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Integrated LCA and Eco-design Process for Hydrogen Technologies: Case Study of the Solid Oxide Electrolyser

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ABSTRACT

The Life Cycle Assessment (LCA) of a solid oxide electrolyser (SOE) has been performed using publicly available data. The system for producing 1 kg of hydrogen at 25bar and 99.9% purity is represented by a modular structure, which includes the 20-kW solid oxide stack manufacturing, balance of plant equipment, operation consumables, and end-of-life processes. A parametrized life cycle inventory modeling approach was developed. The results illustrate that SOE performs better than steam methane reforming only if supplied by electricity from renewable or nuclear sources. The operation consumables have been identified as the most contributive life stage (67%-89% of potential impacts), followed by equipment manufacturing (7%-22%) and stack manufacturing (4%-11%). Considering the predominant contribution of electricity supply in the consumables, no compromise should be made on ensuring clean electricity sourcing and on the stack energy conversion efficiency. The lifetime of the stack and the balance of plant equipment, as well as the heat mix have been identified as sensitive parameters to minimize the environmental impact of the hydrogen technology. These LCA results have been used to produce a tailored eco-design process for hydrogen projects: (i) organization of an eco-design workshop to present LCA results & environmental hotspots and related key parameters where to leverage eco-design innovations through an open discussion (brainstorm); (ii) provide an eco-design tool obtained from a simplified version of the LCA model parametrized around a limited number key life cycle inventory parameters, enabling the designers/developers to independently test the environmental performance of their innovations.

Keywords: Life Cycle Assessment, Eco-design Process, Solid Oxide Electrolyser, Parametrized Life Cycle Inventory

INTRODUCTION

Hydrogen technologies are promising solutions for ecological transition in energy and industry. Electrolysers can produce hydrogen through water electrolysis powered by renewable electricity to replace fossil-based hydrogen obtained by Steam Methane Reforming (SMR), providing industrial processes such as steel production and chemical synthesis with low-impact feedstock. Hydrogen can also serve as an energy carrier to facilitate the shift toward a renewable energy mix. Fuel Cell technologies can convert hydrogen back into electricity, so that hydrogen would provide a flexible energy storage to balance the grid [1]. As the fuel cells and electrolysers (FC&EL) are still emerging technologies, they present an opportunity to integrate effective eco-design strategies early in their conception, when the degree of freedom in design choices are higher. Eco-design refers to the objective of minimizing the potential environmental impacts of a technology while conserving its functionalities [2]. To define these eco-design strategies, assessing the potential environmental impact of the FC&EL is crucial. Life Cycle Assessment (LCA) is a methodology for evaluating the environmental impacts of a product or system throughout its entire life cycle, from raw material extraction to disposal. LCA has been widely used for eco-design [3]. It allows identifying the hotspots and key technological parameters that mostly contribute to the potential impacts along the supply chain of the product, and to anticipate unexpected burden shifting between impact categories.

The hydrogen technologies studied in this paper rely on solid oxide cells (SOCs). The particularity of this technology is the high-temperature operation (500°C-1000°C) and the possible reversibility of the cells (rSOCs) [4]. It means that the same cells can be used either for electrolyser mode (SOE) or for fuel cell mode (SOFC). Few LCA have already been developed for SOFC system [5], [6], [7], for SOE system [8], [9], [10], [11] and for reversible system [12] but they raised some methodological issues. First, the system boundaries of some studies focus solely on the production of one stack (cradle-to-gate), while others include the operation phase (cradle-to-grave) that represents the largest contributor to the overall environmental impact scores (70-100% depending on energy sourcing and technology). Second, the quality of hydrogen produced (purity, pressure) were rarely explicitly defined. Third, modeling of the balance of plant and the end-of-life of the system have been neglected by many studies. Finally, these LCA have been developed for comparative studies (with other FC&EL technologies or SMR) rather than specifically for eco-design process.

This paper aims (1) to develop a consistent LCA modular structure across all hydrogen technologies, facilitating comparability and harmonization in modeling and interpreting their environmental performances; (2) illustrate its application performing the LCA of a SOE from publicly available data; and (3) to support an eco-design process with quantified metrics from these LCA results.

METHODS

This section describes the methodology followed to compute the LCA of a solid oxide baseline, and to derive eco-design principles from these LCA results. Figure 1 gives a graphical representation of this approach. The LCA has been performed according to ISO 14040 and ISO 14044 standards [13], [14]. The following sections detail each phase of the methodology.

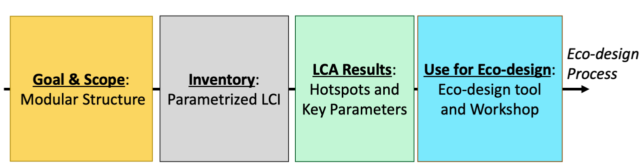

Figure 1. Graphical representation of the methodology for developing an eco-design process based on LCA.

Goal & Scope and Modular Structure

Existing guidelines for the LCA of hydrogen technologies provide valuable guidance for practitioners [2], [15], [16], [17]. However, they lack a standardized framework for defining the goal and scope of hydrogen technologies, limiting the interpretation, comparability of LCA results and hindering interoperability of datasets. This paper offers a first attempt to improve consistency and harmonization defining the LCA scope for H2 technologies: terminology and classification of key processes and their organization in hierarchical supply tiers, providing a structured approach that can be applied across all other hydrogen technologies (Figure 2). This approach requires an explicit functional unit which incorporates pressure and purity conditions, but also the stack power, to enable fair comparisons between systems. For the case study, the functional unit is defined as "producing 1 kg hydrogen @25bar and 99.9% purity, using a 20kW stack, in Europe in 2024". The process tree delivering the functional unit is organized in hierarchical supply tiers. Tier 1 encompasses the following main life cycle stages: the stack manufacturing, the balance of plant equipment, the operation consumables, and the end-of-life of the system. Each of them links to specific upstream supply processes at Tier 2. Typically, the BoP contains standard equipment, and a compressor to ensure the hydrogen is delivered at 25bars (the hydrogen reaches 99.9% at this pressure without additional equipment). Tier 3 maps suppliers of each Tier 2 process, and so on. Tier 4 represents the background system, consisting in processes for which primary data on supply material, energy, and services are not generally available and for which generic datasets are used to estimate cradle-to-gate life cycle inventories of the respective supply chains. Such generic datasets are taken from commercial life cycle inventory databases.

Parametrized Life Cycle Inventory

The LCI data collection mainly concerns the materials used, the energy consumed, and the amount and type of wastes and emissions generated by each process included in the system boundaries. To ensure reproducibility and adaptability of the study, and to facilitate the eco-design process, a parametrized life cycle inventory (p-LCI) is developed. This practice consists in structuring the inventory with raw parameters linked with explicit equations, instead of introducing computed numbers [18].

The parameters introduced in this p-LCI describe the stack geometry, the stack composition, the industrial processes involved in component production, the operational performance of the electrolyser and the energy mixes. The illustrative case study assumes a 100% renewable electricity mix supply and 65% of heat valorized from waste heat supplied by an industrial site where the SOE is operated. This waste heat is assumed impact free. The remaining 35% of heat is assumed to be provided by electric heaters. Table 1 presents the parameters for calculating Tier 1 process flows.

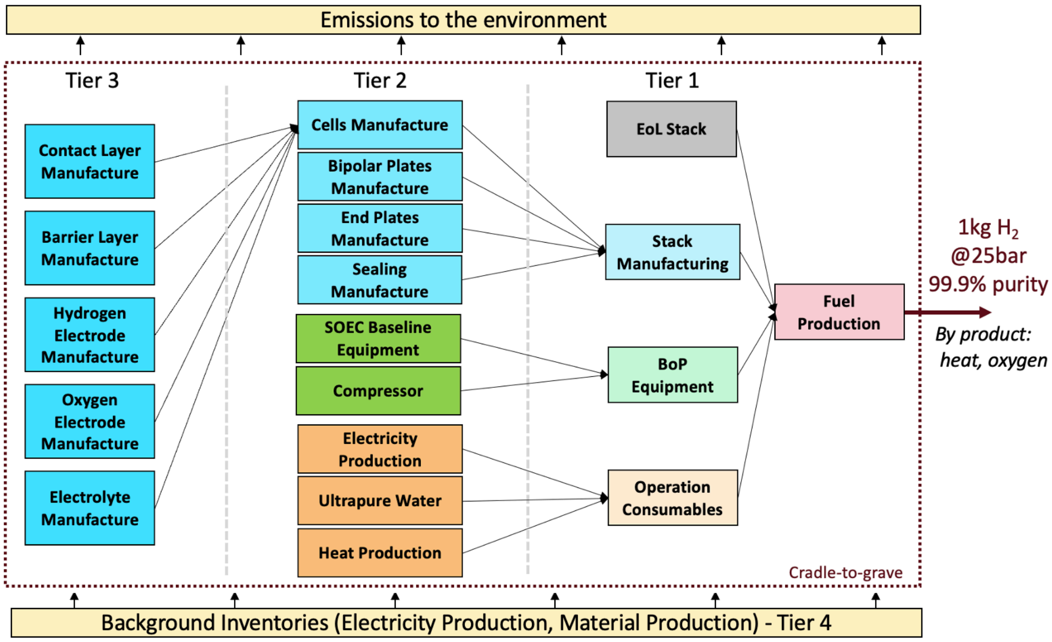

Figure 2: System boundaries of the screening LCA to deliver the functional unit, ordered by supply tier. Tier 1 encompasses the main life stages. Each element is further subdivided in common Tier 2 sub processes and so on.

Table 1: Main foreground parameters introduced in the study for SOE baseline values.

Compo-nent	Description	Baseline Value	Source
Cell	Active Surface	0.02 m^2	[7], [8]
Stack	Stack Power	20 kW	FU
Stack	Current Density	1 A/cm^2	[10]
Stack	Voltage	1.3V	[8], [11]
Stack	Degradation Rate	1%/kh	[11]
BoP	BoP lifetime	80,000h	[19]
Operation	Beginning of life LHV-based System Efficiency	85%	[9]
Operation	Water Demand	14 L/kgH_2	[20]
Operation	Heat Demand	9 kWh/kgH_2	[10]
Electricity Mix	Wind Power	75%	[21]
	PV Power	7%	
	Hydraulic Power	18%	
Heat Mix	Waste heat available	65%	[9]
	Heaters (electricity)	35%	

The complete set of parameters is available in Supplementary Information. Most of secondary data comes from the life cycle inventory (LCI) modules available in the European *Ecoinvent v3.10*
database [19].

LCA results

The impact profile has been computed using the Footprint version of the Impact World+ v2.0 method [22]. Five categories of impacts are assessed: the *Carbon footprint (CC)* in $kgCO_2eq.$, the *Water Scarcity footprint* in m^3 world-eq., the *Fossil and Nuclear Energy Use* in MJ deprived, the *Remaining Human Health (Rem. HH)* in DALY and the *Remaining Ecosystem Quality (Rem. EQ)* in $PDF.M^2.yr$. The categories *Remaining of human health* and *of ecosystem quality* exclude the contributions of *climate change* and *water availability,* avoiding double counting. The OpenLCA 2.0.3 software was used to compute the potential impacts associated with the inventoried emissions.

First, the environmental profile of the production of 1kg of H_2 (@25bar, 99.9% purity) using the 20-kW stack is performed. The efficiency of the system (78%) is determined as the average efficiency that includes a typical ohmic degradation of the stack over its useful life (based on a 10% maximum degradation) and the energy for compression. A comparison is made with hydrogen production from Steam Methane Reforming (SMR) (@25bar and 99.9% purity). The SMR process is modeled using the *Ecoinvent* database, specifically tailored to the European context. Second, a contribution analysis is performed to take a deep dive into the results. The contribution analysis is made stepwise, by progressively disaggregating the processes following the tiers of the modular structure. This work clarifies which life cycle stages, unit processes, then components mainly contribute to the overall impact scores and therefore identify the hotspots of the SOE baseline layout. Third, sensitivity analyses are

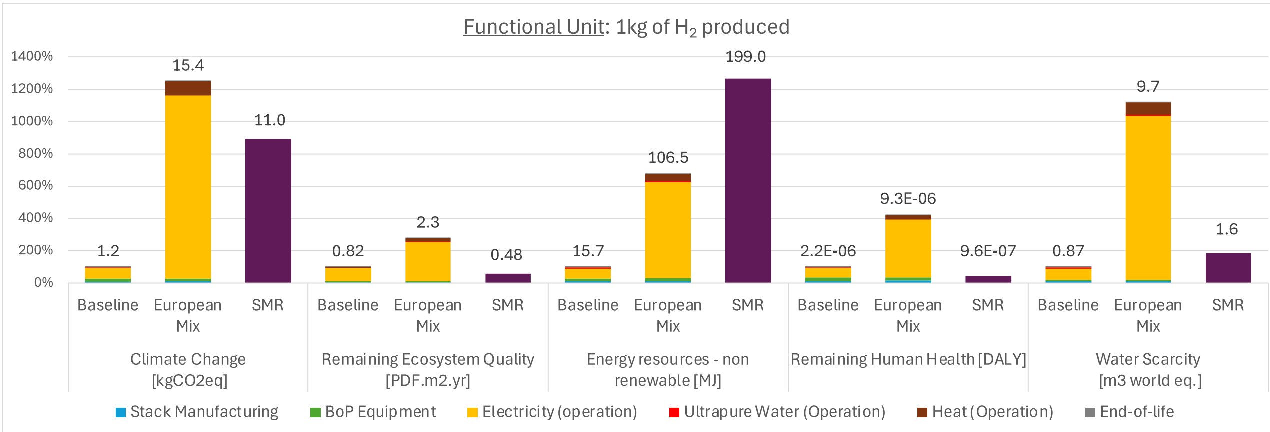

Figure 3: Comparative environmental profile of the SOE baseline scenario (Green Mix), the European Mix Scenario (sensitivity analysis) and the production of H_2 by SMR. Absolute values of the different indicators are given on the

performed to check the results robustness to the scenarios, and to provide valuable insights on the most critical processes and key parameters for reducing the environmental impacts. The sensitivity to energy mixes, to the purity requirement and to the system size are performed. A systemic sensitivity analysis of the foreground parameters introduced in the p-LCI is also performed.

Deriving an eco-design process from LCA results

The interpretation of the LCA results provides the foundation for defining the key eco-design messages. The eco-design process relies on two complementary elements. First, an eco-design workshop is organized to translate the LCA findings into actionable design innovations. The workshop initiates with a knowledge-sharing presentation. The principles of life cycle thinking, and the risks of burden shifting are introduced to the project partners. The LCA results are communicated to the participants, emphasizing the most contributive processes, components, and the most sensitive parameters, fostering a collective understanding of the key priorities and key leverages for reducing the environmental impacts. The second part of the workshop aims at stimulating the creativity of the engineers/designers around the innovations aimed to improve the environmental performance of the baseline technology. The eco-design wheel developed by the HEU eGhost, which outlines eight core eco-design principles [2], was used as a step-by-step framework for guiding partners discussions. The second element consists in providing an eco-design tool obtained from a simplified version of the LCA model parametrized around a limited number of key LCI parameters. This tool enables designers to independently test the environmental performance of their innovations, providing immediate feedback on the environmental performance of their ideas and fostering an iterative improvement process.

RESULTS

The LCA of the SOE baseline has been performed to evaluate the impact scores across the five different categories to produce 1 kg of hydrogen. The 'Baseline' bars in the figure 3 illustrate this environmental profile compared with the SMR impact scores (in purple). The baseline performs better than SMR for *Climate Change* (factor 9), *Energy Resource* (factor 12.5) and *Water Scarcity* (factor 2), while the results are reversed for *Remaining Ecosystem Quality* (factor 2) and *Remaining Human Health* (factor 2) impact scores. An additional comparison using the IW+ expert version, which aggregates the five categories of the footprint version into two damage indicators (*Human Health* and *Ecosystem Quality*), has been performed to clarify the trade-offs illustrated by the footprint version. This work reveals that the SOE baseline outperforms SMR for both indicators (see Supplementary Information).

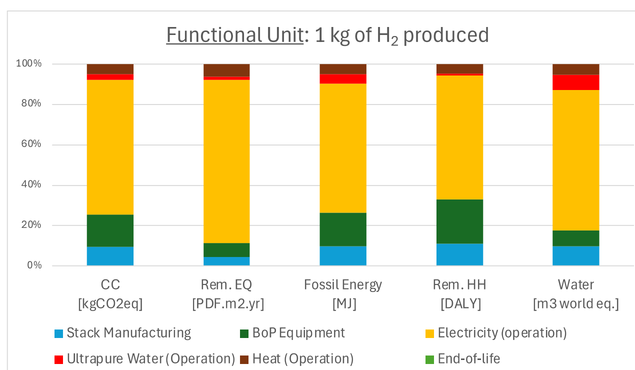

Figure 4. Contribution Analysis of the main life stages of the baseline SOE supplied with a 100%-renewable electricity mix. Operation phase is detailed at Tier 2 level.

Contribution analyses

The contribution analysis shows that the operation phase dominates all impact categories by contributing 67%-89%, followed by the Balance of Plant (7%-22%), while stack manufacturing remains low at 4%-11%, and End-of-Life is negligible (Figure 4).

The Tier 2 analysis of the operation life stage highlights that electricity consumption drives the consumables impact scores (61%-81%), while heat consumption (5-6%) and ultrapure water consumption (1%-7%) are less contributive.

Figure 5 shows the contribution analysis of the stack manufacturing according to two different groupings of processes, with results normalized to the impacts of the production of 1 unit of stack of 20kW (cradle-to-gate).

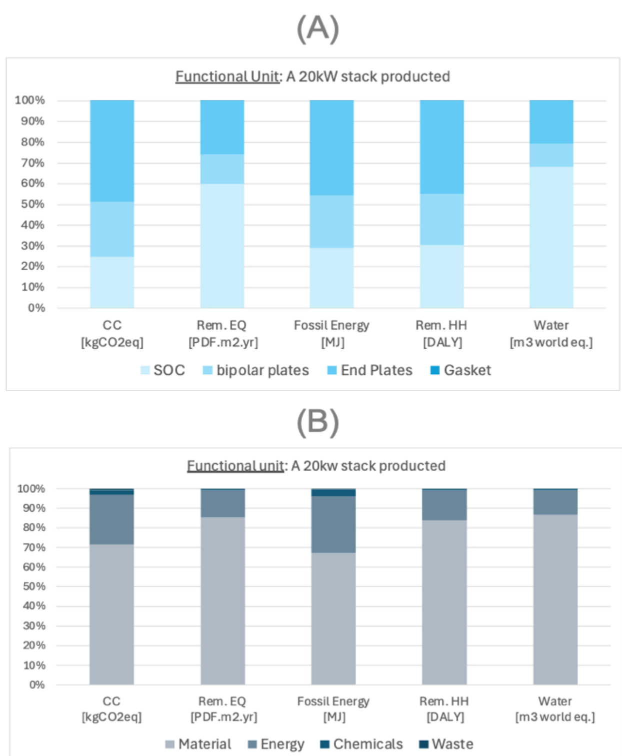

Figure 5. Contribution Analysis of the solid oxide stack manufacturing. The processes are decomposed following (A) the tier 2 of the stack manufacturing and (B) the tier 4 of the stack manufacturing.

The first group (A) corresponds to the Tier 2 elements of the stack as presented in the Figure 2 (SOC, Bipolar Plates, Gasket and End Plates). The second group (B) aggregates the impact scores of the Tier 4 processes (Energy, Material, Chemical and Waste). Figure 5A illustrates that the stack manufacturing impacts are driven by the cells, the bipolar plates, and the end plates productions. The cells manufacturing dominates the *Remaining Ecosystem Quality* and the *Water Scarcity* with respectively 61% and 66% of the impacts of the stack production. The end plates are the largest contributor to *Climate Change* (39%) and *Energy Use* (36%). The bipolar plates dominate the *Remaining Human Health* (36%) category. Moreover, the Figure 5B highlights that the materials used to produce the stack components are the main source of impacts for all categories with a relative contribution of 70-86% of the impact scores. The impact contribution of waste treatments generated during manufacturing are negligible. Energy required for manufacturing is the second highest contributor (15-25%), followed by the chemicals production used as solvent during the manufacturing (2%).

Sensitivity Analyses Results

The sensitivity analysis on the electricity mix supply illustrates that low-carbon electricity from renewable or nuclear sources is essential for the SOE to outperform the environmental performance of hydrogen production by SMR (Figure 3). Supplying the SOE with the 2024 European electricity grid instead of the 100% renewable mix of the baseline would considerably increase the impacts of hydrogen production, for all impact categories between a factor of 6.5 and 12. Hydrogen produced by the SOE baseline supplied with this 2024 European electricity mix would lead to higher impacts than SMR for all categories except the Energy Resources indicator.

Other sensitivity analyses on heat supply, scalability of the SOE at market scale, hydrogen purity and other key technical parameters are provided in Supplementary information with numerical and graphical results. The use of natural gas to supply heat should be avoided as it increases *Climate Change* and *Energy Resources* scores (factor 2.5-3). As the scalability of SOE is more sensitive to the system size than the stack itself [23], we modeled a scenario scaling the BoP equipment to the power of the system by applying the method developed by Zhang et al. [24]. Scaling up the BoP from 20kW to 20MW may reduce the system's potential impacts by 7-19%. Moving from 99.9% to 99.999% hydrogen purity using a Pressure Swing Adsorption process increases the potential impacts by 9-11%. A systematic sensitivity analysis of key parameters was performed on the *Climate Change* indicator by independently varying each foreground parameter by 10% and calculating the corresponding relative change in impact scores. This analysis highlights stack efficiency being the most critical parameter causing an 8.4% change in impact score, followed by BoP equipment lifetime (1.5%) and stack degradation rate (0.9%). Parameters influencing stack manufacturing are less sensitive: end plates, bipolar plates, and hydrogen electrode thicknesses (around 0.2%).

Interpretation for eco-design

The results emphasize that no compromises should be made regarding stack efficiency. Achieving a high energy conversion efficiency is the most critical objective to minimize environmental burdens of hydrogen production. Any innovation that would affect energy efficiency of the stack has a high risk to decrease the environmental performance of the SOE technology. While the stack and the equipment processes are less impactful than the operational phase, their design plays a role in reducing the project's overall impact. Extending the lifespan of equipment and components has also been identified as sensitive eco-design strategies. The materials used, particularly for the cell elements, bipolar plates, end plates, but also for the BoP, are the most contributive processes of the manufacturing of the stack components. Potential solutions include minimizing material use through redesign and exploring alternative low emission materials, if these solutions do not affect system efficiency.

DISCUSSION

The limitations of both the LCA model and the eco-design process are discussed here. Regarding LCA limitations, as few datasets of the Balance of Plant equipment have been found in the literature, the representativeness of the equipment potential impacts is low, while being quite contributive. Some life stages, such as the maintenance phase, have not been modeled due to lack of accurate datasets in the literature. Future efforts should focus on these processes to improve the completeness of the inventory. Moreover, solid oxide electrolysers are still an emerging technology, and it induces at least three limitations. (a) The background inventories may contain data gaps and uncertainties for the modeling of specific processes, like specific materials production (e.g. Yttrium, Zirconium); (b) A prospective electricity mix needs to be selected to anticipate the grid conditions in which the technology will be used, but this prospective approach is intrinsically associated with uncertainties; (c) As the hydrogen industry is in rapid evolution, the presented inventories may not be representative of state-of-the-art technologies. Finally, the electrolysers are known to consume critical raw material [2], [17]. Yet, the impact assessment methods selected do not offer indicator to assess this environmental issue which is still poorly addressed in LCA [25].

Regarding the eco-design process, three main limitations have been identified. First, economic viability of the innovations was not assessed. Future works should focus on developing a common structure to couple LCA model with economic approaches such as Techno-Economic Assessment (TEA) or Life Cycle Costing (LCC) to identify correlations and trade-offs between environmental and cost dimensions of design choices such as increasing efficiency, reducing the thickness of materials, etc. Second, the influence of the operation context (load range, flexible operation) on the use phase parameters (lifetime, efficiency) are still missing and should be modeled. And third, as a 20kW-stack is not representative of the potential scaled-up technology that would penetrate the market, the model of SOE should be improved by incorporating prospective life cycle inventories, and by considering potential improvements in materials and in manufacturing processes associated with large-scale development.

DIGITAL SUPPLEMENTARY MATERIAL

Data sheets presenting the LCA model, including the p-LCI, unit processes, and results, are available at LAPSE:2025.0030.

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REFERENCES

1. Fuel Cells and Hydrogen 2 Joint Undertaking. Hydrogen roadmap Europe – A sustainable pathway for the European energy transition. Publications Office; 2016.
2. Gramc J, Stropnik R, Hojkar D, Sekavcnik M, Iribarren D, Dufour J, et al. Ecodesign as a key concept for improving the life cycle environmental performance of proton-exchange membrane fuel cells. Int J Hydrogen Energy. 2024 Aug;
3. Bovea MD, Pérez-Belis V. A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. J Clean Prod. 2012 Jan;20(1):61–71.
4. Brisse A, Schefold J, Zahid M. High temperature water electrolysis in solid oxide cells. Int J Hydrogen Energy. 2008 Oct;33(20):5375–82.
5. Mehmeti A, McPhail SJ, Pumiglia D, Carlini M. Life cycle sustainability of solid oxide fuel cells: From methodological aspects to system implications. J Power Sources. 2016 Sep;325:772–85.
6. Bicer Y, Khalid F. Life cycle environmental impact comparison of solid oxide fuel cells fueled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation. Int J Hydrogen Energy. 2020 Jan;45(5):3670–85.
7. Lee YD, Ahn KY, Morosuk T, Tsatsaronis G. Environmental impact assessment of a solid-oxide fuel-cell-based combined-heat-and-power-

generation system. Energy. 2015;79(C):455–66.
8. Häfele S, Hauck M, Dailly J. Life cycle assessment of the manufacture and operation of solid oxide electrolyser components and stacks. Int J Hydrogen Energy. 2016 Aug;41(31):13786–96.
9. Zhao G, Kraglund MR, Frandsen HL, Wulff AC, Jensen SH, Chen M, et al. Life cycle assessment of H2O electrolysis technologies. Int J Hydrogen Energy. 2020 Sep 3;45(43):23765–81.
10. Gerloff N. Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. J Energy Storage. 2021 Nov 1;43.
11. Wei X, Sharma S, Waeber A, Wen D, Sampathkumar SN, Margni M, et al. Comparative life cycle analysis of electrolyzer technologies for hydrogen production: Manufacturing and operations. Joule. 2024 Dec;8(12):3347–72.
12. Di Florio G, Macchi EG, Mongibello L, Baratto MC, Basosi R, Busi E, et al. Comparative life cycle assessment of two different SOFC-based cogeneration systems with thermal energy storage integrated into a single-family house nanogrid. Appl Energy. 2021 Mar 1;285.
13. ISO. ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework. 2006.
14. ISO. ISO 14044:2006 - Environmental management - Life cycle assessment - Requirements and guidelines. 2006.
15. Melideo D, Ortiz Cebolla R, Weidner Ronnefeld E. Life cycle assessment of Hydrogen and Fuel Cell Technologies. Luxembourg; 2020.
16. Lozanovski A, Schuller O, Faltenbacher M. Guidance Document for performing LCAs on Fuel Cells and H2 Technologies . 2011.
17. Bargiacchi E, Puig-Samper G, Iribarren D, Dufour J. D2.2 Definition of FCH-LCA Guidelines. 2022.
18. Cooper JS, Noon M, Kahn E. Parameterization in Life Cycle Assessment inventory data: review of current use and the representation of uncertainty. Int J Life Cycle Assess. 2012 Jul 3;17(6):689–95.
19. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. International Journal of Life Cycle Assessment. 2016 Sep 1;21(9):1218–30.
20. Simoes SG, Catarino J, Picado A, Lopes TF, di Berardino S, Amorim F, et al. Water availability and water usage solutions for electrolysis in hydrogen production. J Clean Prod. 2021 Sep;315:128124.
21. Santecchia A, Castro-Amoedo R, Nguyen TV, Kantor I, Stadler P, Maréchal F. The critical role of electricity storage for a clean and renewable European economy. Energy Environ Sci. 2023;16(11):5350–70.
22. Bulle C, Margni M, Patouillard L, Boulay AM, Bourgault G, De Bruille V, et al. IMPACT World+: a globally regionalized life cycle impact assessment method. International Journal of Life Cycle Assessment. 2019 Sep 1;24(9):1653–74.
23. Memorial Institute, Fuel Cell Systems for Primary Power and Combined Heat and Power Applications. 2017. Accessed: Mar. 05, 2025. Available:https://www.energy.gov/sites/prod/files/2018/02/f49/fcto_battelle_mfg_cost_analysis_1%20_to_25kw_pp_chp_fc_systems_jan2017_0.pdf
24. X. Zhang, C. Bauer, C. L. Mutel, and K. Volkart, "Life Cycle Assessment of Power-to-Gas: Approaches, system variations and their environmental implications," Appl Energy, vol. 190, pp. 326–338, Mar. 2017, doi: 10.1016/j.apenergy.2016.12.098.
25. Greffe T, Margni M, Bulle C. An instrumental value-based framework for assessing the damages of abiotic resources use in life cycle assessment. Int J Life Cycle Assess. 2023 Jan 16;28(1):53–69.