

# Working with uncertainty in life cycle costing: New approach applied to the case study on proton exchange membrane water electrolysis

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**Abstract** Hydrogen, recognized as a critical energy source, requires green production methods, such as proton exchange membrane water electrolysis (PEMWE) powered by renewable energy. This is a key step toward sustainable development, with economic analysis playing an essential role. Life cycle costing (LCC) is commonly used to evaluate economic feasibility, but traditional LCC analyses often provide a single cost outcome, which limits their applicability across diverse regional contexts. To address these challenges, a Python-based tool is developed in this paper, integrating a bottom-up approach with net present value (NPV) calculations and Monte Carlo simulations. The tool allows users to manage uncertainty by intervening in the input data, producing a range of outcomes rather than a single deterministic result, thus offering greater flexibility in decision-making. Applying the tool to a 5 MW PEMWE plant in Germany, the total cost of ownership (TCO) is estimated to range between €52 million and €82.5 million, with hydrogen production costs between 5.5 and 11.4 €/kg H<sub>2</sub>. There is a 95% probability that actual costs fall within this range. Sensitivity analysis reveals that energy prices are the key contributors to LCC, accounting for 95% of the variance in LCC, while iridium, membrane materials, and power electronics contribute to 75% of the variation in construction-phase costs. These findings underscore the importance of renewable energy integration and circular economy strategies in reducing LCC.

**Keywords** life cycle costing (LCC), green hydrogen, proton exchange membrane (PEM) water electrolysis, uncertainty, Monte Carlo method, Python

## 1 Introduction

Life cycle costing (LCC) aims to provide a comprehensive understanding of all costs associated with a product or project throughout its entire life cycle, extending beyond initial investment outlays [1,2]. It is a method to analyze the total cost of ownership (TCO) of a facility or product system [3]. Given the increasing significance of hydrogen energy, achieving a thorough understanding of its associated expenditures has become exceptionally important [4,5].

However, current LCC standards and tools exhibit limitations when applied to emerging technologies. For example, ISO 15686-5 defines LCC steps and elements

specific to buildings and constructed assets but does not address water electrolysis plants for hydrogen production, nor does it include the key metric of levelized cost of hydrogen (LCOH) [6]. Similarly, the European Commission provides an LCC tool in Excel form, which is limited in scope and delivers only a single deterministic result [7–11]. Standards such as VDI 2884 and DIN EN 60300-3-3 provide detailed explanations of LCC components and enumerate the possible costs and their scope involved [12,13]. However, depending on the specific product or project, variations in the calculation may and, in some cases, must be made to account for specific characteristics [14]. This is one of the reasons why the results of LCC exhibit significant uncertainty [15], which makes it difficult for decision-makers to accurately assess the product's and project's economic feasibility.

In the case of a 5 MW proton exchange membrane

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water electrolysis (PEMWE) system, this uncertainty can be attributed to two main factors:

1) Capital expenditures (CAPEX): Costs related to emerging technology are inherently uncertain. The accuracy of the results is challenging to state, and no specialized tool can provide a range of CAPEX outcomes along with their probability distributions.

2) Energy costs: As a major component of operational expenditure (OPEX), energy costs vary under different circumstances, such as location, time, plant capacity, and data availability.

Given that the operational lifetime of a water electrolysis plant often exceeds 20 years, there is a clear need for a suitable tool to support decision-makers [16]. This need is particularly pronounced in Germany, where federal offices are required to conduct LCC assessments when evaluating offers for purchasing energy-consuming products and services [17].

To address these challenges, this paper introduces a tool specifically developed to analyze the complex cost structures of emerging technologies across their life cycles while effectively managing uncertainty. The proposed tool generates range-based outputs and performs sensitivity analysis to identify critical cost drivers, thereby offering valuable insights for informed decision-making. The functionality and outcomes of the tool are demonstrated through a case study involving LCC analysis of a 5 MW PEMWE plant. A detailed overview of the research framework is presented in Fig. 1.

## 2 Literature review

This paper uses the example of calculating the LCC for a 5 MW PEMWE to showcase the functionality of the proposed tool. Therefore, this section focuses on presenting the methods used by other researchers to calculate the LCC of hydrogen production via water electrolysis. This is presented in the form of a map chart (Fig. 2) with information on content, publication date, research location, and the type of plant studied. The literature map chart aims to help readers quickly

understand the research dynamics of this field and reveal the evolution and trends in research content. The respective results and methods used are further summarized in Table 1.

Scanning the map from left to right, it can be observed that from 2012 to 2023, a total of 28 studies related to the cost of hydrogen production via water electrolysis were identified. The content scope of these studies is reflected on the vertical axis. Over time, it is evident that there is a significant increase in studies focusing on CAPEX, OPEX, and LCOH, especially with a noticeable increase in studies from Asia and Africa after 2021. This trend underscores the growing importance of conducting thorough and accurate hydrogen cost assessments in emerging markets.

The colors within the cells in Fig. 2 represent regional distribution: Europe (blue) dominates, followed by globally-oriented studies (yellow). North America (red) is represented in three studies, while Asia (purple) and Africa (green) each account for two studies. Colored circles at the top of each cell represent the type of electrolysis plants studied in each case. Of the reviewed works, 22 focus on alkaline water electrolysis (AWE), 20 on PEMWE, and 6 on HTE. However, four studies do not focus on specific hydrogen production technologies but instead provide general recommendations for LCC calculation. Additionally, 13 compares the costs across different hydrogen production technologies, with 9 of them specifically comparing the costs of AWE and PEMWE, currently the most widely adopted water electrolysis methods.

From the perspective of LCC calculation methods, Fig. 2 shows that although these studies span various countries and technologies, their calculation approaches are largely consistent. Most adopt a net present value (NPV)-based approach for CAPEX, OPEX and LCOH, generally without considering revenue. This aligns with the methodologies specified in DIN EN 60300-3-3 and ISO 15686-5 [6,13].

However, variations in calculation methods still arise due to differing research objectives, which lead to diverse results. For example, some studies use scenario analyses to explore the impact of energy price and source

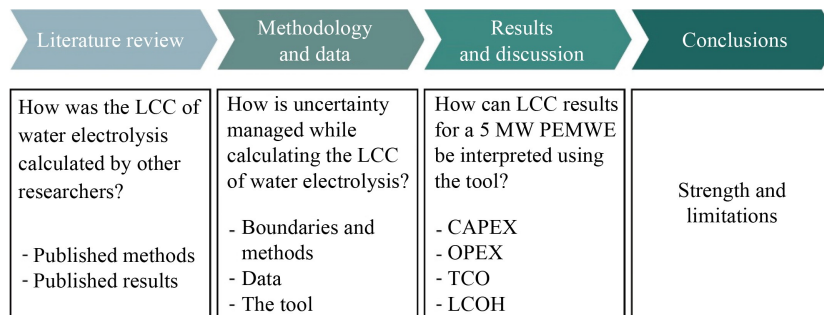
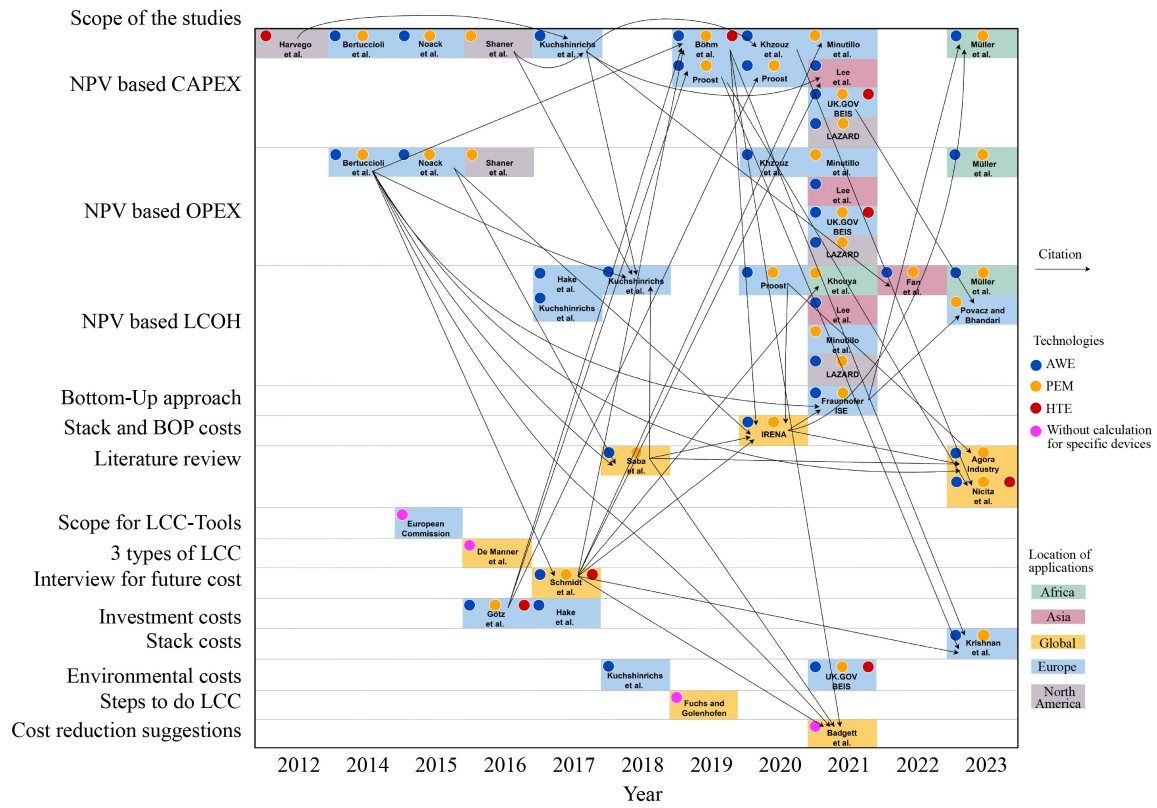


Fig. 1 Framework of this paper. TCO, total cost of ownership.



**Fig. 2** Literature map of LCC for hydrogen production using electrolysis (BOP: balance of plant; HTE: high temperature electrolysis; IRENA: International Renewable Energy Agency; UK.GOV BEIS: Department for Business, Energy, and Industrial Strategy in UK).

**Table 1a** (Part 1) LCC results from the reviewed literature (All data were directly sourced from reviewed literature; no estimations were provided.)

Ref.	Year	LCOH	CAPEX	OPEX
Harvego et al. [23]	2012	4.87 \$/kg H <sub>2</sub>	n.a.	n.a.
Bertuccioli et al. [24]	2014	n.a.	AWE: 580–1100 €/kW, PEMWE: 760–2090 €/kW	AWE: 9–51 €/(kW·a <sup>-1</sup> ), PEMWE: 12–66 €/(kW·a <sup>-1</sup> )
Noack et al. [25] <sup>1</sup>	2014	n.a.	n.a.	AWE: app. 2%–7% of the investment volume per year, PEMWE: app. 1.5%–2.0% of the investment volume per year
Shaner et al. [26]	2016	5.5 \$/kg H <sub>2</sub>	\$34 MM	n.a.
Schmidt et al. [27] <sup>2</sup>	2017	n.a.	AWE: 700–1400 €/kW, PEMWE: 800–2200 €/kW, SOEC: 2500–8000 €/kW	n.a.
Kuckshinrichs et al. <sup>3</sup> [28]	2017	DE: 3.64 €/kg H <sub>2</sub> , AT: 4.22 €/kg H <sub>2</sub> , ES: 4.31 €/kg H <sub>2</sub>	n.a.	n.a.
Hake et al. [29]	2017	DE: 4.63 €/kg H <sub>2</sub> , AT: 5.38 €/kg H <sub>2</sub> , ES: 5.55 €/kg H <sub>2</sub>	n.a.	DE: 4.07 €/kg H <sub>2</sub> , AT: 4.85 €/kg H <sub>2</sub> , ES: 5.03 €/kg H <sub>2</sub>
Kuckshinrichs and Koj [30] <sup>3</sup>	2018	DE: 3.64–4.39 €/kg H <sub>2</sub> , AT: 4.22–6.34 €/kg H <sub>2</sub> , ES: 4.31–6.73 €/kg H <sub>2</sub>	n.a.	n.a.
Böhm et al. [31]	2019	n.a.	AWE: 900 €/kW, PEMWE: 1450 €/kW,	n.a.

**Table 1a** (Part 1) LCC results from the reviewed literature (All data were directly sourced from reviewed literature; no estimations were provided.)  
(continued)

Ref.	Year	LCOH	CAPEX	OPEX
Proost [32] <sup>4</sup>	2019	3–20 €/kg H <sub>2</sub>	SOEC: 2300 €/kW AWE: app. 550–750 €/kW, PEMWE: 700–app.1300 €/kW	n.a.
Khzouz et al. [33] <sup>1,5</sup>	2020		\$840000–29234000	n.a.
Proost [34] <sup>1,6</sup>	2020	2 €/kg H <sub>2</sub>	500–2800 €/kW	n.a.
Minutillo et al. [35] <sup>1,7</sup>	2021	9.20–12.48 €/kg H <sub>2</sub>	€5213000–4219000	€13013000–55991000
Khouya [36] <sup>7</sup>	2021	7.48–5.63 \$/kg H <sub>2</sub>	n.a.	n.a.
Lee et al. [37] <sup>7</sup>	2021	1.26–5.32 \$/kg H <sub>2</sub>	6%–49% of LCOH	51%–94% of LCOH
UK Department for Business, Energy and Industrial Strategy [38]	2021	n.a.	500–1200 £/kW H <sub>2</sub>	82–175 £/kW H <sub>2</sub>
LAZARD Ltd. [39] <sup>1</sup>	2021	AWE: 1.6–2.4 \$/kg H <sub>2</sub> , PEMWE: 1.9–2.9 \$/kg H <sub>2</sub>	AWE: 310–2150 \$/kW, PEMWE: 460–2490 \$/kW	n.a.
Holst et al. [40] <sup>1,8</sup>	2021	n.a.	Before cost reduction: AWE: 663–949 €/kW, PEMWE: 718–978 €/kW; After cost reduction: AWE: 444–726 €/kW, PEMWE: 502–729 €/kW	n.a.
Fan et al. [41] <sup>1,3,7</sup>	2022	AWE: 16.43–40.91 yuan/kg H <sub>2</sub> , PEMWE: 23.96–51.80 yuan/kg H <sub>2</sub> , CCS: 13.07–19.41 yuan/kg H <sub>2</sub> , Coal-to-hydrogen without CCS: 7.24–10.13 yuan/kg H <sub>2</sub>	n.a.	n.a.
Agora Industry and Umlaut [42] <sup>6,9</sup>	2023	7.11–7.88 €/kg H <sub>2</sub>	800–1700 €/kW	3% of CAPEX
Müller et al. [43] <sup>10</sup>	2023	3.7–9.9 €/kg H <sub>2</sub>	1.82–2.50 €/kg H <sub>2</sub>	0.037–0.062 €/kg H <sub>2</sub>
Povacz and Bhandari [44] <sup>7</sup>	2023	3.08–13.12 €/kg H <sub>2</sub>	n.a.	n.a.

Notes: AT, Austria; CCS, Coal-to-hydrogen with carbon capture and storage; DE, Germany; ES, Spain; n.a., not available; SOEC, Solid oxide electrolyze cell. <sup>1</sup> Results differ from different plant sizes. <sup>2</sup> Results differ from different time periods and R&D scenarios. <sup>3</sup> Results differ from different sites. <sup>4</sup> Results differ from different annual operating hours and scenarios. <sup>5</sup> Results compare the costs of methane reforming and electrolysis, only electrolysis is presented here. <sup>6</sup> Results differ from different energy prices. <sup>7</sup> Results differ from different energy sources. <sup>8</sup> Results differ from different time periods. <sup>9</sup> Results differ from different plant models. <sup>10</sup> Results differ from different scenarios.

variations on hydrogen production costs, while others examine different plant capacities or operational periods. Some focus exclusively on construction costs, whereas others include investment (construction), operation, maintenance, and environmental charges. These methodological differences, as detailed in Table 1, result in a wide range of final LCOH values, from less than 2 to as high as 20 €/kg H<sub>2</sub>. Studies that consider operation and maintenance costs consistently highlight energy costs as the dominant driver of total LCC, regardless of the electrolysis technology. Raw materials are the main cost factor during construction, (excluding energy), particularly in PEMWE, where the use of precious metals such as iridium significantly increases CAPEX, followed by membrane costs. These factors underscore the influence of the two factors contributing to cost uncertainties identified earlier.

Since 2023, LCC methodology and sensitivity analyses have become relatively mature. Consequently, many studies have shifted toward cost projection. For example,

Franzmann et al. [18] predicted that hydrogen production costs for systems integrated with PV could fall below 2.3 €/kg H<sub>2</sub> by 2050. Zun et al. [19] estimated that the cost of hydrogen production from solar- and wind-powered water electrolysis could drop to 5 \$/kg H<sub>2</sub> by 2030. Frieden et al. [20] projected a reduction from 5.3 €/kg H<sub>2</sub> in 2020 to 2.7 €/kg H<sub>2</sub> in 2050, with AWE costs in Asia potentially dropping to as low as 1.8 €/kg H<sub>2</sub>. Koj et al. [21] anticipated that by 2045, the cost of hydrogen production via electrolysis in Germany could range from 2.25 to 3.8 €/kg H<sub>2</sub>, largely depending on production technology and energy source.

These cost projection studies show that changes in energy sources are the primary variable in predicting future hydrogen production costs. Based on this, Kotowicz et al. [22] applied Monte Carlo simulations to assess the impact of energy prices, finding that hydrogen production costs could range from as low as €4/kg H<sub>2</sub> to as highest as €16.5/kg H<sub>2</sub>, depending on energy cost levels.

**Table 1b** (Part 2) Calculation method of LCC and other results from the reviewed literature (All the data were directly sourced from reviewed literature; no estimations were provided.)

Ref.	Year	Used method and other results
Harvego et al. [23]	2012	DDCC + IDCC = 40.93% of total cost, operating cost = 40.07% of total cost
Bertuccioli et al. [24]	2014	The longer the duration of use, the lower the cost
Noack et al. [25] <sup>1</sup>	2014	Investment costs: AWE = 520–1070 €/kW, PEMWE = 305–957 €/kW
European Commission [45]	2015	Direct costs: acquisition costs + post-acquisition costs (use + maintenance + end of life), indirect costs: external costs (monetization of environmental impacts)
De Menna et al. [46]	2016	Conventional LCC = product, service and investment life span, environmental LCC = externalities e.g., CO <sub>2</sub> taxes, societal LCC = costs covered by anyone in society e.g., employs housing, etc.
Götz et al. [47] <sup>2</sup>	2016	Specific investment: AWE = €4000–app.7000·h/m <sup>3</sup> H <sub>2</sub> , PEMWE = €10000–app.12000·h/m <sup>3</sup> H <sub>2</sub> , SOEC = app. €11000·h/m <sup>3</sup> H <sub>2</sub> . Currently, AWE, at 1000 €/kW, is the most cost-effective and mature technology, followed by PEMWE, which has the potential for higher-performance plants. SOEC remains in the development stage
Schmidt et al. [27] <sup>3</sup>	2017	In the future, R&D dominate the cost reduction
Kuckshinrichs et al. [28] <sup>4</sup>	2017	Cash Flow for DE is €–50 million EUR, for AT is €–56 million, and for ES is €–59 million
Hake et al. [29]	2017	Investment cost in DE = 0.42 €/kg H <sub>2</sub> , in AT = 0.41 €/kg H <sub>2</sub> , and in ES = 0.40 €/kg H <sub>2</sub>
Kuckshinrichs and Koj [30] <sup>4</sup>	2018	Cash Flow for DE is €–60.5 million, for AT is €–61.5 million, and for ES is €–65 million, environmental costs: 0.2–1.5 €/kg H <sub>2</sub>
Saba et al. [48] <sup>1,5</sup>	2018	R&D has huge cost reduction potential. In 1990s: AWE: 873–2347 €/kW higher heating value-output (HHV-output), PEMWE: 360–4748 €/kW HHV-output; In future (2030): AWE: 787–906 €/kW HHV-output, PEMWE: 397–955 €/kW HHV-output
International Renewable Energy Agency (IRENA) [49]	2020	PEMWE is 50%–60% more expensive than AWE
Khzouz et al. [33] <sup>1,6</sup>	2020	Cost of H <sub>2</sub> production and storage: 2.92–4.30 \$/kg H <sub>2</sub> , cost of H <sub>2</sub> transportation: 0.92 \$/kg H <sub>2</sub> , IDCC: \$92400–2923400, non depreciable costs: \$25000–50000, installation costs: \$84000–5846800, labor costs: \$10000–25000
Badgett et al. [50]	2021	Raw material requirements, durability of the system, realization of economies of scale, and the benefits of learning-by-doing effects can help reduce costs
Department for Business, Energy and Industrial Strategy of UK [38]	2021	Carbon cost = 28 £/t CO <sub>2</sub>
LAZARD Ltd. [39] <sup>1</sup>	2021	Operating costs vary based on different elements
Müller et al. [43] <sup>7</sup>	2023	Electricity costs = 1.76–6.76 €/kg H <sub>2</sub> , water costs = 0.031–0.047 €/kg H <sub>2</sub> , LCOH could drop to 1.8–3.0 €/kg H <sub>2</sub> , when there is improvement in techno-economic technology and system efficiency

**Table 1b** (Part 2) Calculation method of LCC and other results from the reviewed literature (All the data were directly sourced from reviewed literature; no estimations were provided.) (continued)

Ref.	Year	Used method and other results
Nicita et al. [51]	2023	LCC studies on hydrogen (2012–2021): 67 papers analyzed; Technologies: Fuel cells, Electrolysis and other H <sub>2</sub> production methods; Methodology: NPV is the most used financial tool; Often ignored: Maintenance (63% of all papers are ignored), end-of-life (70%), external costs (73%); Recommendations: Standardize methods (e.g., ISO guidelines), expand cost coverage, use multiple financial tools, etc.
Krishnan et al. [52]	2023	AWE total stacks costs: baseline (2020) = 242–388 €/kW, advanced (2030) = 52–79 €/kW; PEMWE total stacks costs: baseline (2020) = 384–1071 €/kW, advanced (2030) = 63–234 €/kW

Notes: GE, Germany; AT, Austria; ES, Spain; DDCC, Direct depreciation capital cost; IDCC, Indirect depreciation capital cost. <sup>1</sup> Results differ from different plant sizes. <sup>2</sup> Results are aimed at power-to-gas, i.e., not only electrolysis but also catalytic methanation, biological methanation, and the process chain. <sup>3</sup> Results differ from different time periods and R&D scenarios. <sup>4</sup> Results differ from different sites. <sup>5</sup> Results differ from different maturity of technology. <sup>6</sup> Results compare the costs of methane reforming and electrolysis, and only electrolysis is presented here. <sup>7</sup> Results differ from different scenarios.

Taken together, this literature review offers a solution-oriented perspective. Given that most studies use similar (primarily NPV-based) LCC methods and that the primary differences stem from the input parameters such as raw material types and prices, energy sources, and cost data, and considering that current studies focus on predicting future hydrogen production costs, several key questions arise: Is it feasible to develop a tool that can estimate hydrogen costs simply by simply adjusting input parameters? Can such a tool provide not just a single-point estimates but also a range of values that account for uncertainty? Could it also incorporate prediction of future energy costs?

The answers to these questions are affirmative, and the following section elaborates on the principles and practical implementation of such a tool in detail.

### 3 Methodology and data

This section presents the methodology used to develop and apply the LCC tool, and describes how the two previously identified sources of uncertainty are addressed.

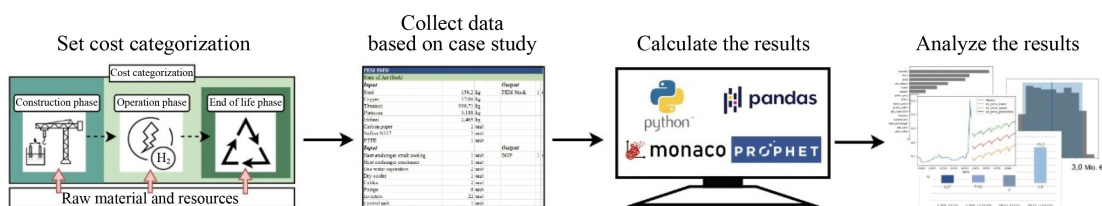
While the uncertainty inherent in LCC results can be reduced and controlled through methods such as predefined cost ranges, data source validation, and sensitivity analysis, it cannot be entirely eliminated.

Therefore, the focus of this study is on how to effectively manage uncertainty to achieve the desired results to support sound decision-making.

Figure 3 illustrates the workflow of the study in five steps: costs categorization, case study assumption and data collection, calculation, and results interpretation. First, the costs are categorized into different categories, followed by collecting specific data for each category based on the case study. Subsequently, the tool is developed, and the collected data are input into the tool for calculation. Finally, the results are analyzed. The LCC tool is developed in Python, and its open-source nature facilitates broader development and ongoing enhancement by a wide range of stakeholders, including the research community, industrial partners, and other relevant contributors [53].

#### 3.1 Cost categorization and methodology

The LCC calculation in this study is conducted with reference to ISO 15686-5 [6], in conjunction with the VDI 2884 [12] and DIN EN 60300-3-3 [13] standards, as well as methodologies employed in relevant literature. Based on this framework, the cost categories throughout the life cycle of a water electrolysis plant are illustrated in Fig. 4, where the costs appeared at each life stage of a 5 MW PEMWE are categorized based on the respective phase; costs incurred during the construction phase are



**Fig. 3** Work scheme of this study.

categorized in CAPEX, whereas costs arising during the operation and decommissioning phases are belong to OPEX; life stages and system boundaries of this plant are based on Gerhardt-Mörsdorf et al. [56]. The costs incurred during the construction phase are assigned to CAPEX, while both operational and end-of-life (EoL) costs are incorporated into OPEX [2,54,55].

OPEX includes expenses related to energy and water consumption, labor, maintenance, and EoL costs. Maintenance costs cover both routine maintenance and stack replacements, while EoL costs encompass decommissioning, waste disposal, and material recycling.

This initial cost categorization simplifies data collection and classification, providing a structured framework for cost analysis. Additionally, it helps mitigate uncertainties by establishing clear boundaries for cost allocation [16]. It is important to note that users can adapt and modify these categories to accommodate specific requirements and regional differences.

Once the cost has been categorized, the next step is to define the methodology for cost calculation, specifically the mathematical equations. The equations applied in this

study, which utilize a bottom-up LCC approach combined with an NPV-based calculation model excluding revenue considerations, are presented in Table 2, based on Refs. [28,30,38,57], where SV stands for salvage value; real WACC for real weighted average cost of capital.

The equations presented collectively establish a comprehensive framework for evaluating the LCC of the plant, encompassing CAPEX, OPEX, and associated tax impacts. This framework ultimately facilitates the calculation of the LCOH. CAPEX (Eq. (2)) captures initial investment costs, including expenditures for stack construction, balance of plant (BOP), housing, and labor. These costs are adjusted for investment tax credits and discounted to their present value. OPEX (Eq. (3)) includes recurring costs such as water and energy consumption, maintenance expenses, and EoL costs. EoL costs are further detailed in Eq. (4), which accounts for expenses related to dismantling, transportation, and the SV of materials, as defined in Eq. (5). SV represents the revenue obtained from selling discarded materials. While EoL costs contribute to total expenditures, the SV of

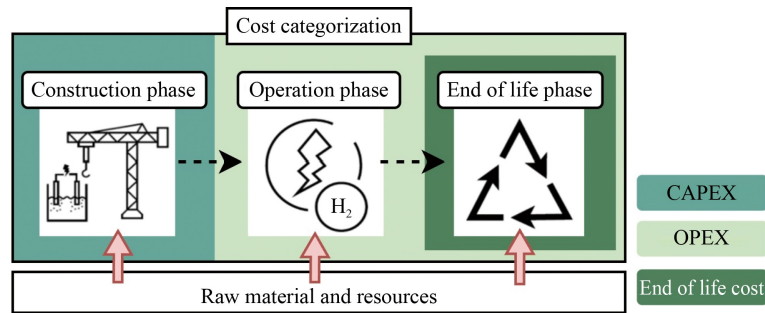


Fig. 4 Cost categorization.

Table 2 Equations applied for this LCC tool

Name	Equations	No.
LCOH	$\frac{TCO}{\sum_{t=1}^{t=n} \frac{M_t}{(1 + \text{real WACC})^t}}$	(1)
CAPEX	$\sum_{t=0}^{t=n} \frac{C_t^S + C_t^{\text{BOP}} + C_t^H - \text{invest tax credit of grant}_t}{(1 + \text{real WACC})^t} + C_t^L$	(2)
OPEX	$\sum_{t=1}^{t=n} \frac{C_t^R + C_t^M + \text{EoL}}{(1 + \text{real WACC})^t} + C_t^L$	(3)
EoL cost	$\sum_{t=20}^{t=n} C_t^D + C_t^T - \text{SV}$	(4)
SV	$\sum_{t=20}^{t=n} r_t^R \times p_t^S$	(5)
Tax impact	$\text{Tax rate} \times \sum_{t=1}^{t=n} \frac{C_t^R + \text{Dep}_t + \text{Int}_t}{(1 + \text{real WACC})^t}$	(6)
TCO	$\text{CAPEX} + \text{OPEX} - \text{Tax impact}$	(7)
real WACC	$\left( \frac{1 + \left( \frac{e}{e+d} \times e_r + \frac{d}{e+d} \times d_r \right)}{1 + \text{inflation rate}} \right) - 1$	(8)

recovered materials serves to partially offset these costs. To achieve a more precise assessment of cash flows, Eq. (6) addresses the tax impact, accounting for recoverable taxes on resource consumption, depreciation, and debt interest. This adjustment reduces the TCO, as outlined in Eq. (7). Subsequently, the TCO is combined with the discounted hydrogen production volume over the operational lifetime of the plant (Eq. (1)) to determine the LCOH, a key metric for evaluating the economic feasibility of the case study. The cornerstone of these calculations is the determination of the discount rate, expressed as the real WACC, Eq. (8). Real WACC integrates the weighted contributions and returns of both equity and debt capital, while also adjusting for inflation, to provide a realistic representation of financing costs and their impact on plant feasibility. Together, these equations offer a robust and systematic methodology for cost evaluation, enabling informed investment decisions and precise feasibility analyses.

### 3.2 Case study assumptions

This case study analyzes the LCC of a 5 MW PEMWE plant in Germany, covering its entire lifespan—from installation and operation to eventual decommissioning and disposal. All CAPEX-related costs are treated as global, as they are not limited to the procurement of construction components from specific regions. Consequently, remittances are considered, with exchange rate data detailed in Section 3.3. The plant installation requires two 2.5 MW PEMWE stacks, each with a lifespan of 10 years, resulting in a total of four stacks over the 20-year operational period [56]. It is assumed that the entire investment for constructing all stacks is made in the first year.

In contrast, OPEX costs are sourced locally in Germany, with energy and water prices based on historical data from 2008 to 2023. It is important to note that depreciation and interest on debt are not considered in this study. At the end of the 20-year lifespan, the plant is assumed to be fully dismantled, incurring decommissioning and disposal costs. However, the sale of scrap materials may generate potential revenue.

This case study considers two scenarios. The first goal in setting these scenarios is to assess and illustrate the potential for cost reduction, emphasizing the need to forecast annual energy prices over the plant's 20-year operation rather than relying on an average value. The second goal is to demonstrate how price predictions can be adjusted to align more closely with specific objectives, using energy forecasting as an example. Scenario 1 (S1) uses historical energy prices (2004–2023) and water prices (2008–2023) to forecast the next 20 years. Scenario 2 (S2) assumes that the effects of the pandemic and the war will influence prices for only 3 years, after which prices are expected to normalize. In S2, energy

prices for the next 3 years are predicted using data from 2004 to 2023, followed by a projection based on data from 2004 to 2018 to reflect trends before the pandemic and the war. These two sets of predictions are then combined to create the projection for S2. The water price is assumed to remain constant throughout the analysis.

### 3.3 Data collection

This subsection presents the technical data utilized in this case study, collected based on the cost classification outlined in Section 3.1 and the case study assumptions detailed in Section 3.2. The technical specifications for the PEMWE system are derived from prior research, which provides a detailed bottom-up life cycle inventory of a 5 MW PEMWE plant [56]. Table 3 summarizes the material prices and the costs associated with the BOP during the construction phase, in which the material prices are at the construction phase. The quantities, units, and prices of various materials and BOP components required for the construction of a 5 MW PEMWE plant are listed, with the corresponding references. The quantities are based on Gerhardt-Mörsdorf et al. [56]. Any differences in the units of the original price for a material or references to specific material types are noted in the comment section.

The materials listed in Table 3, ranging from steel to fluor-elastomer (FKM), represent the quantities required to construct four stacks, as outlined in Section 3.2. Their prices reflect the average values from 2018 to 2023. Additionally, power electronics are required for a 5 MW system. Since the system capacity exceeds 1 MW, these electronics must be custom-made. Customization introduces a high degree of price uncertainty, as cost can vary depending on factors such as alternating current (AC) input and direct current (DC) output voltages, efficiency requirements, and the scope of supply. For instance, some plants may require transformers, rectifiers, and control cabinets, while others may not require a full set of equipment [71]. Therefore, the price used in this study is an estimated cost provided by Green Power Co., Ltd., China, for a 5 MW PEMWE system.

The labor costs during the construction phase are assumed to be 5% of the total material costs [52]. As noted in the comments section of Table 3, the prices of carbon paper, gas water separators, and the dry cooler are listed in US dollars, while the price of power electronics is listed in CNY, as these components are not sourced from German suppliers as noted in Section 3.2. When converting US dollars and CNY to euros, the average exchange rate from January 2018 to May 2023 is applied [75].

Finally, the CAPEX value can be determined by incorporating the data required to calculate the actual WACC, as provided in Table 4 in which the data adapted from Kuckshinrichs et al. [28] are used to calculate real

**Table 3** Data for material cost

Materials and BOP	Quantity	Unit	Price per unit	Price unit	Ref.	Comment
Stainless steel	625	kg	0.78	€/kg	E.L.F Hallen und Maschinenbau GmbH [58]	–
Copper	68	kg	6.70	€/kg	Statistisches Bundesamt [59]	–
Titanium	3987	kg	6.11	€/kg	Trading Economics [60]	–
Platinum	0.75	kg	27243	€/kg	Johnson Matthey Plc [61]	–
Iridium	9.86	kg	87782	€/kg	Johnson Matthey Plc [61]	–
Carbon paper	329	pcs	80.62	€/pcs	Toray Industries Inc [62]	91 \$/pcs
Nafion N117	88.54	m <sup>2</sup>	6288	€/m <sup>2</sup>	DuPont de Nemours (Deutschland) GmbH [63]	€15.72/5 cm × 5 cm
FKM	1	pcs	796	€/pcs	Garlock, an Enpro Industries, Inc [64]	–
Stack cooling heat exchanger	1	pcs	48000	€/pcs	DACE Price Booklet Edition 35 [65]	–
Condenser	1	pcs	42000	€/pcs	DACE Price Booklet Edition 35 [65]	–
Gas water separators	2	pcs	2481	€/pcs	Mingyi Intelligent Equipment Co., Ltd. [66]	2800 \$/pcs
Dry cooler	1	pcs	1595	€/pcs	Dalian Changyong Technology Co., Ltd. [67]	1800 \$/pcs
Power cable	50	m	92	€/m	DACE Price Booklet Edition 35 [68]	–
Data cable	2000	m	0.67	€/m	MAG Micro Accessories Germany GmbH [69]	–
Pumps	6	pcs	9300	€/pcs	DACE Price Booklet Edition 35 [70]	22 kW/pcs
Power electronics	1	set	320699	€/set	Green Power Co. Ltd. [71]	2500000 yuan/set
Control unit	1	pcs	6600	€/pcs	Siemens AG [72]	160 kW/pcs
Housing	2	pcs	4950	€/pcs	ACM Abfall-&Containerservice Moers GmbH [73]	40 ft. container
Foundation	4.5	m <sup>3</sup>	181	€/m <sup>3</sup>	SCHWENK Beton Berlin-Brandenburg GmbH [74]	Concrete type: C35/45

WACC for CAPEX, OPEX, TCO, and LCOH. To apply the calculation tool, users may simply input their own material cost data to obtain the corresponding CAPEX.

**Table 4** Values for real WACC

Element	Value	Unit
Equity	0.25	–
Equity rate of return	7	%
Debt	0.75	–
Debt interest rate	4.5	%
Inflation rate	1	%

As illustrated in Fig. 4, in addition to CAPEX, this study also considers OPEX within the cost categories defined in this paper. Over a 20-year lifespan, a 5 MW PEMWE plant can produce a total of 17796460 kg of hydrogen, with each kilogram requiring the consumption of 9.30 kg of water and 56.33 kWh of energy [56]. To predict the trends of these costs over the next 20 years, historical data on water prices (2008–2023) were sourced from Berlin's water pricing records [76], while energy price data (2004–2023) were obtained from Eurostat [77,78]. Both the energy and water prices used in this study exclude VAT and all recoverable taxes.

As outlined in Section 3.2, the operation phase is assumed to take place in Germany, where water fees and energy costs consist of many variables. For example, wastewater treatment fees are included in water pricing, while various taxes and charges are included in the

energy price. Furthermore, water prices in Germany can fluctuate significantly depending on region; data set from Berlin was chosen because it includes a wide range of cost variables, offering greater flexibility for users to input values aligned with local conditions. Refining such variables supports improved prediction accuracy.

With respect to energy costs, Eurostat does not provide very detailed variables, such as charges related to the Renewable Energy Sources Act. Additionally, detailed cost lists with variables are only available for plants or equipment with energy consumption below 20 million kWh per year. Since the annual electricity consumption of a 5 MW PEMWE plant exceeds this threshold, the energy pricing data used in this study are sourced from Eurostat. However, more detailed cost lists with variables have also been stored in the calculation tool, allowing users to import them when necessary.

In addition to energy and water consumption, the annual maintenance cost for the PEMWE system is assumed to be 15 €/kW<sub>AC</sub> [40]. The costs associated with recycling and disposal phases are also included in the analysis.

Table 5 provides the recycling rates of materials at the EoL, along with their respective selling prices. The recycling rates and corresponding selling prices of discarded materials and BOP from a 5 MW PEMWE plant at the EoL phase are presented. Data in Table 5 are utilized to calculate the EoL costs.

The recycling rates represent the proportion of each material or component that can be recovered during the

**Table 5** Recycling rate and selling price of discarded materials

Materials and BOP	Recycling rate	Source (Recycling rate)	Unit	Selling price	Unit	Source (Selling price)
Stainless steel	88%	Lotrič et al. [79]	kg	0.27	€/kg	[80]
Copper	70%	European Recycling Industries' Confederation (EuRIC) [81]	kg	7.13	€/kg	[82]
Titanium	40%	Matz et al. [83]	kg	–	–	–
Platinum	76%	Matz et al. [83]	kg	16780	€/kg	[84]
Iridium	40%	Matz et al. [83] and Minke et al. [85]	kg	–	–	–
Carbon paper	0%	Lotrič et al. [79]	kg	–	–	–
Nafion N117	0%	Lotrič et al. [79]	kg	–	–	–
FKM	0%	Lotrič et al. [79]	kg	–	–	–
Stack cooling heat exchanger	85.5%	DESTATIS Statistisches Bundesamt [86]	kg	0.27	€/kg	Schrott24 GmbH [80]
Condenser	85.5%	DESTATIS Statistisches Bundesamt [86]	kg	0.27	€/kg	Schrott24 GmbH [80]
Gas water separators	72%	Statistisches Bundesamt [87]	kg	0.27	€/kg	Schrott24 GmbH [80]
Dry cooler	72%	Statistisches Bundesamt [87]	kg	0.27	€/kg	Schrott24 GmbH [80]
Cables	72%	Statistisches Bundesamt [87]	kg	1.95	€/kg	Schrott24 GmbH [88]
Pumps	72%	Statistisches Bundesamt [87]	kg	0.27	€/kg	Schrott24 GmbH [80]
Inverters	72%	Statistisches Bundesamt [87]	kg	0.08	€/kg	Schrott24 GmbH [89]
Control unit	72%	Statistisches Bundesamt [87]	kg	0.08	€/kg	Schrott24 GmbH [89]
Housing	88%	Statistisches Bundesamt [87]	kg	0.27	€/kg	Schrott24 GmbH [80]
Foundation	89%	Statistisches Bundesamt [87]	kg	–	–	–

disposal process, as documented in various studies. The corresponding selling prices reflect the market value of the recyclable portions. For instance, copper is priced at 7.13 €/kg, while platinum, a precious material, has the highest price at 16780 €/kg. Iridium and titanium also exhibit recycling rates of 40%; however, no specific selling prices are provided for these materials. Non-recyclable materials, such as carbon paper, Nafion N117, and FKM, have a recycling rate of 0%. Cables are valued at 1.95 €/kg, based on the value of their copper content. The foundation shows a high recycling rate of 89%, although no selling price is provided. These data are crucial for assessing the potential economic benefits of material recovery during the EoL phase.

In the final disposal phase, transportation costs are an additional expense. Table 6 presents the two different transportation costs considered in this study, corresponding to the different types of waste listed in Table 5. One cost applies to transporting recyclable waste, while the other pertains to transporting the foundation. The transportation costs for non-recyclable materials are not included in the analysis. The weight data of materials and BOP components used calculate salvage values and transportation costs are sourced from Gerhardt-Mörsdorf et al. [56].

It is important to note that the data listed in Tables 3 to 6 are subject to significant limitations. Even though some material prices are based on the average price over five years, the applicability of other cost elements, especially BoP, is relatively limited, as they are derived from specific models supplied by individual manufacturers.

**Table 6** Transportation cost

Types of waste	Price per 100 kg (without VAT)	Price unit
Waste for recycling	23.36	€
Gypsum board, gypsum waste	10.01	€

Notes: Here are the costs of transporting two types of waste, as provided by Kopp Umwelt GmbH [90], during the EoL phase of a 5 MW PEMWE plant. The data in this table are used to calculate the EoL costs.

This limitation primarily stems from the restricted availability of detailed price information during data collection, often due to confidentiality agreements, making it extremely difficult to access data from various manufacturers.

Given these constraints, range-based results provide greater value than single-point estimates. When input data are limited, a single cost estimate offers limited reliability or insight. In contrast, presenting results across a range better reflects the inherent uncertainties and improves the robustness of the analysis.

### 3.4 Computational model

This subsection describes the structure and components of the computational model developed in Python. It is important to note that equations and data can be fully customized based on users' specific requirements. The source code is available on GitHub: [github.com/LCC-Tool/LCC\\_Tool\\_5MW-PEMWE](https://github.com/LCC-Tool/LCC_Tool_5MW-PEMWE). The process for calculating LCC using the tool, along with the corresponding Python packages and modules used for each stage, is shown in Fig. 5, where the LCC results in this paper are

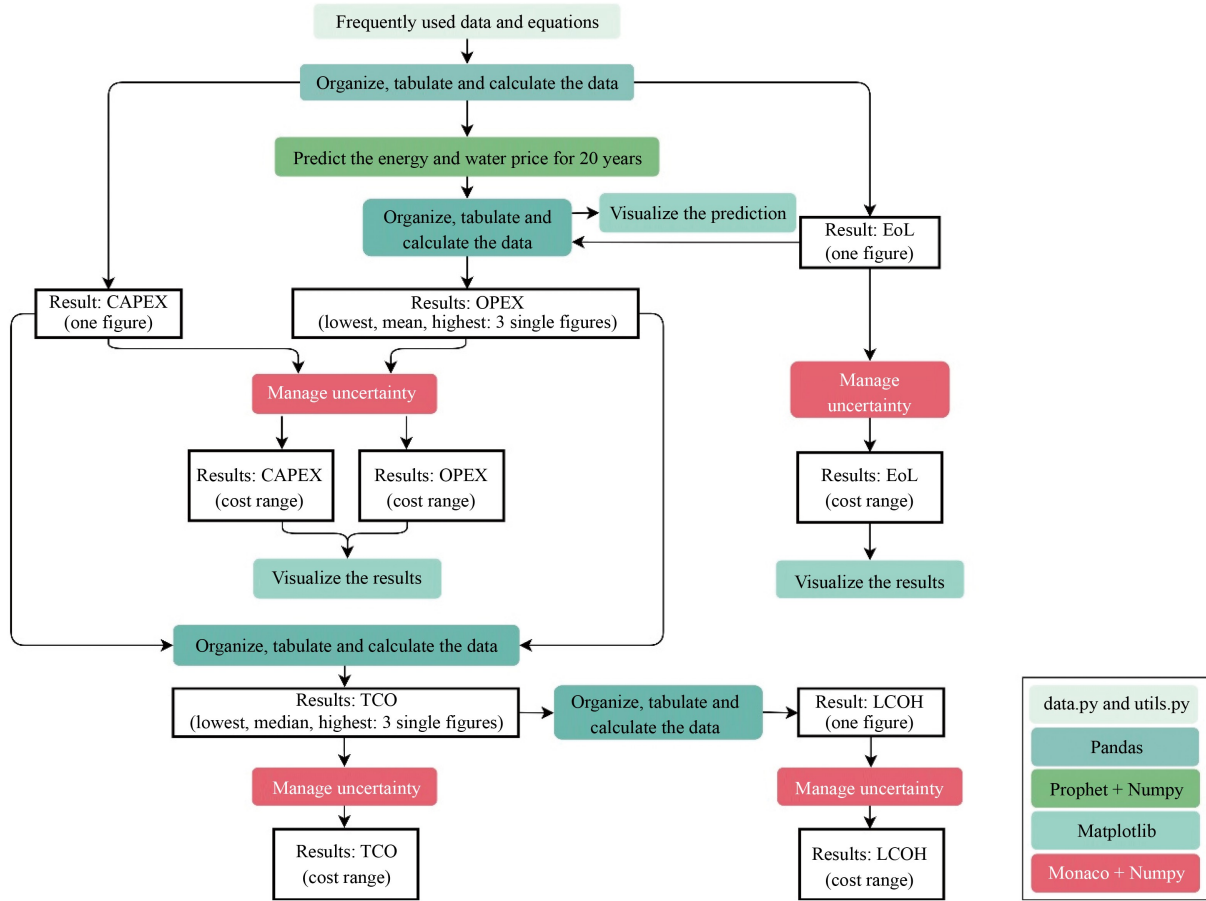


Fig. 5 Program flowchart.

calculated by using this process. Equations from Table 2 are integrated into `utils.py`, historical energy, and water prices are inputted into `data.py`. These data serve as the basis for Prophet predictions, which are then processed in Pandas to calculate OPEX. Data from Table 4 are loaded into Pandas and processed using corresponding equations from `utils.py` to calculate CAPEX, EoL, associated labor costs, etc. EoL costs and predicted energy and water prices are used for OPEX calculations. Costs in CAPEX, OPEX, and EoL—including materials and labor—are manually adjusted in Monaco to determine its cost ranges. TCO and LCOH calculations follow the same approach. Finally, different cost ranges are visualized using Matplotlib.

The file `Utils.py` contains all the equations from Table 2 as well as the prediction functions, while `data.py` stores the historical energy and water price data. This structure enables users to make unified modifications, thereby improving overall efficiency. Matplotlib is used to visualize the final results [91]. Data from Tables 3 to 6 are prepared, visualized, and processed using Pandas [92]. It is important to note that the outputs generated by Pandas are typically single numerical values. However, the tool is designed to extend beyond isolated outputs by offering a more comprehensive analytical framework.

To address uncertainty in CAPEX, this study applies the Monte Carlo method from the Monaco package [93]. By introducing randomness into otherwise deterministic processes, this approach quantifies uncertainty and allows for the exploration of a range of potential outcomes, ultimately performing a sensitivity analysis of the results [94]. In this sensitivity analysis, the sensitivity indices are primarily used to measure the relationship between the variance of a scalar output variable and the variance of each input variable, i.e., to identify which input parameters have the most significant effect on the output. The resulting sensitivity ratios are then displayed in sensitivity ratio and ranked by their impact [93]. Furthermore, Sobol’s sequences are utilized as the sampling technique [93], to enhance the robustness of the results [95,96].

In this process, adjustments to the `loc` value (representing the lower bound of the distribution) and `scale` value (denoting the interval length of the distribution) of the sampled variables, allow for effective management of uncertainties, such as those arising from variations in the prices of raw materials. Due to hardware limitations, only 350 cases were simulated. The results indicate that the cost is expected to fall within the calculated range with a probability of 95% [93].

To address OPEX uncertainty and integrate a predictive functionality, the tool utilizes Prophet, an open source predicting algorithm developed by Facebook. Designed for time series analysis, Prophet automatically detects and handles seasonality, holidays, and outliers, enabling users to make accurate predictions with minimal domain-specific knowledge or complex parameter tuning [97]. Its straightforward interface and flexibility have made it a widely adopted tool across various fields, including energy price prediction [98].

To ensure the reproducibility of results across different runs involving Monaco algorithms, a fixed random seed is used. This is necessary because both the Sobol-random solver within Monaco and the Prophet predictor involve elements of randomness [99,100].

This tool is particularly effective in aligning with real-world scenarios. When input data vary due to user-specific conditions, such as changes in raw material or energy prices based on geographic location, full recycling and reuse of stacks, or longer transportation distance during disposal, these deviations can be manually adjusted and accommodated within the model. After understanding the principles and functionality of the tool, the next step involves interpreting and analyzing the results generated by the tool.

## 4 Results and discussion

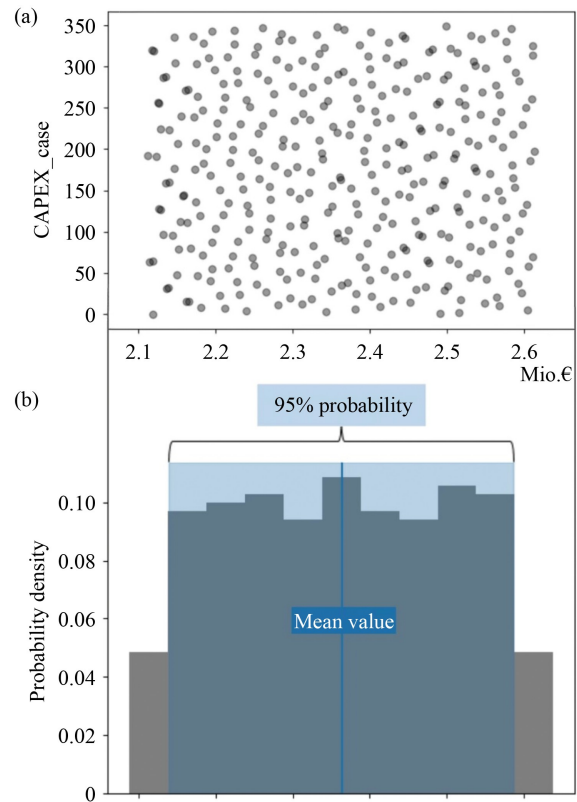
In this section, results of applying the LCC tool to the case study of a 5 MW PEMWE are presented and discussed. Additionally, guidance is provided for users on how to interpret and analyze the results generated by the tool. Finally, a comparison of all results is conducted.

### 4.1 CAPEX results

Using the CAPEX results as an example, Fig. 6(a) illustrates the probabilistic distribution of CAPEX results derived from 350 random sampling cases generated using Sobol sequences. In Fig. 6(a), each dot represents a distinct simulation scenario, with the density of points in specific cost ranges reflecting the likelihood of CAPEX outcomes falling within those intervals. For instance, the €2.3 million to €2.4 million range exhibits the highest density of points, indicating a greater probability of CAPEX occurring in this interval.

Figure 6(b) complements this by presenting the CAPEX distribution. The blue shaded region represents a 95% probability range, indicating that CAPEX is most likely to fall between approximately €2.14 million and €2.58 million, while the gray area denotes the remaining 5% probability. The blue vertical line in Fig. 6(b) marks the mean CAPEX value across all simulations, providing a benchmark for reference.

This probabilistic outcome results from the flexibility



**Fig. 6** CAPEX results.

(a) CAPEX samplings result from Monaco; (b) CAPEX range of a 5 MW PEMWE plant, with a total of 17796460 kg of hydrogen production within a 20-year lifetime

provided to users in defining input parameter ranges, such as material costs, labor rates, and interest rates. By specifying these input uncertainties, the model incorporates them into the random sampling process, producing a distribution of potential CAPEX values. This systematic aggregation of outcomes effectively transforms the uncertainty of individual inputs into a 95% certainty range for CAPEX, offering users a more reliable and actionable estimation. This approach bridges the gap between input variability and decision-making by quantifying uncertainty and presenting results within a high-confidence interval.

The relationship between Figs. 6(a) and 6(b) lies in the connection between point density and probability distribution. A higher point density in a specific cost range in Fig. 6(a) corresponds to taller gray bars in Fig. 6(b), indicating a greater probability of final CAPEX falling within that range. For example, the €2.3 million to 2.4 million range in Fig. 6(b), represented by the tallest gray bar, corresponds to the densest clustering of points in Fig. 6(a). Additionally, overlapping points in Fig. 6(a) represent cases with similar CAPEX outcomes, further reinforcing the reliability of this range.

Although the tool currently does not provide the precise percentage probability of CAPEX falling within a

specific range (e.g., €2.3 million to €2.4 million), the broader probability distribution still offers significant practical insights. By turning input variability into a robust probabilistic range, this methodology enables users to better understand and manage uncertainties. Consequently, it serves as a valuable tool for evaluating the financial viability of the project, providing a credible basis for informed decision-making.

Based on Eq. (5), various cost factors required for calculating CAPEX can be inferred, and Fig. 7(a) illustrates the impact of these different variations. The results indicate that raw material costs contribute most significantly to the variance in CAPEX, accounting for over 90% of the total variance, followed by labor costs, which contribute less than 10%. The sensitivity ratio refers to the contribution or influence (expressed as a percentage) of each internal variable in the cost function on the variance of the outcome [93].

Figure 7(b) further highlights that the cost of iridium is the most significant component of material costs, contributing nearly 35% on the variance of total material cost. This can be attributed to its critical nature and consequent high expense [52]. While platinum is also a precious metal, its impact on CAPEX is relatively minor, primarily due to its much lower usage compared to

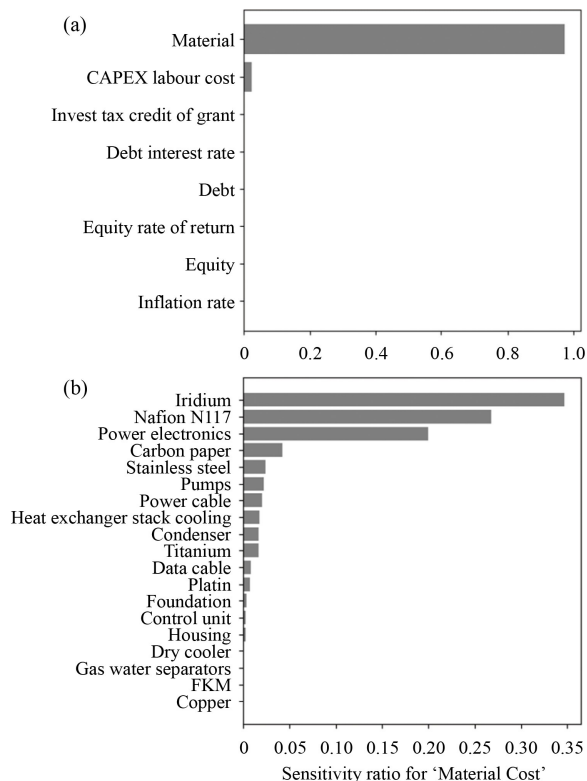


Fig. 7 Sensitivity ratio.

(a) Monaco generated the sensitivity ratio for CAPEX of a 5 MW PEMWE plant; (b) Monaco generated the sensitivity ratio for material costs in construction phase of a 5 MW PEMWE plant.

iridium, as detailed in Table 3. The next significant contributor is the Nafion N117 membrane, which accounts for over 25% of the variance in total material cost. This finding aligns with the research of Alipour Moghaddam et al., who also identified its high cost [101]. Additionally, power electronics contribute approximately 20% to the variance of material costs. Together, these three components contribute over 75% of the total variance in material costs.

As such, there is considerable potential for cost reduction. For instance, reusing Nafion N117 membrane [101] could lead to significant savings. Furthermore, incorporating the concept of a circular economy may further reduce costs. For example, since approximately 60% of the variance in total raw material price comes from iridium and membrane in the stack, a leasing model could be applied: after usage, the old stacks could be exchanged for new ones, and the components from the old stacks could then be reused as materials for constructing new stacks. Although the lifetime of the stacks may be limited to only 20 years, the BOP components typically last longer and can also be recycled and reused, thus further lowering construction costs.

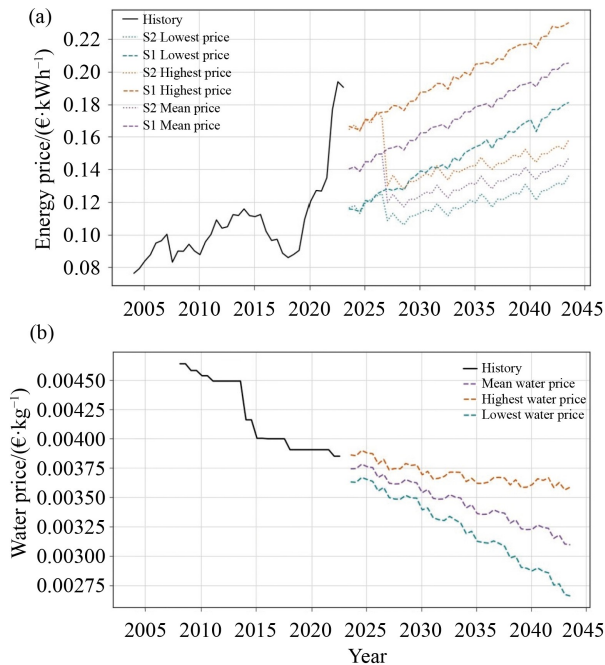
Through this tool, a CAPEX range that meets the requirements of the case study has been obtained, and the sensitivity ratios of its cost components have been demonstrated. Thus, the first issue raised at the beginning of this paper—managing uncertainty in CAPEX—has been effectively addressed. The next focus shifts to how the uncertainty regarding OPEX is addressed through the results.

## 4.2 Energy and water costs

As indicated by Eq. (4), the OPEX cost structure includes not only water and energy costs but also costs associated with EoL factors. However, despite the impact of EoL costs on OPEX, their volatility is relatively low, as these costs typically arise at the end of the plant's lifecycle and can be more reliably predicted through effective planning and early evaluation. In contrast, fluctuations in energy and water prices tend to persist throughout the operational phase, having a more direct and significant impact on annual OPEX changes. Therefore, greater emphasis is placed on the variation in energy and water prices and their impact on OPEX. This approach enables a more accurate understanding of the uncertainty surrounding OPEX over the entire lifecycle.

Given that the operational period can extend up to 20 years, predicting future prices for energy and water presents a significant challenge due to the inherent uncertainty in long-term market trends. To address this uncertainty, the Prophet model was employed to generate three distinct price predictions: the mean, upper bound, and lower bound, providing a range of possible future outcomes. As shown in Fig. 8, these predictions help

capture the uncertainty and offer a more comprehensive view of potential price fluctuations over the projected period. The black curve in Fig. 8 represents the historical data provided by Refs. [77,78]. In S1, energy prices (highest, medium, lowest) show a continuous upward trend. In S2, the first three years of predictions mirror S1. However, starting from the third year, predicted energy prices sharply decline before gradually increasing again.



**Fig. 8** Prediction of energy and water prices.

(a) Prophet generated energy price predictions for 20 years in both scenarios; (b) prophet generated water price predictions for 20 years. The black curve shows the historical data provided by Berliner Wasserbetriebe [76].

Figure 8(a) illustrates the variations in energy prices under both scenarios. In scenario S1, due to the expected prolonged impact of the pandemic and war over the next 20 years, all three predicted prices show a continuous rise. In contrast, the energy prices in scenario S2 are predicted to decrease significantly, reflecting the assumption that prices will return to pre-pandemic and pre-war levels after a period of sustained growth over three years, as discussed in Section 3.2. Interestingly, the highest energy price forecast in S2 is predicted to remain lower than the lowest price forecast in S1 after 2035.

A notable difference is observed in the gap between the three energy price predictions. In S1 this gap is larger than in S2, as shown in Fig. 8(a). This can be attributed to the influence of historical price spikes. Specifically, in predicting energy prices for S1, the model incorporates the sharp increase in energy prices between 2018 and 2023, resulting in significant divergence among the three predicted energy prices for S1. In contrast, S2 does not account for this sharp increase post-2026, leading to

smaller discrepancies among the three predicted energy prices.

Figure 8(b) shows the water price trends predicted by the model. Similar to energy prices, water prices also exhibit some fluctuation, though the variations are less pronounced.

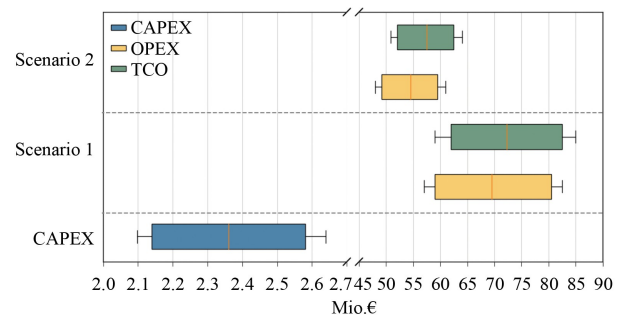
Once the energy and water price predictions for both scenarios are obtained, they are applied to calculate OPEX and, subsequently, TCO. The variations in energy prices, particularly the significant differences observed between the two scenarios, demonstrate the considerable uncertainty involved in predicting long-term operational costs. These uncertainties directly influence the overall OPEX, highlighting the importance of accounting for energy price volatility in economic analyses.

### 4.3 OPEX and TCO results

In this subsection, the calculated results for CAPEX, OPEX, and TCO are presented and analyzed, with a focus on the impacts of input parameter variations on these outcomes.

Since the impact of taxation is not considered in this case study, TCO is determined solely by the combination of CAPEX and OPEX, as defined in Eq. (7). The two scenarios are different based on variations in energy prices, which directly affect OPEX, while CAPEX remains constant. Consequently, two distinct TCO outcomes are generated for the respective scenarios, as illustrated in Fig. 9. In Fig. 9, the box in the box plot represents the range with a 95% probability of containing the actual cost, corresponding to the blue shaded area in Fig. 6(b). The numerical values discussed in the following text also fall within this probabilistic range. The whiskers indicate the remaining 5% probability, showing the extreme ends of the result distribution. Results of CAPEX, OPEX, and TCO for a 20-year lifespan of a 5 MW PEMWE, with a total of 17796460 kg of hydrogen production within a 20-year lifetime.

As shown in Fig. 9, CAPEX ranges from €2.14 million to €2.58 million. For OPEX, uncertainty introduced by fluctuating energy prices is addressed by calculating the values corresponding to the lowest, highest, and mean



**Fig. 9** LCC results.

energy prices, with the predicted lowest and highest energy prices input into the Monaco package to determine the OPEX distribution range. This approach ensures a robust probabilistic analysis, moving beyond deterministic calculations commonly applied in similar studies. In S1, there is a 95% probability that the OPEX range lies between approximately €59 million to €80.5 million, while in S2, the range is reduced to approximately €49.2 million to €59.5 million. The cost analysis of OPEX across different scenarios highlights the dominant influence of energy prices. In every scenario, the sensitive ratio shows that the energy costs contribute over 95% of the variance in total OPEX, underscoring their significant impact.

As illustrated in Fig. 9, the greater difference between the minimum and maximum OPEX values in S1, indicated by the longer box, is attributed to the higher variability in energy prices under S1 compared to S2, as discussed in Section 4.2. This comparison clearly demonstrates the direct impact of energy price fluctuations on OPEX, with S1 showing greater sensitivity to external factors such as war and the pandemic. These findings suggest that measures such as long-term contracts or renewable energy adoption could help mitigate such volatility.

As shown in Fig. 9, the TCO range in S1, with 95% probability, lies between approximately €62 million and €82.5 million, while in S2, it falls between approximately €52 million and €62.5 million. Similarly, to the method used for calculating OPEX, the highest and lowest TCO values are input into Monaco, the highest and lowest TCO values are input into Monaco to determine the cost range for TCO. As indicated in Eq. (5), both CAPEX and OPEX contribute to TCO. Since CAPEX remains constant in both scenarios, the variation in TCO is directly driven by the differences in OPEX. In the cost analysis of TCO, the sensitivity ratio shows that OPEX contributes over 90% of the variance of TCO in both scenarios, while CAPEX contributes less than 10%. Moreover, these results underscore the strategic importance of stabilizing operational inputs, as reducing uncertainty in OPEX could substantially narrow the TCO range, thereby improving accuracy and reliability of plant feasibility evaluations.

#### 4.4 LCOH results

For assessing the economic viability of hydrogen production through PEMWE, it is essential to understand both the LCC and the unit production cost, i.e., the LCOH, expressed as the cost per kilogram of hydrogen. These results are provided below.

LCOH is calculated using Eq. (1), with TCO and the total hydrogen production directly influencing the outcome. The highest and lowest values of TCO were input into the Monaco tool to determine the LCOH range for both scenarios. As shown in Fig. 10, boxes represent a

95% of probability that the real LCOH falls within this range. In S1, the LCOH ranges from 6 to 13.2 €/kg H<sub>2</sub>, while in S2, the range narrows to 4.5 to 9.5 €/kg H<sub>2</sub>.

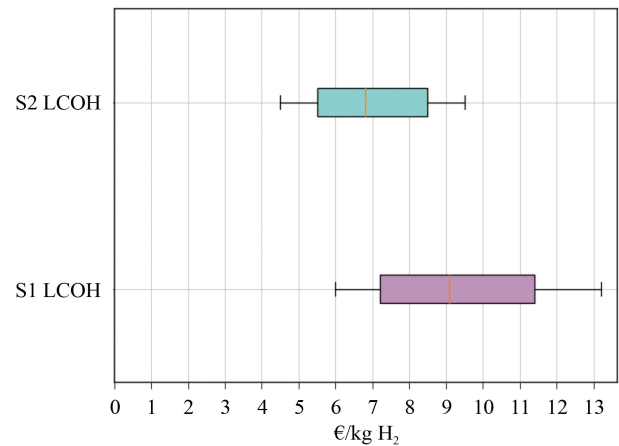


Fig. 10 LCOH results.

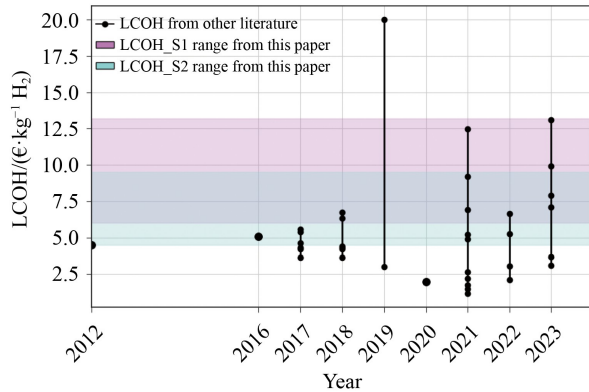
In the subsequent cost analysis, the sensitivity ratio for S1 shows that TCO contributes over 35% to the variance in LCOH, with hydrogen production accounting for over 30% and inflation contributing over 25%. This distribution primarily reflects the impact of war- and pandemic-related factors, which have caused significant fluctuations in energy prices and inflation, making TCO the main source of LCOH uncertainty in S1. In contrast, in S2, where energy prices are more stable, hydrogen production becomes the main contributor to the variance in LCOH at approximately 35%, followed by TCO at over 30% and inflation at around 30%.

These findings suggest that optimizing energy consumption, improving hydrogen production stability, and managing inflation could effectively reduce LCOH uncertainty. By converting these contributing factors into a probabilistic range of costs using the tool, the second issue raised in this paper—uncertainty in OPEX—has been effectively addressed.

#### 4.5 Validation

According to the results, it is evident that managing uncertainty through the tool transforms the outcome from a single value into a defined cost range. To validate the reliability and robustness of the results obtained from the developed tool, a comparison was made with existing literature on LCOH from water electrolysis, as listed in Table 1. This comparison, presented in Fig. 11, highlights the differences and broad range of LCOH values reported in the literature over the past 12 years, emphasizing the inherent uncertainty and variability in hydrogen production cost estimates.

In Fig. 11, each black dot represents a published LCOH result, with the black lines connecting these dots indicating the range of LCOH values reported each year.



**Fig. 11** Overview of different LCOH results of water electrolysis.

Color ranges represent the LCOH ranges of both scenarios calculated in this paper using the LCC calculation tool, covering most cost outcomes from the past 12 years. The notable length of these lines reveals the substantial discrepancies between the reported results, highlighting the significant volatility in LCOH estimates. Specifically, the highest LCOH approaches 20 €/kg H<sub>2</sub>, while the lowest is below 2 €/kg H<sub>2</sub>. This wide range reflects the complexity and multifaceted nature of LCOH calculations, which are influenced by various factors such as energy prices, geographical location, inflation rates, and technological advancements. The significant variability in these estimates underscores one of the primary motivations for developing the tool—to provide a more refined and systematic approach to managing uncertainty in LCOH calculations.

The results, presented through the two-colored ranges in Fig. 11, demonstrate that the tool effectively captures the uncertainty in hydrogen production costs. Notably, although the case study is set in Germany, the range produced by the tool covers most of the LCOH research outcomes from 2012 to 2023 globally. This indicates that the tool can accommodate various input assumptions and produce reliable results consistent with other studies, validating its capability to manage and present uncertainty. By transforming uncertainty into a well-defined cost range rather than a single value, the tool enhances the reliability of economic decision-making.

## 5 Conclusions

This paper presented a Python-based tool for calculating LCC and managing its associated uncertainty. This tool integrates an NPV-based calculation method and Monte Carlo simulation, and is specifically designed to enable global researchers and industry professionals to adjust inputs or assumptions to explore different scenarios, ensuring adaptability to diverse regional contexts and policy environments. This flexibility allows for

continuous updates to the tool's scope. Importantly, the tool outputs a cost range with a 95% probability rather than a single figure, offering a more reliable and adaptable approach to decision-making. Moreover, the tool includes a prediction feature for cost variables: by inputting historical data, users can generate predictions for desired future time intervals, further enhancing its practical application.

The tool was validated through a case study on the LCC of a 5 MW PEMWE plant in Germany. By comparing its results with related literature, the outcomes were confirmed to be reliable. In this case study, the CAPEX ranged between €2.14 million and €2.58 million with 95% of probability. According to the sensitivity analysis, the contribution of OPEX to the variance of TCO exceeds 90%, while the contribution of CAPEX is less than 10%. Within CAPEX, however, 90% of the variation comes from changes in the cost of raw materials. Incorporating circular economy principles—such as reusing precious metals (e.g., iridium) and membrane—to reduce the raw material costs for stacks can significantly reduce variation of total raw material cost by around 60%.

Two energy cost scenarios for Germany were simulated to demonstrate the prediction functionality. Under the low energy cost scenario, it is predicted that by 2045, the energy price may drop to approximately 0.14 €/kWh, with a 5% probability of the TCO reaching a minimum value of €51 million and a 95% probability range between €52 million and €62.5 million, with the corresponding LCOH potentially as low as 4.5 €/kg H<sub>2</sub> and a 95% probability range between 5.5 and 8.5 €/kg H<sub>2</sub>. Conversely, under the high energy cost scenario, the energy price is expected to rise to around 0.23 €/kWh by 2045, leading to a TCO with a 5% probability of reaching up to €85 million and a 95% probability range from €62 million to €82.5 million, while the maximum LCOH could reach 13.2 €/kg H<sub>2</sub>, with a 95% probability range between 7.2 and 11.4 €/kg H<sub>2</sub>.

However, this tool still has certain limitations. The current version primarily focuses on the calculation of basic financial costs and only covers internal costs. External costs of the product system, such as environmental impacts, CO<sub>2</sub> certificate costs, are omitted. This is one of the directions for future development. Another limitation lies in the input data. Although the tool mitigates data limitations to some extent by providing a range-based instead of single-point cost estimates, the accuracy of outputs improves with the inclusion of more input sources. Expanding the tool's database by integrating more input data is a planned next goal.

Currently, the prediction model includes only energy price prediction. In the future, it is necessary to incorporate raw material price forecasts to enhance the database and provide users with more pricing options. At

present, users must use the same energy prediction code and manually input raw material prices to predict the future prices of raw materials.

Future developments could also include utilizing the tool to compare the environmental and economic performance of different hydrogen production technologies, or to analyze the same technology across different countries. Additionally, the results generated from this tool could be used to conduct social analyses, such as exploring the role of hydrogen production in the energy transition through country-specific case studies. Additionally, there is also potential for integrating artificial intelligence to predict trends in hydrogen production costs and to analyze different cost components for identifying optimal cost structures. These advancements could significantly broaden the tool's applicability by providing forward-looking insights and enabling stakeholders to anticipate better anticipate and address the economic dynamics of hydrogen production systems.

Incorporating these features would transform the tool from a cost-focused calculator into a more comprehensive framework for assessing the sustainability of hydrogen production systems, offering multi-dimensional insights for informed decision-making. This tool represents only the first step in a broader effort to address these complex challenges.

## Notations

$C_i^{\text{BOP}}$	Costs of balance of plant of a 5 MW PEMWE
$C_i^{\text{D}}$	Deconstruction cost of a 5 MW PEMWE
$C_i^{\text{H}}$	Costs of site preparation (Housing) of a 5 MW PEMWE
$C_i^{\text{L}}$	Costs of Labor of a 5 MW PEMWE
$C_i^{\text{M}}$	Maintenance costs of a 5 MW PEMWE
$C_i^{\text{R}}$	Costs of resources used to produce hydrogen (Water and energy) of a 5 MW PEMWE
$C_i^{\text{S}}$	Construction and replacement costs of hydrogen production stacks of a 5 MW PEMWE
$C_i^{\text{T}}$	Transportation costs in end of life of a 5 MW PEMWE
$d$	Debt
$\text{Dep}_t$	Depreciation
$d_r$	Debt interest rate
$e$	Equity
$e_r$	Equity rate of return
$\text{Int}_t$	Interest on debt
$M_t$	Hydrogen production volume of a 5 MW PEMWE
$p_i^{\text{S}}$	Selling price of used raw materials and balance of plant
$r_i^{\text{R}}$	Recycling rate of used raw materials and balance of plant

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