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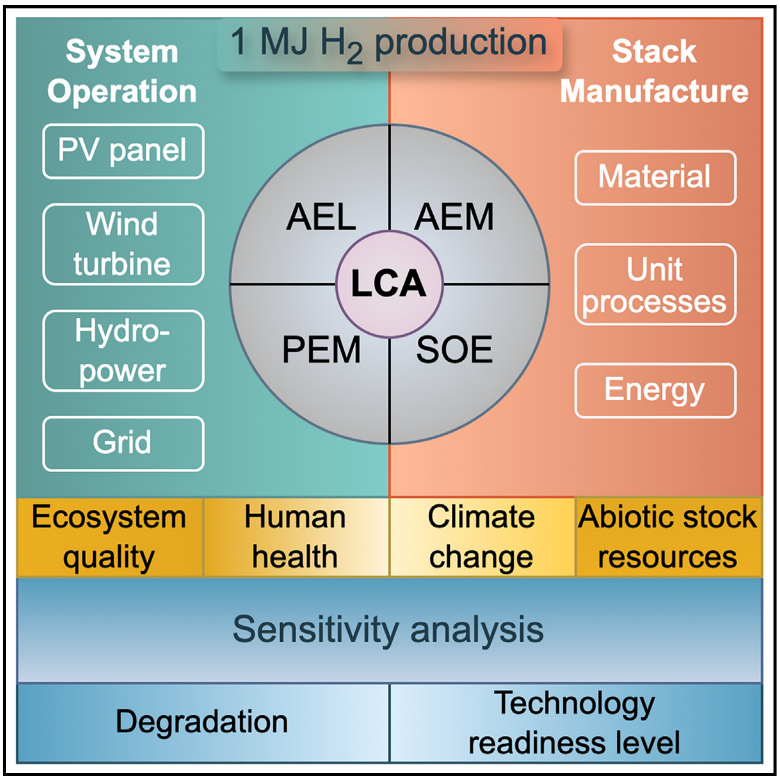
Comparative life cycle analysis of electrolyzer technologies for hydrogen production: Manufacturing and operations

Graphical abstract



Highlights

- A comprehensive LCA study on PEM, AEM, AEL, and SOE electrolyzers
- A detailed analysis of electrolyzer manufacturing and system operation
- A detailed life cycle inventory is provided to support hydrogen sustainability
- The study integrates degradation, efficiency, and lifespan for future energy systems

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In brief

This comprehensive study conducts a detailed life cycle assessment (LCA) of four major electrolyzer technologies, AEL, PEM, AEM, and SOE, highlighting their environmental impacts from manufacturing to operation. It focuses on material usage and system performance across various scenarios. The findings provide comparative insights into the environmental footprints of each technology and identify strategies for enhancing the sustainability of hydrogen production. This work informs strategic decision-making for advancing a sustainable hydrogen economy.

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Article

Comparative life cycle analysis of electrolyzer technologies for hydrogen production: Manufacturing and operations

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CONTEXT & SCALE In the evolving landscape of sustainable energy solutions, hydrogen is recognized as a vital energy carrier, especially for storing renewable energy. Our study performs a comprehensive life cycle assessment (LCA) of four major electrolyzer types, highlighting their role in advancing green hydrogen production. By evaluating the environmental impacts of various electricity sources and manufacturing materials, our research contributes significantly to the field. The findings reveal the potential of electrolyzers in energy systems and identify opportunities to enhance their sustainability. Additionally, the research provides a detailed life cycle inventory (LCI) database, enriching resources available to the hydrogen production community. This study underscores the need for comprehensive decision-making frameworks that integrate technical, environmental, and material factors to boost the adoption and optimization of electrolyzer technologies globally.

SUMMARY

This study conducts a comprehensive life cycle assessment (LCA) of four electrolyzer technologies: alkaline electrolyzer (AEL), proton-exchange membrane (PEM), anion-exchange membrane (AEM), and solid oxide electrolyzer (SOE). It evaluates their environmental impacts across four main categories: climate change (CC), human health (HH), ecosystem quality (EQ), and abiotic stock resources (ASRs). In order to highlight the critical raw materials (CRMs) used in their manufacturing processes, the research identifies potential material replacements and reveals distinct environmental impacts associated with material choices, such as steel in AEL and AEM, platinum in PEM, and nickel in both SOE and AEL. Additionally, we examine the integration of diverse electrolyzer technologies under various scenarios of renewable electricity sources. Together with a sensitivity analysis of regional electricity mixes and the degradation of stacks across different years, the study provides insights into significant opportunities for performance enhancements in emerging electrolyzer technologies.

INTRODUCTION

Europe imports a significant amount of natural gas and oil from the Middle East and Russia.[1,2] Apprehensions regarding the reliability and security of energy supplies have spurred European nations to reassess their energy strategies in light of geopolitical events. Recently, Europe has focused on diversification of natural gas supply to fulfill the immediate energy demands.[3,4] Further, the process of extracting and transporting natural gas leads to the potential leakage of methane, a strong greenhouse gas with substantial global warming potential (GWP). The outlined circumstances underscore substantial environmental challenges and potential risks, emphasizing the critical need to transition from fossil methane to alternative sources such as biomethane, bioethanol, and bio-methanol. These renewable fuels are deemed carbon-neutral or even carbon-negative by utilizing green hydrogen and captured CO_2 for fuel synthesis. Such sustainable energy sources offer significant advantages in achieving a state of net-zero emissions by the year 2050.[5,6]

To achieve long-term energy security and emission targets,[7] Europe is shifting toward cleaner and renewable energy sources.[8–10] In recent times, great efforts have been made to improve energy resilience through the expansion of renewable energy sources, enhancement of energy efficiency, and investment in energy storage and transport infrastructures.[11] Hydrogen has a pivotal role in various industries, functioning as an energy carrier and as a fundamental molecule in diverse industrial processes.[12] Hydrogen is used as a feedstock in ammonia synthesis for fertilizer production,[13,14] crude oil processing[15,16] and also metallurgical reduction in steel refinement[17] as a prospective field with field trials and pilot plants being built. Traditionally, the Haber-Bosch process has been a significant consumer of hydrogen, constituting approximately 25% of total hydrogen consumption. Additionally, hydrogen is required in petroleum refining for desulfurization and methanol synthesis (33% and 10% of total hydrogen consumption, respectively).[18] Further, hydrogen finds applications in the residential, industrial, and transportation sectors, contributing to power and heat generation. Beyond its current applications, hydrogen has the potential to contribute to the energy transition and mitigate climate change (CC) significantly if it can be derived from low-carbon energy sources. Its versatility as an energy vector, with storage in compressed, liquid, or transformed forms such as methane, positions it as a valuable product.[19,20] Hydrogen facilitates energy storage from intermittent renewable sources, eliminating the necessity for oversized power production installations and reducing reliance on fossil fuel-based power sources. Moreover, hydrogen can also serve as a fuel in vehicles, residential areas, and remote locations.[21] Notably, hydrogen presents several advantages over conventional fossil fuels, particularly regarding clean combustion. This allows the transfer of pollution and environmental impacts from the point of use (e.g., urban center) to the point of production, where comprehensive control over emissions is feasible.[22,23]

The large-scale production of hydrogen requires synthetic production processes. In 2019, the projected total hydrogen production reached 90 to 95 million metric tons, with around two-thirds being purified hydrogen.[24] The primary sources of hydrogen production are natural gas (48%), oil (30%), and coal (18%).[25,26] Steam methane reforming, presently the predominant method for hydrogen production, accounts for 7% of emissions from industrial sectors, approximately totaling 630 million metric tons of direct CO_2 emissions.[27,28] The residual hydrogen is generated through alternative methods such as coal gasification and petrol oxidation. In these processes, hydrocarbons undergo oxidation with water and oxygen. The remaining 4% of hydrogen is generated through renewable sources like biomass gasification, water electrolysis (utilizing wind, solar, or hydropower), and fermentation.[29] One of the sustainable hydrogen production methods is using electrolysis (EL) technology with renewable energy. There are various types of electrolyzers, namely alkaline electrolyzer (AEL), anion-exchange membrane (AEM) electrolyzer, proton-exchange membrane (PEM) electrolyzer, and solid oxide electrolyzer (SOE). PEM, AEL, and AEM are normally categorized as low-temperature EL technologies,[30] and SOE is a high-temperature EL technology. The efficiencies of AEL, AEM, PEM, and SOE are recorded at around 60%, 70%, 73%, and 90%, respectively.[31–33]

Despite the European electrolyzer industry having achieved considerable commercial maturity with certain technologies available at several megawatt scales, it confronts significant economic challenges posed by competing technologies. Further, some types of electrolyzers have a fragmented material supply chain heavily dependent on critical raw materials (CRMs). As an illustration, Europe heavily relies on specific countries as the suppliers of crucial materials like platinum group metals and rare earth elements (REEs), as described in the European Commission report. South Africa is a major supplier, supplying 71% of platinum (Pt) and 92% of iridium (Ir), while the Democratic Republic of Congo supplies 68% of cobalt (Co). Further, Russia plays a significant role in the supply chain, providing 40% of palladium (Pd), and China is a dominant source (98%) of REEs. The origin of these materials poses a potential vulnerability to the European electrolyzer market.[34]

The study is motivated by the need to comprehensively evaluate the environmental impacts of four distinct electrolyzer technologies through life cycle assessment (LCA). It initially concentrates on analyzing the contributions of materials used in the manufacturing processes of these electrolyzers. This detailed analysis aims to elucidate the specific environmental footprints associated with the material usage in the manufacturing process of each type of electrolyzer. The objective of this effort is to identify potential opportunities for material substitution that could reduce environmental impacts and enhance the sustainability of the electrolyzer technologies.

Additionally, the study seeks to compare the LCA performance of operating these four electrolyzer systems under a consistent baseline. This comparison focuses on elucidating key factors such as operational efficiency, the choice of electricity sources, stack improvements over different years, and their integration into energy systems across various regions and timelines. By synthesizing environmental impact assessments, material criticality analyses, and technological advancements, the research endeavors to construct a comprehensive framework that aids in informed decision-making within the hydrogen production industry. This framework facilitates the transition toward a sustainable hydrogen economy, supporting long-term environmental and economic sustainability.

State of the art

AEL

The AEL electrolyzer has low manufacturing costs, facilitated by affordable catalysts like nickel and stainless steel, coupled with a prolonged lifespan.[35] Despite these advantages, challenges such as larger size compared with PEM electrolyzer, operational difficulties under pressure, slow startup, and extended emergency response time persist, necessitating the attention of engineers and researchers. Nevertheless, the AEL stands out as the most mature EL technology, boasting the lengthiest history in the field.[36] Consequently, extensive LCA studies have been undertaken to comprehend the environmental impact of hydrogen production using an AEL.

Cetinkaya et al.[37] conducted a comprehensive assessment of integrating wind or solar power with advanced energy storage systems, including the Cu–Cl cycle. The results show that the greenhouse gas emissions for wind power are 0.97 kg CO_2-equiv/kg H_2, whereas the use of photovoltaic (PV) panels yields a greenhouse gas emission of 2.4 kg CO_2-equiv/kg H_2. Lubecki et al.[38] investigated hydrogen refueling and an on-site AEL-based hydrogen production station, revealing a hierarchy of environmental impact for most minor to most damaging energy sources: renewable energy (such as wind and solar) and grid electricity. The study suggests that transitioning from diesel to hydrogen fuel is sustainable in reducing GWP. However, caution is advised due to the potential environmental impact associated with additional equipment installation, which may affect other categories of environmental impact.

Aydin and Dincer[39] examined a pilot hydrogen production facility (200 kg/day) powered by a combination of nuclear and renewable energy sources. They evaluated three hydrogen production technologies: PEM, AEL, and Cu–Cl cycle. The primary environmental impact of hydrogen production was attributed to energy requirements. The construction materials, such as platinum, copper, and steel, particularly in wind turbines, contributed significantly to the overall environmental impact. Notably, nuclear power-based EL exhibited the highest environmental impact among the assessed hydrogen production methods. Ghandehariun et al.[40] focused on the environmental impacts of hydrogen production using AEL electrolysis, which operates on wind power. The findings reveal that the plant has greenhouse gas emissions of about 0.75 kg CO_2-equiv/kg H_2. About 65% of the total emissions from the integrated facility can be traced back to the wind power plant, primarily due to the use of steel and iron in its manufacturing. The rest of greenhouse gas emissions are delineated by three main factors: 22% from hydrogen compression and strict storage conditions of H_2, 7% from the operation of the water EL process, and 6% from hydrogen transportation.

Many researchers have extensively investigated various energy carriers. Federici et al.[41] conducted a comprehensive study on the life cycle environmental impact of methane production, employing an AEL and methanation process. The CC impact varies between 0.034 and 0.8 kg CO_2 per mole of methane, depending on the electricity source (PV or grid) and the origin of CO_2. Lin et al.[42] examined the methanol synthesis process involving CO_2 capture from flue gas, AEL for water EL, methanol synthesis, separation, and purification. They also compared thermo-chemical and electrochemical pathways for hydrogen production. With market-based electricity, energy input contributed significantly, ranging from 50% to 88%, in impact categories such as global warming, terrestrial ecotoxicity, and fossil resource scarcity. Ammonia is recognized as a potential energy carrier, with more than 90% of its hydrogen production stemming from conventional methods such as steam methane reforming or coal gasification. The ammonia production has emissions between 2.6 and 5.2 kg CO_2-equiv/kg NH_3.[43] Kim et al.[35] conducted an LCA on renewable urea production using an AEL. The GWP was about 0.498 kg CO_2-equiv/kg NH_3. Notably, constructing the cell/stack and electricity emerged as dominant factors in several impact categories, including global warming, freshwater eutrophication, and fossil resource scarcity.

AEM electrolyzer

The AEM electrolyzer is an emerging technology currently undergoing active research and development. AEM functions in a slightly alkaline environment. One notable advantage of AEM is its potential to utilize non-precious metal catalysts, a feature that holds promise for reducing costs.[44,45] This attribute has attracted significant interest from the hydrogen production industry, positioning AEM as a technology with the potential for cost-effective and sustainable hydrogen production compared with conventional methods. Pawłowski et al.[46] conducted an LCA study on a green hydrogen plant in Poland employing an AEM electrolyzer. The CO_2 emissions for hydrogen production ranged from 2.73 to 3.85 kg CO_2-equiv/kg H_2. The study underscores the efficacy of the wind-to-hydrogen pathway in minimizing carbon footprint, surpassing the effectiveness of solar-to-hydrogen technology.

While AEM technology is currently in the developmental stage with predominantly lab-scale data available, its potential is increasingly recognized in the scientific community. AEM technology exhibits promising capabilities, substantiated by numerous research findings. Du et al. provided a comprehensive review of AEM electrolyzers' current state and ongoing advancements, highlighting the significant progress made thus far.[47] Complementing this, Kim et al. conducted a techno-economic analysis of AEM water EL, directly comparing it with PEM water EL.[48] This study underscores the economic benefits of AEM systems, notably in terms of lower catalyst and stack component costs. It also projects future cost reductions driven by technological improvements and enhanced longevity of EL stacks, illustrating AEM's potential economic viability for large-scale hydrogen production. Furthermore, Pawlowski et al. explored the role of AEM within broader hydrogen strategies aimed at facilitating global energy transitions.[46] This discussion extends to integrating hydrogen technologies, including AEM, into various sectors, such as transportation and industry. The review also addresses the critical support from policies, the development of necessary infrastructure, and the investments required to scale up hydrogen technologies efficiently.

The comprehensive analyses conducted across various studies collectively underscore the significant role of AEM technologies within the broader strategic frameworks aimed at hydrogen production and integration. These works articulate the expected impact of AEM technologies on future energy systems, illustrating their potential to drive the transition toward sustainable energy solutions. The research emphasizes the strategic importance of including AEM in comparisons of electrolyzer technologies not only to assess its benefits and potentials but also to understand its limitations and directions for future improvements, to fulfill a pivotal role in shaping sustainable energy landscapes, thereby supporting the necessity of continuous research and development efforts to optimize and advance AEM system applications.

PEM electrolyzer

PEM electrolyzer has an emission rate of 0.3 kg CO_2-equiv/MJ H_2 under certain conditions, but a significant reduction (0.02 kg CO_2-equiv/MJ H_2) is expected by the year 2050.[49,50] Aydin et al.[51] investigated hydrogen production using a PEM electrolyzer; subsequently, the generated hydrogen is used in PEM fuel cells for buses in Canada. The study assessed various renewable electricity sources, including PV and wind. In comparison with conventional hydrogen production technologies, emitting approximately 8 kg CO_2-equiv/kg H_2,[52] the proposed system emits 2 to 7 kg CO_2-equiv/kg H_2, depending on the type of renewable electricity. A similar conclusion has been found by Kolb et al.[53] In the case of renewable electricity from PV panels, PEM shows slightly higher emissions than renewable electricity from wind turbines. The electricity production from PV panels or wind turbines is recognized as the principal factor influencing all areas of environmental effect. The quantifiable environmental impact is less than 4 kg CO_2-equiv/kg H_2.[53] Sharma et al.[54] arrived at similar findings for a hydrogen production facility in Marseille (France), which considered both PV panels and wind turbines. The CC impact varied between 2.5 and 5 kg CO_2-equiv/kg H_2.

Terlouw et al.[55] conducted LCA and cost analysis of hydrogen production using PEM, exploring various configurations such as grid-connected, grid-independent, and hybrid systems. Their findings revealed a significant correlation between the emissions, cost, and location of hydrogen production. In the regions abundant in renewable energy sources, greenhouse gas emissions were markedly lower. However, introducing grid electricity in the production system resulted in 3 times more emissions (10 kg CO_2-equiv/kg H_2) than the renewable option. Lee et al.[56] conducted a study examining diverse hydrogen production technologies encompassing AEL and PEM using renewable electricity from a 1 MW PV plant with an energy storage system. Among their noteworthy observations, the study revealed a correlation with scaling up. Notably, it was observed that the rate of CO_2 emissions increase was not linearly correlated with the plant size; specifically, larger plant sizes demonstrated a proportionally reduced CO_2 emission per functional unit.

Zhang et al.[57] investigated the interplay between CO_2 emissions in H_2 production and the system's operational lifespan. The study revealed a variability in CO_2 emissions, ranging from 0.51 to 9.37 kg CO_2-equiv/kg H_2. Instead of solely considering hydrogen as an energy carrier, the researchers have also explored fuel synthesis downstream of PEM. Navajas et al.[58] investigated the power-to-methane system, defining 1 MWh CH_4 production as the functional unit. The system incorporated CO_2 capture from a biomass source for the methanation process, making it carbon-negative due to biogenic CO_2. In the worst-case scenario, the study reported an environmental impact of 10 kg CO_2 per functional unit without CO_2 storage. Hydrogen production via PEM contributes less than 10% to the total GWP, with biogenic CO_2 storage proving advantages in the overall environmental impact. Pratama et al.[59] studied methanol production, where hydrogen is produced using a PEM electrolyzer, and CO_2 is captured using amine-based absorption from a biomass gasification plant. As CO_2 is sourced from biomass, the CO_2 emissions within the boundary of the power-to-methanol process exhibit a negative value, ranging from -1.5 to -0.7 kg CO_2-equiv/kg H_2. Gandiglio et al.[60] investigated the power-to-power system, employing an AEL and PEM fuel cell and incorporating electricity production and hydrogen storage in southern Italy.

SOE

SOE is recognized as the most efficient technology,[61] capable of providing industrial-grade heat alongside hydrogen production without using CRMs. However, it requires heat for certain operation modes.[62] The primary challenge with SOE lies in its high cost and relatively low stability, coupled with the fact that it is still in the developmental stage.[63] However, it is crucial to understand that cost is inherently relative and intricately tied to future developments and an annual number of manufacturing units. When all four technologies exhibit comparable costs, factors such as efficiency and environmental friendliness are the decision factors. Regarding GWP, the impact stemming from the PEM electrolyzer is about 15 times higher than those from SOE and AEL electrolyzer.[64] Therefore, the exploration of SOE-based hydrogen production remains captivating despite the limited research conducted on this electrolyzer compared with the others.

Jolaoso et al.[65] studied the integration of SOE, a wastewater treatment system, and a coal power plant for heat provision. The cumulative CO_2 emissions amount to about 12 kg CO_2-equiv/kg H_2, with a potential 28% reduction in the carbon footprint through heat integration. The predominant contributors to the CO_2 emissions are the balance of plant (BoP) components, as manufacturing entails significant energy consumption and material usage. Delgado et al.[66] combined nuclear power with a fuel production facility to produce liquid fuels like jet fuel and diesel. The analysis involved hydrogen production from SOE and the use of captured CO_2. For Fischer-Tropsch fuel production, LCA results indicated greenhouse gas (GHG) emissions between 0.007 and 0.025 kg CO_2-equiv/MJ H_2, and water and heat sources were identified as the predominant factors. Choe et al.[67] explored a power-to-methane system employing SOE. In contrast to utilizing CO_2 from biomass gasification, the study employed direct air capture and incorporated renewable electricity sources such as onshore/offshore wind turbines and PV panels. The investigation encompassed varying scales (1 or 10 MW) of SOE systems. Notably, the CO_2 emissions exhibited a range from -0.03 to -0.016 kg CO_2-equiv/MJ H_2.

Table 1 presents the key parameters for four types of electrolyzers, as detailed in the literature.[33,68–70] The electrochemical phenomenon for electrolyzers can be found in Figure S17 of the supplemental information. Notably, these electrolyzers differ significantly in their development status. Additionally, variations in overall system efficiency and stack lifetime have substantial impacts on their environmental performance. Comparing electrolyzers at different stages of development can provide valuable insights into each technology's environmental impact, including their advantages and limitations. Such an analysis is crucial for guiding future technological advancements and optimizing environmental outcomes.

Electrolyzer environmental performance comparisons

Gerloff et al. have conducted a comparative analysis of three key water EL technologies—AEL, PEM, and SOE, evaluating their environmental impacts across various energy scenarios.[71] In scenarios that heavily utilize renewable sources like wind and solar, AEL exhibits significantly lower CO_2-equiv emissions, attributed to its effective integration with renewable energies and technological maturity. However, the scope of the study is

Table 1. Technical information of four electrolyzer technologies

	Development status	System efficiency (%)	Voltage range (limits) (V)	Nominal current density (A/cm^2)	Lifetime stack, h
AEL	mature	50–78	1.4–3.0	0.2–0.8	>60,000
AEM	R&D	57–59	1.4–2.0	0.2–2.0	20,000–60,000
PEM	commercialized	50–83	1.4–2.5	1.0–2.0	50,000–80,000
SOE	R&D	50–89	1.0–1.5	0.3–1.0	∼20,000

limited as it excludes AEM electrolyzers, which could offer additional insights under diverse conditions. Moreover, the analysis lacks depth in material impacts and detailed system operations, where richer data could improve understanding of long-term environmental performance. There are also gaps in the discussion of sensitivity analysis, such as stack degradation. Additionally, the limited data availability may hinder the use of the study in setting industry standards and contributing meaningfully to the electrolyzer LCA database.

Zhao et al. conducted an environmental impact assessment of three hydrogen EL technologies—SOE, PEM, and AEL.[64] The analysis reveals that PEM technology has the highest environmental impacts, especially regarding GWP. It highlights critical materials like stainless steel, nickel, platinum, and iridium as significant contributors to these impacts. However, it does not delve into why these materials have such substantial effects from the LCA perspective. Their study also notes that electricity consumption during operations is the predominant factor in the life cycle of the technologies. However, it lacks projections of impacts over various years, with limited consideration of technological advancements like stack performance improvements and future changes in the energy system. Additionally, the assessment does not include a comprehensive system-level LCA incorporating different mixes of renewable electricity, limiting its ability to provide a complete picture of potential environmental impacts.

Gaps and contributions

While most studies tend to concentrate on two or at most three types of electrolyzers, this study takes a more inclusive approach by examining four major types: AEL, AEM, PEM, and SOE from the manufacturing stage to the operational phase. This broader scope allows for a comprehensive assessment of environmental impacts, providing insights into each technology's comparative advantages and disadvantages.

Despite the considerable commercial progress achieved by European electrolyzer technologies, which have been scaled up to several megawatts, they confront significant economic hurdles exacerbated by competitive technological advancements. Moreover, the supply chain is notably fragmented and predominantly dependent on CRMs, posing additional challenges. In light of the Sustainable Development Goals and the mandates of the Paris Agreement, it is imperative to conduct a thorough investigation of the environmental impacts associated with the manufacturing processes of electrolyzers, particularly focusing on CRM utilization. Such research is crucial to fostering the development of novel materials and optimized designs that improve durability, enhance performance and reliability, and reduce reliance on CRMs. Therefore, this research first delves into the intricacies of the electrolyzer manufacturing process. This detailed examination aims to uncover material impacts that might be overlooked at the system level but is crucial for guiding future stack manufacturing and development. Moreover, this study contributes significantly by developing a detailed life cycle inventory (LCI) database for the manufacturing phase of these four electrolyzer types. This database serves as a crucial resource for the hydrogen community, providing comprehensive data that can be used in future research and development efforts in the field.

This study notably highlights the importance of including electrolyzer technologies at various stages of maturity in a comparative analysis to assess their environmental performances by using different key performance indicators. PEM and AEL technologies are relatively mature, characterized by stabilized material usage and minor outcome variations, making their environmental performance more predictable and stable. By contrast, SOE and AEM present different challenges and opportunities. Despite its consistent material usage, SOE faces complexities due to its BoP requirements and degradation issues, which have hindered its transition to large-scale applications. On the other hand, AEM is still in the developmental stage, with varying materials used in the stack manufacturing process, which can significantly impact stack efficiency, longevity, and, ultimately, the conclusions drawn from such studies.

Given the complexities associated with different stages of electrolyzer technology development, it is essential to collectively evaluate the environmental performance of both emerging and mature technologies. This comprehensive approach allows for a balanced comparison that highlights not only the potential and limitations of each technology but also their relative advantages within a broader energy context. Moreover, for technologies like SOE and AEM, which are not yet fully mature, it is imperative to account for variations in material usage and stack lifetime. Including these variables in sensitivity analyses enhances the robustness of the study, allowing for more accurate predictions of performance under a range of potential future scenarios.

Beyond the manufacturing process LCA, this study also conducts a system-level analysis, encompassing twelve scenarios based on various electricity sources: PV panels, wind power, and hydropower. This approach allows for a nuanced understanding of how different renewable energy inputs can influence the environmental impacts of electrolyzer operation. Unlike the majority of LCA studies on electrolyzers, which typically conduct sensitivity analyses on efficiency and lifetime (parameters that exhibit correlation due to stack degradation), this study instead focuses on assessing the GWP impact by including the consideration of the end of life (EoL) of electrolyzer stacks. This involves considering various stack lifetimes and degradation rates across different benchmarks set for the present and future years (2024

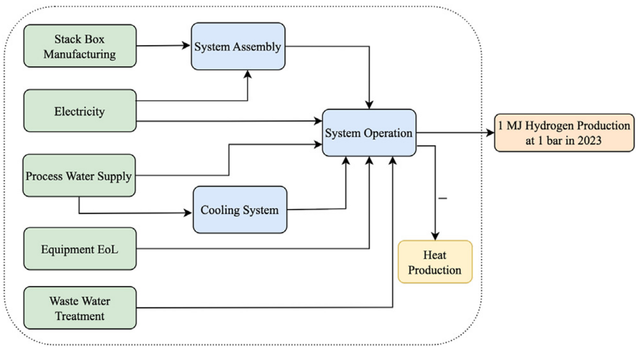

Figure 1. Hydrogen production system process tree and system boundary, for 1 MJ hydrogen production

and 2030) as stipulated by the European Commission. The study also projects the overall application of electrolyzers in the 2050 energy system-conscious energy landscape to understand electrolyzers' potential role in the energy transition.

Finally, this study also incorporates the technology readiness level (TRL) to demonstrate how varying levels of technological maturity impact the environmental performance of electrolyzers, mainly focusing on non-mature technologies such as AEM. Additionally, the analysis highlights the commercial scale of various electrolyzers, underscoring each technology's scalability potential and commercial viability and the current status and readiness of these technologies for market adoption. By addressing these environmental concerns, the hydrogen production industry can play a pivotal role in fostering a more sustainable environment.

Methods

This section presents the definition of goal and scope, the system description and boundary, the function and functional unit (FU), the LCI, the life cycle impact assessment (LCIA), and the sensitivity analysis methodology. This study has been conducted using openLCA software with the Ecoinvent database.

Goal and scope definition

This study compares the environmental emissions for hydrogen production using four types of electrolyzers, namely AEL, AEM, PEM, and SOE. Additionally, it provides insights into the environmental contributions of each electrolyzer manufacturing process by identifying the materials or energy consumed during its production. The study adheres to the guidelines provided by ISO 14040 and ISO 14044 for conducting LCA.

The selection of hydrogen as the product does not necessarily imply that hydrogen is presumed to be the optimal energy carrier. As outlined in the introduction, this study allows the inclusion of fuel synthesis downstream of the electrolyzer. However, the primary focus of this study is not on downstream treatment or upgrading of hydrogen. These aspects are not the main objectives of the LCA study and have been explicitly addressed in the definition of the system boundary and functional unit.

System description and boundary

The envisioned production system encompasses the entire life cycle, from the initial to the EoL, within the system boundary of the four electrolyzers (AEL, AEM, PEM, SOE) utilized for hydrogen production as the primary output. The comprehensive framework incorporates the supply of materials and components essential for constructing the electrolyzer manufacturing facility, the operational phase dedicated to hydrogen production, and the EoL considerations within their respective supply chains.

Figure 1 illustrates a simplified process tree containing the principal units/processes or activities. The units highlighted in green are individually modeled using primary data generated within this study (gate-to-gate assessment) or sourced from LCI databases (cradle-to-gate datasets). Units highlighted in blue color are treated as aggregated processes. It is noteworthy that during the use of an electrolyzer system, the co-production of heat may occur, particularly when employing SOE. Following the guidelines, system expansion is applied to address multi-functionality.

Function and functional unit

The primary function under examination is hydrogen production facilitated by the electrolyzer system, utilizing renewable electricity. Although the system does produce heat (SOE), this aspect is not considered the primary focus. In this study, the chosen functional unit is 1 MJ of hydrogen production at 1 bar pressure in Europe in 2023. In some guidelines, 1 kg of hydrogen production is expected to be used as the functional unit, and this study employs hydrogen as an energy carrier (without considering its optimality for energy storage). Consequently, the unit of energy, MJ, has been selected, and a lower heating value of 120 MJ/kg H_2 has been used. Further, hydrogen compression is essential for its subsequent use in electricity generation. All the electrolyzer systems in this study require compression units, but no hydrogen compression/storage has been included as product hydrogen is maintained at 1 bar pressure.

The influence of system boundaries on research outcomes is critical, particularly in studies concerning hydrogen production technologies. As Amela et al. and Hyonjeong et al. highlight, the choice of hydrogen storage and transportation technologies, such as compressed hydrogen, liquefied hydrogen, liquid organic hydrogen carriers, and ammonia, can significantly affect environmental emissions and system efficiency.[72,73] For example, PEM electrolyzers, which can operate at up to 30 bar pressures, may exhibit superior environmental performance compared with AEL electrolyzers, which typically operate at atmospheric pressure. This is because the higher operating pressure in PEM systems facilitates more energy-efficient hydrogen compression, reducing the need for additional energy input during storage.

The role of hydrogen, as either an energy carrier or a product, also influences system design and assessment. In scenarios where hydrogen is treated primarily as an energy carrier, additional infrastructure for compression and possible expansion is necessary, which introduces further complexity and potential energy losses. This necessitates careful consideration of the entire system from production through to end-use. Previous research studies have shown that the cost-effectiveness of hydrogen storage methods can vary significantly depending on the transport distance.[74,75] Although compressed hydrogen technology is mature and extensively utilized, it may not always be the optimal choice. This presents another significant research opportunity to determine the most suitable combinations of electrolyzer technologies, fuel cell systems, and methods for

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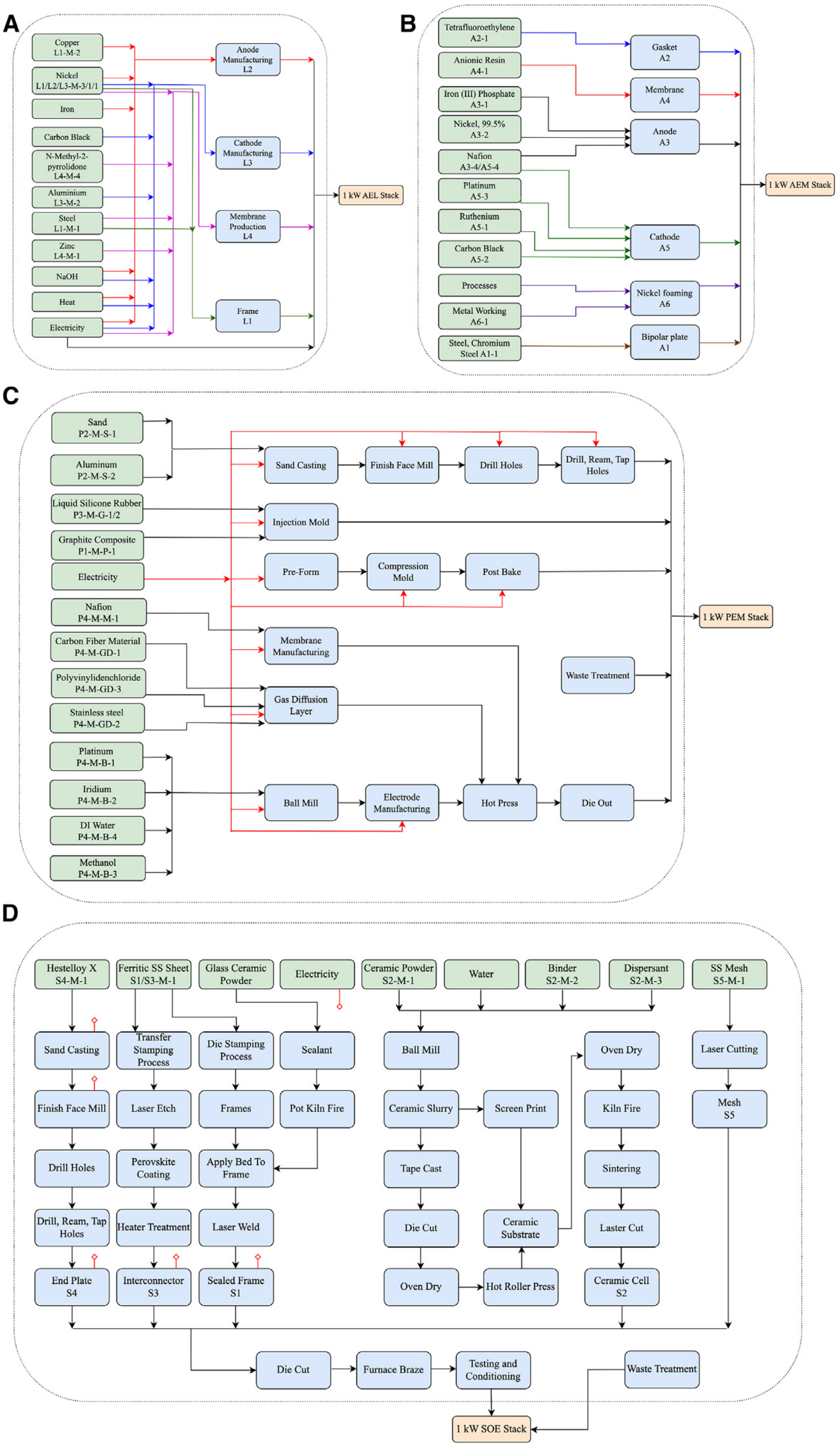

Figure 2. Electrolyzer manufacture process trees

(A) AEL, (B) AEM, (C) PEM, and (D) SOE manufacturing process trees for 1 kW stack.

selected to reflect this focus, while system efficiency calculations incorporate potential energy losses/gains from compression/expansion processes, providing a comprehensive view of electrolyzer performance within the defined scope.

The location of hydrogen production is recognized as a pivotal factor for conducting sensitivity analysis. Europe is considered the region for electrolyzer manufacturing processes and assessing various renewable electricity sources. However, North America and Asia have been incorporated for regional sensitivity analysis. For SOE systems, heat is exclusively regarded as a co-product. The system expansion method has been implemented to accommodate system multi-functionality, following the recommendations from Fuel Cell (FC)-Hyguide, an authority in LCA analysis for fuel cells and electrolyzers.[76] Heat and power co-generation, district or industrial, other than natural gas in Europe' has been utilized to calculate the avoided burden associated with the co-production of heat in the SOE system.

For comprehensive environmental impact analysis of stack manufacturing processes, intricate details of production processes for various electrolyzers have been incorporated. In order to delve deeply into the material usage in electrolyzer manufacturing, process trees have been developed for different electrolyzers, as depicted in Figure 2, considering the production of a 1 kW electrolyzer. Essential explanations of the manufacturing process can be found in the previous studies.[77–80] A general stack structure layout is presented in Figure S18 of the supplemental information. The notable advantage of this approach is the exclusion of lifetime and efficiency considerations at this stage, thereby providing a more focused assessment of material-level impact, which differs from the system-level analysis, where different factors may dilute the contribution of the stack assembly.

hydrogen storage and transportation under various operational scenarios. This study specifically focuses on different types of electrolyzers, deliberately excluding considerations related to subsequent hydrogen storage or expansion methods. Such an approach allows for clarity and prevents the diluting of the primary objectives of the research study. The FU is carefully

Various unit processes have been assigned simplified names for a more accessible presentation of LCA results for electrolyzer manufacturing. As illustrated in Figure 2A, four different unit processes are associated with the production of a 1 kW AEL stack: frame (L1), anode manufacturing (L2), cathode manufacturing (L3), and membrane production (L4). Taking frame (L1) as an

Table 2. Carbon intensity of 1 kWh electricity; kg CO_2-equiv/kWh

Electricity mix from grid			Renewable electricity			
US-NPCC	EU-UCTE	CN	Wind	PV	Hydropower	EU-2050
0.242	0.454	1.010	0.015	0.110	0.166	0.036

example, if the intermediate flow pertains to material, it is denoted as L1-M; if it relates to energy, it is denoted as L1-E. Within frame production, three materials are utilized, resulting in distinct names: steel (L1-M-1), copper (L1-M-2), and nickel (L1-M-3). The nomenclature used in Figure 2 corresponds to the results, facilitating clarity in result interpretation.

LCI

The process tree outlining the hydrogen production system (Figure 1) involves the generation of primary data for the two foreground (or gate-to-gate) processes, namely "system assembly" and "system operation." Additional information can be accessed in Tables S1–S8 of supplementary information. For both processes, inventory data have been compiled from literature or generated through process simulations, taking into account several references.[33,46,81–88] The upstream generic (or cradle-to-gate) processes, which supply materials and energy as intermediary flows to both foreground processes, are sourced from the Ecoinvent database V3.6. These generic processes will be utilized to calculate the comprehensive LCI for the respective supply chains.

LCIA

In the LCIA phase, IPCC, ImpactWorld+, and EPS2000 were selected as impact assessment methods for calculating LCA results. LCIA is the phase where the LCI is translated into an impact profile encompassing a comprehensive set of environmental indicators. CC from IPCC, human health (HH), ecosystem quality (EQ) from ImpactWorld+,[89] and abiotic stock resources (ASRs) impact from EPS2000 categories are selected to compute a comprehensive impact profile of the proposed product system. The GWPs and the underlying model developed by the IPCC are internationally recognized factors and models to assess the CC potential,[90] which is relevant in quantifying the potential contributions of electrolyzer technologies to greenhouse gas emissions. HH and EQ are two recommended areas of protection identified by the harmonized midpoint–damage impact assessment framework recommended by the United Nations Environment Programme (UNEP) Life Cycle Initiative,[91] allowing to aggregate midpoint indicators into a restricted and meaningful number of damage indicators, building on natural science instead of value choices applied through a weighting scheme. ASR has been chosen for the LCA comparison of electrolyzer manufacturing, guided by the insights from the literature.[92,93] While there is an ongoing debate on the optimal method for weighing the environmental impact of critical materials, ASR can still underscore the recognition of CRM and REE's significance in the environmental footprint.

Assumptions for the study

While variations in LCI data and underlying assumptions may result in differing findings, these outcomes remain insightful and align with this study's goals, serving as benchmarks for the industry. Detailed assumptions, including the electrical input for each electrolyzer system, are provided in Tables S5 through S8 in the supplemental information. During regular electrolyzer operations, cooling water is utilized; this water is treated as tap water, and the discharge is naturally expelled. Moreover, the balance of the plant has been included in the "system equipment" unit process, and a twenty-year lifetime has been assumed, according to a previous EU project.[94] All electrolyzer systems are assumed to be well-heat integrated. Furthermore, except for sensitivity analyses addressing geographical influences, the location is consistently set in Europe, as previously indicated.

Table 3. Degradation rate (mV per 1,000 h) and lifetime for four electrolyzers

	State of the art (%)	2024 (%)	2030 (%)	Lifetime (h)
AEL	0.12	0.11	0.10	80,000
AEM	1.00	0.90	0.50	30,000
PEM	0.19	0.15	0.12	60,000
SOE	1.90	1.00	0.50	25,000

Sensitivity analysis

As energy storage via electrolyzers increasingly aligns with renewable electricity sources, particularly in future energy systems, its applications extend beyond conventional uses, notably in power-to-X-to-power systems. This approach involves adjusting the usage based on the dynamics of electricity prices and the availability of excess renewable electricity. During periods when grid electricity prices are low, electrolyzers can efficiently produce hydrogen for storage or direct use in fuel synthesis. Conversely, during peak electricity price periods, the stored hydrogen or synthesized fuel can be converted back to power via fuel cells, offering a method to enhance grid stability and manage energy surpluses.

While it is recognized that power-to-hydrogen (power-to-H_2)-to-power systems typically exhibit lower round-trip efficiencies compared with battery storage solutions, they provide distinct benefits in scenarios where long-duration storage, large-scale energy management, or sector coupling (integrating energy systems with industrial processes) are required. Hydrogen systems can store energy over extended periods and at a larger scale than current battery technologies, making them particularly valuable in industrial applications or regions with significant seasonal variations in renewable energy generation. Therefore, as part of the first sensitivity analysis, grid electricity has been applied in three regions for four electrolyzers, including North America (—North-east Power Coordinating Council [NPCC]), Europe (—Union for the Coordination of Transmission of Electricity [UCTE]), and Asia (using China/CN as an example). The carbon density for producing 1 kWh of electricity can be found in Table 2.

In the second part of the sensitivity check, instead of conducting a Monte Carlo analysis on the system efficiency and lifetime, which may overlook the correlation between these two critical factors, this study follows the guidelines of Clean Hydrogen Europe.[34] Key performance indicators such as degradation rate and lifetime for four electrolyzers in the state of the art (SoA), 2024 and 2030, have been outlined in Table 3. This information has been utilized in the sensitivity analysis, focusing on EoL time points to comprehend the impact of degradation. The significant advantage of this approach lies in directly linking efficiency and lifetime considerations.

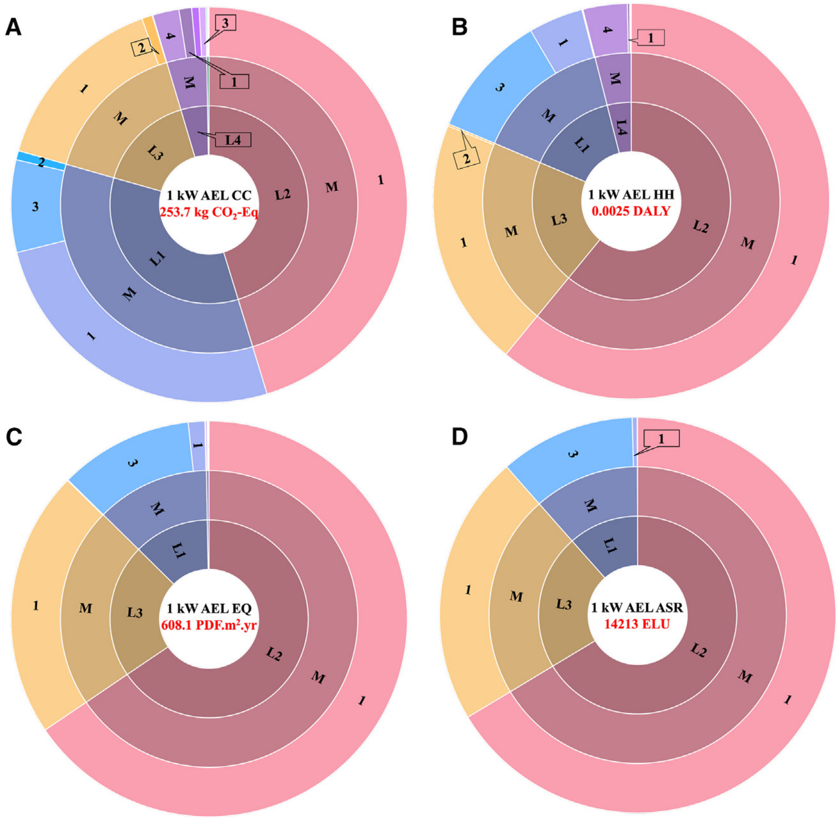

Figure 3. AEL LCA contribution analysis
Contribution analysis on CC impact (A), HH (B), EQ (C), and ASRs (D) on AEL; interested readers can find high-quality plots in the Figures S1–S4.

Additionally, it is projected that by 2050, the objective is to achieve net-zero carbon emissions, indicating that electricity may be sourced entirely from renewable energy. Consequently, for the final scenario, it is assumed that, in 2050, the electrolyzer stack has met the 2030 targets, and European electricity exhibits significantly reduced emissions, at 0.036 kg CO_2/kWh by mixing different types of renewable electricity, as noted in previous research.[95] This scenario demonstrates the potential of using electrolyzers as carriers of renewable energy.

Furthermore, for the base case, the study acknowledges certain limitations due to the scarcity of data, particularly for the AEM technology due to its low TRL level. This study utilizes Sustainion AEMs, with NiFe-layered double hydroxides (LDHs) serving as the anode catalyst and Nafion as the ionomer within the AEM stack manufacturing framework. Additionally, platinum group materials (PGMs), specifically platinum on carbon (Pt/C), have been employed on the cathode side due to their superior catalytic properties, and they enhance the overall efficiency of the hydrogen production systems, according to Xu et al.[46,87,96,97]

The burgeoning field of AEM electrolyzer technology has seen significant research efforts to utilize PGM-free materials. This shift aims to explore and develop more sustainable and economically feasible alternatives to conventional PGM catalysts. While numerous stack materials have been experimented with at the lab scale, this diversity introduces uncertainty to the study's outcomes due to the developmental stage of these technologies. Recognizing the need for equitable LCA comparisons across electrolyzers with varying TRLs, the study incorporates two additional lab-scale AEM stack manufacturing processes that employ PGM-free materials in the sensitivity analysis.[98–105] Additional information can be accessed in Tables S15 and S16 of the supplemental information. The primary objective of this approach is not to determine the superiority of any specific manufacturing process but to provide a broader perspective on the potential market viability of non-mature technologies, acknowledging the inherent uncertainties. This methodology ensures a balanced evaluation of established and emerging technologies and underscores the importance of fostering innovation while maintaining market readiness for developing technological solutions.

RESULTS

This section provides an in-depth analysis of the environmental impacts associated with the manufacturing and operation of electrolyzer systems. The LCA initially concentrates on producing the electrolyzer stack and evaluating its environmental impact across various categories. The main goal is to derive insights into essential processes, material utilization, and how they contribute to different environmental impact categories. Specifically, this analysis focuses on producing a 1 kW electrolyzer, intending to offer guidance for potential improvements in future manufacturing processes and material upgrades.

The following section explores the LCA results at the system operation level, incorporating various renewable electricity sources. Subsequently, the LCA of power-to-H_2 systems is analyzed across different regions to determine the appropriateness of various electrolyzers for specific geographic areas. Additionally, a sensitivity analysis is conducted to evaluate the impact of stack degradation, focusing on EoL considerations for different electrolyzers. This comprehensive approach affords a detailed understanding of the environmental implications associated with electrolyzer technologies throughout their life cycle stages.

Electrolyzer manufacturing LCA

In Figures 3, 4, 5, and 6, the environmental impacts of four electrolyzers are visualized. A naming convention has been used for unit processes and their associated materials to enhance clarity and visualization. These names align with the process trees outlined previously. For instance, in the case of SOE, the chromium steel used in the frame unit process is denoted as S1-M-1, corresponding to Figure 2D. Without the added names, these

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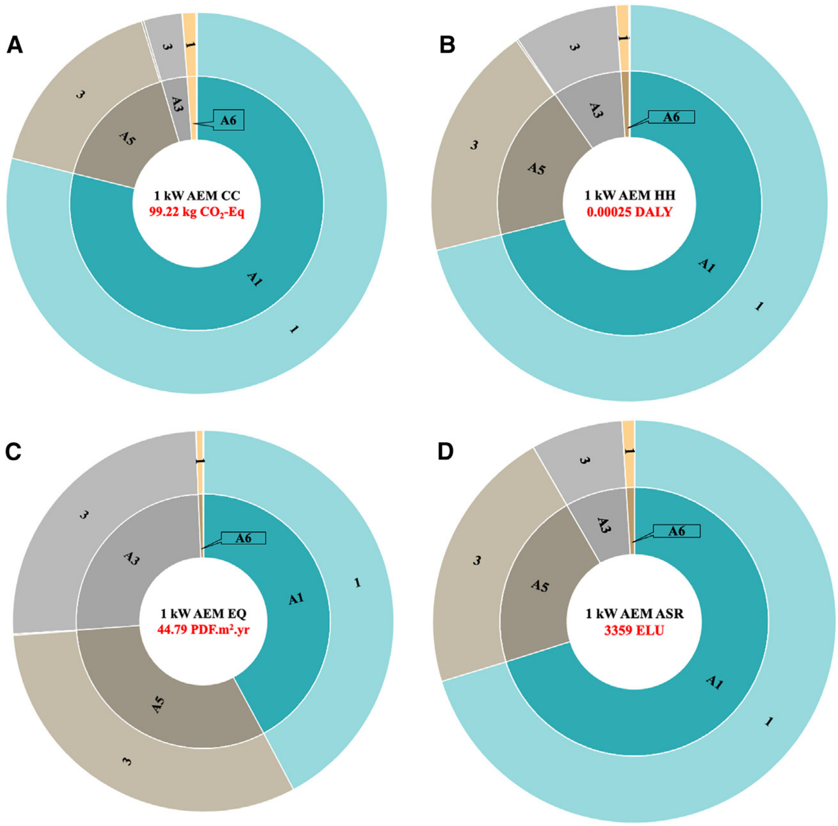

Figure 4. AEM LCA contribution analysis
Contribution analysis on CC impact (A), HH (B), EQ (C), and ASRs (D) on AEM; interested readers can find high-quality plots in the Figures S5–S8.

figures are also available in the supplementary information and Figures S1–S16.

AEL manufacturing process analysis

Figures 3A–3D present the environmental impacts of the AEL manufacturing process. Being one of the mature electrolyzer technologies, AEL has a significant advantage in using common materials. The AEL manufacturing process involves several unit processes, including frame, anode, raney nickel cathode, and gasket production. In Figure 3A, it is observed that nickel, utilized in anode production, contributes 45.22% to the CC impact. This contribution is reasonable as nickel is a suitable material due to its excellent performance in corrosion resistance and durability.[106] On the cathode side, nickel and aluminum are used, contributing 15.07% and 0.87%, respectively, to CC impact. The steel utilized in frame production contributes 25.81% to the CC impact. The membrane production contributes 4.33%, encompassing various materials such as zirconium oxide (1.03%), polyphenylene sulfide (0.60%), polysulfones (0.55%), and N-Methyl-2-pyrrolidone (2.15%). The inclusion of these materials aids in ion transport within the membrane.[107] Overall, producing a 1 kW AEL electrolyzer emits 253.7 kg CO_2-eq into the environment.

The analysis reveals no significant surprises in the HH impact category. Nickel, utilized in producing the anode, cathode, and frame, contributes 60.9%, 20.3%, and 10.15% to the HH impact. Unalloyed steel used in frame production accounts for 4.45%, while N-Methyl-2-pyrrolidone, involved in membrane production, contributes 3.6%. Similar patterns of impact contributions are observed for EQ and ASR impacts. Table S9 of the supplemental information provides detailed results for EQ and ASR impacts.

The LCA analysis of AEL manufacturing shows that nickel, the primary material used in stack production, is the main contributor to all impact categories. Despite AEL being considered a well-developed electrolyzer technology and nickel as a common material, AEL stack still faces several challenges, including issues related to degradation,[108] limitations in withstanding relatively high temperature and current density,[109] and stability concerns.[110] From an LCA standpoint, stack degradation and stability significantly impact its lifetime and efficiency, directly influencing the electricity input during the system operation stage. In the context of stack manufacturing, nickel is not classified as a CRM but has become a strategic raw material.

Recent developments in AEL technology are concentrated on updating materials to enhance electrolyzer performance, as discussed by Konovalova et al.[111,112] Concurrent research efforts are exploring potential alternatives to nickel. In adopting new materials, decisions must be made based on LCA principles, which involve evaluating the environmental impact and criticality of the materials. This decision-making process is inherently complex, often involving trade-offs. Due to low system performance, materials deemed non-critical with low environmental impacts during stack manufacturing might produce higher emissions during the system operation phase. Additionally, even when a material meets all required specifications, the cost per unit of the stack may increase, though this financial aspect needs to be covered in this study. However, these considerations are essential for guiding the sustainable development of AEL technology.

AEM manufacturing process analysis

Figures 4A–4D present the LCA contribution analysis of the AEM manufacturing process. The unit processes are similar to those of other electrolyzers, encompassing bipolar plate, anode, cathode, and membrane production. The bipolar plate, essential for collecting electrons and facilitating water splitting into H_2 and O_2, predominantly utilizes steel due to its excellent electronic conductivity and cost-effectiveness. Steel contributes 78.83% to the CC impact, a reasonable outcome considering the steel quantity used in the bipolar plate and the typical involvement of coal or fossil fuels in the steel production process. Platinum, employed in the cathode production unit process, significantly contributes 16.48% to the CC impact. The utilization of this noble

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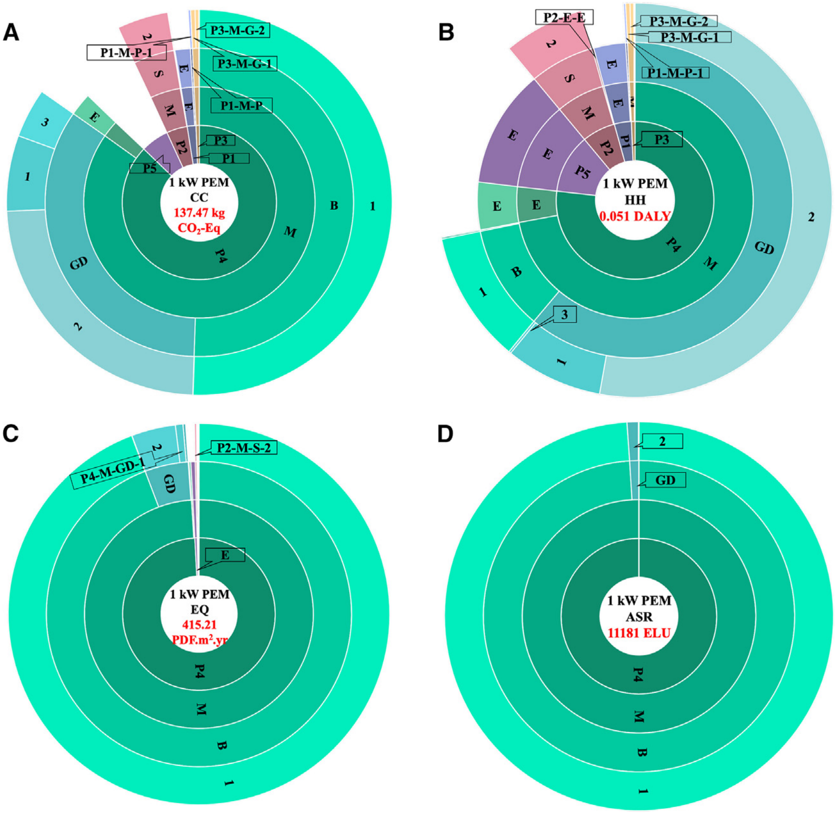

Figure 5. PEM LCA contribution analysis

Contribution analysis on CC impact (A), HH (B), EQ (C), and ASRs (D) on PEM; interested readers can find high-quality plots in the Figures S9–S12.

metal is primarily justified by its demonstrated excellence in hydrogen evolution reaction activity in a pH-universal environment.[113] Nickel, used in the anode production, contributes 3.3% to the CC impact. The CC impact also has other material flows, such as carbon black (0.16%), anionic resin (0.02%) that is used in the membrane production process, and steel used for nickel forming (1.11%). In summary, 1 kW AEM stack production releases 99.22 kg CO_2-eq into the environment.

The contributions in the HH impact category remain consistent with the CC impact analysis. Steel contributes 71.2%, platinum contributes 19.16%, and nickel contributes 8.41%. In the EQ impact analysis, the impact of each material is slightly shifted. Platinum now constitutes 31.69% of the HH impact, primarily attributed to the emissions released during mining. Steel and nickel contribute 42.15% and 25.44%, respectively, to the HH impact. Finally, in the ASR impact analysis, which primarily captures the impact on metal and mineral resources, the predominant contributors remain consistent. Steel constitutes 70.21%, platinum contributes 21.42%, and nickel accounts for 8.37% to the ASR impact. In the case of the AEM electrolyzer, where platinum is not the primary material, the ASR impact category reveals that the usage of platinum does not exhibit an overwhelmingly dominant value. This underscores again that the ASR category may not accurately represent the impact or can potentially mitigate the impact of CRMs usage. Detailed results for different impact categories can be found in Table S10 of the supplemental information.

Discussing the use of platinum in the cathode production process is noteworthy. The inclusion of platinum in the inventory may be attributed to its potential role in enhancing the efficiency and durability of the AEM stack. The development of AEM technology is still in the early stages. Many researchers are actively engaged in the quest to discover catalysts that are both cost-effective and efficient without significantly compromising the lifespan of the stack. One prevalent research direction involves the exploration of PGM-free metal catalysts, exemplified by studies using nickel and copper metals.[87,114,115] A change from CRM to transition-metal catalysts necessitates careful consideration of the trade-offs in terms of efficiency, cost, and environmental impact.

To comprehensively assess the environmental performance of PGM-free AEM stacks, it is recognized that there is a scarcity of LCA data inventory for these emerging technologies, a common issue given their developmental status. Despite this data gap, this study has incorporated two types of lab-scale PGM-free AEMs into the sensitivity analysis. This inclusion aims to preliminarily gauge the potential environmental impacts of these technologies. By analyzing different lab-scale models, the study endeavors to project and understand the broader environmental implications once these technologies mature and are potentially implemented at a commercial scale. This approach not only enriches the study with a forward-looking perspective but also provides crucial insights into the viability and sustainability of PGM-free material usage, enhancing the electrolyzer society's understanding of their potential role in future energy systems.

PEM manufacturing process analysis

Figures 5A–5D present the LCA of the PEM manufacturing process. Figure 5A illustrates the flow contributions to CC impact. The production of PEM electrolyzers involves five key unit processes: membrane electrode assembly (MEA), bipolar plates, end plates, and gasket production. In the MEA process, for the material part, significant contributions to the environmental impact come from the ball mill process and the production of the gas diffusion layer. Platinum, utilized in the ball mill process, accounts for 50.53% of the CC impact. This significant contribution is primarily attributed to the substantial power input required in platinum production, estimated at around 200 GJ per kg of platinum.[116] The gas diffusion layer comprises stainless steel, a quite promising material compared with titanium, which is normally used. Carbon fiber-reinforced plastic (CFRP) and polyvinyl chloride (PVC), facilitate even the distribution of gases produced in the EL process. Steel and CFRP contribute 23.73% and 6.36%

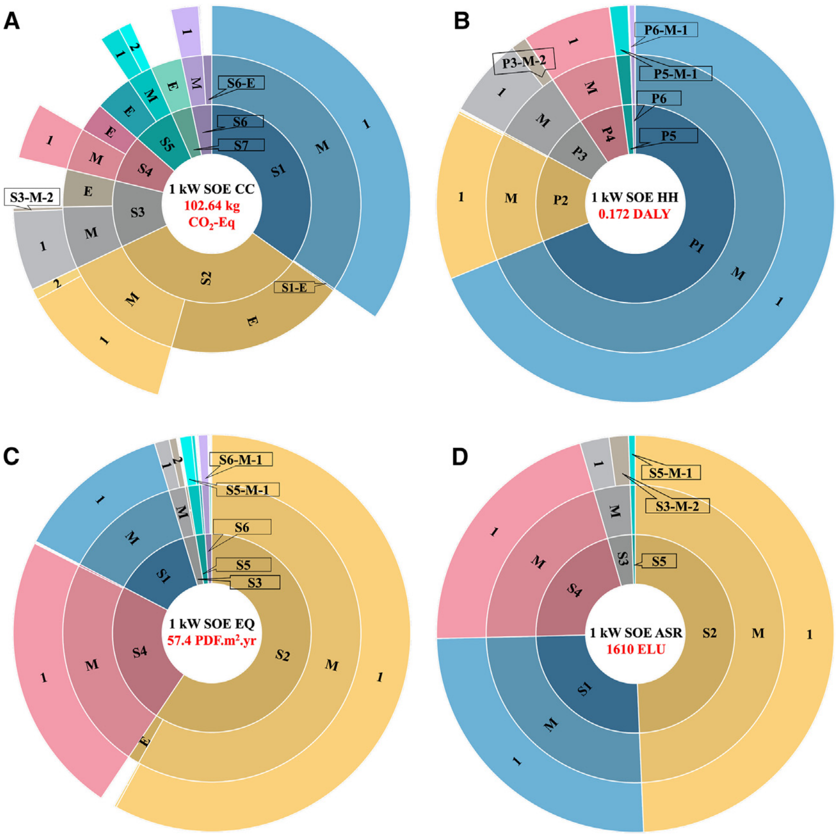

Figure 6. SOE LCA contribution analysis

Contribution analysis on CC impact (A), HH (B), EQ (C), and ASRs (D) on SOE; interested readers can find high-quality plots in the Figures S13–S16.

to the CC impact, respectively. Notably, the energy consumption for carbon fiber production is not negligible, potentially attributed to using acrylonitrile in the precursor production step.[117] PVC accounts for 4.15% of the CC impact, mainly attributed to the energy requirements in various steps of PVC production, including polymerization, filtration, drying, etc.[118] Aluminum is used in the sand-casting process, which is one of the processes for end plate production. The aluminum, employed to ensure uniform pressure distribution, contributes 4.28% to CC impact, and it is mainly attributed to the fuel, electricity, and chemical usage in various processes, including bauxite mining, alumina refining, etc.[119,120] Other minor contributions stem from various flows. Silicone and rubber in the gasket process contribute 0.36% and 0.30%, respectively.

Additionally, using sand in the sand-casting process makes a negligible contribution of 0.01%. The overall contribution of energy used in various processes amounts to 10.00%, including electricity usage in processing (5.92%), bipolar plate (1.60%), end plate (0.09%), gasket (0.05%), and MEA (2.39%). Interested readers can check Table S11 in the supplemental information for more details. Overall, the production of a 1 kW PEM stack releases 137.47 kg CO_2-eq into the environment.

In the HH impact category, as depicted in Figure 5B, material flows from the MEA process contribute 71.96% to the overall impact. The stainless steel used in the gas diffusion layer (GDL) process contributes 52.89%. Platinum used in the ball mill process contributes 10.78%, primarily attributed to the platinum mining process.[121] CFRP contributes 7.96% to the HH impact, mainly due to the grinding and sieving processes.[122] Aluminum used in the sand-casting process contributes 6.61% to the HH impact. The release of minerals, dust, and impurities during bauxite mining, as well as erosion and sedimentation of soil, can have a significant impact. Additionally, there are minor contributions from various flows. Silicone and rubber in the gasket production process contribute 0.35% and 0.31%, respectively. Graphite material from the pre-form process contributes 0.17%, PVC in the gas diffusion layer production contributes 0.20%, and Nafion in the membrane production process contributes 0.12%. The electricity consumption has a total contribution of 20.58% to the HH impact. More information is available in Table S11 of the supplemental information. Overall, 1 kW PEM stack production results in 0.051 DALY in the HH impact category.

As the analysis extends to the EQ impact category (Figure 5C), platinum usage has a significant impact (94.24%), which is attributed to similar reasons observed in the HH impact category, where waste released during mining can damage the ecosystem.[123] Stainless steel contributes 3.74%. CFRP use in the gas diffusion process contributes 0.66% to the EQ impact. There are other minor contributions from various flows. Aluminum contributes 0.17%, PVC contributes 0.20%, and electricity used in the final stage of processing and testing contributes 0.48% to the EQ impact. Overall, manufacturing a 1 kW PEM stack has 415.21 PDR $\cdot$ m$^2\cdot$ yr in the EQ impact category. Additional information is available in Table S11 of the supplemental information. In the ASR impact category (Figure 5D), which analyzes the usage of metals and minerals, platinum used in the ball mill process is the ultimate contributor (more than 95.0%). The contributions from other material usage and energy consumption are almost negligible. The overall ASR impact is quantified at 11181 ELU per kW PEM electrolyzer production.

In this study, stainless steel has been selected to replace titanium, reflecting a broader research trend aimed at utilizing nonrare materials. However, the environmental impact of stainless steel, particularly in the HH category, remains significant and should not be overlooked. Additionally, although iridium, together with platinum, is employed in the coating process, its environmental impact appears negligible. This may be attributable to the absence of specific data for Iridium in the Ecoinvent database, so the impacts associated with PGMs are used in this analysis. It is recommended that the LCA community

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consider enhancing the database to include a more detailed analysis.

Overall, the LCA analysis of the PEM manufacturing process highlights a significant contribution of platinum to all impact categories, as indicated in Figures 5A–5D, where it is shown in green. Platinum or PGMs are CRMs in Europe for two primary reasons. First, the significant sources of PGMs are located outside Europe, in countries such as South Africa, Russia, Zimbabwe, Canada, and the United States, leaving Europe highly dependent on these suppliers.[116] A disruption in the supply chain could lead to shortages, adversely affecting industries that rely on platinum, including the electronics sector. Secondly, the extraction of PGMs is currently limited to terrestrial sources, posing a substantial risk in evaluating the future viability of PEM technology. There is a growing concern that the terrestrial sources of platinum may eventually prove insufficient to meet global demands. Even though the material used in the production can vary, this situation underscores the need to explore alternative materials and technologies to ensure the long-term sustainability and viability of PEM electrolyzer technology.[64,124] Furthermore, although the ASR impact category captures the usage of platinum to some extent, it still lacks a clear differentiation between CRMs and regular metals. This highlights an important direction for future LCA efforts: to consider the specific factors associated with CRMs and integrate them into a distinct impact category.

SOE manufacturing process analysis

The CC impact analysis for SOE is presented in Figure 6A. Seven unit processes are involved in SOE production, encompassing frame production for the stack, ceramic cell manufacturing, interconnection production, end plate production, mesh fabrication, sealant production, and testing and processing. The contribution of intermediate flows in each process has been categorized into material and energy parts. In frame production, chromium steel contributes significantly, accounting for 34.65% of the total impact. This finding aligns with the high energy consumption in steel production, often using coal and fossil fuels.[125,126] Similar findings have been observed in the interconnection unit process, which also uses steel, contributing 6.47% to the total impact. This choice is justified by its consistent area-specific resistance.[127] Steel is also employed in the mesh production process, serving as a cathodic current collector and flow field,[128] with a modest contribution of 1.66%. Nickel-yttria-stabilized zirconia (Ni-YSZ), used on the anode side, and nickel oxide (NiO), employed in producing the ceramic cell, contribute significantly to the GWP. The anode catalyst Ni-YSZ, produced by using NiO covered with YSZ powder,[129] accounts for about 12.64% of the total impact. This substantial contribution is primarily attributed to the extraction and processing of nickel ore for the nickel production process, which demands substantial power input and results in indirect CO_2 emissions.[130] The iron-nickel-chromium alloy used in the end plate production contributes 4.57% to the total impact, primarily due to the usage of coke, coal, silicon, or aluminum as the reducing agent in the alloy production process.[131] Lastly, lanthanum oxide contributes 2.22% to the overall impact.

Regarding energy consumption within the SOE manufacturing process, various stages exhibit noteworthy contributions to GWP. Specifically, the production of ceramic cells accounts for 19.54% of GWP due to electricity usage. In interconnection production, electricity usage contributes 4.1%. Similarly, mesh production and end plate production have reasonable contributions, each representing 4.09% and 3.15%, respectively. The testing and processing stage, which includes quality checks, contributes 3.38%. Lastly, frame production exhibits a relatively lower contribution, contributing 0.18%. 102.64 kg CO_2-equiv is emitted in producing 1 kW SOE stack. Comparing the net CO_2 emission values across the four types of electrolyzers is only meaningful if they share the same lifetime and system efficiency.

Figure 6B presents the results of the HH impact category. The calculation method for HH impact is based on the recommended literature,[89] and all long-term impact categories and emissions are not considered in this assessment. Not surprisingly, material contributions have seen minimal changes in the HH impact category compared with the CC impact category. The steel usage in the framing process contributes significantly to HH impact compared with CC impact, which has been highlighted in different blue colors, accounting for 68.86%. The anodic catalyst contributes 13.69% to the HH impact. Other materials making contributions include iron-nickel-chromium alloy, chromium steel used in interconnect and mesh productions, and perovskite coating used in interconnect production (mainly due to the usage of nickel sulfate), contributing 7.21%, 6.47%, 1.48%, and 1.24%, respectively. Additionally, there are smaller contributions from other unit processes, such as hydrogen used in the mesh process contributing 0.06% and the glass used in the sealant process contributing 0.01%. The total energy contributes around 0.34% to HH impact. In producing a 1 kW SOE stack, the HH impact category is quantified at 0.172 DALY (disability-adjusted life year).

As the analysis moves to the EQ impact category (Figure 6C), there is a notable shift in the order of material flow contributions. Nickel usage becomes the predominant contributor, accounting for more than half (57.99%) of the total impact. This can be attributed to the extensive usage of rocks and acid chemicals in the extraction process during nickel production. Consequently, nickel production has a relatively high impact on specific midpoint categories, including human carcinogenic toxicity and ozone formation, contributing to the HH impact.[132] Iron-nickel-chromium alloy has the second highest contribution (23%), followed by steel usage in the frame process (12.67%). Other intermediate flows do not significantly contribute to the EQ impact; precise contribution values can be found in Table S12 of the supplemental information. The EQ impact of manufacturing a 1 kW SOE stack is computed as $57.4\ \mathrm{PDR} \cdot \mathrm{m}^2 \cdot \mathrm{yr}$.

The final impact category under consideration is ASR, which assesses the depletion impacts stemming from metals, minerals, and fossil resources.[133,134] As illustrated in Figure 6D, the contributions in this impact category are as follows: NiO contributes 49.32%, the steel used in the frame production contributes 25.3%, and iron-nickel-chromium alloy employed in the end plate production contributes 20.89%. Additionally, there are supplementary contributions from other material flows, such as perovskite coating (1.57%). A detailed breakdown of the contributions for all material flows is provided in Table S12 of the supplemental information. In summary, the 1 kW SOE stack production has an environmental impact of 1610 ELU (environmental load units) in the ASR impact category.

In Figures 6A–6D, the significant contributors identified are the use of NiO, steel, and various alloys. However, when considering the broad range of impact categories beyond merely GWP, it is apparent that the weight factors for assessing material impacts differ across these categories. This variation is distinctly visualized in the sunburst plot depicted in Figure 6. These observations provide crucial insights into the SOE manufacturing process, informing strategies for future technological enhancements. For instance, efforts should focus on reducing steel usage in the frame and exploring the feasibility of substituting nickel catalysts with alternative metals like copper, as suggested by recent research.[135] Additionally, while the impact of lanthanum usage may not be immediately apparent in current SOE assessments, it is vital to consider its implications on REEs in future evaluations.

Advancing material assessments in electrolyzer manufacturing

This sub-section meticulously evaluates the environmental impact of manufacturing processes for four electrolyzer types (AEL, AEM, PEM, and SOE), each analyzed through the lens of their specific materials and process contributions to environmental footprints. It specifically examines the impacts of producing a 1 kW stack/unit, focusing on the material aspects without accounting for operational usage patterns or downstream hydrogen production.

Traditionally, LCA analyses in this field have concentrated on system-level evaluations, often overlooking the critical nuances of material usage during the manufacturing phase. This analysis fills a significant research gap by focusing exclusively on these aspects, which have been insufficiently studied in the past. It provides a foundational reference, offering a broad perspective on potential environmental consequences and outlines how manufacturing processes can be improved to reduce the environmental impacts. However, direct comparisons across electrolyzers should be cautiously approached due to variations in manufacturing methods and material usage within each electrolyzer type. While not exhaustive of all material impacts, the findings emphasize the importance of material selection and spotlight opportunities for technological enhancements. In navigating the evolving field of electrolyzer production, achieving sustainability entails a balanced consideration of environmental impacts, material criticality, and economic factors, guiding strategic decisions toward sustainable technological advancements. This section underscores the critical importance of addressing these material-specific factors, paving the way for substantial improvements in electrolyzer manufacturing.

Electrolyzer system environmental analysis

This study uses 1 MJ hydrogen production in Europe in 2023 as the functional unit. Figure 1 illustrates it in the system process tree. In the previous section, the analyses focused solely on the stack manufacturing process without accounting for the lifetime, conversion efficiency, and hydrogen production. This section delves into the LCA of electrolyzer system operation. This analysis uses three renewable electricity sources, namely wind power, PV power, and hydropower, based on four chosen environmental impact categories. The summary of the results can be found in Tables S13 and S14 of the supplemental information. Moreover, a sensitivity analysis was performed, utilizing grid electricity from three different regions: the United States, Europe, and China. The assessment concludes with a comprehensive reexamination of the electrolyzer system performance, emphasizing stack degradation at different time points: the SoA, the year 2024, and a forward-looking projection for 2030.

CC

In Figure 7, the LCA findings for the hydrogen production system are presented for four types of electrolyzers, concentrating on the CC impact category. Three types of renewable electricity sources have been employed for each electrolyzer, represented using a distinct color set. For instance, SOE is visualized using light to dark gray colors. Figure 7A presents net CO_2 emissions for 1 MJ hydrogen production using four electrolyzers. Across all electrolyzers, those utilizing wind electricity exhibit the minimum emissions, followed by PV electricity and hydropower. The AEM wind scenario has minimum CO_2 emissions (0.008 kg CO_2-equiv/FU), whereas the AEL hydropower scenario has maximum CO_2 emissions (0.083 kg CO_2-equiv/FU). With PV electricity, CO_2 emissions vary from 0.044 to 0.057 kg CO_2-equiv/FU across all electrolyzers, while, with hydropower, emissions vary from 0.061 to 0.083 kg CO_2-equiv/FU.

SOE with PV electricity and hydropower consistently outperforms other electrolyzers, and PEM, AEM, and AEL follow in the performance order, which is in line with electrolyzer conversion efficiency. However, SOE exhibits the worst performance with wind electricity. A detailed contribution analysis is presented in Figure 7B to gain a comprehensive understanding of these findings. Hydrogen production using the electrolyzer system has four contributions: system assembly/equipment, process operation (i.e., water usage and heat input—specifically for SOE system operating in thermal-neutral mode), electricity, and potential co-product heat (particularly for SOE system). In Figure 7B, CC impacts are normalized to the worst scenario (AEL hydropower, set to 100%) to facilitate comparison. As expected, the primary contribution stems from electricity usage, which is strongly correlated with electrolyzer efficiency. The impact of the system assembly is scarcely evident, as the functional unit is tied to the electrolyzer lifetime, thereby mitigating the material impact over the extended lifetime. Once again, this underscores the significance of conducting a separate LCA for stack manufacturing, offering insights into material-based improvements for stacks.

While electricity usage constitutes the primary contribution in most scenarios, this differs for the SOE wind scenario. Unlike other electrolyzers, SOE operates in the thermal-neutral mode, requiring additional heat input. This study selected "heat, district, or industrial, other than natural gas" from the Ecoinvent database for the heat input. Unlike PEM, AEL, and AEM electrolyzers, SOE operates between 600°C and 800°C. This operational characteristic enables the SOE system to produce heat as a co-product. As mentioned previously, system expansion was employed to address multi-functionality, resulting in a negative 4.9% contribution of heat to the SOE system, highlighted in orange color (Figure 7B). Despite having the highest conversion efficiency, the SOE wind scenario exhibits the poorest performance. While it demands less electricity, resulting in lower

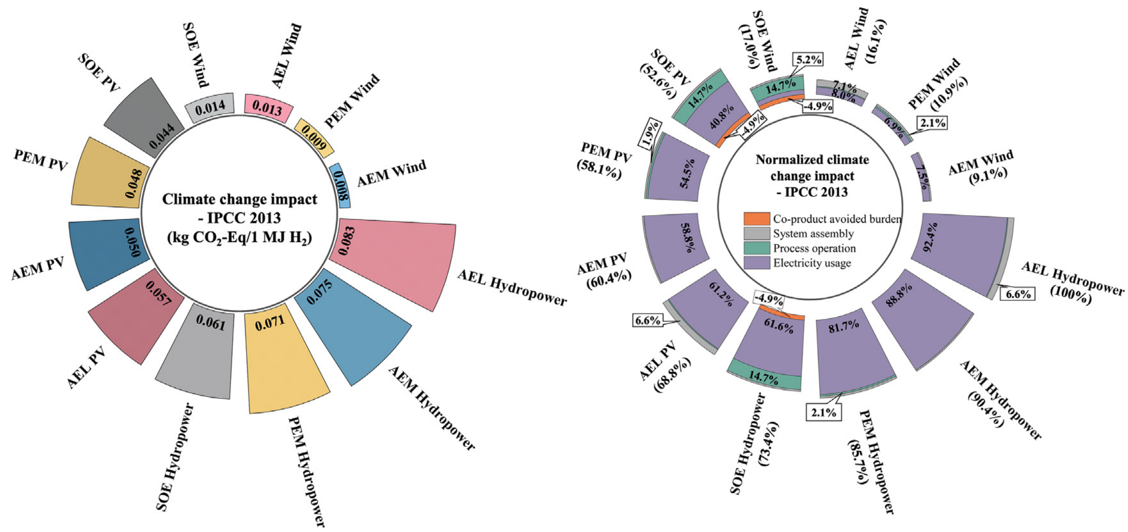

Figure 7. Climate change impact of electrolyzer systems

System-level CC impact results: (A) Net CO_2 emission and (B) contribution analysis for four electrolyzers.

electricity usage emissions, it introduces extra emissions from the heat input. Further, relatively low emission of wind electricity fails to offset the emissions from the heat input. By contrast, PV electricity and hydropower have higher emissions, and the high conversion efficiency of SOE stack reduces the electricity usage emissions compared with AEL, AEM, and PEM electrolyzers. These nuances underscore the intricate interplay between energy sources and electrolyzer performance.

HH and EQ

In the HH impact category, the hierarchy of impacts for four electrolyzers varies, depending on the source of electricity (Figure 8A). The HH impact ranges between 1.87 and 14.60 E-08 DALY/FU. The lowest impact is observed for the AEM wind scenario, while the highest is noted for the AEL PV scenario. For the AEL electrolyzer, the HH impact is usually on the higher side. For an easier understanding, Figure 8B presents the normalized HH impact results, wherein the values are normalized to the worst scenario (AEL PV, set to 100%). This figure emphasizes that electricity remains the predominant contributor, particularly for hydrogen production using AEM and PEM technologies. The impact of equipment becomes obvious in the outcome of AEL technology. Unlike the CC impact, where all four electrolyzers, using the same type of renewable electricity, exhibit similar values, the significant quantities of nickel and steel utilized in AEL production result in the equipment contributing more to HH impact, even with a long lifespan. Additionally, similar to the CC impact, in all SOE scenarios, process operation continues to have noticeable impacts on the

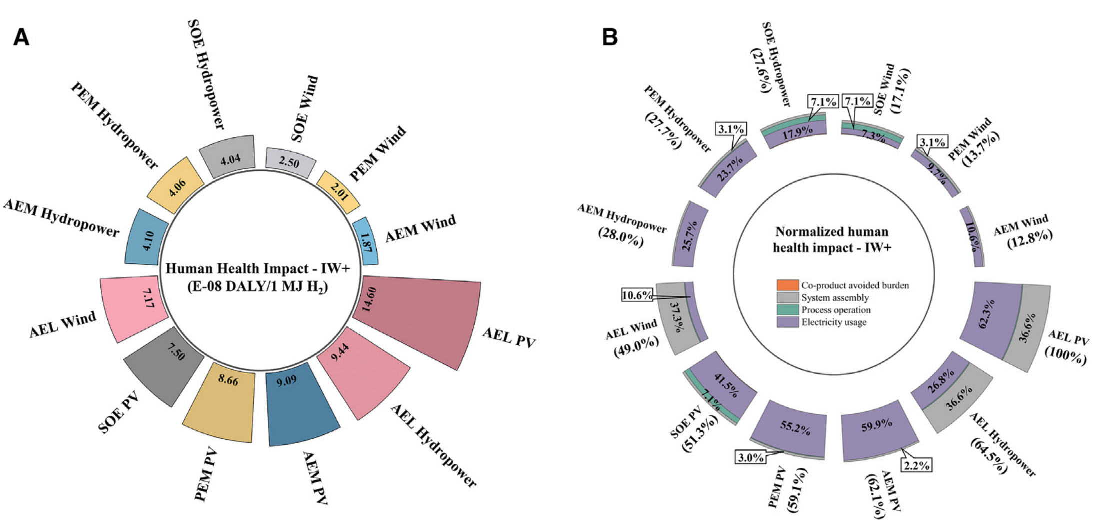

Figure 8. Human health impact of electrolyzer systems

System-level HH impact results: (A) Net CO_2 emission and (B) contribution analysis for four electrolyzer types.

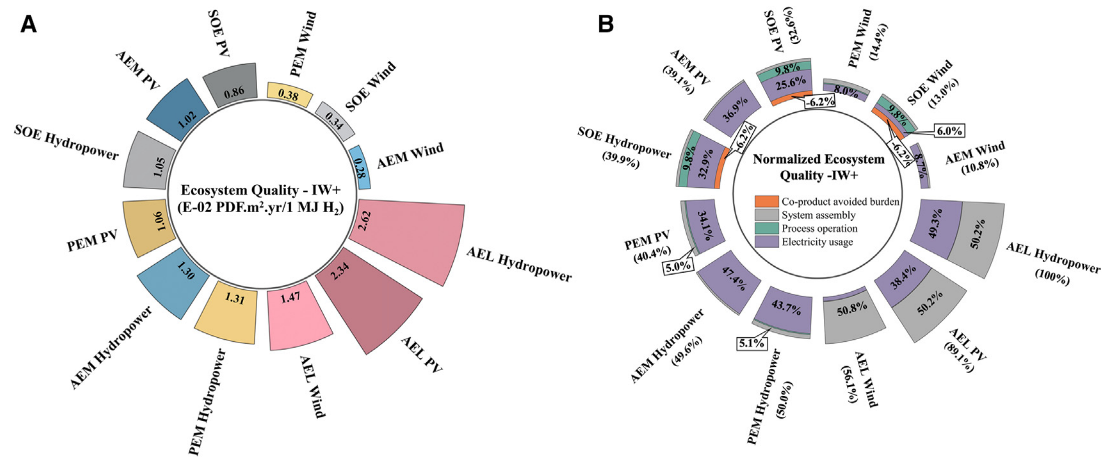

Figure 9. Ecosystem quality impact of electrolyzer systems

System-level EQ impact results: (A) Net CO_2 emission and (B) contribution analysis for four electrolyzer types.

total outcomes. This is primarily attributed to heat utilization, given that SOE operates in thermal-neutral mode at high temperatures. The higher system efficiency and application of system expansion for multi-functionality help improve SOE outcomes.

Figure 9 illustrates the results for the EQ impact category, which has a range between 0.28 and 2.62 E−02 PDF.m^2.yr/FU. AEM wind has the lowest impact, while AEL hydropower has the highest impact. The worst case of SOE using hydropower has a value of 1.05 E−02 PDF.m^2.yr/FU, ranking 6th among all scenarios. AEM and PEM electrolyzers show similar trends for different types of renewable electricity. Notably, the three AEL scenarios occupy the last three positions in the ranking. Subsequently, the analysis extends to the contribution analysis, as illustrated in Figure 9B, where all values are normalized based on the AEL hydropower scenario. For different AEM and PEM scenarios, electricity emerges as the primary contributor. For all SOE scenarios, the "avoided burden" highlighted in orange becomes more visible, contributing around 6.2%. Intriguingly, for the SOE wind, the electricity contribution is almost negligible. This observation suggests that when the emission associated with renewable electricity is low, the high conversion efficiency of SOE (nearly 90%) makes electricity a minor contributor, and equipment, tap water, and heat carry the majority of the contribution.

Compared with the CC impact category, the HH and EQ impact categories focus on contributors beyond electricity, even though electricity remains a significant factor in the final results. While the trends/results for four electrolyzers largely align with system efficiency, including other impact categories provides valuable insights and suggestions for improvement in material usage, taking nickel and steel in AEL production as an example. This section underscores the importance of GWP as an indicator but emphasizes the necessity of considering multiple impact categories for a comprehensive understanding of a technology. Relying solely on global warming metrics may limit the depth of analysis and hinder a holistic assessment.

ASRs

The ASR impact category introduces a distinct perspective, particularly concerning using CRMs at the system level. As depicted in Figure 10A, the SOE wind scenario exhibits a minimum ASR value of about 0.03 ELU/FU. SOE and AEM scenarios consistently demonstrate similar results, securing the top six positions. This is due to the relatively lower use of metals or critical materials in SOE and AEM electrolyzers. Even with hydropower, SOE and AEM electrolyzers exhibit a smaller impact than the other two electrolyzers using different electricity, highlighting the significance of CRM usage in the ASR impact category.

PEM exhibited better results in certain scenarios than AEM or SOE in the previous impact categories, and a noteworthy observation emerged in the ASR impact category. In three PEM scenarios, ASR varies between 0.19 and 0.24 ELU/FU, significantly higher than the minimum value (0.03 ELU/FU). These high values are primarily attributed to platinum, which has been extensively explained in the manufacturing section. This observation is corroborated by Figure 10B. The impact primarily arises from the system assembly for PEM wind and hydropower scenarios. In the PEM PV scenario, with substantial electricity emissions, the role of electricity in contributing to environmental impact becomes evident, where electricity contributes 17.7% to the overall impact. In the case of wind electricity or hydropower, the impact of electricity is minimal and often overshadowed by the influence of CRMs. However, when electricity emissions are high, they begin to assert their impact, competing with CRMs to influence the overall environmental performance. The scenarios involving AEL, irrespective of the type of electricity used, consistently occupy the last three positions, with ASR impact values ranging from 0.33 to 0.38 ELU/FU. This impact can be attributed to the substantial use of nickel and steel materials within the system assembly category.

Environmental implications at the system level

This section expands the analysis beyond component manufacturing to address the broader environmental

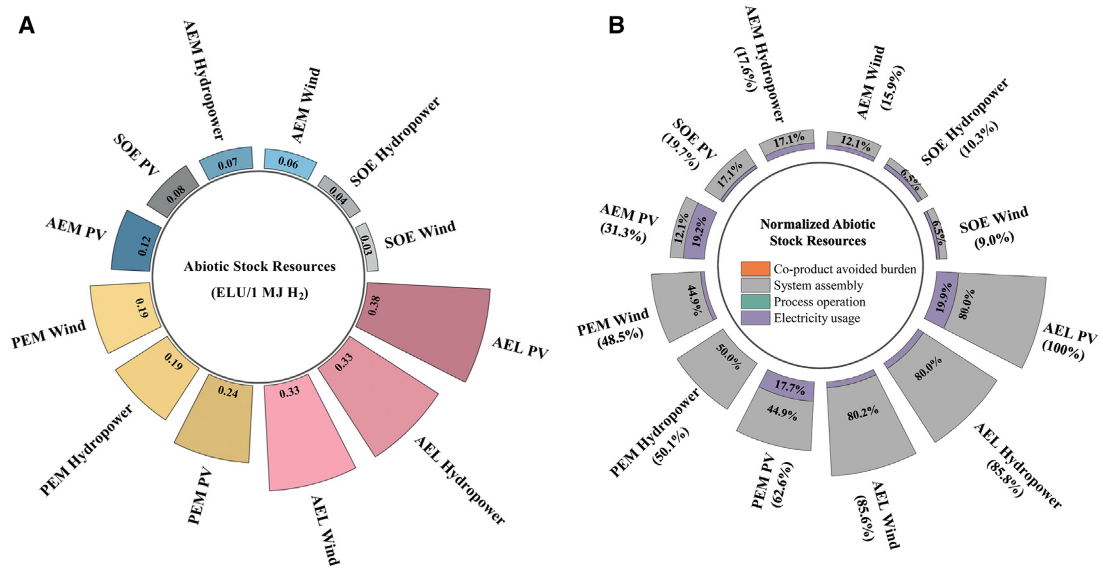

Figure 10. Abiotic stock resources impact of electrolyzer systems

System-level ASRs impact results: (A) Net CO_2 emission and (B) contribution analysis for four electrolyzer types.

implications of the electrolyzer technologies at the system level. The analysis captures the full spectrum of environmental influences by incorporating an LCA approach that includes a diverse array of impact categories—CC, HH, EQ, and ASRs. A comprehensive evaluation has been conducted on four types of electrolyzers, utilizing three distinct sources of renewable electricity: wind, hydropower, and PVs. This approach is crucial, as different countries have varied access to the types of renewable electricity that can influence electrolyzer performance.

It is important to recognize that this study assumes a uniform utilization rate for all electricity sources to isolate the impact of electricity type on the environmental performance of the electrolyzers. This approach allows for a direct comparison of the results under standardized conditions, highlighting the intrinsic differences in emission profiles and efficiencies of each power source. However, the actual operational utilization of electrolyzers can vary significantly with different sources of electricity, particularly with renewables such as solar power, which may only provide 10% to 20% utilization in regions like Europe due to variability in solar irradiance. While this factor is crucial for a complete system analysis and operational design, it was beyond the scope of this study, which focuses on assessing the potential impacts under a hypothetical scenario of constant electricity supply.

The results demonstrate that electricity consumption is the predominant factor affecting most environmental impact categories, except for ASR, which is reasonable as the electricity used in the stack and the heat provided by electrical heaters are considered the major inputs. Therefore, electrolyzers with higher operational efficiencies exhibit superior environmental performance, underscoring the importance of system efficiency.

Moreover, it is also noteworthy that system-level results differ from those observed at the stack manufacturing level. This divergence is largely due to the dilution of material impacts over the operational lifetime of the electrolyzers. This factor is often overlooked in studies focusing solely on CC impacts. This observation highlights the necessity of integrating broader environmental impact criteria to ensure material impacts are fully considered. Such integration is essential for providing comprehensive guidelines that reflect the complexities of electrolyzer operation and the potential for sustainable technological advancements.

Sensitivity analysis

Electrolyzers can be used for energy storage, transforming renewable power into the energy carrier hydrogen. When grid electricity is inexpensive or has a high share of renewable electricity, it becomes viable to produce hydrogen, which may later be transformed into electricity and sold in the market at a high price. Therefore, it is interesting to investigate the CO_2 emissions for the use of grid electricity and renewable electricity in an electrolyzer system. In the previous analysis, electrolyzer efficiency was maintained constantly in the most favorable circumstances. The efficiency tends to decline throughout the operation period, necessitating a more significant amount of power input to generate an equivalent amount of hydrogen, particularly toward the EoL of the stack. Traditionally, efficiency and longevity have been evaluated separately regarding sensitivity and uncertainty. However, these two factors demonstrate a significant correlation. The second part of the sensitivity analysis considers the efficiencies at the initial and final stages of the electrolyzer's lifespan.

Electricity origin sensitivity analysis

Figure 11 presents sensitivity analysis results for different electricity origins based on the CC impact category. Figure 11 extracts the CC impact results for four electrolyzers that use electricity from PV panels. The emissions for AEL, AEM, PEM, and SOE vary from 0.476 to 0.332 kg CO_2-equiv/FU when utilizing

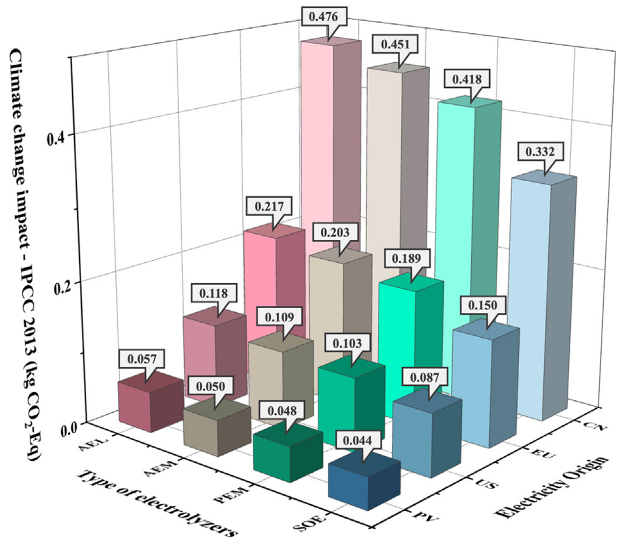

Figure 11. CC impact for 1 MJ H_2 production using various electrolyzers and different electricity sources

the electricity mix from China (CN), which has the worst performance. This represents an over eightfold increase compared with the PV electrolyzer scenario in Europe. This outcome is expected due to higher carbon content in China (1.01 kg CO_2-eq/kWh electricity). When employing electricity from Europe (UCTE) in electrolyzers, emissions vary from 0.15 to 0.22 kg CO_2-equiv/FU. The US exhibits the best performance among the regions. Still, the emissions for different electrolyzers are more than twice that of the PV electrolyzer scenario in Europe. As discussed earlier, the SOE demonstrates the best performance due to its high system conversion efficiency. The enhanced efficiency of SOEs is primarily attributed to optimal heat integration within the system. However, this integration increases the complexity of system design, notably in the configuration and number of heat exchangers. Nevertheless, there is a decreased reliance on external heat sources, such as electrical heaters for steam production, since a significant portion of the system's heat is effectively reused.

These results highlight the potential drawback of using grid electricity for hydrogen production, emphasizing hydrogen production using renewable electricity. The results presented in Figure 11 may represent the worst-case scenario (maximum CO_2 emission) when using the electricity mix from the grid. In the current energy supply system, traditional technologies, such as coal or natural gas power plants, often supply electricity to meet the electricity demand. However, if renewable electricity is directly integrated into the grid, it is possible that during periods of excess electricity generation, a significant portion could originate from renewable sources. Hence, the carbon content of the grid electricity could be lower due to the integration of renewable sources. Consequently, the results in Figure 11 should be regarded as the upper bound on CO_2 emissions. This consideration is essential when comparing emissions between grid and renewable sources. Moreover, steam methane reforming (SMR) based hydrogen production releases approximately 0.117 kg CO_2-equiv/FU.[52] In the US, electrolyzers using grid electricity may still be considered a viable option, given that they perform better than SMR. However, economic considerations must be considered for making such decisions, although this goes beyond the scope of this study.

Electrolyzer degradation sensitivity analysis

Figure 12 presents the sensitivity analysis results for stack degradation. In the SoA case, all four electrolyzers exhibit slightly higher values compared with those presented in Figure 7 when using PV electricity. This discrepancy can be attributed to the use of optimal electrolyzer efficiency in Figure 7, which primarily addresses the beginning of the life of the stack. When degradation is included, the average CO_2 emissions per MJ H_2 production shows a slight increase in the SoA case.

As expected, SOE demonstrates the best performance even when degradation impacts are included, largely due to its high system efficiency. Upon including degradation targets for the years 2024 and 2030, it becomes evident that the AEL electrolyzer experiences minimal variation (0.0588 to 0.0591 kg CO_2-equiv/FU) as it is a mature technology. Similarly, PEM displays a relatively narrow range, 0.0499 to 0.0507 kg CO_2-equiv/FU, indicating stable degradation characteristics. AEM electrolyzer demonstrates a 6% reduction in CO_2 emissions compared with SoA, reaching 0.0538 kg CO_2-equiv/FU in the year 2030. The reduction in CO_2 emissions is more pronounced in SOE, which exhibits a nearly 10% reduction from 0.0502 kg CO_2-equiv/FU at SoA to 0.0453 kg CO_2-equiv/FU in the year 2030. These observations are reasonable, given that AEM and SOE are still in the developmental phase, which indicates promising performance after overcoming the degradation issue. Addressing degradation issues is critical for the scaling up and commercial production of these electrolyzers.

The analysis presented focuses on the impact of stack degradation across different years, specifically updating only the foreground data related to electrolyzer performance. It is crucial to note that the background LCA database remains unchanged, as it does not incorporate adjustments for the decarbonization of the overall energy system. This decision stems from the inherent challenges in predicting the exact nature and impacts of such systemic changes. To ensure a fair and accurate assessment while acknowledging potential future transformations in the energy system, a scenario for the year 2050 was examined. This scenario presupposes that all electricity is sourced from a renewable mix in alignment with net-zero emission targets. The assumed carbon intensity for this future scenario is significantly lower, as detailed in Table 2.

Under these conditions, the emissions from the SOE are calculated at 0.0140 kg CO_2-equiv/FU, showing a considerable reduction compared with the optimal case utilizing only PV panels. For the PEM electrolyzer, emissions are estimated at 0.0163 kg CO_2-equiv/FU. This is followed by 0.0176 kg CO_2-equiv/FU from the AEM and 0.0192 kg CO_2-equiv/FU from the AEL. This scenario highlights the significant environmental benefits that could be realized with a transition to a fully renewable energy supply for electrolyzer operations.

The sensitivity analysis presented in this study emphasizes the importance of the origin of electricity when assessing the

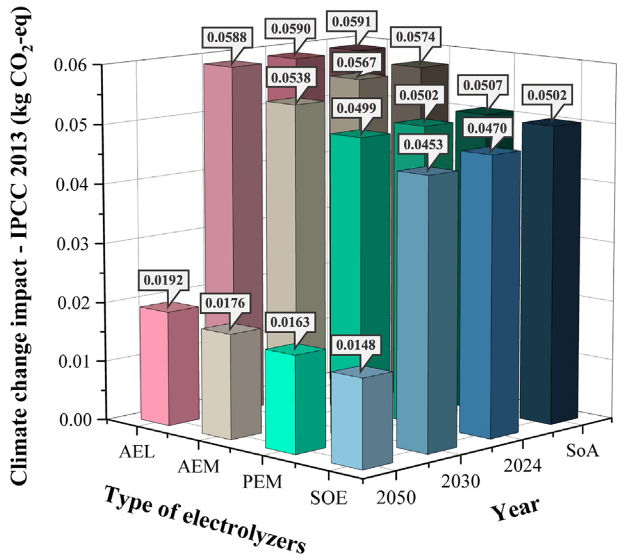

Figure 12. CC impact of various electrolyzers for 1 MJ H_2 production under different degradation conditions: SoA, 2024, 2030, and 2050

CC impact of an electrolyzer system. The sensitivity analysis on electricity origin underscores a significant decrease in CO_2 emissions when utilizing renewable electricity compared with grid electricity. This highlights the necessity of prioritizing hydrogen production during periods of renewable electricity abundance to mitigate CO_2 emissions. Moreover, the sensitivity analysis on electrolyzer degradation offers insights into the electrolyzer's long-term performance (operational lifespan). Encouragingly, AEM and SOE demonstrate notable reductions in CO_2 emissions in the future, suggesting potential technological advancements. These findings underscore the importance of integrating stack efficiency and degradation impact rather than treating them as separate entities.

PGM-free AEM manufacturing and system impact analysis

As detailed in the preceding section, careful consideration of degradation and potential enhancements underscores the promising nature of emerging technologies, particularly SOE and AEM. AEM indeed experiences several degradation challenges; however, the literature review reveals that most AEM research is still at the laboratory scale, with significant variability in the materials used for stack manufacturing. Additionally, the research emphasis has largely shifted toward developing efficient, PGM-free stacks. To facilitate a deeper understanding of these improvements and to provide practical guidelines, this study has incorporated two additional PGM-free types of stacks into the analysis, utilizing laboratory data. This inclusion is designed to assist industrial professionals and academic researchers in recognizing further advancements and refining their approaches to stack development.

Figures 13A and 13C illustrate the environmental impact assessments for type one AEM (T1) in terms of CC and abiotic resource depletion. These assessments highlight distinct aspects of the material usage within the electrolyzer stack. The analysis shows that stainless steel, utilized in the conductive plate, bipolar plate, and support material, has the most significant impact, contributing 50.4%, 33.5%, and 9.15%, respectively. Nickel, employed in anode production, accounts for 5% of the impact, and a smaller contribution of 0.7% is associated with cathode production. Polysulfone, used in membrane production, contributes 0.88%, while carbon employed in the cathode accounts for 0.25% of the environmental impact. Overall, the production of a 1 kW of T1 type AEM stack results in the emission of 22 kg CO_2-equiv. When the analysis shifts to ASR impact, nickel emerges as the dominant factor compared with steel. In this scenario, nickel usage dominates, particularly in anode production, accounting for 50% of the impact and contributes 7% in cathode production. Nickel-based steel adds approximately 42% to the total environmental burden. Overall, the production of a 1 kW AEM electrolyzer stack results in emissions amounting to 181.2 ELU.

Figures 13B and 13D detail the environmental impact assessments for the second type (T2) of AEM electrolyzer, using a consistent color scheme for clarity, with pink representing the anode production unit process, for example. The results from these assessments show marked differences from those observed for the first type (T1). In this instance, stainless steel, utilized in the end plates, accounts for a significant 85% of the impact, while its use in bipolar plates contributes 9.25% to the impact. The CO_2 emissions associated with the production of anodes and cathodes are almost negligible. Similarly, negligible impacts are observed in the ASR category. This figure highlights distinct environmental footprints between the two types of lab-scale AEM electrolyzers.

The sensitivity analysis extends to encompass the system-level environmental performance by integrating two types of PGM-free electrolyzers, as presented in Table 4. Upon comparison with the previously utilized AEM in the study, the differences in CC, EQ, and HH impacts are relatively minor. However, the variance in ASR impact is notably more substantial. This table highlights that the outcomes of the LCA can significantly vary depending on the specific lab-scale designs employed.

The objective of this section is not to identify the optimal AEM stack but rather to illustrate the inherent uncertainties in the LCI of AEM technologies. This analysis demonstrates that for technologies at a low TRL, future environmental impacts can substantially alter as the technology evolves. On the other hand, this analysis also unveils the potential advancements and market opportunities that could materialize as these technologies mature. This perspective is essential for stakeholders who are navigating the rapidly changing landscape of energy technologies, providing them with a clearer understanding of both the current limitations and future possibilities.

DISCUSSION

After conducting a comprehensive LCA of four types of electrolyzers, evaluating them from a broader perspective becomes particularly insightful. As detailed in Table 5, the table illustrates the industrial demonstration sizes and capital expenditures for four distinct electrolyzer technologies, providing insights into

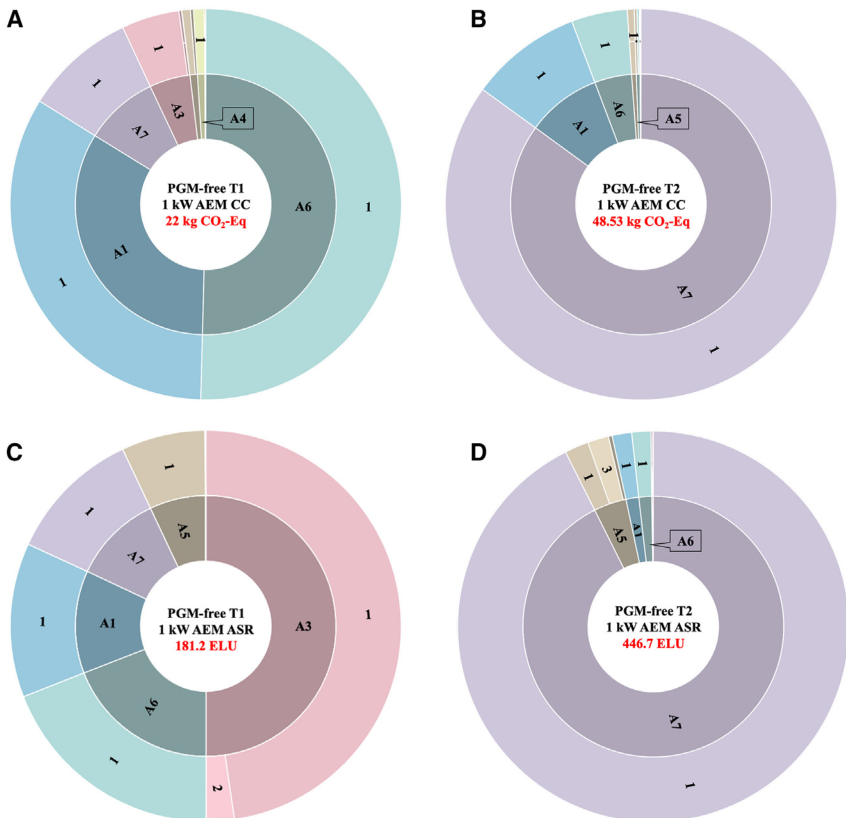

Figure 13. LCA impacts for two AEM electrolyzer types

LCA results for two types (T1 and T2) of AEM electrolyzer: CC impact (A and B), and ASR impact (C and D).

how these factors correlate with their respective TRLs. Notably, the mature technology (high TRL), such as the AEL, currently boasts the largest demonstration at 150 MW and demonstrates the lowest capital cost. Similarly, the PEM electrolyzer, despite its relatively shorter history compared with AEL, also exhibits a moderate cost profile.

Conversely, less mature technologies (low TRL), like the AEM and SOE, have smaller demonstration sizes and higher costs. However, from an LCA perspective, both SOE and AEM show promising performance. Nonetheless, they face significant challenges that must be addressed — SOE grapples with the complex BoP and system control complexities. Meanwhile, AEM contends with issues related to degradation and uncertainties in stack material usage. Overcoming these challenges could significantly reduce costs, especially as production scales up due to increased international market involvement, supportive governmental policies, and other factors.

On the other hand, mature technologies such as AEL and PEM also possess substantial market potential. AEL is renowned for its extensive testing duration, indicating its stability, while PEM is considered advantageous for transportation applications, including in ships and trucks. However, both technologies must continue to evolve toward more environmentally friendly solutions to remain competitive and align with global sustainability goals. This balanced approach to technological development and market adaptation is essential for the future viability and environmental alignment of electrolyzer technologies.

Conclusions

This study pioneers a comprehensive LCA investigation encompassing four types of electrolyzers: AEL, AEM, PEM, and SOE. Notably, this work marks the first instance of studying these four electrolyzers together, considering both stack manufacturing and system-level analyses. The system expansion method's application addresses the electrolyzer systems' inherent multi-functionality.

Initially, this study focuses on a comprehensive evaluation of the electrolyzer manufacturing process, where a standardized unit of 1 kW stack was employed. CC, HH, EQ, and ASRs have been included in the LCIA. Throughout this analysis, material selection emerged as a pivotal factor, shaping the environmental footprint of electrolyzer production. Materials like nickel, platinum, and steel substantially influenced the impact categories, underscoring their significance in determining environmental outcomes. For instance, in SOE production, chromium steel and nickel-based catalysts emerge as prominent contributors to the impact of CC, highlighting the need for sustainable material sources. Similarly, platinum utilization in PEM electrolyzers underscores the reliance on CRMs and associated supply chain challenges. AEL uses common materials. Its reliance on nickel underscores the imperative for alternative materials. Despite its nascent stage, AEM electrolyzer presents promising avenues for non-noble metal catalysts.

Subsequently, this study focuses on the LCA of electrolyzer system operation, where 1 MJ of H_2 production in Europe is considered the functional unit. In total, twelve scenarios were explored based on the source of electricity, namely PV electricity, wind electricity, and hydropower. The findings highlight the impact of CRMs, operational efficiency, and electricity sources in determining the overall environmental footprint. Electricity usage emerged as the primary contributor to the impact of CC on all electrolyzers, with nuances depending on the electricity source and electrolyzer efficiency. The AEM wind scenario has the best performance, while the AEL hydropower scenario shows the worst performance. Despite its high efficiency, SOE demonstrated variable performance depending on the electricity source. Moreover, the analysis expanded beyond conventional metrics such as CO_2 emissions, delving into HH, EQ, and ASRs. While electricity consumption remained a primary factor, the findings underscored significant contributions from the system assembly. The ASRs assessment offered insights into the effects of critical and other raw materials.

Table 4. Environmental emissions per FU for different types of AEM electrolyzers

	T1	T1	Base case
CC, kg CO_2-equiv	4.45E−02	4.60E−02	5.02E−02
EQ, PDF.m^2.yr	8.85E−03	9.16E−03	1.02E−02
HH, DALY	8.07E−08	8.35E−08	9.09E−08
ASR, ELU	6.98E−02	7.24E−02	1.20E−01

Table 5. Industrial demonstration sizes and capital expenditures of four electrolyzer technologies

	Industrial demonstrations size, MW	CAPEX (SoA)[34], Euro/kW
AEL	150[136]	600
PEM	10[137]	900
AEM	1[138]	1,000
SOE	4[139]	2,130

A sensitivity analysis underscores the necessity of hydrogen production via electrolyzers using renewable electricity instead of grid electricity. The findings reveal stark differences, with emissions from grid electricity potentially eight times higher than PV electricity. The US exhibits superior performance of electrolyzer hydrogen production compared with SMR. Including EU degradation targets, a critical parameter linked to system efficiency and lifetime highlights varying improvement potentials. While PEM and AEL, being mature technologies, offer limited room for enhancement, significant CO_2 reductions are achievable for SOE and AEM electrolyzers, both of which are still under development. The superior environmental performance of SOE underscores the pivotal role of system efficiency.

Finally, this study underscores the multifaceted considerations for transitioning to green hydrogen production. A comprehensive assessment of electrolyzer manufacturing processes and system operations illuminates critical factors shaping environmental sustainability, including material selection, operational efficiency, electricity source, technology improvement, and their integration into the energy system. In this study, including data inventory uncertainty for low TRL technologies illuminates the challenges and efforts required to transition these technologies from early-stage development to higher TRLs. By acknowledging and quantifying these uncertainties, the study highlights the critical areas where further research, development, and validation are necessary.

Overall, this research study lays the groundwork for informed decision-making in hydrogen production by pioneering a holistic approach that integrates environmental impact assessments, material criticality analyses, and technological advancements. As the world endeavors toward decarbonization and renewable energy adoption, initiatives aimed at optimizing electrolyzer technologies, reducing reliance on CRMs, and enhancing process efficiencies are essential for realizing a sustainable hydrogen economy. This study is a foundational step toward achieving these objectives and navigating the complexities of transitioning to green hydrogen production as the energy carrier.

While this study provides insights into the environmental impacts of electrolyzer technologies, it also highlights some limitations and future improvements. For instance, the integration of SOE with renewables is currently theoretical due to its relatively slow responsiveness. Despite this, conducting an LCA study on SOE remains crucial, as it provides robust evidence that could support future technological enhancements. For example, applying predictive analytics could significantly improve the integration of SOE within a renewable energy framework by optimizing operational responsiveness. For non-mature technologies, system-level efficiency may fluctuate due to variations in heat integration and the configuration of the BoP, which can subsequently impact the overall outcomes. Additionally, future research should incorporate variable utilization rates to reflect more realistic operational conditions. This would involve dynamic modeling of electrolyzers with intermittent renewable sources to better understand their environmental implications across various scenarios and locations.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Xinyi Wei (xinyi.wei@epfl.ch).

Materials availability

This study did not generate new materials.

Data and code availability

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization, X.W.; methodology, X.W.; investigation, X.W.; writing—original draft, X.W. and S.S.; writing—review and editing, X.W., S.S., A.W., D.W., and S.N.S.; supervision, J.V.h., M.M., and F.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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