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Life cycle costing approaches of fuel cell and hydrogen systems: A literature review

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HIGHLIGHTS

- Literature review with 141 publications on LCC of FCH technologies was carried out.
- The number of relevant publications has been increasing since 2011.
- Production and utilization of hydrogen were most frequently analysed (>60%).
- 33 different tools and 32 different databases were used in LCC of FCH technologies.
- The Levelized Cost method was mostly used in the reviewed publications (>40%).

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ABSTRACT

Hydrogen is a versatile energy carrier which can be produced from variety of feedstocks, stored and transported in various forms for multi-functional end-uses in transportation, energy and manufacturing sectors. Several regional, national and supra-national climate policy frameworks emphasize the need, value and importance of Fuel cell and Hydrogen (FCH) technologies for deep and sector-wide decarbonization. Despite these multi-faceted advantages, familiar and proven FCH technologies such as alkaline electrolysis and proton-exchange membrane fuel cell (PEMFC) often face economic, technical and societal barriers to mass-market adoption. There is no single, unified, standardized, and globally harmonized normative definition of costs. Nevertheless, the discussion and debates surrounding plausible candidates and/or constituents integral for assessing the economics and value proposition of status-quo as well as developmental FCH technologies are steadily increasing—Life Cycle Costing (LCC) being one of them, if not the most important outcome of such exercises.

To that end, this review article seeks to improve our collective understanding of LCC of FCH technologies by scrutinizing close to a few hundred publications drawn from representative databases—SCOPUS and Web of Science encompassing several tens of technologies for production and select transportation, storage and end-user utilization cases. This comprehensive review forms part of and serves as the basis for the Clean Hydrogen Partnership funded SH2E project, whose ultimate goal is the methodical development a formal set of principles and guardrails for evaluating the economic, environmental and social impacts of FCH technologies. Additionally, the SH2E projects will also facilitate the

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proper comparison of different FCH technologies whilst reconciling range of technologies, methodologies, modelling assumptions, and parameterization found in existing literature.

Introduction

Hydrogen has versatile functions in decarbonized energy systems. It can be produced from a variety of feedstocks, can be used for transportation and storage media of renewable and low carbon resources, does not emit carbon dioxide directly when used, and can be used in many sectors to produce heat and electricity via fuel cells and other hydrogen demand technologies. Thus, fuel cell and hydrogen (FCH) related technologies connect low carbon and renewable resources with energy demand sectors for carbon neutrality [1,2]. According to Zhu et al. more than 30 countries around the world have published hydrogen strategies or hydrogen roadmaps [3] differentiated by geography, sector(s) prioritized and application areas. While most of the countries try to decarbonize the energy, transport or industry sector, Australia and South Korea in contrast aim to foster economic growth [4]. The U.S. is targeting the light- and heavy-duty vehicles as the major market for hydrogen, thereby implying a growth in the demand and adoption rate of FCVs [5]. Several European countries see also the industry sector with steel and chemicals production as an application area for hydrogen [4], either domestically produced or imported hydrogen. These instances illustrate the role and importance of advancing diverse FCH technologies to fully realize their decarbonization potential.

Economics and value proposition strongly influence the research and development support, public and private sector investments, supply-demand dynamics and the adoption rates of new technologies. Naturally, a plethora of studies have analysed the cost of FCH systems in the last decade. The range of methodological choices, technology parameterization and model assumptions gleaned from such studies often poses numerous interpretative challenges, despite using the same metric or a homogenous set of criteria for comparative assessment. To that end, the Society of Environmental Toxicology and Chemistry (SETAC) published a code of practice in 2011 for Life Cycle Costing (LCC) [6]. Other studies might use the approach of ‘Total Cost of Ownership’ (TCO), which also includes the full life cycle of a product from cradle-to-grave. Regarding FCH systems, LCC is currently of utmost importance, because several FCH technologies are on the edge of commercialization, e.g. water electrolysers. Thus, in this study a comprehensive literature review was performed on LCC approaches for FCH systems to determine the most important methodological influencing factors and identify best practices.

This study is part of the Clean Hydrogen Partnership funded SH2E project [7] where eventually guidelines for Life Cycle Sustainability Assessment (LCSA) of FCH technologies are being developed. Although LCSA encompasses a broad concept of sustainability [8,9], LCSA integrates three assessment methods that reflect economic, environmental and social aspects in this project. LCSA uses the triple-bottom-line approach for describing sustainability [11]. However, more recent discussion led to a nested understanding of sustainability. Without a functioning environment neither social nor economic development is possible as economic development is intertwined with social relationships [12]. This means economic development must align with the planetary boundaries and social restrictions. Within the context of climate change, many hydrogen strategies and roadmaps mainly consider their economic aspects. The social dimension, however, is only mentioned in few European strategies as well [4]. The economic development of FCH technologies, in contrast, is an important topic in all these strategies and roadmaps. In the actual implementation of different FCH technologies LCC approaches are of utmost importance provided that social and environmental framework conditions are complied with.

This review aims to clarify overall trends in LCC approaches and indicators (including both conventional life-cycle economic indicators and life-cycle economic indicators based on externalities—also known as environmental LCC), identifying their main features and discussing their suitability for the assessment of FCH systems in order to establish LCC guidelines to be subsequently developed. The review investigates the objectives, the scope, the entity of assessment, stakeholder involvement, the facilities considered, calculation methods, discounting (social vs private, low vs high investment risk) or EoL treatment, etc.

So far, several review publications about FCH topics have been published by considering different perspectives and focuses. For example, a specific FCH technology – water electrolysis, is analysed in Gigoriev et al. [10]. They are mentioning costs, but only in absolute terms regarding the different technologies. Hydrogen supply chains are the technological topic of Fredershausen et al. [13]. In the example of hydrogen supply chains (i.e. usually all process stages from production to consumption), methodological aspects regarding sustainability evaluations are discussed. They classify the economic evaluations in four different types, i.e., macroeconomics, microeconomics, long-term competitiveness and innovation capability. However, they do not go further into methodological details, which were carried out in this study. Further publications compare different production technologies [14,15], focus on production and distribution issues in geographic contexts [16,17], or consider different transport options [18,19] in connection with LCC aspects, for example. Parra et al. [20] review hydrogen energy systems in four categories from various aspects, including cost and value creation for commercialization, but they do not go into methodological aspects in detail. Kannah et al. [21] compare hydrogen costs of various production technologies using data from the reviewed publications and discuss barriers to commercialization. However, they do not provide a detailed

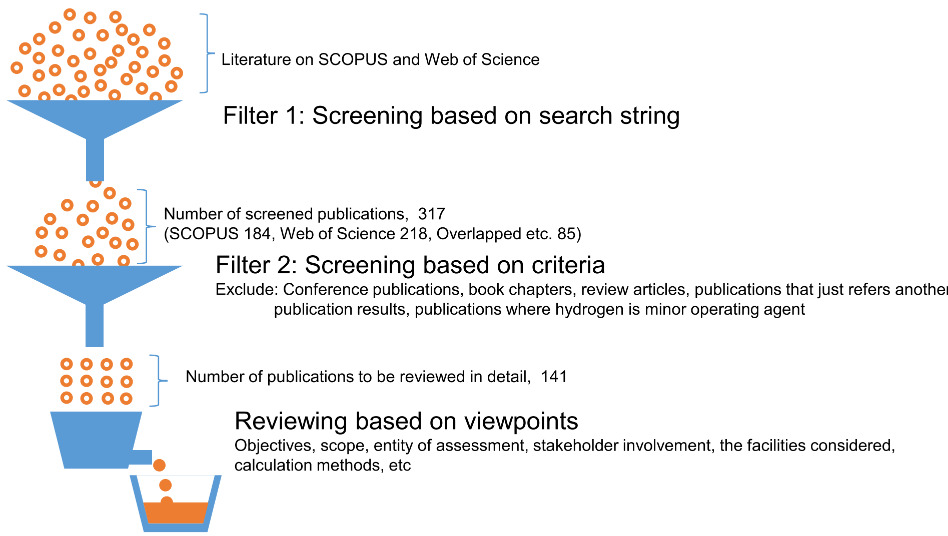

Fig. 1 – Procedure of literature review on LCC publications.

methodological analysis and use the levelized cost method to calculate hydrogen costs.

Rest of the paper is organized as follows. Section 2 describes the procedure for this review including the Scope and Methodology. Section 3 begins with a breakdown of temporal and technological traits and the selection criteria adopted followed by a short overview of a few of the commonly used LCC models, their mathematical formulation and cost constituents. We synthesize our findings and discuss its applicability in Section 3. We conclude this article with our final thoughts, broader implications and takeaways in Section 4.

Scope and Methodology

The procedure of this review is illustrated in Fig. 1. Scientific publications listed in two literature databases used in this review were screened with their respective filters. Peer-reviewed publications were extracted from SCOPUS [22] and Web of Science [23], dated January 1, 2011 to May 21, 2021, with the search words in their titles, abstracts or keywords shown in Table 1. Overall, 402 publications were extracted, 317 of which were unique without overlapping and the remainder were common to both databases. The used search strings in both databases are shown in the Supplementary material (text document).

The publications were then briefly checked based on their abstract, equations, figures, tables, and conclusions using the selection criteria in order to identify the publications warranting a detailed review.

- Include: Publications with peer review on LCC of FCH related facilities or equipment (production, storage, transport and utilization);
- Exclude: Conference proceedings, book chapters, review articles, publications that just refer to the results of other publications, articles where hydrogen is not in the focus, non-English written publications.

A total of 141 publications were scrutinized based on the viewpoints categorized as shown in Table 2. First, the framework conditions and thematic characteristics (technology, entity, etc.) were detected. In addition, the relevant

Table 1 – Time span and keyword used in the databases.

Items	Value or keyword
Time span	From 2011-01-01 to 2021-05-21
Search words	hydrogen OR "fuel cells" AND "life cycle" OR lifecycle AND "sustainability assessment" OR lcsa OR costing OR lcc OR "economic analysis"

Table 2 – Viewpoints of literature review.

Viewpoints	Descriptions
Technology	Short term description, divided into hydrogen production, transportation, storage and utilization
Technology detail	Description of contained technologies and their connection
Entity of assessment	Academia and/or industry
Stakeholder involvement	Entities other than authors involved or not
Modelling approach	How to convert systems or processes into mathematical models in the publications
Calculation methods	Used economic calculation method
Indicators	Economic indicators used in the publication
Cost items included	Considered cost items for costing (e.g. investment or maintenance cost)
Discounting	Percentage point for discounting, social vs private, low vs high investment risk

methodological aspects (applied method(s), indicators, cost items, etc.) were identified. Information on the considered viewpoints was qualitatively recorded/coded through textual descriptors for technology, entity of assessment and so on. As a second type of detection yes/no questions about viewpoints such as stakeholder involvement, inflation considered and so on were used. If yes, additional items were examined and partly expanded to include quantitative data collected, e.g., who is involved (entities) or what percentage was used (e.g. inflation rate).

The authors recognize that the number of literature databases and viewpoints selected for the review could possibly introduce errors. Regarding the first point, only single database may not be sufficient from a "coverage" perspective. In fact, the different publications were extracted from the two databases using equivalent search terms, although there was a lot of overlap. We take advantage of improved coverage by relying on the two representative databases most relevant to this review—Scopus and Web of Science. Admittedly, it is desirable to have access to multiple databases, but given the resources and priorities of the SH2E, restricting to the above databases has no bearing on the critical findings and implications of this study.

Results and discussion

The analysis of the 141 publications reviewed in detail is sectioned roughly according to the viewpoints mentioned in Table 2. First, the temporal development of the publications is illustrated. Second, the entities of assessment are discussed. In the third section the FCH technologies tackled in the different publications are clustered. The fourth section has a focus on methodological aspects and tools used for LCC. In addition to these results, the list of the reviewed publications and detailed information on used software and databases in them are available as the Supplementary Materials (text file, Table 1).

Temporal development of the reviewed publications

Fig. 2 shows the number of the reviewed publications by year of publication. The number of LCC publications about FCH technologies increases with time as observed. This could reflect the scientists' interests in the economics of such technologies because of their greenhouse gas (GHG) reduction potential.

The Green Deal is the comprehensive initiative for energy transition [25] in the context of European climate policy context. The Hydrogen Roadmap Europe [26] emphasizes the role and importance of hydrogen in European's energy transition towards mid-century and beyond climate goals obligated by the Paris accords [24]. Actualizing such ambitious GHG reduction targets necessitates that the broader objective of carbon neutrality supersedes any and all sectoral and subsectoral energy transition roadmaps. This is especially critical for the developmental prospects of FCH technologies since its cross-sectoral applicability and true GHG mitigation potential is strongly influenced by the macroeconomic climate policy goals *vis-à-vis* carbon neutrality. Due to technical and or economic reasons, direct electrification may not be the best strategy to decarbonize hard-to-abate sectors—-steel, chemicals, long-distance freight (e.g., heavy-duty trucks), off-road heavy vehicles (e.g. mining trucks), shipping and aviation. Hydrogen technologies, some of which are still in the research and development (R&D) phases, have shown promise in partially or fully substituting fossil based, sourced, dominant or derived processes and transformation activities are applicable. Using hydrogen instead of coal or natural gas for chemically reducing iron ore in the steel-making process and harnessing the flexibility potential of hydrogen storage for tackling the volatility and intermittency of renewables are salient cases in point [27]. Among other things, the above-mentioned dates, the resulting political framework conditions and shifting technology focuses can explain the increased interest and number of publications for FCH technologies.

Entity of assessment

Fig. 3 shows the entity of assessment in the reviewed publications. Academia (universities and research institutes) is a major assessment entity because peer-reviewed publications are set for the review scope. Peer-reviewed publications were used because there is a lot of literature on FCH technologies to ensure a certain quality of the publications for this article.

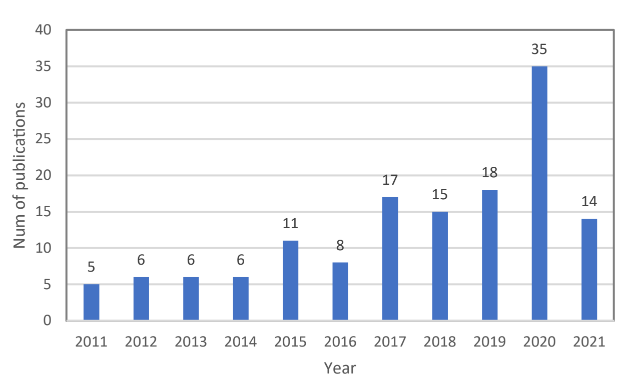

Fig. 2 – Number of the reviewed publications by published year, until May 2021.

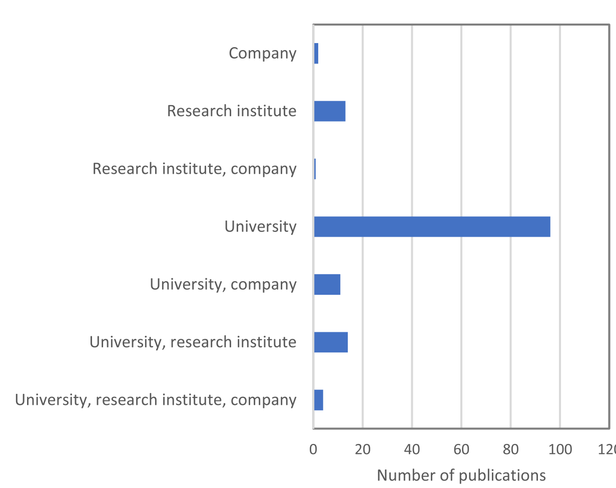

Fig. 3 – Absolute numbers of assessing entities in the reviewed publications.

Table 3 – Absolute numbers and relative shares of additional stakeholder involvement in reviewed publications.

	Number of publications	Share
Yes	9	6%
No	132	94%
Total	141	100%

Companies participate to reviewed publications as a partner of academia rather than writing a publication alone. About 70% of all publications considered were written by universities alone, another 20% were realized by universities in cooperation with research institutes and companies. The remaining 10% represent the sole work of research institutes, companies, or their collaborations.

Table 3 shows the absolute number and shares of reviewed publications that have additional stakeholder involvement in their work. Stakeholder involvement is the inclusion of stakeholders other than authors for information, analysis, and so on. Explicit stakeholder involvement was implemented in a small number of cases (6% of the total) among the reviewed publications and is therefore an exceptional case. Examples of participation are the use of the survey to select indicators [28], expert interviews to define the range of assumptions [29] and the involvement of a ship operating company to provide data on ship operation [30]. Hoque et al. [28] implemented an LCSA of fuels for the transportation sector in Western Australia, surveying experts from industry and academia to screen the indicators extracted from the literature review. Kang et al. [29] interviewed experts as one source of information to determine parameter ranges for sensitivity analysis in the techno-economic analysis of fuel cells. The specific parameters were stack life, operating rate, gas consumption, water consumption, heat recovery, rate, electricity losses, initial investment cost, stack replacement cost, maintenance cost, system marginal price, renewable energy certificate price, and gas price. Wu et al. [30] used data provided by bus operators to conduct a life cycle cost analysis of alternative fuels for buses. Specifically, the data include fuel, labour, maintenance and labour costs.

Technology

A significant share of reviewed publications (86%) dealt with production and utilization technologies, whereas only a minority focused on storage and transport, Fig. 4. The publications that include production technologies represent about 72% (~100) of the reviewed publications. The publications that include utilization technologies represent about 62% of the reviewed publications.

Table 4 enumerates production, storage and transportation technologies, and end-uses reviewed in this article. The multifaceted nature of FCH technologies is reflected in the variety of technologies available for a specific purpose (eg. production) as well as in the combinatorial possibilities when more than one process of the supply chain is considered.

Cost analysis methodology

Fig. 5 shows the modelling approaches used in the reviewed publications. There is a wide range of “System Assessment” from detailed analysis to aggregated high-level analysis depending on the analysis objectives and the envelope of technologies assessed. The detailed analysis could be defined as using a combination of fundamental processes using physical, mechanical and chemical, data to determine the amount of material, energy, and equipment required by the FCH technologies. Then the performances of the system such as environmental and economic aspects are obtained based on the calculation of each process. A typical example is the comparative analysis of hydrogen production technologies using process simulator software. In this example, there are multiple reactions such as desulfurization, reforming, shift, CO_2 capture, and purification reactions, as well as heat exchange, and the required energy inputs and CO_2 emissions per unit of hydrogen are evaluated by integrating the obtained calculation results. In the high-level analysis, the entire supply chain or multiple processes in the supply chain of FCH are considered, such as hydrogen production, transportation and storage, and utilization, using energy consumption per final product and energy efficiency obtained from the combination of multiple fundamental reactions. Literature values are often used for

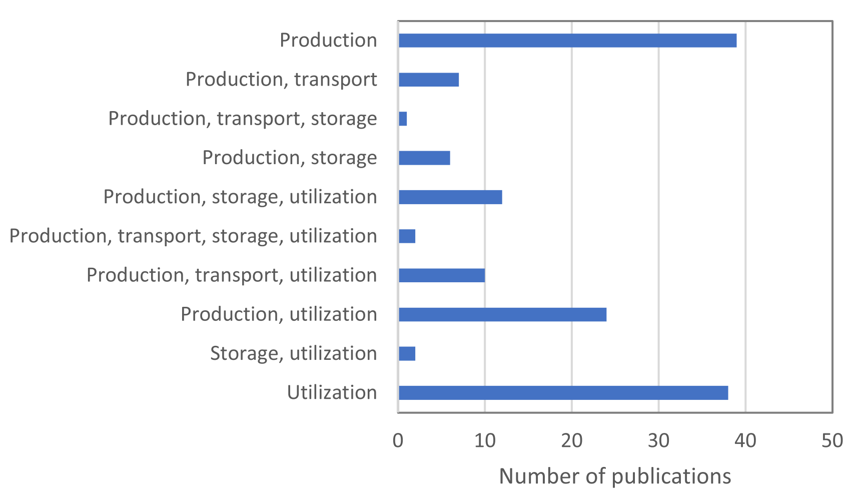

Fig. 4 – Assessed technology areas considered in the reviewed publications.

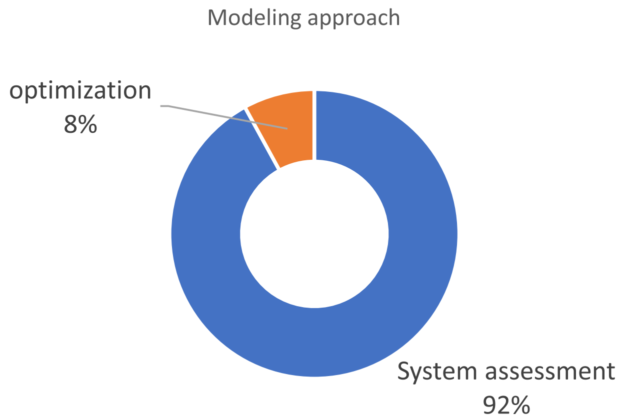

Fig. 5 – Modelling approach used in the reviewed publications.

estimating energy consumption per unit final product. It is difficult to parse and compare the granularity and fidelity of different technologies analysed in the reviewed publications. Optimisation (e.g. production, transport, distribution and storage costs) is easily distinguished as a specific methodology in Fig. 7, although also a kind of system assessment.

Besides the general type of modelling described above, the specific implementation of assessments in the reviewed publications differed clearly. Distinguishing features could be found in the technical framework conditions of the actual assessment implementation (used software and databases) and in the applied calculation methods.

Used software and databases

For practitioners, the software tools and databases can be a limiting factor in the implementation of LCC in terms of availability and accessibility. The compendium of 141 publications reviewed were screened to get an overview of potentially available tools and databases Aim of the screening was to identify the used software, tool or database and their provider in conjunction with a brief description of purpose, content or function properly contextualized. The search within the publications was realized by a document scan with the key words "software" and "database". A subsequent "reverse search" with identified specific products (software, tool or database) offered the possibility of identifying usage in publications not marked by the keywords. Due to a certain degree of commonality in tools, platforms, and databases for performing life cycle environmental (LCA) and economics (LCC), in several instances, the keyword search extended into such domains as well as S-LCA which integrates environmental, economic and social aspects. The inclusion of tools and databases for LCA or Social Life Cycle Assessment (S-LCA) is still useful, since dependencies on LCC (or vice versa) are usually given (e.g. by considered flows or system modelling). Furthermore, tools usually used for LCA (e.g. SimaPro) can contain also economic assessment or estimation tools. An overview of the identified software tools and databases with allocations to the corresponding publications can be found in SI table 1 and SI table2.

The keyword "software" resulted in 83 publications (ca. 59%), while the keyword "database" led to 57 publications (ca. 40%).

The identified publications offer extended information on applied software tools by 115 single references. In 16 reviewed publications, two different software products were given, in eight cases three different identifiable software tools were used in the study. The number of identified different software applications was 33 (see Table 2 of Supplementary material (excel file)), 22 of which were only used once. As shown in Fig. 6, the most used software tools in the identified publications were "Aspen PLUS", "SimaPro", and "MATLAB", whereby MATLAB represents a plenty of different implemented applications. The differentiation of the software according to purpose (LCC, LCA, TEC (technology simulation)) shows that

Table 4 – Overview of considered technologies within the technology areas in the reviewed publications.

Technology area (N = number of technologies)	Technologies
Production (N = 15)	SMR (Steam Methane Reforming), ATR (AutoThermal Reforming), gasification (coal, coke, oil, biomass), partial oxidation, AER (Absorption Enhanced Reforming) gasification, chemical looping gasification, supercritical water gasification, pyrolysis, water electrolysis (Alkaline, PEM (Polymer Electrolyte Membrane), SOEC (Solid Oxide Electrolyser Cell), microbial), fermentation (dark, photochemical), thermochemical cycle (Al + HCl, Cu–Cl, Al redox, S–I), chlor-alkali electrolysis, direct photobiological splitting, solar thermal dissociation, plasma methane splitting, molten metal methane splitting, FT (Fischer-Tropsch) Synthesis, ammonia synthesis, methanation, methanol synthesis
Storage (N = 7)	Pressurized tank, liquefied hydrogen, LOHC (Liquid Organic Hydrogen Carrier), metal hydride, adsorption, underground caverns
Transportation (N = 7)	Trucks, high-pressure tanks, cryogenic tanks, LOHC tanks, hydrogen refuelling stations, H_2 pipeline, H_2 injection into natural gas grid
Utilization (N = 21)	FCEV (Fuel Cell Electric Vehicle), FC (Fuel Cell) buses, FC truck, FC tram, subsonic aircraft, range extender, FC scooters, FC inner costal ferry, FC ship, H_2 turbine tanker, PEMFC, SOFC (Solid Oxide Fuel Cells), MCFC (Molten Carbonate Fuel Cells), PAFC (Phosphoric Acid Fuel Cell), microbial FC, H_2 ICEV (Internal Combustion Engine vehicle), duel fuel trucks (H_2+diesel), H_2 turbine, FC CHP (Combined Heat and Power) System, ICE CHP, APU (auxiliary power unit) for track using HTPEM (High Temperature PEM)

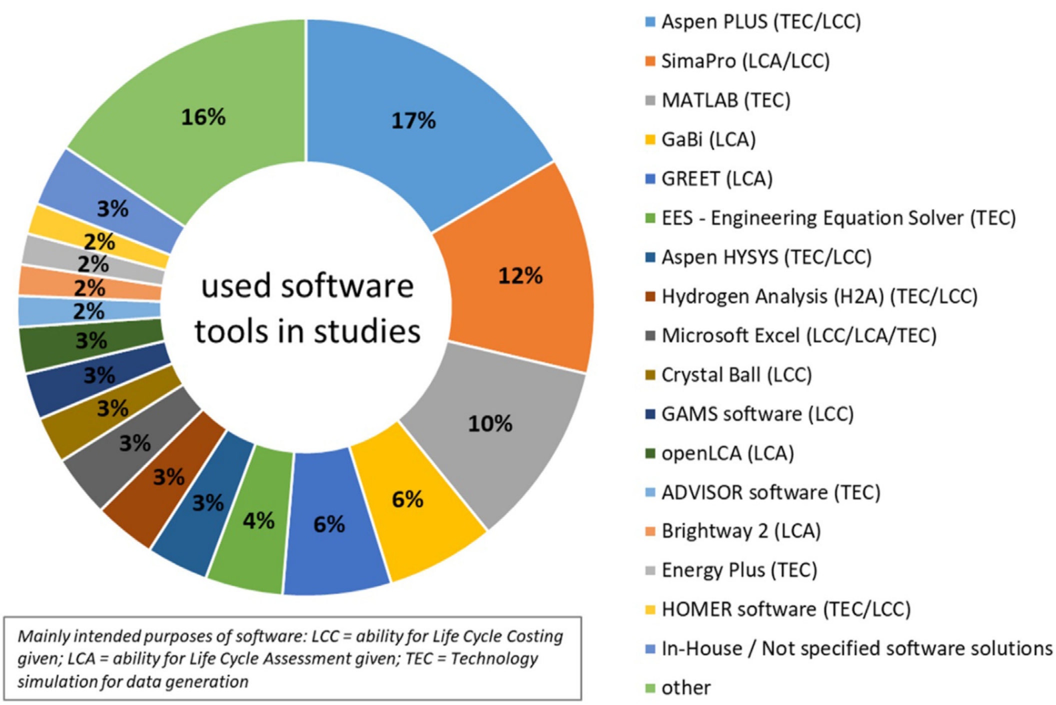

Fig. 6 – Overview of relative shares of used software tools in reviewed studies differentiated by mainly intended purpose of the software; other: tools used less than two times.

approximately 55% of the identified software uses (18 different software tools) are directly related to LCC. A mix of uses (e.g. technology simulation and LCC) was observed in most of these cases (see Table of Supplementary material (excel file)).

The number of single references on database products in the reviewed publications was 92, whereby the number of different databases was 32 (18 were used one time; see Table 1 of Supplementary material (excel file)). The most used databases were found to be "ecoinvent" [31], the "IEA databases" (International Energy Agency) [32], and the "EIA databases" (Energy Information Administration) [33] as shown in Fig. 7. The content of databases is related to economic data in approximately 27% of the identified database uses (seven different databases). There are only two cases of more or less pure economic data provision (see Table 1 of Supplementary material (excel file)). Like in the case of software tools, most databases provide a mix of different contents (e.g. environmental and economic data).

The quantitative and qualitative variety of software tools and databases (see Tables of Supplementary material (excel file)) offers plenty of thematic starting points (e.g. energy market, agriculture, automotive). The providers can be located in the private and publicly financed sector. Accessibilities and availabilities differ by free and fee-based offerings. Regarding the considered databases it has to be noted that some data contained is limited to specific regions of the world (e.g. New Zealand [34], Australia [35], Germany [36]).

After the identification of used software tools and databases and their revealed frequencies of use, the identification of general dependencies was the subject of research. Besides the previously mentioned topic-related dependencies of software or database choice (e.g. regional relations may require region specific databases), dependencies of compatibility can be found in the considered data. While individual databases can only be used in combination with specific software (e.g. PSILCA database in openLCA), most published studies reveal "voluntary dependencies", meaning that the applied software tool provides or includes a database (e.g. Aspen databases, GaBi database), but allows the use of external software-independent databases (e.g. ecoinvent).

With regard to other possible dependencies, the most commonly considered technologies (production, utilization) and study-specific tools and databases were analysed (see Supplementary Figure (excel file)). Despite the relatively small number of studies per applied software (Aspen PLUS (18 studies), SimaPro (14 studies), MATLAB (ten studies)), trends could be derived from the data. Compared to the average rate of considered technologies, specific software tools (e.g. Aspen PLUS in studies considering only production) show above or below average shares. Accordingly, Aspen PLUS for example, is used more frequently for studies that deal exclusively with production technology (61% of all studies using Aspen PLUS deal with "production only"), while MATLAB is used more often than average in studies that deal with production and further technology (90%) as well as utilization and further technology (90%). In general, utilization technology is underrepresented in studies using Aspen PLUS (6–17%), while SimaPro has never been used in studies concerning the production technology only (0%) but for studies with production or utilization and further technologies. Regarding the most used databases, the deviations from the average usage rate are not so strong. Exceptions are the non-usage of the IEA database for studies with utilization technology only (0%) and the above average use for studies dealing with production or

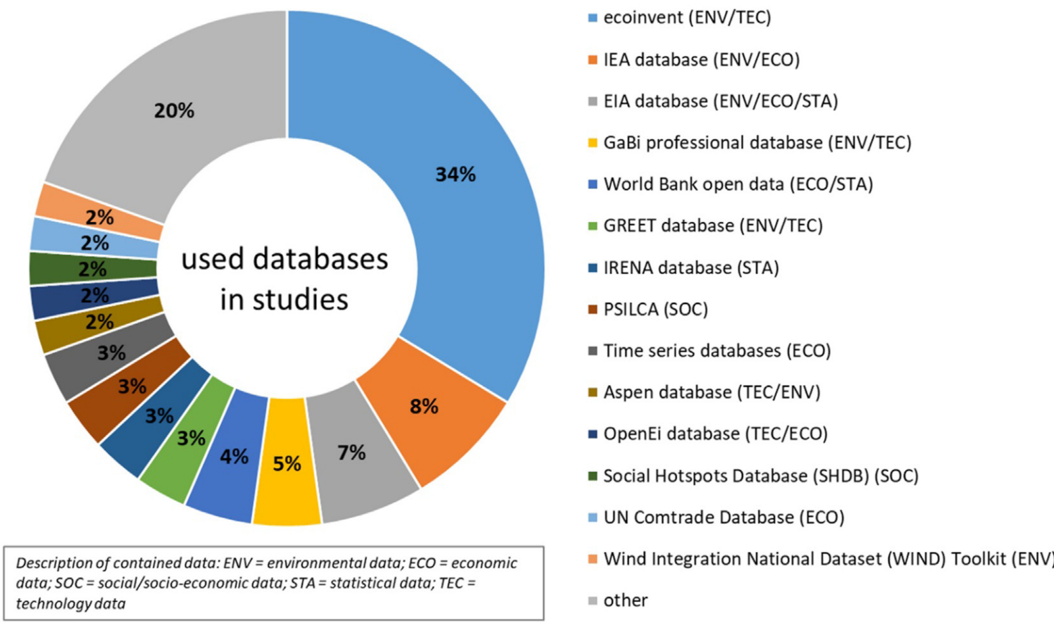

Fig. 7 – Overview of relative shares of used databases in reviewed studies differentiated by the type of contained data; other: databases used less than two times.

utilization and further technologies (86%). At the level of specific technology details (e.g. PEMEL or SMR), it is very difficult to identify dependencies from software tools or databases. Although, for example, individual technology details such as SMR or natural gas use are more often found than other software tools when Aspen PLUS is applied, this data is only of limited reliability due to the small sample size (see also Supplementary Figure (excel file)).

In summary, there no reliable, clear dependencies between the evaluated technologies and the software or databases used can be determined. Only tendencies could be identified, which can also be traced back to individual decisions by practitioners and not to availability and accessibility. Nevertheless, the extracted data overview can be used as a first reference for your own studies.

Calculation methods

Fig. 8 shows the cost calculation methods used in the reviewed publications. A specific cost calculation method and an indicator are combined closely, e.g. Levelized Cost method and Levelized Cost of Hydrogen (LCOH). The calculation method for LCOH was derived from the one for Levelized Cost of Electricity (LCOE) [37].

Although one can look at a wide variety of methods used in the reviewed publication, some of the methods are grouped into the "Discount Cash Flow method" family. Levelized Cost Method, Net Present Value (NPV), annuity cost, H2A (Hydrogen Analysis Production Models), and Discount Cash Flow method are categorized in this family. Discounting is also considered in the calculation of ownership costs.

Discounted cash flow method is to convert costs and revenues incurred in each period into present value using a discount rate in order to make different cost and revenue streams comparable. The method is common to NPV and the Levelized Cost method. The Levelized Cost method is mostly used in the reviewed publications [e.g. 38, 39]. The Levelized Cost is obtained by dividing the total costs incurred over the lifetime of the product or equipment by the total amount of the product or service as shown in Eq. (1). The total cost of service often takes into account a discount rate. This method provides the cost of a unit product or service when the total cost and revenue through the lifetime are balanced. It also defines the minimum real price of the product, necessary to ensure an acceptable return, given the chosen discount rate from a private financial perspective. Using LCOH, unit hydrogen costs can be compared regardless of the characteristics of the facility (i.e., differences in technologies such as hydrogen production, transportation, and storage and

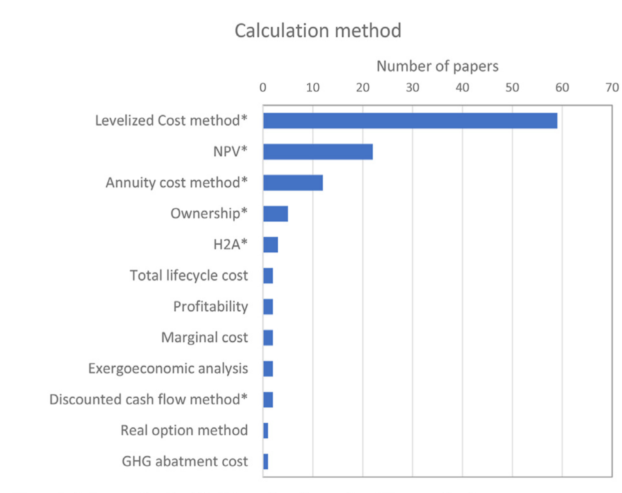

Fig. 8 – Cost calculation methods used in the reviewed publications.

their volumes). In other words, the levelized cost method has broad applicability to FCH technologies. However, this requires the user of the cost results to check if the assumptions made are relevant to their objectives. If users focus only on the cost results without considering the assumptions, the implication derived from consideration of the cost results may not be in accordance with their objectives. Although this point is not a drawback of the method itself, practitioners should be aware of this point when the method is used for cost calculation.

To see if the analysed technology area has an influence of the application of the levelized cost method, the ratio of the publications using this method to the number of publications of the same technology area in the total reviewed publications was calculated. The ratio that uses the levelized cost method of all reviewed publications is about 40%. More than 40% of publications which analyse the whole supply chain and combination of production and storage use the levelized cost method. The number of publications that analyses the whole supply chain using the levelized method is limited (only two). This could indicate the levelized cost method is used in general regardless of technology areas and its combination.

NPV is a method (and indicator) to determine the present value of a product or facility by the balance of costs and revenues over the lifetime of the whole project or facility like shown in Eq. (2). If the NPV value of the project is negative, the investment is considered to have no value (lower returns than investment). NPV is basically used to consider and compare the profitability of the projects with varying discount rates and other assumptions. However, the break-even selling price is the levelized cost of the product, which is calculated by setting the NPV of the project is equal to zero [40,41]. Annuity cost is obtained as the ratio of the annualized total costs to the annual production amount. The annual total costs consist of each annualized cost item. To annualize investment in year 0, investment in year 0 can be converted into an annual cost using a cash recovery factor. The costs that vary year to year also must be levelized as annualized costs when using this method. Annuity Cost method is considered to be a special case of the Levelized cost method.

Equations for LCOH and NPV are as follows:

$$LCOH = \frac{\sum_{t=0}^{t_e} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{t_e} \frac{P_t}{(1+r)^t}} \tag{1}$$

$$NPV = \sum_{t=0}^{t_e} \left(\frac{R_t}{(1+r)^t} - \frac{C_t}{(1+r)^t} \right) \tag{2}$$

where, C_t, P_t, R_t denote cost (C), amount of product (P; e.g. hydrogen and electricity), and revenue (R) in a period t, respectively, r denotes discounting rate and t_e denotes the last period of the project considered.

H2A, which consists of multiple spreadsheets is a hydrogen cost estimation tool developed by the US Department of Energy, which estimates the LCOH [42]. Ownership cost is also called TCO and often refers to the total cost of ownership of a car or the cost per unit (e.g. mile or km) driven. TCO often includes purchase, energy (fuel, hydrogen, or electricity), maintenance, and component replacement costs. However, mainly due to claiming technical uncertainty, the EoL cost of the vehicle is often excluded [43–45]. Profitability is a concept similar to NPV and is to estimate profit based on lifetime costs and income. As an example, profitability index for a microgrid is defined as the ratio of its NPV to the capital investment [34]. Generally, also internal rate of return and payback Time are used for comparisons. Exergo-economic analysis combines the exergy and incurred costs of the processes. The exergy cost of output flow balances the sum of the exergy cost of inflow to the

Table 5 – Considered cost items in capital costs.

Items	Representative cost items	General descriptions
Capital costs	CAPEX	Capital Expenditure includes costs for purchasing equipment, building facilities, civil work, and so on. These costs are sometimes depreciated through a part of or all project year.
	Investment	Financial resources to implement a project. Similar to CAPEX
	Replacement	The cost of replacing a major piece of equipment or a facility over a specified period of time. Consumables are excluded.
	Land	Cost to purchase or rent land for the project
	EPC	Cost for engineering, procurement and construction. Included items: Direct, Indirect, Equipment, Install, Control, Civil, Erection, Assembly, Piping, BOP (balance of plant)
	Purchasing	Cost to purchase equipment
	Depreciation	Allocated costs to a specific period of time, usually a year, over the lifetime of the technology
	Deferred asset	Expenditure that is recorded in a specific period and that effects continue over multiple periods, such as investment for R&D.
	EoL	End of life cost. The costs incurred at the end of utilizing a product, equipment, facility. Similar or included items: Salvage, Decommissioning
	Safety	The costs for equipment and facilities to ensure project implementation safe.
	Subsidy	Funding support (a negative cost) from municipality and national governments
	Interest	Cost of capital, such as stocks, loans obtained from bank etc.

process and the capital and maintenance costs of the process. The unit exergy cost of the system is obtained by calculating the exergy costs of all processes in the system, [48–51].

The real options method is used for project evaluation that applies the option pricing theory used in financial engineering [52]. GHG abatement cost method is to calculate the required cost per unit of CO_2 emission reduction by taking the difference between the cost and CO_2 emissions of the technology to be evaluated and the cost and CO_2 emissions of the reference technologies [53–55]. The cost items categorized in capital and operation and maintenance (O&M) costs are shown in Table 5 and Table 6, respectively. It should be mentioned that these cost items in each table are not necessarily mutually exclusive and collectively exhaustive as they are extracted from the reviewed publications and their scope may sometimes overlap.

The reasons for choosing the indicators are occasionally mentioned in the reviewed publications. The major reason for using the Levelized Costs (LCOH and LCOE), which are the mostly used indicators in the reviewed publications, is that it provides a metric commonly used to evaluate the economic competitiveness among technologies options [58–61] and clearly indicates the cost of production of an unit of energy [40]. Another reason is that LCOH is appropriate because it is a cost-based indicator and does not include energy market uncertainty as compared to other indicators (e.g. payback period, and internal rate of return) [38]. However, for a comprehensive investment analysis (private perspective) the revenue side needs to be taken into account, too. Revenues, NPV, and LCOH is used as standard economic indicators and allow for the comparison of each project from the perspective of a potential investor [63]. In Hoque et al. [28], interviews were conducted with experts, and indicators considered important by more than half of the experts were adopted. The savings-to-investment ratio (SIR) is utilized to calculate the profitability of the sellers of molten carbonate fuel cell systems and generators. This indicator is equivalent to ratio of discounted accumulated revenues and costs, therefore the indicator of above 1 means profitability [29,62].

Fig. 9 shows the Top 20 cost items considered. Frequently considered items are capital-related items, investment, replacement, equipment, installation, salvage, and direct costs.

Table 6 – Considered cost items in O&Mcosts.

Items	Representative cost items	Descriptions
O&M costs	OPEX	Operational expenditure that is incurred in operational activities in facilities and equipment Similar items: Operation cost
	Fuel	Fuel cost for heating, driving, etc.
	Electricity	Electricity cost for lighting, driving, etc.
	Feedstock	Cost for purchasing raw materials
	Labour	Cost for purchasing labour cost for workforce for operation
	Insurance	Insurance cost for monetary loss due to accidents
	Storage	Cost to store feedstock or products in the outside of the project
	Transport	Cost to transport feedstock or products to/from outside of the project Similar or included items: Shipping
	Administration	Cost for general administration that is allocated to the project. This includes divisions of accounting, human resources and sales in the headquarter. Some miscellaneous cost items are also included. Similar or included items: General, Overhead, Support, Working capital, Service, Exploitation
	Credit	A kind of revenue, such as tax credit or heat credit that is obtained by selling surplus heat outside of the boundary. This is interpreted as negative costs.
	Utilities	Cost for cooling water, steam, electricity used in a facility. Similar or included items: Consumables, Chemicals, Catalysts
	Externalities	External costs due to project implementation that are generally not directly borne by the project owner. Cost for Similar or included items: Carbon, Emission, Air quality, Waste treatment (externality defines these costs as not yet internalized)
	Revenues	Cash flow from outside of the project. Typical revenue is obtained by selling product and by-product Similar or included items: By-product, Savings
	Tax	Cost for having fixed assets or on profits.
	License	Costs for using licensed technologies Similar or included items: Patent
	Permits	Cost to obtain legal permission.
	Intangible	This cost is sometimes difficult to quantify. In Li et al. [56], this cost is expressed by purchase restriction (e.g. auction cost) and driving restriction cost
	Start-up	Costs for start-up a plant that includes initial loading of catalysts and other consumables
	Opportunity	Benefits that would have been obtained from other most favourable alternatives.

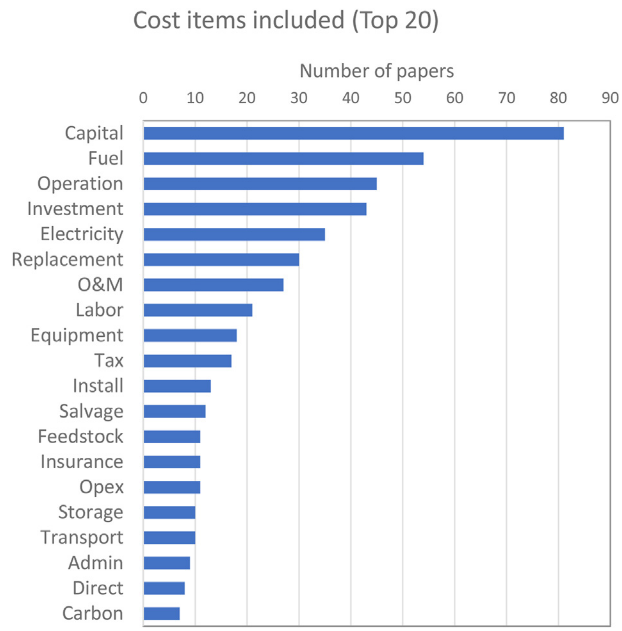

Fig. 9 – Top 20 items of cost items considered.

O&M related items considered in the reviewed publications were fuel, electricity, labour, tax, feedstock, and so on. Although it depends on the capital intensity of a technology, these seem to have major contributions to the total costs of the analysed technology. The end-of-life costs or values were rarely considered even if the words "life cycle cost" were used in the publications. External costs were rarely considered either.

Recently, the importance of technology-specific discount rates was discussed [64]. However, there is still little recognition in the LCC literature. Most frequently used nominal discount rates ranged between more than 4% up to 6% as shown in Fig. 10. Averaged value was used in the case of the publications with more than two discount rates such as for sensitivity or case analysis. Mohseni et al. [34] used the highest discount rate of 16.19%, which is based on averaged offered interest rates from different banks for business in New Zealand. Low discount rates that is less than 2% is based national government bond [39] and ones in developed countries such as Canada, France, Japan and US [65]. A few of the reviewed publications, specifically mentioned inflation rates or which kind of discount rate they used. The utilized inflation rate ranges from 1% [66] to 11.7% in India [65]. The inflation rates in many regions may have raised significantly compared with ones in last years, reflecting the changes of financial situations in those regions.

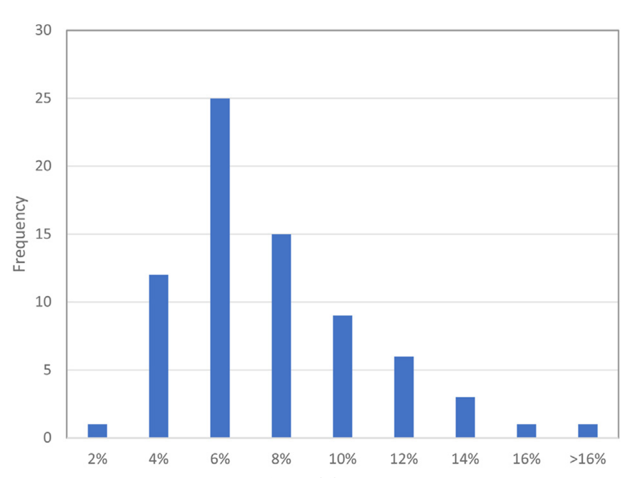

Fig. 10 – Distribution of the nominal discount rate in the reviewed publication.

Conclusion

A comprehensive literature review of LCC approaches from over the 300 publications was performed to serve as the basis for the subsequent development of LCC guidelines for FCH technologies as part of the Clean Hydrogen partnership funded SH2E project. A total of 141 publications were extracted to be reviewed in detail. The selected publications were reviewed from the following vantage points—objectives, the scope, the entity of assessment, stakeholder involvement, calculation methods, used software and databases, discounting, and whether or not EoL is included.

Almost all assessment entities in reviewed publications include authors with academic affiliations because peer-reviewed publications were targeted in this study. There are several examples of stakeholder involvement to obtain practical data or support for their analysis such as operation data and indicator screening. The analysis covered hydrogen production mostly, followed by hydrogen utilization, and combination of production and utilization studies. Since LCC analysis is often performed in conjunction with LCA in the reviewed publications, LCA-based tools and databases are often used. Most of the software used is commercial software such as ASPEN, SimaPro, MatLab, and others. The databases mostly used are ecoinvent, IEA database, and EIA database. The most common methodology used in the reviewed publications is the Levelized Cost method. The rationale for using LCOH is that it converts the cost of hydrogen over its lifetime into costs per unit volume or mass, and it can be compared regardless of the technology used or the scale of production and transportation, provided the scope and boundaries are harmonized. Though LCC is claimed in some instances, it does not necessarily provide a cradle-to-grave perspective from manufacturing, use to EoL. Many studies exclude EoL mainly due to data availability, technology and financial risks, EoL uncertainties posed by nascency of FCH technologies. On a related note, the lack of FCH-related data may result in large uncertainties as the research and development are still in progress. One would hope as more information about the EoL of FCH technologies becomes available, researchers could at least determine whether EoL effects need to be even included in the LCC of FCH technologies.

In other cases, LCC refers to the total cost during the product life cycle or the project. A variety of capital and O&M costs were accounted for in the reviewed publications. Rather than including environmental impacts as external costs, standalone LCAs were conducted. The calculation methods with discounted cash flow analysis are the most common, and the indicators used differ depending on the objective of the publication such as the profitability of the entire project or the unit cost. Discount rates are often used in the reviewed publications. Guidance on how to determine an appropriate discount rate for the FCH projects can also be useful, especially since higher capital costs have a significant impact on the total cost.

In summary, the results of the publication research show a wide variety of understandings and approaches to mapping LCC aspects. In order to generate comparable study results in the future and to be able to carry out a technology/topic-oriented evaluation for FCH technologies, it is necessary to establish a methodical procedure that is as uniform and defined as possible. The necessary guidelines for such optimized LCCs for FCH technology are developed based on the identified trends and other criteria in the SH2E project.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.04.035.

REFERENCES

[1] European commission. European hydrogen strategy. 2020. Brussels.
[2] International Energy Agency. Global hydrogen review 2021. 2021. Paris.
[3] Zhu Bei, Chu Wei. A green hydrogen era: hope or hype? Environ Sci Technol 2022;56(16):11107–10. https://doi.org/10.1021/acs.est.2c04149.
[4] World Energy Council. Hydrogen on the horizon: national hydrogen strategies. 2021. https://www.worldenergy.org/publications/entry/working-paper-hydrogen-on-the-horizon-national-hydrogen-strategies.
[5] FCHEA, Road. Map to a US hydrogen economy (ExectivRoad map to a US hydrogen economye summary). 2021. https://www.fchea.org/us-hydrogen-study.
[6] Swarr TE, Hunkeler D, Klöpffer W, Pesonen H-L, Ciroth A, Brent AC, et al. Environmental life cycle costing: a code of practice. 2011. Pensacola, Brussels: [SETAC].
[7] https://sh2e.eu/. Accessed on December 3, 2021.
[8] Visentin Caroline, da Silva Trentin Adan William, Braun Adeli Beatriz, Thome Antonio. Life cycle sustainability assessment: a systematic literature review through the application perspective, indicators, and methodologies. J Clean Prod 2020. https://doi.org/10.1016/j.jclepro.2020.122509.
[9] Wulf Christina, Werker Jasmin, Ball Christopher. Petra zapp and Wilhelm Kuckshinrichs, review of sustainability assessment approaches based on life cycles. Sustain 2019. https://doi.org/10.3390/su11205717.
[10] Grigoriev SA, Fateev VN, Bessarabov DG, Millet P. Current status, research trends, and challenges in water electrolysis science and technology. Int J Hydrogen Energy 2020;49:26036–58.
[11] Elkington John. Partnerships from cannibals with forks: the triple bottom line of 21st-century business. Environ Qual Manag 2007;8:37–51. https://doi.org/10.1002/tqem.3310080106.
[12] Scott Cato Molly, Green Economics, An Introduction to Theory, Policy and Practice, 2009. 978-1-84407-571-3.
[13] Fredershausen S, Lechte H, Willnat M, Witt T, Harnischmacher C, Lembcke T-B, et al. Towards an understanding of hydrogen supply chains: a structured literature review regarding sustainability evaluation. Sustain 2021;13:11652.
[14] Salkuyeh YK, Saville BA, MacLean HL. Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes. Int J Hydrogen Energy 2018;43(20):9514–28. https://doi.org/10.1016/j.ijhydene.2018.04.024.
[15] Wulf C, Kaltschmitt M. Hydrogen supply chains for mobility—environmental and economic assessment. Sustain 2018;10(6):1699. Retrieved from, https://www.mdpi.com/2071-1050/10/6/1699. Retrieved from.
[16] He C, Sun H, Xu Y, Lv S. Hydrogen refueling station siting of expressway based on the optimization of hydrogen life cycle cost. Int J Hydrogen Energy 2017;42(26):16313–24. https://doi.org/10.1016/j.ijhydene.2017.05.073.
[17] Sun H, He C, Yu X, Wu M, Ling Y. Optimal siting and sizing of hydrogen refueling stations considering distributed hydrogen production and cost reduction for regional consumers. Int J Energy Res 2019;43(9):4184–200. https://doi.org/10.1002/er.4544.
[18] Wulf C, Zapp P. Sustainability assessment of innovative energy technologies – hydrogen from wind power as a fuel for mobility applications. J Sustain Dev Energy Water Environ Syst 2021. https://doi.org/10.13044/j.sdewes.d8.0371.
[19] Sun H, He C, Wang H, Zhang Y, Lv S, Xu Y. Hydrogen station siting optimization based on multi-source hydrogen supply and life cycle cost. Int J Hydrogen Energy 2017;42(38):23952–65. https://doi.org/10.1016/j.ijhydene.2017.07.191.
[20] Parra David, Valverde Luis, Pino F Javier, Patel Martin K. A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. Renew Sustain Energy Rev 2019. https://doi.org/10.1016/j.rser.2018.11.010.
[21] Kannah R Yukesh, Kavitha S, Preethi, Karthikeyan O Parthiba, Kumar Gopalakrishnan, Dai-Viet N Vo, Banun J Rajesh. Techno-economic assessment of various hydrogen production methods – a review. Bioresour Technol 2021. https://doi.org/10.1016/j.biortech.2020.124175.
[22] SCOPUS, https://www.scopus.com/.
[23] Web of Science, https://www.webofscience.com/wos/woscc/basic-search.
[24] United Nations Framework convention on climate change. Paris agreement. 2015. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
[25] European Commission, A European Green deal, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en, (accessed 2023-January-17).

[26] Fuel cells and hydrogen 2 Joint undertaking, hydrogen roadmap Europe : a sustainable pathway for the European energy transition. Publications Office; 2019. https://data.europa.eu/doi/10.2843/341510.

[27] International Energy Agency. The future of hydrogen. 2019.

[28] Hoque N, Biswas W, Mazhar I, Howard I. Conceptual design of coke-oven gas assisted coal to olefins process for high energy efficiency and low CO2 emission. 2014. https://doi.org/10.3390/su12145565.

[29] Kang H, Hong J, Hong T, Han D, Chin S, Lee M. How does intensification influence the operational and environmental performance of photo-Fenton processes at acidic and circumneutral pH. 2019. https://doi.org/10.1016/j.apenergy.2018.12.070.

[30] Wu P, Bucknall R. Copper oxide coated stainless steel mesh for flexible electrodes. 2021. https://doi.org/10.1016/j.ijhydene.2019.11.152.

[31] ecoinvent Database. ecoinvent Association. Zurich (CH). https://ecoinvent.org/the-ecoinvent-database (accessed 2022-December-2).

[32] iea databases. International Energy Agency. Paris (FR). https://www.iea.org/data-and-statistics (accessed 2022-December-2).

[33] eia databases. U.S. Energy Information Administration. Washington DC (US). https://www.eia.gov/opendata (accessed 2022-December-2).

[34] Mohseni S, Brent AC. Economic viability assessment of sustainable hydrogen production, storage, and utilisation technologies integrated into on- and off-grid micro-grids: a performance comparison of different meta-heuristics. Int J Hydrogen Energy 2020;45:34412–36. https://doi.org/10.1016/j.ijhydene.2019.11.079.

[35] Hoque N, Biswas W, Mazhar I, Howard I. Life cycle sustainability assessment of alternative energy sources for the Western Australian transport sector. Sustain 2020;12:5565.

[36] Weinberg J, Kaltschmitt M. Life cycle assessment of mobility options using wood based fuels – comparison of selected environmental effects and costs. Bioresour Technol 2013;150:420–8.

[37] Internatiaonal Energy Agency. Projected costs of generating electricity. 2020. 2020.

[38] Valente A, Iribarren D, Dufour J. Comparative life cycle sustainability assessment of renewable and conventional hydrogen. Sci Total Environ 2021. https://doi.org/10.1016/j.scitotenv.2020.144132.

[39] Wulf C, Zapp P. Sustainability assessment of innovative energy technologies-hydrogen from wind power as a fuel for mobility applications. J Sustain Dev Energy Water Environ Syst 2021. https://doi.org/10.13044/j.sdewes.d8.0371.

[40] Skorek-Osikowska A, Martín-Gamboa M, Dufour J. Thermodynamic, economic and environmental assessment of renewable natural gas production systems. Energy Conv Manag X 2020. https://doi.org/10.1016/j.ecmx.2020.100046.

[41] Meunier N, Chauvy R, Mouhoubi S, Thomas D, De Weireld G. Alternative production of methanol from industrial CO2. Renew Energy 2020. https://doi.org/10.1016/j.renene.2019.07.010.

[42] H2A: hydrogen analysis production models, https://www.nrel.gov/hydrogen/h2a-production-models.html, visited on 17th October 2022.

[43] Miotti M, Hofer J, Bauer C. Integrated environmental and economic assessment of current and future fuel cell vehicles. Int J Life Cycle Assess 2017. https://doi.org/10.1007/s11367-015-0986-4.

[44] Bekel K, Pauliuk S. Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany. Int J Life Cycle Assess 2019. https://doi.org/10.1007/s11367-019-01640-8.

[45] Cox B, Bauer C, Beltran AM, van Vuuren DP, Mutel CL. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Appl Energy 2020. https://doi.org/10.1016/j.apenergy.2020.115021.

[48] Ogorure OJ, Oko COC, Diemuodeke EO, Owebor K. Energy, exergy, environmental and economic analysis of an agricultural waste-to-energy integrated multigeneration thermal power plant. Energy Conv Manag 2018. https://doi.org/10.1016/j.enconman.2018.05.093.

[49] Owebor K, Oko COC, Diemuodeke EO, Ogorure OJ. Thermo-environmental and economic analysis of an integrated municipal waste-to-energy solid oxide fuel cell, gas-, steam-, organic fluid- and absorption refrigeration cycle thermal power plants. Appl Energy 2019. https://doi.org/10.1016/j.apenergy.2019.02.032.

[50] Fiaschi D, Manfrida G, Petela K, Rossi F, Sinicropi A, Talluri L. Exergo-economic and environmental analysis of a solar integrated hermos-electric storage. Energies 2020. https://doi.org/10.3390/en13133484.

[51] Mehrpooya M, Ansarinasab H, Mousavi SA. Life cycle assessment and exergoeconomic analysis of the multi-generation system based on fuel cell for methanol, power, and heat production. Renew Energy 2021. https://doi.org/10.1016/j.renene.2021.03.111.

[52] Mckellar JM, Bergerson JA, Kettunen J, Maclean HL. Predicting project environmental performance under market uncertainties: case study of oil sands coke. Environ Sci Technol 2013. https://doi.org/10.1021/es302549d.

[53] Verma A, Olateju B, Kumar A. Greenhouse gas abatement costs of hydrogen production from underground coal gasification. Energy 2015. https://doi.org/10.1016/j.energy.2015.03.070.

[54] Timmerberg S, Kaltschmitt M, Finkbeiner M. Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas – GHG emissions and costs. Energy Conv Manag X 2020. https://doi.org/10.1016/j.ecmx.2020.100043.

[55] Watabe A, Leaver J, Shafiei E, Ishida H. Life cycle emissions assessment of transition to low-carbon vehicles in Japan: combined effects of banning fossil-fueled vehicles and enhancing green hydrogen and electricity. Clean Technol Environ Policy 2020. https://doi.org/10.1007/s10098-020-01917-9.

[56] Li, JJ; Liang, M; Cheng, WJ; Wang, SH, Life cycle cost of conventional, battery electric, and fuel cell electric vehicles considering traffic and environmental policies in China, 10.1016/j.ijhydene.2020.12.100.

[58] Mehmeti A, McPhail SJ, Ulgiati S. Life cycle inventory data and metrics for high-temperature fuel cells: a streamlined decision-support tool and case study application. Energy 2018. https://doi.org/10.1016/j.energy.2018.06.139.

[59] Li Y, Chen DW, Liu M, Wang RZ. Life cycle cost and sensitivity analysis of a hydrogen system using low-price electricity in China. Int J Hydrog Energy 2017. https://doi.org/10.1016/j.ijhydene.2016.12.149.

[60] Trendewicz AA, Braun RJ. Techno-economic analysis of solid oxide fuel cell-based combined heat and power systems for biogas utilization at wastewater treatment facilities. J Power Sources 2013. https://doi.org/10.1016/j.jpowsour.2013.01.017.

[61] Surywanshi GD, Patnaikuni VS, Vooradi R, Anne SB. 4-E and life cycle analyses of a supercritical coal direct chemical looping combustion power plant with hydrogen and power co-generation. Energy 2021. https://doi.org/10.1016/j.energy.2020.119418.

[62] Lee J-Y, Cha K-H, Lim T-W, Hur T. Eco-efficiency of H2 and fuel cell buses. Int J Hydrog Energy 2011. https://doi.org/10.1016/j.ijhydene.2010.10.074.

[63] McDonagh S, Ahmed S, Desmond C, Murphy JD. Hydrogen from offshore wind: investor perspective on the profitability of a hybrid system including for curtailment. Appl Energy 2020. https://doi.org/10.1016/j.apenergy.2020.114732.

[64] Steffen Bjarne, Waidlich Paul. Determinants of cost of capital in the electricity sector. Prog Energy 2022;4:033001. https://doi.org/10.1088/2516-1083/ac7936.

[65] Raj Arun S, Ghosh Prakash C. Standalone PV-diesel system vs. PV-H2 system: an economic analysis. Energy 2012. https://doi.org/10.1016/j.energy.2012.03.059.

[66] Arsalis, A; Alexandrou, AN; Georghiou, GE, Thermoeconomic modeling of a small-scale gas turbine-photovoltaic-electrolyzer combined-cooling-heating-and-power system for distributed energy applications, 10.1016/j.jclepro.2018.04.001.