	-431,294		-6,704,7	-419,351	-1,345,0
3 €/kg H2	914,996	283,306	86,721		-763,321	458,487	176,502		-4,297,6	327,371	-598,280
4 €/kg H2	2,578,14	827,790	631,205		899,830	1,066,28	784,298		-1,890,4	1,074,09	148,441
5 €/kg H2	4,241,30	1,372,27	1,175,68		2,562,98	1,674,07	1,392,09		516,785	1,447,45	895,162

■ 2 €/kg H2 3 €/kg H2 4 €/kg H2 5 €/kg H2

Fig. 11 NPV results of AEC, PEMEC, and SOEC for the years 2022 and 2045

263 to the AEC. In addition, the sensitivity analysis was limited to operation with wind power and thus to the production of green hydrogen. The results are illustrated in Fig. 12.

As shown in Fig. 12, a variation in electricity demand leads to significant changes in GWP_{100} results. This is valid for both points in time considered. A variation in electricity demand of ± 10% also leads to changes in the GWP_{100} of approximately ± 10% (0.197 kg CO_{2eq}/kg H_2).

A reduction in FLH leads to lower hydrogen production during the considered time horizon, which causes an increase in GWP_{100} per specific amount of hydrogen of 1.6% (0.032 kg CO_{2eq}/kg H_2) in 2022. An increase in FLH in 2045 leads to higher hydrogen production and to decreasing GWP_{100} if assessed without stack replacement requirements in 2045. However, for a 10% reduction in FLH, the reduction in specific GWP_{100} results is counteracted by the need to replace one cell stack, causing a GWP_{100} increase of 8.97% (0.177 kg CO_{2eq}/kg H_2) in 2022. The stack lifetime of 40,000 h and assumed FLH per year in the base case in 2022 (see Fig. 5) imply that stack replacements are not necessary. A reduction in the lifetime to less than 40,000 h, however, necessitates one stack replacement, and goes along with a GWP_{100} increase of 11.3% (0.224 kg CO_{2eq}/kg H_2). In all the other cases for which the lifetime is varied, the

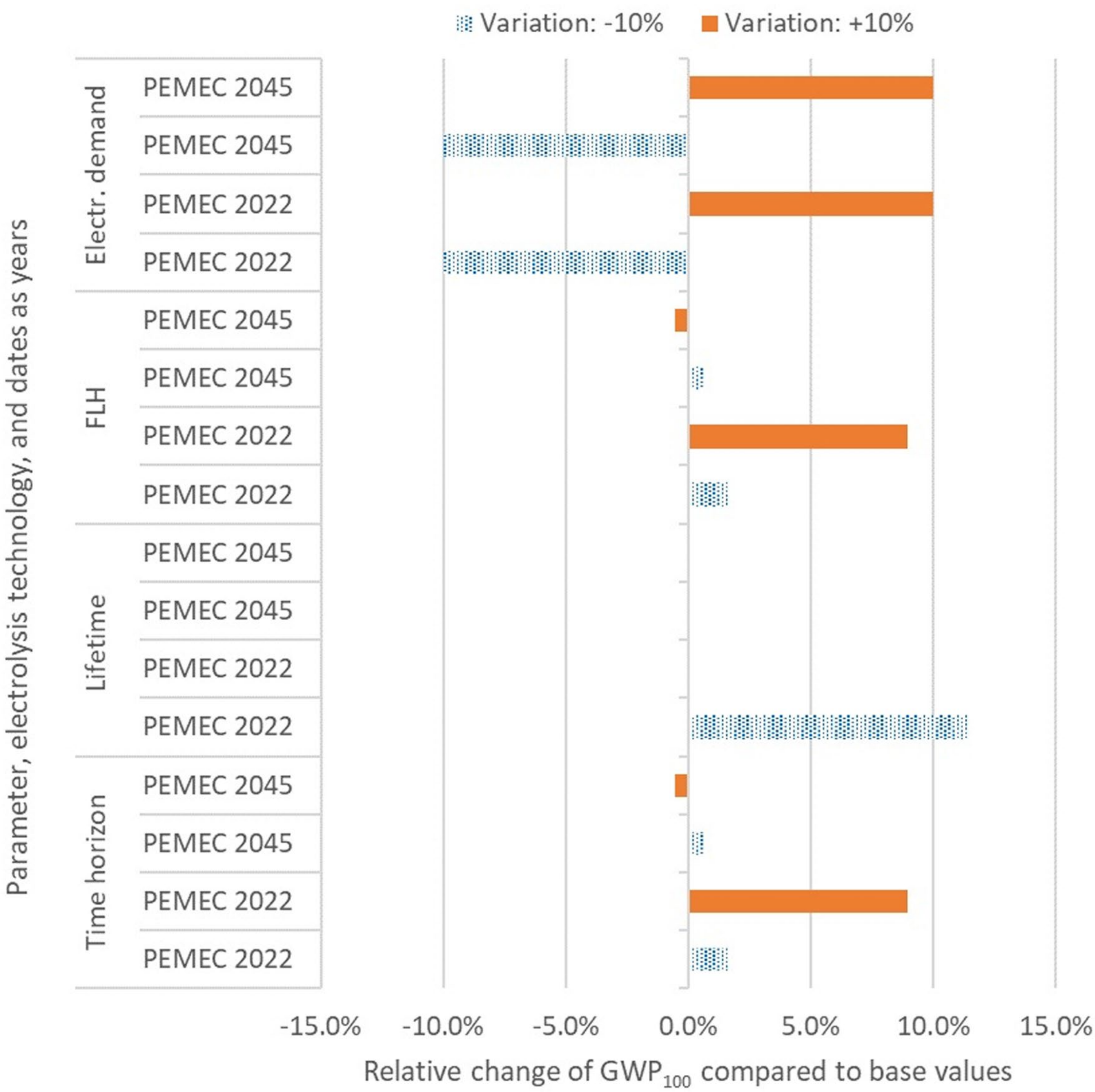

Fig. 12 Effects of parameter variations (electricity demand, FLH, lifetime, time horizon) of ± 10% on the GWP_{100} results for PEMEC operation with wind power

GWP_{100} results remain unchanged compared to those of the base case. In these instances, the lifetime is high enough to enable operation without stack replacement. Consequently, no changes are illustrated.

The effects due to time horizon variations are similar to those of the FLH. Thus, a reduction of the time horizon also causes an increase in GWP_{100} per specific amount of hydrogen of 1.6% (0.032 kg CO_{2eq}/kg H_2) in 2022 and 0.7% (0.010 kg CO_{2eq}/kg H_2) in 2045. An increase in FLH in 2045 leads to decreasing GWP_{100} as there is no stack replacement. However, with the lifetime assumption of 2022 an increase in the time horizon from 20 to 22 years leads to one stack replacement, accompanied by an increase in the GWP_{100} results by 8.97% (0.177 kg CO_{2eq}/kg H_2).

Due to the observed outstanding importance of electricity demand on the GWP_{100} results, its variation of ± 10% and effect on GWP_{100} is additionally assessed for all electrolysis technologies and points in time. The results of this sensitivity analysis are illustrated in Fig. 13.

For the PEMEC and AEC systems, the effects of varying the electricity demand on the GWP_{100} (Fig. 13) were comparably high for both points in time. In 2022, the effect of varying the electricity demand was significantly greater for these technologies than for SOEC systems due to the considerably lower share of electricity demand on the total GWP_{100} results for SOEC systems (see

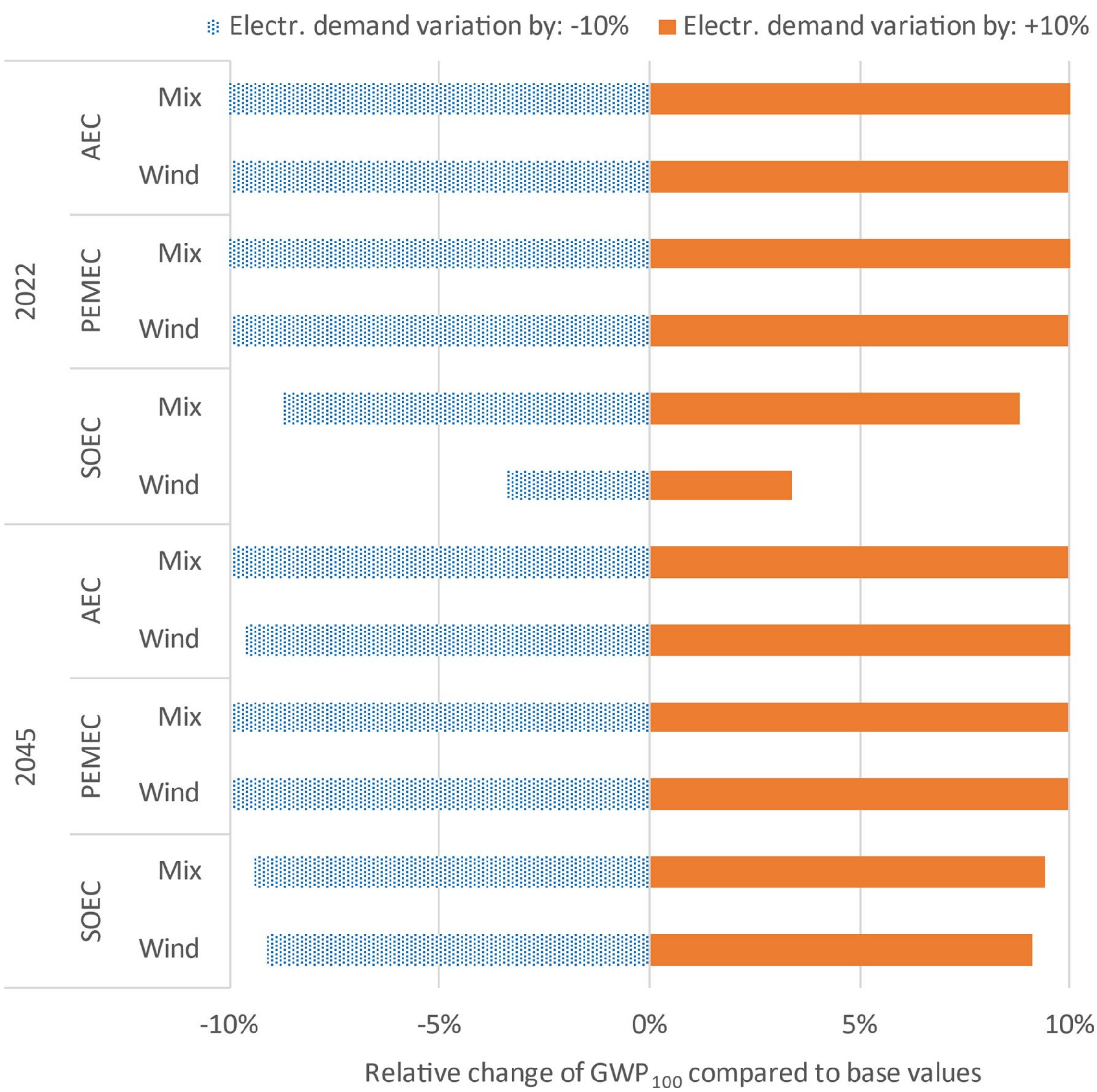

Fig. 13 Effects of electricity demand variations of ± 10% on the GWP_{100} results for three electrolysis technologies

also Fig. 7 and Fig. 8), especially for 2022. The GWP_{100} results for SOEC systems changed by 3.4–8.8% for 2022 and by 9.1–9.4% for 2045 if the electricity demand varies by ± 10%. When looking at the PEMEC and AEC systems, the GWP_{100} results change linearly by approximately ± 10% for both 2022 and 2045 if a ± 10% variation was assumed. When operating with wind power, there is a tendency towards lower results than when operating with an electricity mix. This is due to the slightly lower contribution of the operating phase when using wind power compared to the electricity mix.

Building on the previous presentation of the environmental sensitivity analyses, the following section is dedicated to a sensitivity analysis relating to the LCC. The influences of various parameters can be shown particularly well with a sensitivity analysis of the LCOH indicator. Due to the similarity of the indicators and the fact that a supplementary sensitivity analysis is not expected to add substantial value, it is not conducted for NPV. In addition to the electricity demand and FLH, which are also considered for LCA, the parameters of CapEx and interest rate are also assessed. In particular, the latter two parameters are of interest due to the previously mentioned debate in academia and beyond on the cost of capital [43–45] and associated uncertainties. Consequently, the inclusion of both parameters in the sensitivity analyses helps to quantify the degree of uncertainty caused by varying these assumptions.

Figure 14 illustrates the effects on the LCOH results for all three electrolysis technologies and the variation in the four parameters by ± 10%. As shown in Fig. 14, the AEC and PEMEC reveal the greatest effects on the variation in the parameter electricity demand (El. dem.). This result reflects the dominant influence of electricity demand on the LCOH, as shown in Fig. 10. The highest relative change observed for electricity demand variation, ± 10%, was 7.8%. For the remaining cases, a variation of the FLH parameter has the greatest influence on the LCOH results. The highest relative change in LCOH determined for the FLH parameter variation was 7.3%. However, it can also be determined that FLH variations in one direction or the other lead to different values. For the other parameters, the amount was the same in both directions. This shows that the relationship between FLH and LCOH is not linear, while the other parameters change linearly. Thus, an increase of 10% in FLH leads to a smaller proportional change in hydrogen production costs than a 10% decrease.

Figure 14 also illustrates a noticeable effect on the results for a variation in the CapEx assumptions of ± 10%, causing changes in the range of 2.1–6.5%. Although the effects of varying the interest rate parameter [variable i in Eq. (2)] are comparatively small (0.5–1.8%), these changes are still not negligible. The cases considered here do not result in any variation in the stack numbers. Accordingly, the stack numbers correspond to the results and description for the base case (Fig. 5).

Discussion

A key finding of the analyses presented is that the production of hydrogen using water electrolysis technologies will be accompanied by decreasing GWP_{100} in the long term (up to 2045). Future improvements are also evident for the results of eight additionally analyzed environmental impact indicators. These findings confirm the fundamental conclusions of previous publications regarding the prospective environmental impacts of hydrogen production and provide new insights into the considered case study. In the period under consideration, the highest GWP_{100} is 27.5 kg CO_{2eq}/kg H_2 and the lowest 1.33 kg CO_{2eq}/kg H_2. Compared to the production of green hydrogen with low CO_2 emissions, which was achieved using the AEC and PEMEC systems in 2022, technological improvement could reduce CO_2 emissions by up to almost a quarter by 2045. The origin and demand for electricity were the most significant factors in the environmental impacts of all of the electrolysis variants considered. Although the considered German electricity mix for 2022 provokes 497 g CO_{2eq}/kWh_{el}, the assumed mix in 2045 only emits 54 g CO_{2eq}/kWh_{el}. The GWP_{100} value (30 g CO_{2eq}/kWh_{el}) related to the considered wind electricity data set is once again well below the current and future grid mix levels. Even with the use of wind electricity, electricity demand remains a determining factor in environmental results. Consequently, its prospective reduction, which is a common assumption in the literature and employed in this study, is particularly relevant in terms of environmental improvements. The additional expected reduction in the use of construction materials, as well as increasing lifetimes, can also be expected to reduce the environmental impacts. In the case of SOEC systems, the results are particularly dependent on assumptions regarding heat supply. For 2022, this study assumes a heat supply that is still largely based on fossil fuels. In the event of a particularly low-emission heat supply in the future, SOEC systems have the potential to produce hydrogen with a very low environmental impact due to their particularly high efficiency. A comparison of the electrolysis technologies shows a convergence in the GWP_{100} results to the extent that this is not already the case.

Under the assumptions made and depending on the electrolysis technology, the LCOH can be reduced from a maximum of 5.4 €/kg H_2 in 2022 to a minimum of 2.3 €/kg H_2 in 2045. This is also consistent with the NPV analyses. It can be seen that, under the assumptions

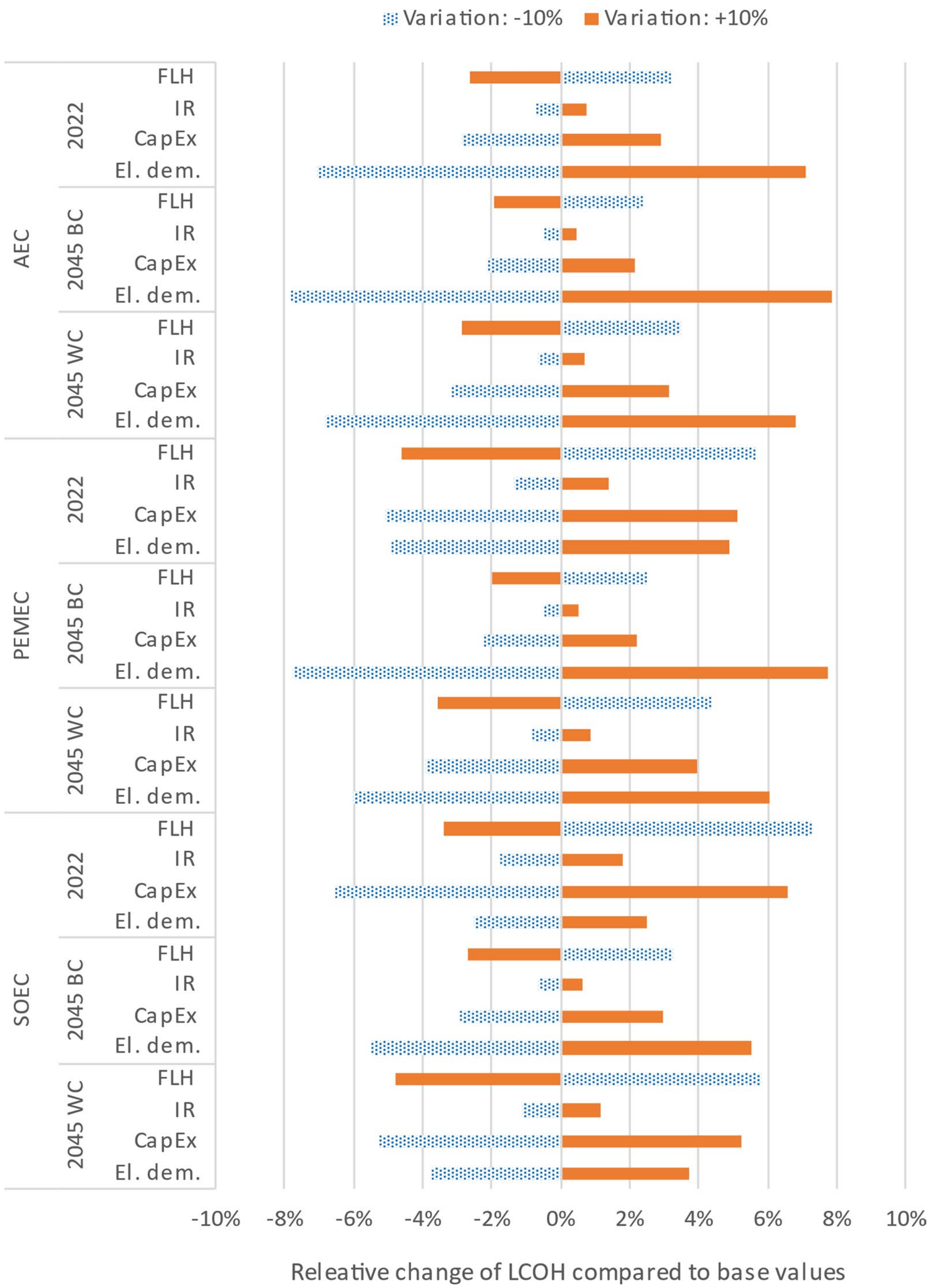

Fig. 14 Effects of parameter variations (FLH, IR, CapEx, El. dem.) of ± 10% for three electrolysis technologies on the LCOH results for three electrolysis technologies—including prospective best cases (BC) and worst cases (WC)

made, electrolysis can only be carried out economically at a hydrogen price level of over 2 €/kg H_2. As for the LCA results, the electricity demand and its reduction are of the greatest importance for the LCOH of AEC and PEMEC systems. In 2022, the LCOH results for the three technologies diverged more strongly than those for the other economic indicators. Analyses through 2045 show that the LCOH will also converge on a comparable level in the future. As the learning rates for the technologies are likely to differ between the technologies due to their different degrees of maturity, even further convergence is conceivable. With SOEC systems, a high learning rate is more likely than with already more mature AEC systems. It is therefore possible for the learning rate of AEC systems to not be significantly higher than that assumed for WC calculations.

In the long term, the differences between these technologies will become more apparent regarding the materials used for manufacturing, especially in terms of the type of critical raw materials used and their quantities. Due to the diminishing differences in environmental and economic performance and the possibility of diversifying the use of critical raw materials, there is a strong argument to be made for the combined use of these three technologies in the future.

In the literature, there are numerous assessments of the current state-of-the-art and potential target values for electrolysis technologies. Due to the breadth of usable data and its consistency, a key database selected in this study is that of the DOE on the status quo and the target values of the three electrolysis technologies. Compared to the literature, some assumptions within the DOE documents [52–54] as essential data sources of this study can be critically discussed. On the one hand, sources such as those published by Boehm et al. or Chatenet et al. [47, 51, 68] do not see such large differences in CapEx values between AEC and PEMEC systems for 2022. On the other hand, regarding the operation phase, in other publications [22, 55, 69, 70] there is a tendency towards lower electricity demand values for AEC (48–52 kWh/kgH_2) than for PEMEC systems. Thus, the overall LCOH results based on the assumptions of this study are within a realistic range and do not indicate that one technology option is preferred. Furthermore, the learning curve approach applied to CapEx developments is based on assumptions regarding the capacity developments of water electrolysis systems. The number of publications on differentiated forecasts of capacity development for the three technologies examined over time is still very low. However, these assumptions determine the possible future of CapEx developments, such that significantly different assumptions about capacity developments would also influence the overall LCOH results. With respect to interest rates, a range between 3.6% and 4.4% was assessed within the sensitivity analyses. However, some of the publications addressing interest rates assume significantly different percentages. For the interest rate, which is highly dependent on location, time, and actor perspective, typical assumptions of between 5.5 and 10% can be found for Germany [41, 71]. Interest rates varying by several percentage points would result in LCOH deviations of several percent.

The database used for the LCA almost exclusively contains data sets that can be used as background data, which correspond to the status quo and are not extrapolated into the future. This is why, for example, the data records for materials such as steel or copper are also used in the analyses for 2045 in this study. However, it is likely that such processes will change in the future. This will also tend to lead to lower environmental impacts. Consequently, the background data used in this study are associated with greater environmental impacts than could be the case in the future because of process optimization.

The specific results of this study can only be transferred to locations outside Germany with restrictions. Differences between locations are primarily caused by the operating phase of water electrolysis due to differences in the environmental and economic properties of the electricity supply. There are locations outside Germany and Europe where renewable electricity can be generated with significantly lower levelized costs due to better availability of renewable energy sources. In some regions, favorable production costs arise for individual renewable energy sources, and the costs for grid electricity are significantly lower. In addition, interest rates can vary by country. For such regions, the cost component shares on the LCOH would strongly differ from those determined in this study for Germany. Consequently, previous studies on production costs, especially those on LCOH, point to significantly lower costs for hydrogen imports to Germany than for domestic production. A review by Breuer et al. [72] noted domestic hydrogen production costs between 3.3 and 7.3 €/kg H_2 assumed for Germany in 2050 in previous publications. Furthermore, the review revealed costs of between 1.4 and 2 €/kg H_2 for imports to Germany in 2050. Thus, the LCOH values obtained in this study for 2045 and domestic production in Germany could be considered very low compared to the values of the review. Possible reasons for this are potential considerations of taxes, overhead costs, decommissioning costs, or other cost components in the studies considered.

With respect to the GWP_{100} results, a review by Wilkinson et al. [5] identified values mainly below 5 kg CO_{2eq}/kg H_2 for this kind of water electrolysis configuration. However, the review states that in earlier publications on hydrogen production by electrolysis in Germany, even GWP values below 0.9 kg CO_{2eq}/kg H_2 were determined. Thus, the calculated GWP values in this study are within the range of values from previous studies on water electrolysis technologies using renewable electricity.

With regard to the products of water electrolysis, it is usually assumed that oxygen is an unintended and nonharmful by-product and therefore all environmental impacts are attributed to hydrogen [69, 73, 74]. This approach is also used in this study.

However, if it is possible to use the oxygen produced by water electrolysis, allocation or substitution could be a way of allocating parts of the environmental impact to oxygen. Analyses by Bargiacchi et al. and de Kleijne et al. [73, 74] suggest that significant environmental impacts could be attributed to oxygen in this case. In addition to reducing the specific environmental impact of hydrogen production, downstream reuse could also have a positive effect on the economics of electrolysis systems. The oxygen produced can be sold or used in addition to hydrogen (e.g., in hospitals or industrial plants) [75–77]. Although the use of oxygen in fuel cells and for medical and other applications is expected to increase in the future, it is questionable whether it is possible to fully utilize the quantities of oxygen that are likely to be produced.

Conclusions

This study provides a particularly far-reaching, differentiated, transparent, and consistent comparison of the three electrolysis technologies of AEC, PEMEC, and SOEC. A unique combination of possible technological, environmental, and economic developments in the production of green hydrogen up to the year 2045 is presented.

A comprehensive literature review identified several research gaps, and research questions were posed and answered, e.g., how the results differ for the years 2022 and 2045. Nevertheless, the current study reveals the need for subsequent research. As a result of the presented findings, prospective research should not be limited to one type of water electrolysis but should be carried out with an openness to all three technologies.

The data from the literature that can be used for the LCA and LCC of water electrolysis technologies differ considerably in some cases. Therefore, there is still a need for extensive research into the material inventories for plant construction and the energy and mass balances of plant operation, i.e., foreground data. Even for current plants, the availability and transparency of published data are still low and can be expanded upon.

Recent research activities on the adaptation of background data for prospective LCA should be intensified. Future overall systemic developments could therefore be better reflected in prospective LCA studies.

In some cases, there is also the possibility of material substitution in the manufacturing of electrolysis technologies. As one example, a possible ban on per- and polyfluoroalkyl substances (PFAS) is discussed at the EU level, and alternative materials for components such as PTFE-containing gaskets are needed. The material substitution topic offers R&D potential, especially for materials and raw materials research, as well as for manufacturers. New knowledge gained in this way should be made available to experts and for research in the field of LCA to provide this research with the best possible data.

Regarding the environmental impacts considered, several particularly robust indicators beyond the GWP_{100} were selected for this LCA study. This provides a more diverse range of knowledge about the various environmental impacts. Nevertheless, there are other indicators and methodologies that can be used in future assessments to gain further insights into the environmental impacts and life cycle costs of water electrolysis technologies.

There has been some recent research on the recycling and disposal of water electrolysis technologies. However, clear standardizations or regulations in this regard could not be identified during a literature review for this study and were therefore not taken into account for the sake of simplicity. As clarity in this regard increases, future research should also include corresponding data and its possible further development, e.g., by increasing recycling rates of individual raw materials [16].

Due to its outstanding importance for LCA and LCC results the electricity demand assumptions must also be confirmed by future research or, if necessary, modified.

With respect to LCC in general and LCOH calculations in particular, the inclusion of recycling or commissioning costs would be an interesting complement. In addition, further indicators, such as levelized revenue/profit, could contribute to new LCC insights into electrolysis technologies. Future research on the LCC of electrolysis technologies should also take into account the newest developments in CapEx and interest rates.

For LCA studies EF indicators with recently lower robustness, e.g., water use, resource depletion and human toxicity could be included after their robustness improvement and deliver additional knowledge.

From a technological perspective, there is also a particular need for research into emerging water electrolysis technologies, which are currently at a significantly lower stage of development than the options under consideration (e.g., anion exchange membrane technology, AEM).

This study provides a particularly broad and transparent database that can be used as a basis for exploring the previously listed research opportunities.

Abbreviations

ABS	Acrylonitrile–butadiene–styrene
AC_t	Administration costs
ae	Accumulated exceedance
AP	Acidification
AEC	Alkaline electrolysis cell
AEM	Anion exchange membrane
AR6	Sixth assessment report of the intergovernmental panel on climate change
BC	Best case
BoP	Balance of Plant

CapEx	Capital expenditures
CHJU	Clean hydrogen joint undertaking or clean hydrogen partnership
COP28	The 28th conference of the parties to the UN framework convention on climate change
DIN EN ISO	Deutsches Institut für Normung, European norm, International Organization for Standardization
DOE	Department of energy
EC_t	Electricity costs per year
EF	Environmental footprint
EP-fw	Eutrophication, freshwater
EP-mar	Eutrophication, marine
EP-ter	Eutrophication, terrestrial
FLH	Full load hours
FU	Functional unit
GWP_{100}	Global warming potential (GWP) over a 100-year time horizon
HC_t	Heat costs per year
hee	Human exposure efficiency
ihh	Impact on human health
IR	Interest rate
IC_t	Insurance costs
IEA	International energy agency
IPCC	Intergovernmental panel on climate change
IR	Ionizing radiation
KOH	Potassium hydroxide
KPIs	Key performance indicators
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCOH	Levelized costs of hydrogen
LR	Learning rate
$MHydrogen_t$	Annual amount of hydrogen provided in kWh
n	Service life of water electrolysis systems
NPV	Net present value
NMP	N-methyl-2-pyrrolidone
ODP	Ozone depletion
OFC_t	Fixed operating costs
OP EFRE/ERDF NRW	Operational Program for the promotion of investments in growth and employment for North Rhine–Westphalia from the European Regional Development Fund
OpEx	Plant operating expenditures
PEMEC	Polymer electrolyte membrane electrolysis cell
PGMs	Platinum group metals
PM	Particulate matter
POCP	Photochemical ozone creation potential
PTFE	Polytetrafluoroethylene
PtX	Power-to-X
RC_t	Cell stack replacement costs
SMR	Steam methane reforming
SOEC	Solid oxide electrolysis cell
t	Year under consideration.
TFE	Tetrafluoroethylene
toci	Tropospheric ozone concentration increase
US	United States
WC	Worst case
WaC_t	Water costs per year

Supplementary Information

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Additional file 1

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Author contributions

"J.C.K. was responsible for the conceptualization and methodology, wrote the main manuscript text, and prepared all figures. P.Z., C.W., K. G., and W.K. supervised the work and reviewed draft versions of the manuscript. K.G. was responsible for the project administration and funding acquisition of the underlying project. All authors reviewed the manuscript."

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Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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