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Prospective life cycle sustainability assessment and benchmarking of hydrogen from solid oxide electrolysis coupled with concentrated solar power

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ABSTRACT

Achieving sustainable hydrogen systems requires balancing environmental, economic and social aspects. In this regard, research on the life-cycle sustainability of emerging pathways such as solid oxide electrolysis (SOE) coupled with concentrated solar power (CSP) remains limited. This study presents a prospective life cycle sustainability assessment (LCSA) of hydrogen production via SOE coupled with CSP, benchmarked against hydrogen from steam methane reforming (SMR) as a conventional counterpart. By following the latest guidelines for LCSA of hydrogen-related systems developed within the SH2E project, this study applies consistent methodological choices across sustainability dimensions (e.g. functional unit definition), while transparently addressing model asymmetries. Results highlight notable differences in hotspots across dimensions and indicators. The CSP section dominates environmental impacts due to high material demand, while economic hotspots additionally include electrolysers and operational wages. Social impacts are primarily linked to the high relative share of worker hours in the Spanish hydrogen production facility itself, with added supply chain risks associated with chromium extraction in Kazakhstan and natural gas sourcing from Algeria. Even though conventional hydrogen from SMR outperforms hydrogen from SOE in four out of seven sustainability indicators, the latter offers promising results in terms of lower carbon footprint, reduced fair salary risk, and enhanced prospects for economic growth. Overall, these findings highlight the potential of SOE to contribute to a sustainable hydrogen economy, while they also stress areas (e.g. cost competitiveness, resource efficiency, and supply chain risk management) where sustainable-by-design research is essential to mitigate burden-shifting across impact categories and sustainability dimensions.

1. Introduction

The accelerating effects of climate change and biodiversity loss are among the most critical global challenges, prompting urgent action from governments worldwide. These issues are directly linked to pollution, overexploitation of resources and land/sea use change, driving national efforts towards net-zero carbon targets and sustainability [1,2]. As part of this response, substantial investments and strategies are being directed at promoting cleaner energy sources, particularly in critical sectors such as energy production and transportation [3,4]. Within the European context, the EU has started to implement plans and policies that emphasise the role of clean energy technologies, including the Green Deal Industrial Plan [5] and the Net Zero Industry Act [6]. In particular, technologies related to green hydrogen are gaining interest in the global transition to a decarbonised society. In this context, hydrogen from renewable energy sources could substantially contribute to reducing greenhouse gas (GHG) emissions, particularly in hard-to-abate sectors such as heavy industry and long-haul transportation [7].

However, most of hydrogen technologies currently remain in the development stage, and the structural transformations needed for large-

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scale hydrogen deployment to achieve GHG emission reductions may have unexplored and multidimensional impacts beyond direct environmental considerations [8,9]. For instance, hydrogen production technologies involve the development of complex value chains worldwide, often requiring new infrastructure, increased demand for energy, and reliance on critical raw materials [10,11]. These factors may introduce new sustainability challenges in terms of both positive and negative consequences. On the one hand, the deployment of green hydrogen technologies and their associated value chains can offer benefits such as increased productivity, technology dissemination and poverty alleviation [12]. On the other hand, concerns include potential issues related to resource depletion, biodiversity impacts, and potential social disruptions in regions where raw material extraction occurs [13,14]. Therefore, the pursuit of sustainable hydrogen systems must be guided not only by environmental and economic factors but also by social responsibility and a commitment to holistic well-being.

In order to ensure that hydrogen technologies contribute appropriately to the global Sustainable Development Goals (SDGs), it becomes imperative to assure their holistic evaluation considering not only environmental outcomes but also economic viability and social implications [9]. This form of analysis serves as a fundamental starting point for decision-makers, leading to the identification of areas where the most significant impacts occur within the system's value chains and to the prioritisation of actions, strategies or policies that balance competing sustainability objectives. The availability of robust methods and tools for such evaluations is crucial in ensuring that the sustainability implications of hydrogen technologies are thoroughly understood [15]. Life cycle sustainability assessment (LCSA) stands out as a widely recognised framework for this purpose [16]. By integrating environmental, economic and social dimensions, LCSA provides a comprehensive analysis of the sustainability performance of product systems across their life cycle [17].

LCSA application has already contributed to the evaluation of existing energy systems [18]. In particular, several studies have explored the life-cycle sustainability performance of hydrogen production systems, covering both renewable and conventional pathways [15,19–22]. These analyses have yielded valuable insights into the environmental, economic and social aspects of hydrogen systems. However, substantial gaps remain regarding the sustainability assessment of emerging hydrogen technologies [23]. Palmero-González et al. [24] identified similar concerns when reviewing life-cycle studies of concentrated solar power (CSP) technologies, revealing gaps in addressing emerging solutions and updated inventory data. Similar findings were reported by Longo et al. [25] and Kumar et al. [26], who also emphasised the importance of further standardisation and uniform assessment practices. Within this context, the present study addresses the prospective LCSA of hydrogen produced through solid oxide electrolysis (SOE) coupled with a CSP plant in 2030, when full maturity of the SOE technology is expected [27]. In particular, this novel study provides an illustrative application of the harmonised guidelines proposed within the European project SH2E, which offers methodological guidance on performing LCSA of fuel cells and hydrogen (FCH) systems to facilitate informed decision-making, promote sustainability, and ensure consistency and harmonisation in the assessment process [28].

2. Materials and methods

This research aims to explore whether SOE powered by CSP could become a sustainable pathway for hydrogen production by 2030. This is done by comprehensively evaluating the prospective sustainability profile of this emerging technology using the LCSA methodology, including benchmarking against conventional hydrogen production via steam methane reforming (SMR).

2.1. Case study definition

The CSP + SOE case study was selected as representative of a relevant and emerging hydrogen-related technology since high-temperature electrolysis presents advantages in terms of efficiency and electricity consumption when compared to currently more mature electrochemical pathways such as alkaline or proton-exchange membrane water electrolysis [29]. Furthermore, the comparison with conventional hydrogen production from SMR explores potential benefits and trade-offs associated with this alternative hydrogen production route. The system under evaluation consists of three main sections: CSP generation, electrolysis, and hydrogen conditioning. Fig. 1 shows a simplified process diagram of the integrated plant based on the detailed model developed for the year 2030 by Puig-Samper et al. [27]. A comprehensive technical description of the system and its operational parameters can be found in that reference.

According to previous choices in Puig-Samper et al. [27], the entire plant was designed to operate in Spain (SH2E project coordinator location) in solar-only mode, meaning that solar energy is the primary power source, with an auxiliary gas boiler used only for anti-freezing protection and initial start-up. Thus, the study is case-specific, with Spain representing a relevant choice due not only to its geographical location but also to supportive policies that promote the development and deployment of CSP plants and strong technical expertise that enables continuous improvement in this technology. In the CSP section, a parabolic trough collector (PTC) solar field generates heat, which is used to drive a conventional regenerative Rankine cycle with a net power output of 3.48 MW, producing electricity for the electrolysis process. The steam used in the Rankine cycle is superheated by the heat transfer fluid (HTF) from the solar field and reheated by recovering excess heat from the hydrogen production process. The cooling system employs an evaporative condenser and a natural draft cooling tower, reducing water consumption, which is crucial for CSP plants located in arid regions. The extra heat produced by the PTC solar field is stored in a two-tank thermal energy storage (TES) system. This enables the plant to operate even during periods of low solar irradiance.

The electrolysis section operates at a temperature of 800 °C, powered by the CSP-generated electricity. It includes two electric heaters, one air compressor and three heat exchangers to ensure an appropriate temperature for the electrolytic process. The system recirculates part of the cathode outlet stream to prevent nickel oxidation in the cathode, which is critical for maintaining the performance and durability of the solid oxide electrolyser.

The hydrogen conditioning section handles the compression and purification of the produced hydrogen. After drying, hydrogen is compressed in a five-stage process to a final pressure of 700 bar, suitable for various downstream applications, including transportation. The intercooling system between compression stages ensures hydrogen remains at safe operational temperatures, using water from the plant's cooling tower.

To ensure continuous operation, the plant uses stored thermal energy from the TES system during periods of low solar irradiance. If neither solar power nor TES is sufficient, grid electricity is consumed to maintain nominal capacity, especially during winter months when solar energy is less abundant.

2.2. LCSA framework

The LCSA of hydrogen produced via SOE powered by CSP was conducted following the methodological guidelines developed within the SH2E project specifically for hydrogen-related systems [28]. In this sense, this study not only aims to evaluate the prospective life-cycle sustainability of hydrogen from CSP + SOE but also serves as a case study to test the applicability of the SH2E guidelines for FCH-specific LCSA. These guidelines are rooted in the framework proposed by Valdivia et al. [16] and harmoniously combine three key life-cycle

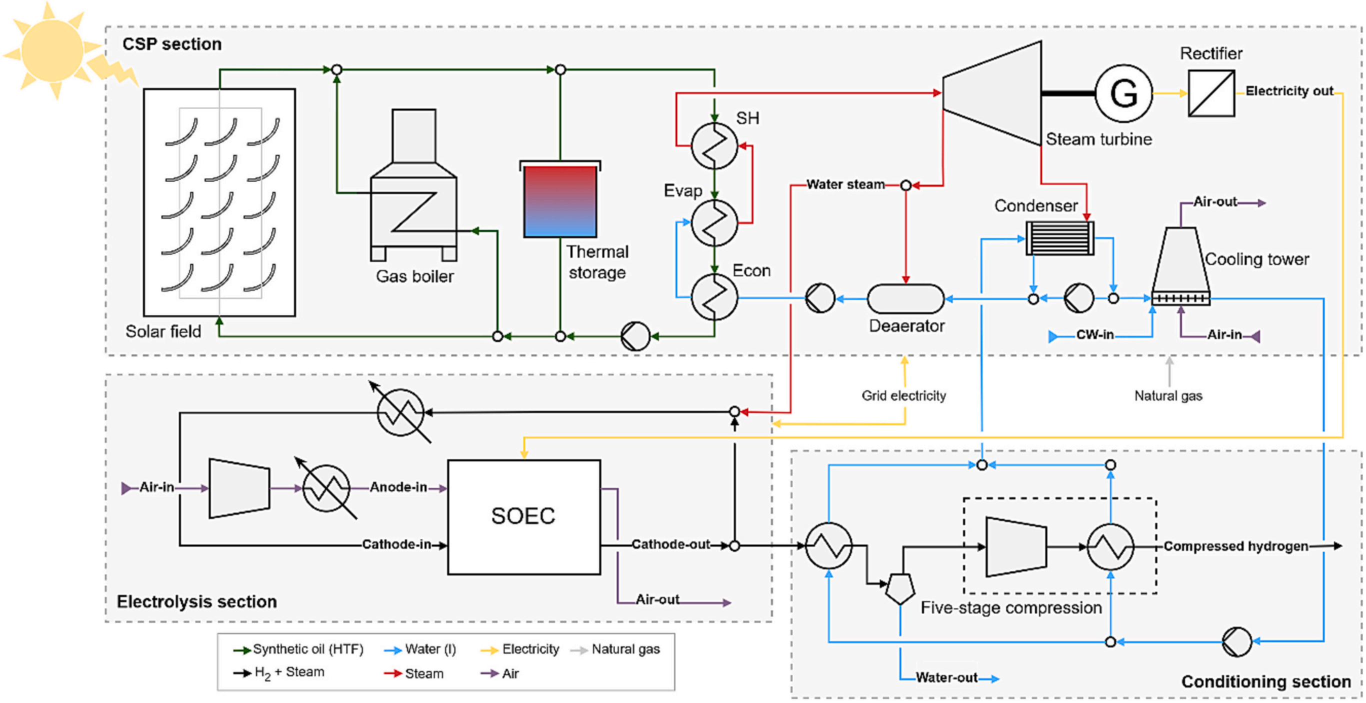

Fig. 1. Simplified process diagram of the integrated CSP + SOE plant.

techniques: environmental LCA [30,31], LCC [32], and S-LCA [33]. The joint interpretation of the outcomes from these single techniques provides a comprehensive understanding of the environmental, economic and social aspects of CSP + SOE hydrogen production, facilitating the identification of sustainability hotspots.

The application of a harmonised LCSA framework ensures that common aspects across the three sustainability dimensions, such as the functional unit (FU), were homogeneously applied. The goal of this LCSA study is to evaluate the prospective sustainability profile of hydrogen from CSP + SOE and benchmark it against that of conventional hydrogen from SMR. Although the progressive adoption of renewable hydrogen pathways is expected to have large scale effects, this study focuses on evaluating prospective sustainability impacts of a specific hydrogen product, with decision support limited to the product level (i.e. micro-level decision support). Since this LCSA study is not intended for meso- or macro-level decision-making, its findings are case-specific and should not be generalised. In this regard, a prospective attributional modelling approach was followed, without direct stakeholder involvement in the assessment. The performance of the CSP + SOE system was evaluated for the year 2030. This aligns the analysis with future scenarios in the hydrogen sector for a year when this type of electrolysis is anticipated to reach full maturity [34].

The FU chosen for this study is 1 kg of hydrogen with ≥99.999% (vol) purity, at 700 bar and 40 °C. The case study location was set in Spain, assuming a 30-year operational lifespan for the hypothetical hydrogen production plant. Replacement needs for capital goods with shorter durability were considered. Regarding system boundaries, following the nomenclature of the SH2E LCSA guidelines [28], a cradle-to-gate 3 scope was implemented, reaching hydrogen compression. The data used for the life cycle inventory (LCI) were primarily based on the process simulation in Puig-Samper et al. [27].

Apart from common aspects, the SH2E LCSA methodological guidelines also account for model asymmetries, i.e., specific elements that cannot be fully harmonised across the three sustainability dimensions. These asymmetries are inherent to the nature of each single life-cycle technique. For instance, the approach to prospectivity differs across sustainability dimensions, reflecting the unique characteristics of each dimension. Moreover, the LCI and life cycle impact assessment (LCIA) phases were adapted to each specific methodology within the LCSA framework. The specific methodological choices for each technique are further detailed in the following sections, while Table 1 summarises the main technical and methodological features of the product system under study.

2.2.1. *Specific LCA methodological choices*

The specific goal of the environmental LCA study is to evaluate the environmental profile of hydrogen produced through CSP + SOE in 2030, and to benchmark it against that of conventional hydrogen from SMR in 2030. The system boundaries of the environmental LCA study cover from raw material extraction to hydrogen compression, as shown in Fig. 2. In line with the SH2E guidelines for FCH-specific LCA [36], no cut-off was applied and capital goods (including pertinent replacements and plant decommissioning) and energy and material flows entering or leaving the system were accounted for.

The prospective LCI of the foreground system was retrieved from Puig-Samper et al. [27], which makes in turn use of process specifications (cf. Section 2.1) and literature sources. The suitability of the involved CSP + SOE model to represent the behaviour of the integrated plant was previously explored in Puig-Samper et al. [27], showing values (e.g. capacity factor, solar-to-electricity efficiency and water consumption of the solar plant, and specific electricity and heat demand of the electrolyser) in agreement with those expected [37–40]. The implemented inventory of the foreground system is provided as Supplementary Information. Activities within the background system were gathered from a prospective version of the *ecoinvent* 3.8 cut-off database [41] generated making use of the *premise* Python package [42], which –in order to reflect a future economic context– adapts the activities within the original database to a given integrated assessment model (IAM). The selected IAM is the REMIND SSP2-NDC 2030 [43], which relates to a business-as-usual scenario where nationally determined contributions (NDCs) are implemented by 2030 and no increase in the radiative forcing through 2100 is quantified.

Regarding the LCIA phase, the Environmental Footprint version 3.1 (EF 3.1) method was used [44]. Its use is compelled by the SH2E LCA

Table 1
Main technical and methodological features of the CSP + SOE hydrogen production system.

Aspect	Specification nature	Specification description
CSP section	Technical	Based on the process simulated in Puig-Samper et al. [27]: Spain, solar-only mode, parabolic trough collector, Rankine cycle (3.48 MW net power output), two-tank thermal energy storage
SOE section	Technical	Based on the process simulated in Puig-Samper et al. [27]: Spain, 800 °C operating temperature, 3.41 MW nominal power, 6 bar operating pressure
Conditioning section	Technical	Based on the process simulated in Puig-Samper et al. [27]: Spain, ≥ 99.999% vol purity, five-stage compression, 700 bar final pressure, 0.027 $kg \cdot s^{-1}$ nominal hydrogen yield
Functional unit	Methodological (LCSA)	1 kg of hydrogen (≥ 99.999% vol purity, 700 bar, 40 °C) produced in Spain in 2030
Intended use	Methodological (LCSA)	Micro-level decision support
Modelling approach	Methodological (LCSA)	Prospective attributional
System scope	Methodological (LCA, LCC)	Cradle-to-gate 3 scope, reaching hydrogen compression [28]
System scope	Methodological (S-LCA)	Product-specific supply chain definition according to the protocol by Martín-Gamboa et al. [35]
Inventory data	Methodological (LCA, LCC, S-LCA)	Provided as Supplementary Information; foreground data based on Puig-Samper et al. [27]; background data sources: ecoinvent v3.8 (cut-off) and premise (REMIND SSP2-NDC 2030) for LCA, PSILCA v3.1 for S-LCA, and LCC references in Supplementary Information
Evaluation method	Methodological (LCA)	Environmental Footprint 3.1 (all indicators)
Evaluation method	Methodological (LCC)	Levelised cost of hydrogen
Evaluation method	Methodological (S-LCA)	PSILCA (all indicators)
Benchmarking	Methodological (LCSA)	SMR hydrogen production system in Spain in 2030 (Section 2.2.4 and Supplementary Information)

guidelines [36] following the recommendations of the European Commission on the matter [45]. All impact categories within this method were assessed. As growing concerns exist regarding the effect of direct hydrogen emissions in terms of global warming [46], additional calculations were performed to evaluate the potential climate change impact of hydrogen leaks at the electrolysis stage. For this purpose, a 0.03% loss rate was assumed [46]. The global warming characterisation factors attributed to the emitted hydrogen were 8 kg CO_2-eq per kg H_2 for a 100-year time horizon [47] and 33 kg CO_2-eq. per kg H_2 for a 20-year time horizon [48]. Finally, regarding computational implementation of the environmental LCA study, it was conducted in the Activity Browser environment [49].

2.2.2. Specific LCC methodological choices

The purpose of the LCC study is to estimate the levelised cost of hydrogen (LCoH) from CSP + SOE in 2030 based on the process simulated in Puig-Samper et al. [27], and to benchmark it against that of conventional hydrogen from SMR in 2030. According to the aforementioned cradle-to-gate 3 scope, the analysis covers all relevant costs encountered by the producer. Costs were categorised into capital expenditure (CAPEX) and operating expenditure (OPEX). CAPEX includes direct, indirect and supplementary costs. Direct costs involve expenses related to land acquisition and equipment acquisition and installation, while indirect costs cover engineering, procurement and construction (EPC), owner's cost, site improvements, and commissioning. Supplementary costs account for decommissioning and contingencies. OPEX consists of wages and salaries, equipment maintenance, purchased materials and services, and insurance. The "purchased materials and services" category includes items such as water, electricity, natural gas, and diesel. The detailed cost structure can be found in the Supplementary Information.

The direct cost of the CSP section was calculated based on the plant's nominal capacity of 3.48 MW, using cost estimations provided by IRENA [50]. For the electrolysis and conditioning sections, equipment costs derived from the literature were employed, rescaling according to Eq. (1):

$$C_A = C_B \cdot \left(\frac{Q_A}{Q_B}\right)^n \tag{1}$$

where:

C_A: cost for design scale (€).
C_B: cost according to data source (€).
Q_A: capacity value for design scale.
Q_B: capacity value according to data source.
n: scale factor.

Direct costs were projected to the year 2030, considering learning and economies of scale phenomena. For the CSP section, prospective data regarding future capacity were retrieved from the International Energy Agency [51]. The most ambitious scenario presented by the IEA for reducing GHG emissions, entitled 'Net Zero Emissions by 2050', was selected. According to this scenario, 64 GW of CSP capacity will be installed by 2030. When no learning rates were found in the literature, a standard learning rate of 10% was assumed.

Regarding the hydrogen production and delivery unit, the future cost of SOE stacks depends on different factors concerning technology and market development [52]. In this study, a cost estimate of 1893 $€_{2023}$ per kW for SOE stacks in 2030 was adopted, based on information for a scenario with production scale-up and a tenfold increase in budget for research and development [52].

The costs associated with land acquisition, cleaning trucks, electricity converters, site improvements, heat exchangers, pumps, and the overall balance of the electrolysis plant were assumed to remain constant from 2023 to 2030. The scale factors, learning rates, scientific articles, and reports used for these estimations are provided in the Supplementary Information.

Regarding OPEX, the cost of electricity was assumed to decrease from 0.23 $€_{2023}$ per kWh in 2023 to 0.075 $€_{2023}$ per kWh in 2030, according to the normal year scenario of Guerra et al. [53]. The future cost of natural gas was taken from IEA [51], where a cost of 5 USD/MBtu (i.e. 4.72 USD/GJ) is stated in the Net Zero scenario. The cost of diesel was assumed to increase 32% from 2023 to 2030 [54]. The maintenance costs for the different technologies were considered as functions of their direct cost. Wages and salaries, as well as the cost of water, were considered to remain constant from 2023 to 2030. Insurance, as the last part of the operation and maintenance cost, was considered as a function of the total direct cost (7.5%).

The LCoH method recommended by the SH2E guidelines for FCH-specific LCC was used [55]. For calculating the selected economic indicator (i.e. LCoH), 30 years of operation were considered along with two years for construction. Discounting was applied to all economic calculations. The discount rate (r) used for the present-day value calculations is 5%. The average value of the Spain's harmonised index of consumer prices (HICP) over the past 26 years [56] was calculated and used as the inflation rate (2.30%). All capital assets (except the electrolysers and the cleaning trucks) were depreciated in the first 15 years of operation. As the electrolysers and the trucks have a useful life of 10 and 18 years, respectively, they were assumed to be depreciated over five and ten years. The full cash flow of the project can be found in the

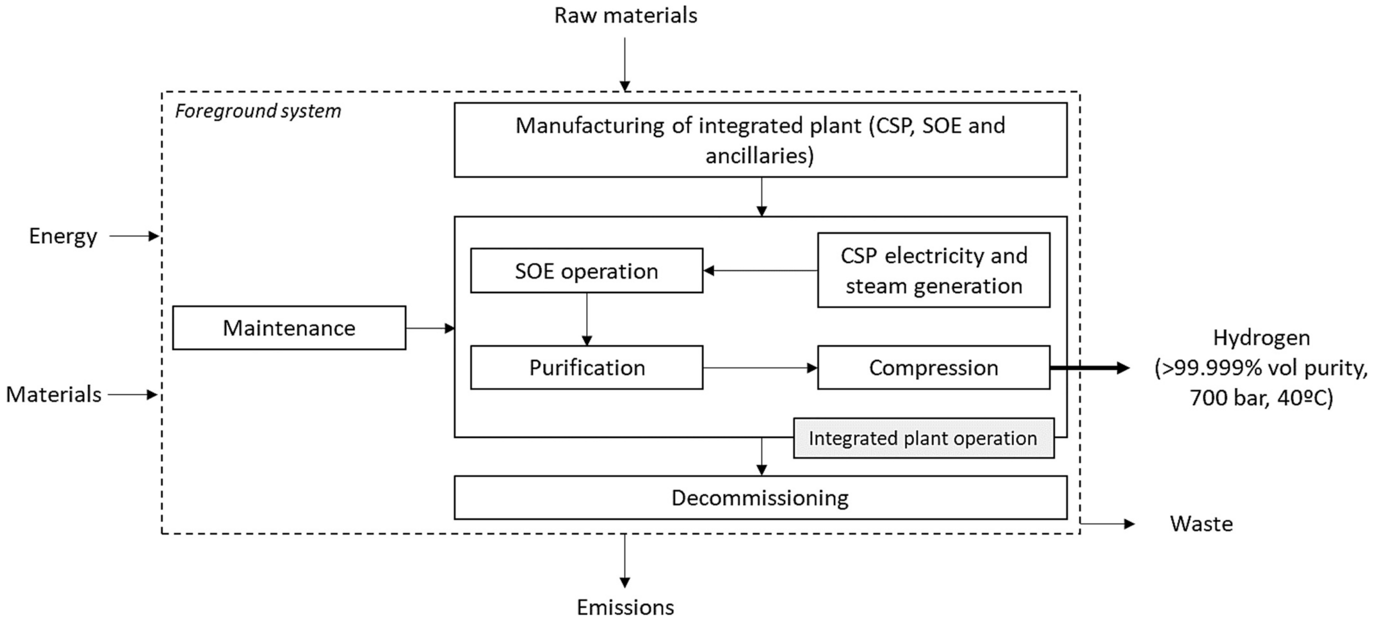

Fig. 2. System boundaries for the LCA of the integrated hydrogen production system, adapted from Puig-Samper et al. [27].

Supplementary Information.

2.2.3. Specific S-LCA methodological choices

The specific goal of the S-LCA study is to evaluate the potential social impacts of hydrogen produced through CSP + SOE in 2030, and to benchmark its social performance against that of conventional hydrogen from SMR. The system boundaries of the study were defined according to the protocol described in Martín-Gamboa et al. [35] for product-specific supply chains in S-LCA. This protocol involves the combined use of trade and conventional LCA databases to define the processes included in a given supply chain. An economic cut-off criterion of 10%, based on the LCC results, was used for defining the product-specific supply chain, which means that all those processes contributing above 10% to the final output's economic value were included in the assessment. This criterion was adopted as a trade-off between completeness and practicality. In this regard, while the SH2E guidelines [28] do not prescribe a fixed threshold –showing flexibility as long as the rationale is transparent–, future studies specifically focused on the social dimension could implement a lower cut-off criterion (e.g. 5%) to address a larger supply chain.

The unit processes within the product-specific system boundaries were geographically assigned at the country level, with Spain as the location selected for the hydrogen production plant. The geographical location of the remaining entities was determined according to the aforementioned protocol [35], with the corresponding information available in the Supplementary Information. It is important to note that, while this S-LCA study adopts a prospective approach to the technical aspects of the CSP + SOE plant, a retrospective social context was considered due to limited data availability, especially concerning the countries involved in the supply chains and their associated social conditions.

The social life cycle inventory (S-LCI) was primarily based on both the modelling of the foreground system with data obtained from Puig-Samper et al. [27] and the LCC study. The S-LCI covers operation and maintenance as well as capital goods. In addition to worker hours, utilities and services, the inventory explicitly includes construction of the CSP plant and manufacture of SOE stacks and balance of plant (BoP). Further inclusion of items such as solar receiver, mirrors and SOE stack components followed the economic cut-off criterion. The complete product-specific S-LCI of the system as well as the specific data sources behind this study are provided in the Supplementary Information. Unitary social risk levels for each plant in the product-specific supply chain representative of the CSP + SOE hydrogen production pathway were sourced from the PSILCA v3.1 database [57]. This was done by selecting a country-specific sector within the database as a proxy for the social risk levels of each product-specific plant. Activity variables were either retrieved directly in the form of worker hours or indirectly as economic flows from the LCC results. It should be noted that, since social risk levels and indirectly-estimated worker hours were based on sectoral proxies using PSILCA, future studies could consider an increased use of relevant primary data for key components in order to partly overcome this common simplification in S-LCA studies. Finally, regarding the social life cycle impact assessment (S-LCIA) stage, the PSILCA method and the involved set of social indicators [57] were used. Hence, a reference scale approach (Type I) was followed [33].

2.2.4. Sustainability benchmarking

The life-cycle sustainability performance of conventional hydrogen from SMR in Spain in 2030 was evaluated as the reference product for benchmarking the performance of hydrogen from the CSP + SOE system. To ensure consistency, the same methodological guidelines, requirements and choices (in terms of, e.g., FU, system boundaries, and impact assessment methods) as in the assessment of the CSP + SOE system were followed in the assessment of the SMR case study. In this sense, this section focuses on describing the key differences in data sources and model asymmetries with respect to the CSP + SOE system, avoiding redundancy with previously detailed methodological aspects.

The choice of hydrogen from SMR as the reference product aligns with both its still leading role expected in 2030 according to the hydrogen outlook in Europe [58] and common practice in comparative life-cycle studies of hydrogen production systems according to Puig-Samper et al. [23]. The SMR system was adapted from Susmozas et al. [59]. Process simulation tools were employed to model the SMR system projected to the year 2030, with an enhanced efficiency of 85% according to Valente et al. [60], in contrast to 78% in Susmozas et al. [59]. This efficiency improvement is expected to be a key factor in defining the performance of SMR in 2030 [61]. The increase in efficiency was implemented through improved heat integration and novel catalytic conditions in the reformer, considering hydrogen compression to 700 bar in both the original and the improved process.

The novel catalytic system considered in the reformer allows operation at a lower temperature (700 °C, compared to 850 °C in the original

SMR process) while enhancing kinetic and yield performance. The reduced heat consumption in the reformer decreases natural gas consumption in the combustor. Moreover, the improved yield in the reformer enables the use of a low-temperature water-gas shift (WGS) unit instead of a high-temperature one. This lower temperature requirement at the WGS unit inlet is facilitated by the lower temperature at the reformer outlet and integration with steam preheating exchangers. Consequently, cooling water consumption is reduced at the WGS inlet and downstream at the condenser, due to the lower temperature at the WGS outlet. Additionally, the implementation of a more efficient combustor, capable of operating at lower excess air ratios, enhances combustion and heat utilisation.

The inventory of the foreground system for each sustainability dimension was primarily derived from the process simulation adapted from Susmozas et al. [59]. Additional data sources were used to refine specific aspects of the model. In particular, the prospective version of the *ecoinvent* 3.8 cut-off database using the REMIND SSP2-NDC 2030 IAM model was consistently used for prospective environmental LCA [42], while economic data for the LCC model were based on Mullen et al. [62] and Spallina et al. [63]. For the S-LCI, worker hours, geographical information and unitary social risk levels were consistently based on the LCC model, the protocol by Martín-Gamboa et al. [35] and the PSILCA database [57], respectively. The complete inventories and impact assessment results for the SMR system in each sustainability dimension can be found in the Supplementary Information.

3. Results and discussion

3.1. Environmental results

While the complete environmental LCA results of hydrogen from CSP + SOE are provided in the Supplementary Information, Fig. 3 shows the environmental hotspot analysis in terms of three key environmental indicators in line with Puig-Samper et al. [23,27]: climate change, acidification, and material resource use (minerals and metals). Although the LCA results are similar to those reported for hydrogen from CSP + SOE by Puig-Samper et al. [27], differences arose due to divergence in terms of some methodological choices such as the use of a prospective background database in the present study. Moreover, compared to other LC(S)A studies including climate change and acidification results for other electrochemical hydrogen options powered by renewable energy [15,64], the present study assesses an emerging hydrogen production system following a prospective approach.

For all three indicators, the overall CSP section was found to dominate the environmental impacts [27]. However, there are notable differences in the hotspot analysis across these indicators. In the climate change indicator, the CSP section aggregately accounts for a contribution of 77%. In particular, the main contributor to the climate change impact stems from the operation of the plant, primarily due to direct emissions from the auxiliary use of natural gas. At this specific impact category, in line with other electrochemical hydrogen options powered by renewable energy and explored in prospective carbon footprint studies [60,65], it is also remarkable that the estimated carbon footprint (1.88 kg CO_2-eq per kg H_2) positions hydrogen from CSP + SOE as a renewable, low-carbon alternative in 2030, well below the common threshold of 3 kg CO_2-eq per kg H_2 [23]. Hydrogen leaks were not found to have a relevant effect on the assessed global warming indicators, as their quantification increased the GWP-100 and GWP-20 results by less than 1%.

In the acidification indicator, the CSP section was found to contribute around 80%. The primary hotspot is the production of the HTF [27,66], specifically the diphenyl ether compound. Similarly, the CSP section accounts for 86% of the material resource use impact for minerals and metals. The analysis reveals two primary hotspots related to ore extraction: one associated with the copper requirements for the power block system, and another linked to the production of nitrates used in the TES system [27,66].

The influence of using a prospective background database to carry out the LCA study was found to depend on the nature of the assessed impact category. When qualitatively contextualising the results with respect to those in Puig-Samper et al. [27], it can be noted that, by placing the hydrogen production plant in a prospective economic

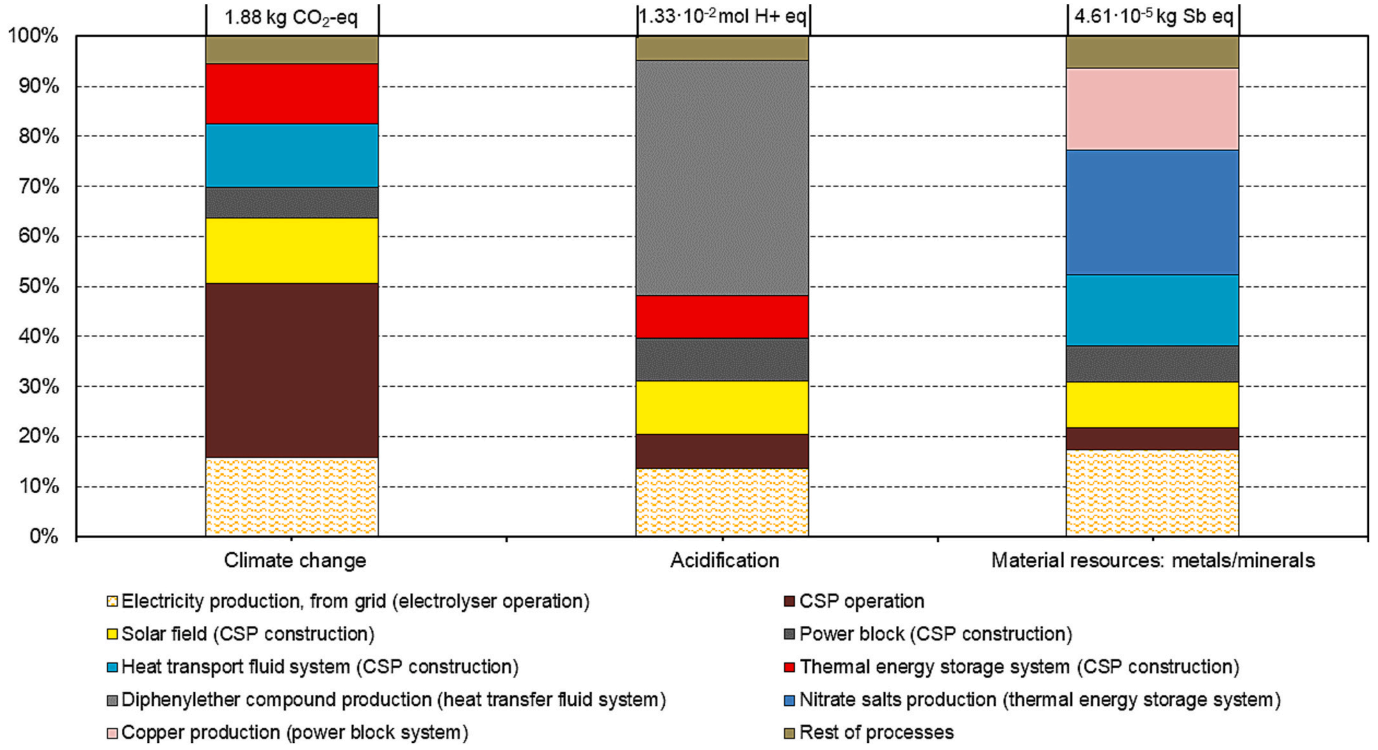

Fig. 3. Environmental hotspot analysis of the CSP + SOE system.

context, environmental impacts related to gaseous emissions are reduced while environmental impacts related to resource extraction are increased. This finding is in line with the forecasts that relate renewable energy progress to more material-intensive technologies [67], and it highlights the importance of promoting a circular economy to avoid burden-shifting across environmental impact categories.

3.2. Economic results

Fig. 4 shows the contribution of each component to the total direct cost of the future CSP + SOE plant. The total capital investment includes direct costs for CSP (14.1 $M€_{2023}$), electrolysis (7.8 $M€_{2023}$) and conditioning (0.2 $M€_{2023}$) systems. When adding indirect costs for EPC, site improvements, and additional contingency costs, the total investment reaches 29 $M€_{2023}$ to start operating in the year 2030. Further cost details can be found in the Supplementary Information.

The LCoH associated with the CSP + SOE pathway was found to be 7.64 $€_{2023}$ per kg of hydrogen, a value higher than that reported in non-prospective LCSA studies for other electrochemical hydrogen options powered by renewable energy [15] but similar to the average LCoH for renewable hydrogen production projects submitted to the second Hydrogen Bank auction in 2025 [58]. Fig. 5 shows that, with this price, the net present value (NPV) reaches zero by the end of the plant's operational life. The economic impacts of SOE stack replacements and truck cleaning requirements are also visible in the figure. The analysis of the economic flows over the plant's lifespan led to estimating the contribution of each cost category to the overall LCoH. Direct costs were found to account for the largest share (37%), followed by operational wages (30%). While the most expensive individual equipment in the entire plant is the electrolyser, the majority of capital and maintenance costs were found to be linked to the CSP section. The remaining categories show a lower contribution, being the cost of materials and services (10%) the most important among them. Further details on cost category contribution to the LCoH can also be found in the Supplementary Information.

Beyond identifying economic hotspots (such as the costs associated with the electrolyser, the CSP plant, and wages), it should be acknowledged that the reported LCC results are specific to this particular case study and they do not necessarily reflect the general performance of the SOE technology. The outcomes presented in this prospective study depend on the specific assumptions and parameters considered in the analysis, including the plant's geographical location and site-specific conditions for CSP and SOE operations. Hence, while these findings provide valuable insights into potential economic drivers of CSP + SOE systems, they should be understood within the specific context of the study.

3.3. Social results

Fig. 6 shows a breakdown of the social impacts of the CSP + SOE system, calculated using the PSILCA method. In order to streamline the discussion, lessons from Martín-Gamboa et al. [11] –based on a systematic procedure that combines data quality assessment, materiality screening, literature review, and social risk analysis– were considered to place the focus on a reduced set of social impact categories relevant to hydrogen technologies. Hence, this section focuses on three key social indicators linked to SDG 8 “decent work and economic growth”: child labour, contribution to economic development (as the only positive social indicator), and fair salary. Processes contributing less than 5% to each indicator were grouped under the label “Rest of processes”. Detailed results for the full set of social indicators are available in the Supplementary Information. Compared to other life-cycle studies including social results (e.g. child labour) for other electrochemical hydrogen options powered by renewable energy [15,68], the present study assesses an emerging hydrogen production system following a prospective approach.

The analysis highlights that the hydrogen production facility in Spain accounts for the majority of the social impacts across the assessed (positive and negative) indicators, primarily due to the relatively high labour input (worker hours) associated with this unit process. This dominance is particularly notable in the “child labour” indicator, where hydrogen production shows a significant contribution. Nevertheless, it is important to note that the child labour risk level for the corresponding country-specific sector was classified as ‘very low’ according to the PSILCA's reference scale, overall indicating minimal concerns in this area. Beyond quantitative results, the dominance of worker hours in the Spanish hydrogen facility suggests a significant opportunity to foster decent work locally. This potential should be realised through local job creation during both construction and operation. Targeted skills development programmes and local training initiatives will be essential to support workforce capacity and long-term employability.

Other notable contributors to the social impact indicators include the manufacture of metal products in Spain, as well as the production of electrical machinery and equipment in China. These unit processes, while not as prominent as hydrogen production, still represent substantial shares across the three selected indicators. For instance, according to PSILCA's reference scale within the child labour indicator, these processes fall within the ‘very low’ and ‘low’ risk levels for the specific sectors in Spain and China, respectively.

Furthermore, there are some differences between the specific unit processes contributing to each indicator. In this sense, the contributions of specific sectors such as “operational water production”, “insurance & financial services” and “engineering” in Spain also represent an opportunity to contribute to the national economic development. On the other hand, the production of chromium in Kazakhstan and the extraction and refining of natural gas in Algeria arose as additional potential sources of risk related to ensuring minimum wages that enable workers to meet their basic needs. Upstream risks highlight the need for robust human rights due diligence and responsible extraction and manufacturing practices aligned with climate justice principles to mitigate vulnerabilities in affected regions. Recommended actions include implementing supplier codes of conduct consistent with international labour

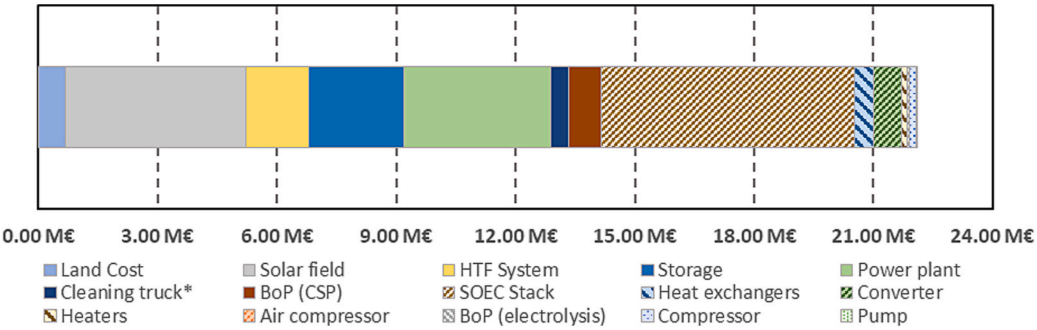

Fig. 4. Direct CAPEX of the CSP (solid colours), electrolysis (striped) and conditioning (dotted) sections.

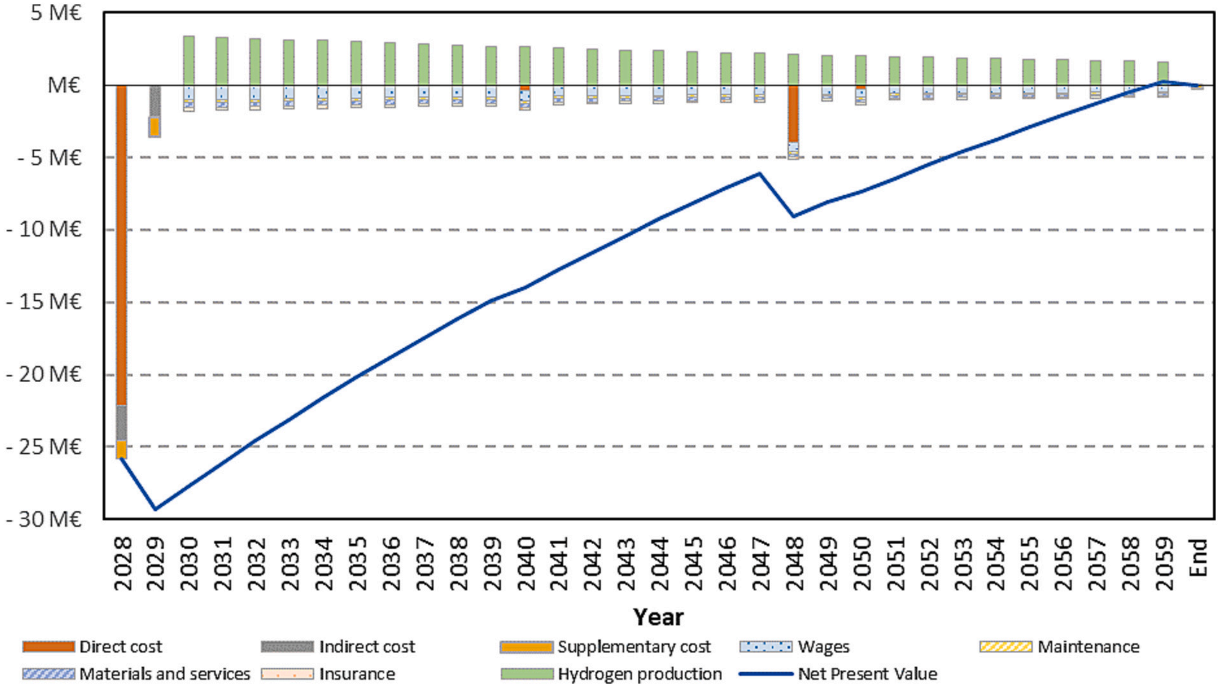

Fig. 5. Present expenses and incomes and net present value evolution (M€$_{2023}$) of the CSP + SOE system.

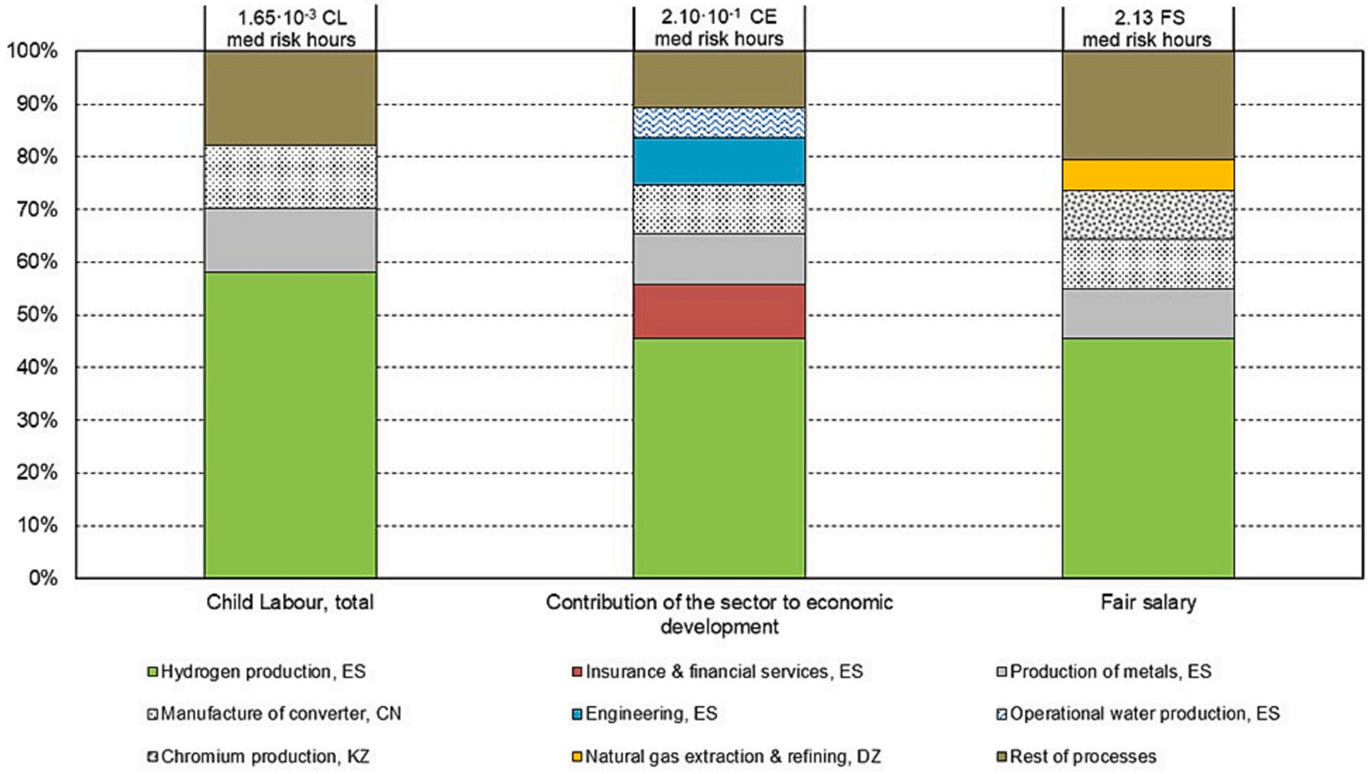

Fig. 6. Social hotspot analysis of the CSP + SOE system.

standards, ensuring traceable procurement, and promoting circular strategies. Additionally, policy measures such as local taxation schemes or prioritisation of activities that maximise local benefits across value chains can contribute to a just transition and address structural inequities, supporting decolonial approaches.

Overall, the distribution of social impact contributions across categories emphasises the role of domestic hydrogen production, but it also points out the influence of global supply chains in other social dimensions, particularly regarding fair salary standards. These findings highlight the importance of identifying social hotspots through a product-specific supply-chain approach. Further discussion and interpretation for each sustainability dimension is addressed in Section 3.4

through benchmarking against conventional hydrogen from SMR.

3.4. Joint interpretation and sustainability benchmarking against SMR hydrogen

Fig. 7 shows a visualisation of the selected set of results following the reporting recommendations in the SH2E project [28]. This figure presents the life-cycle sustainability benchmarking of hydrogen from the CSP + SOE system against its conventional counterpart, conventional hydrogen from SMR. The benchmarking results are shown relative to the sustainability impact values of conventional hydrogen, whose sustainability performance is therefore represented by the red vertical line in Fig. 7. In other words, the relative scores shown in Fig. 7 were calculated by dividing the indicator results of hydrogen from the CSP + SOE system by those of conventional hydrogen from the reference SMR system. Conventional hydrogen was found to outperform CSP + SOE hydrogen in four out of the seven sustainability indicators selected for analysis, while the full set of comparative results can be found in the Supplementary Information.

Regarding the environmental dimension, it is important to highlight that hydrogen from CSP + SOE offers a noticeably lower carbon footprint (1.88 kg CO_2-eq per kg of hydrogen) than conventional hydrogen from SMR (8.75 kg CO_2-eq per kg of hydrogen). This places CSP + SOE hydrogen as a low-carbon hydrogen option, well below the threshold of 3 kg CO_2-eq per kg of hydrogen commonly required for hydrogen to qualify as renewable [23]. However, a number of trade-offs were identified under other environmental indicators such as the use of material resources.

Concerning the economic dimension, the prospective LCoH of conventional hydrogen from SMR (1.31 $€_{2023}$ per kg of hydrogen) was found to be approximately 83% lower than that of CSP + SOE. This highlights a substantial need to improve the cost competitiveness of high-temperature (solid oxide) electrolysis at the case-study level. Optimising plant location and exploring alternative heat sources could significantly enhance the economic performance of hydrogen from SOE. Nevertheless, it is important to note that the reported cost of SMR hydrogen does not account for a potential future carbon dioxide tax on natural gas, which would increase this cost (although it would likely not bring it to the level of hydrogen from SOE).

The social benchmarking of CSP + SOE hydrogen against conventional SMR hydrogen reveals varying trends across indicators. This emphasises the importance of carefully selecting relevant social aspects for evaluation [11]. Among the indicators selected for discussion, CSP + SOE hydrogen shows an 8% higher impact in terms of child labour risk. Even though this increase is relatively minor and the involved processes present reduced risk levels, it highlights a need to monitor working conditions within the supply chain of the CSP + SOE system. In terms of fair salary risk, CSP + SOE hydrogen shows a 65% reduction, suggesting a significant improvement. This indicates that workers within the CSP + SOE supply chain are more likely to receive equitable wages than those in the conventional supply chain. While this represents an important improvement, additional mechanisms are needed within companies in terms of robust minimum wage standards' implementation, transparency, and further collaboration with local governments aimed at creating local decent jobs and inclusive employment opportunities. Finally, in terms of contribution to economic development, the CSP + SOE system shows an 88% higher impact. Since this is a positive indicator, a higher value reflects greater potential for economic growth and regional development, particularly beneficial for the host country (Spain in this case study). This should be accompanied by measures that ensure this growth is equitably distributed across different segments of society. Examples include the creation of energy communities, policies that reduce energy costs for local consumers, and frameworks that channel part of the economic gains into community development projects and public facilities.

3.5. Final remarks

Overall, the reported findings highlight the potential of high-temperature (solid oxide) electrolysis to significantly contribute to the European hydrogen economy deployment. However, in line with previous life-cycle sustainability benchmarking studies on hydrogen production systems [15,69], they also point out the need for further sustainable-by-design research and development to prevent burden-shifting across different impact categories and sustainability dimensions. In order to operationalise the concept of sustainable-by-design CSP + SOE hydrogen systems, the ecodesign strategy wheel could be considered, thus addressing aspects at the component level

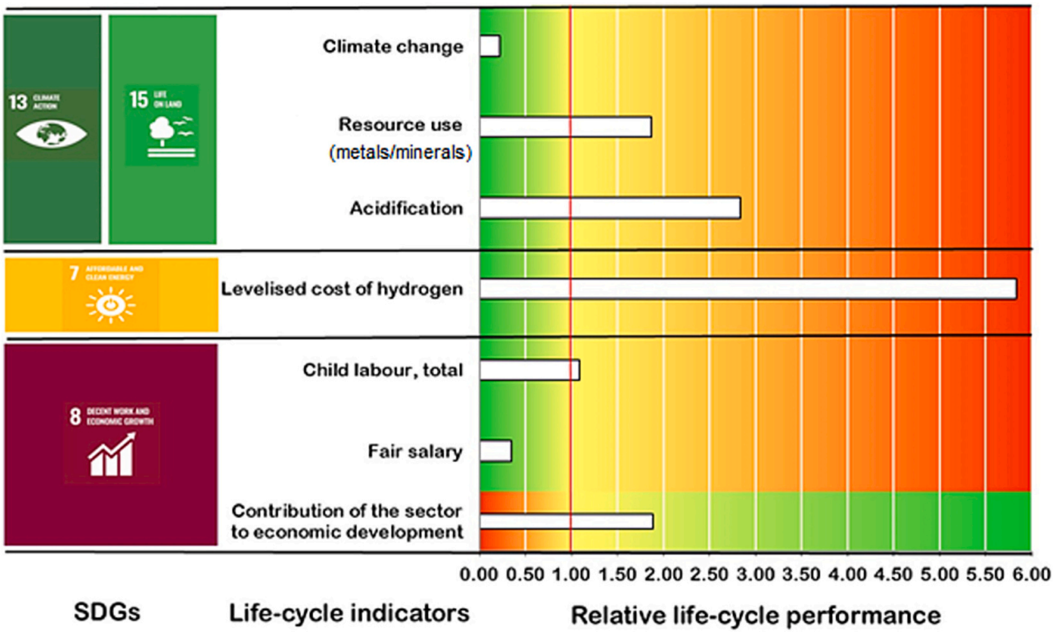

Fig. 7. Comparison of the life-cycle sustainability profile of hydrogen from CSP + SOE and conventional hydrogen from SMR (results relative to the sustainability impact values of conventional hydrogen).

(selection of low-impact materials and reduction of materials usage), at the structure level (optimisation of production techniques and distribution, and reduction of impact during use), and at the product system level (optimisation of lifetime and end-of-life strategy). Campos-Carriedo et al. [70] proposed a parametric life-cycle framework to promote sustainable-by-design product development and applied it to a SOE stack for hydrogen production, showing how different product concepts progressively improve the sustainability performance of the technology mainly through reduced material intensity.

It should be noted that this LCSA study is case-specific. Hence, different results are expected to be obtained when exploring alternative (operational and/or methodological) conditions. For instance, a better technical performance could be achieved in other locations (e.g. MENA region or northern Chile), whose environmental, economic and social implications would require a specific LCSA study. Future studies could also consider alternative methodological choices (e.g. a lower economic cut-off criterion for supply chain definition in S-LCA) and sustainability benchmarking against other hydrogen production technologies such as autothermal reforming with CO_2 capture. In this regard, beyond the scope of this work, it should be acknowledged that future efforts regarding aspects such as sensitivity analysis and materiality assessment could provide further insights into the life-cycle sustainability performance of the hydrogen system under study [28]. For illustrative purposes, Fig. 8 shows the sensitivity of the economic indicator (LCoH) to the SOE stack price, the discount rate, and the labour cost considered in this study. As expected, variations of up to ±50% in these parameters were found to lead to changes in the absolute value of the LCoH. However, within the range of variation considered, these changes would not alter the overall conclusions of the study, suggesting that the results are reasonably robust to uncertainties in the selected parameters.

4. Conclusions

This study successfully conducted a prospective LCSA of hydrogen produced via SOE powered by CSP in Spain in 2030, prospectively benchmarking its performance against conventional hydrogen from SMR. Sustainability hotspots were identified across environmental, economic and social dimensions. Environmentally, the CSP section contributes the most to the indicators selected for discussion, i.e., climate change, acidification, and use of material resources. Specific hotspots were identified in the operational stage, notably from direct emissions of natural gas for climate change and diphenyl ether production for acidification, and in the infrastructure, primarily from copper requirements in the material resource use indicator. Economically, the LCoH of CSP + SOE hydrogen was estimated at 7.64 $€_{2023}$ per kg of hydrogen. Wages represent a major cost driver (30% of the LCoH) followed by the CSP (27%) and electrolysis (19%) systems. Finally, social impacts are concentrated in the hydrogen production stage due to high labour demands. Additionally, upstream supply chain risks, such as those related to chromium production in Kazakhstan and natural gas extraction and refining in Algeria, indicate areas needing careful monitoring of working conditions.

Although conventional SMR hydrogen outperforms CSP + SOE hydrogen in four out of the seven sustainability indicators selected for discussion, the latter shows promising sustainability advantages, including a significantly lower carbon footprint (around 80% reduction), reduced risks related to fair wages (65% reduction), and enhanced potential for regional economic development (88% increase). These findings suggest that SOE, when coupled with CSP, has strong potential to support the European hydrogen economy. However, further sustainable-by-design research and innovation are essential to improve cost-competitiveness and address potential environmental concerns and supply chain risks, thereby mitigating burden-shifting across impact categories and sustainability dimensions.

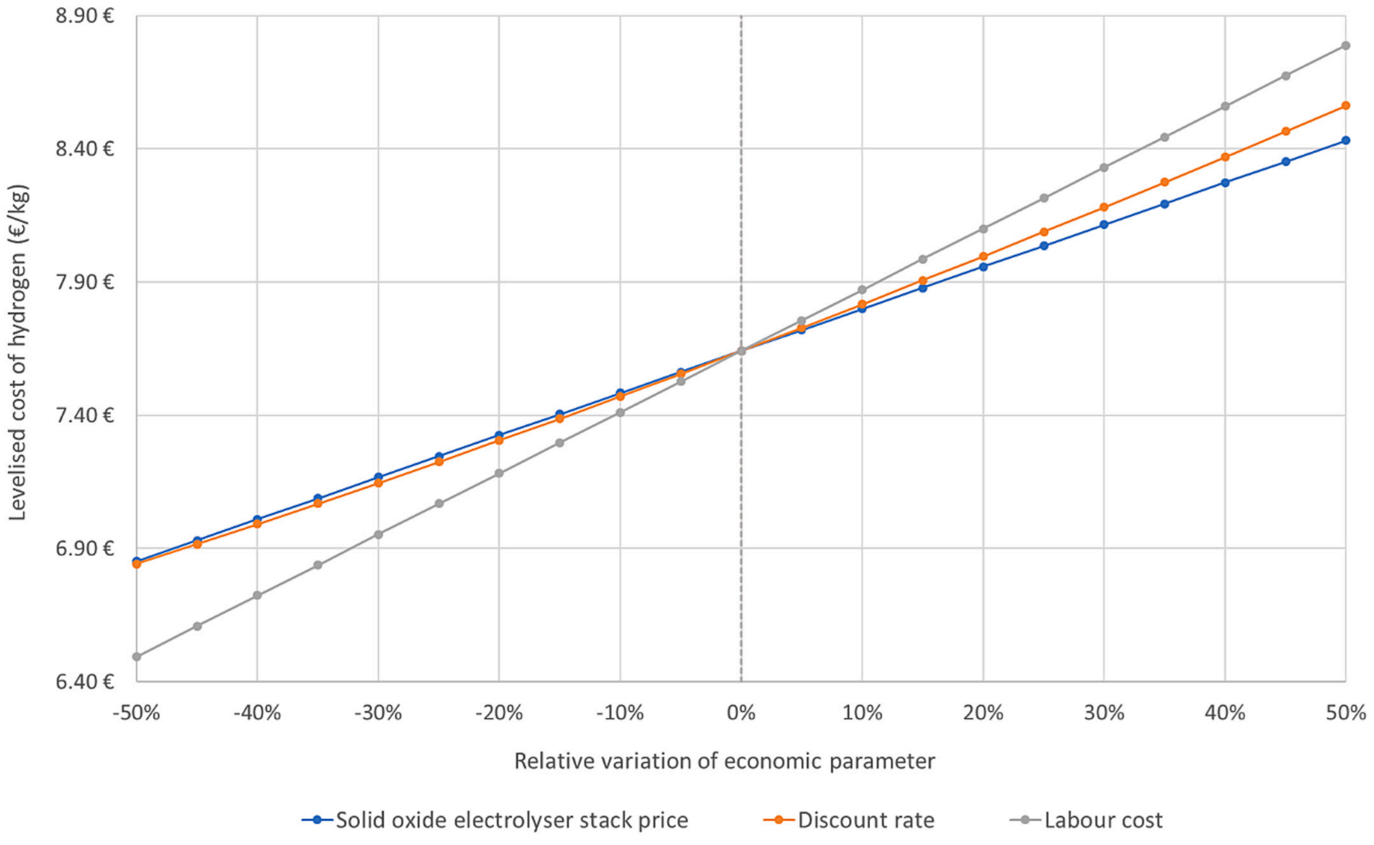

Fig. 8. Sensitivity of the levelised cost of hydrogen from the CSP + SOE system to variations in stack price, discount rate, and labour cost.

The successful application of the SH2E guidelines in the present case study, utilising a harmonised LCSA framework, highlights the relevance of addressing methodological consistency across sustainability dimensions, particularly through common methodological decisions and transparency on model asymmetries. This opens the door to a broader use of the SH2E guidelines, which are designed for any practitioner conducting LCSA of FCH systems. The guidelines steer core methodological choices (functional unit, system boundaries, etc.) and FCH-specific topics (e.g. supply-chain segmentation and data sources), providing a robust foundation for LCSA in this context. Looking ahead, harmonised practice is essential when it comes to generating consistent and comparable sustainability results; otherwise, studies may reach misleading conclusions that hinder trust and action. Future assessments can build upon these guidelines to deliver reliable evidence that supports informed decisions by industry, policy-makers and society, thus contributing to a sustainable deployment of hydrogen systems.

CRediT authorship contribution statement

Mario Martín-Gamboa: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Felipe Campos-Carriedo:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Santiago Abelleira:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Pedro L. Cruz:** Writing – original draft, Investigation, Formal analysis. **Christina Wulf:** Writing – original draft, Methodology, Investigation, Formal analysis. **Javier Dufour:** Writing – review & editing, Project administration, Funding acquisition. **Diego Iribarren:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuproc.2026.108417.

Data availability

Data used in this research work is available in the article, including supplementary material.

References

[1] European Commission, The European Green Deal – Brussels, 11.12.2019 COM (2019) 640 Final, European Commission, Brussels, 2019.

[2] General Assembly UN, Transforming our World: The 2030 Agenda for Sustainable Development, United Nations, New York, 2015.

[3] IEA, World Energy Investment 2024, International Energy Agency, Paris, 2024.

[4] OECD, Investing in Climate, Investing in Growth, OECD Publishing, Paris, 2017.

[5] European Commission, A Green Deal Industrial Plan for the Net-Zero Age (COM (2023) 62 Final), European Commission, Brussels, 2023.

[6] European Commission, COM (2023) 161 Final 2023/0081(COD) – Proposal for a Regulation of the European Parliament and of the Council on Establishing a Framework of Measures for Strengthening Europe's Net-zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act), European Commission, Brussels, 2023.

[7] European Commission, A Hydrogen Strategy for a Climate-Neutral Europe (COM (2020) 301 Final), European Commission, Brussels, 2020.

[8] EU Platform on Sustainable Finance, Final Report on Social Taxonomy, EU Platform on Sustainable Finance, Brussels, 2022.

[9] EU Platform on Sustainable Finance, The Extended Environmental Taxonomy: Final Report on Taxonomy Extension Options Supporting a Sustainable Transition, EU Platform on Sustainable Finance, Brussels, 2022.

[10] S. Carrara, S. Bobba, D. Blagoeva, P. Alves Dias, A. Cavalli, K. Georgitzikis, et al., Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU – A Foresight Study, Publications Office of the European Union, Luxembourg, 2023.

[11] M. Martín-Gamboa, L. Mancini, U. Eynard, A. Arrigoni, A. Valente, E. Weidner, F. Mathieux, Social life cycle hotspot analysis of future hydrogen use in the EU, Int. J. Life Cycle Assess. 30 (2025) 1379–1396, https://doi.org/10.1007/s11367-024-02335-5.

[12] IRENA, Shaping Sustainable International Hydrogen Value Chains, International Renewable Energy Agency, Abu Dhabi, 2024.

[13] L. Cremonese, G.K. Mbungu, R. Quitzow, The sustainability of green hydrogen: an uncertain proposition, Int. J. Hydrog. Energy 48 (2023) 19422–19436, https://doi.org/10.1016/j.ijhydene.2023.01.350.

[14] S. Moreira, T.J. Laing, Sufficiency, Sustainability, and Circularity of Critical Materials for Clean Hydrogen, World Bank, Washington, 2022.

[15] A. Valente, D. Iribarren, J. Dufour, Comparative life cycle sustainability assessment of renewable and conventional hydrogen, Sci. Total Environ. 756 (2021) 144132, https://doi.org/10.1016/j.scitotenv.2020.144132.

[16] S. Valdivia, C.M.L. Ugaya, G. Sonnemann, J. Hildebrand, et al., Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products, UNEP/SETAC Life Cycle Initiative, Paris, 2011.

[17] S. Sala, F. Farioli, A. Zamagni, Life cycle sustainability assessment in the context of sustainability science progress (part 2), Int. J. Life Cycle Assess. 18 (2013) 1686–1697, https://doi.org/10.1007/s11367-012-0509-5.

[18] L. Stamford, Life cycle sustainability assessment in the energy sector, in: J. Ren, A. Scipioni, A. Manzardo, H. Liang (Eds.), Biofuels for a more Sustainable Future: Life Cycle Sustainability Assessment and Multi-Criteria Decision Making, Elsevier, Amsterdam, 2020, pp. 115–163, https://doi.org/10.1016/B978-0-12-815581-3.00005-1.

[19] H. Li, X. Yao, M.A. Tachega, D. Ahmed, M.G.A. Ismaail, Technology selection for hydrogen production in China by integrating emergy into life cycle sustainability assessment, J. Clean. Prod. 294 (2021) 126303, https://doi.org/10.1016/j.jclepro.2021.126303.

[20] J. Ren, S. Toniolo, Life cycle sustainability decision-support framework for ranking of hydrogen production pathways under uncertainties: an interval multi-criteria decision making approach, J. Clean. Prod. 175 (2018) 222–236, https://doi.org/10.1016/j.jclepro.2017.12.070.

[21] A. Valente, D. Iribarren, J. Dufour, Life cycle sustainability assessment of hydrogen from biomass gasification: a comparison with conventional hydrogen, Int. J. Hydrog. Energy 44 (2019) 21193–21203, https://doi.org/10.1016/j.ijhydene.2019.01.105.

[22] C. Wulf, P. Zapp, A. Schreiber, W. Kuckshinrichs, Integrated Life Cycle Sustainability Assessment: Hydrogen Production as a Showcase for an Emerging Methodology, in: Z.S. Klos, J. Kalkowska, J. Kasprzak (Eds.), Towards a Sustainable Future – Life Cycle Management, Springer, Cham, 2022, pp. 97–106, https://doi.org/10.1007/978-3-030-77127-0_9.

[23] G. Puig-Samper, E. Bargiacchi, D. Iribarren, J. Dufour, Life-cycle assessment of hydrogen systems: a systematic review and meta-regression analysis, J. Clean. Prod. 470 (2024) 143330, https://doi.org/10.1016/j.jclepro.2024.143330.

[24] M.A. Palmero-González, E. Batuecas, C. Marugán-Cruz, D. Santana, Life cycle assessment studies of concentrated solar power technology: a literature review, Sustain. Energy Technol. Assess. 75 (2025) 104257, https://doi.org/10.1016/j.seta.2025.104257.

[25] S. Longo, R. Rincione, M. Cellura, F. Rossi, A. Sinicropi, M.L. Parisi, Life cycle assessment of concentrating solar power systems and concentrating photovoltaic systems: a review, Energy Rep. 14 (2025) 4526–4539, https://doi.org/10.1016/j.egyr.2025.11.067.

[26] R. Kumar, V. Yadav, R. Suman, K. Gidwani, M. Agrawal, Life cycle assessment (LCA) of high-temperature solar thermal technologies, in: C. McGregor, V.P. Singh, A. Kumar (Eds.), High-Temperature Solar Thermal Systems, Springer, Cham, 2025, pp. 391–406, https://doi.org/10.1007/978-3-032-07641-0_18.

[27] G. Puig-Samper, E. Bargiacchi, D. Iribarren, J. Dufour, Assessing the prospective environmental performance of hydrogen from high-temperature electrolysis coupled with concentrated solar power, Renew. Energy 196 (2022) 1258–1268, https://doi.org/10.1016/j.renene.2022.07.066.

[28] M. Martín-Gamboa, F. Campos-Carriedo, D. Iribarren, J. Dufour, C. Wulf, A. Schreiber, et al., SH2E Guidebook for LCSA. SH2E Project, 2024.

[29] IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, International Renewable Energy Agency, Abu Dhabi, 2020.

[30] ISO, ISO 14040:2006a Environmental Management — Life Cycle Assessment — Principles and Framework, International Organization for Standardization, Geneva, 2006.

[31] ISO, ISO 14044:2006b Environmental Management — Life Cycle Assessment — Requirements and Guidelines, International Organization for Standardization, Geneva, 2006.

[32] T.E. Swarr, D. Hunkeler, W. Klöpffer, H.-L. Pesonen, A. Ciroth, A.C. Brent, R. Pagan, Environmental Life Cycle Costing: A Code of Practice, SETAC, Brussels, 2011.

[33] UNEP, Guidelines for Social Life Cycle Assessment of Products and Organizations 2020, United Nations Environment Programme, Paris, 2020.

[34] A.M. Bazzanella, F. Ausfelder, Low Carbon Energy and Feedstock for the European Chemical Industry, DECHEMA, Frankfurt, 2017.

[35] M. Martín-Gamboa, A.C. Dias, L. Arroja, D. Iribarren, A protocol for the definition of supply chains in product social life cycle assessment: application to bioelectricity, Sustain Energy Fuels 4 (2020) 5533–5542, https://doi.org/10.1039/d0se00919a.

[36] E. Bargiacchi, G. Puig-Samper, F. Campos-Carriedo, D. Iribarren, J. Dufour, A. Ciroth, et al., Definition of FCH-LCA Guidelines. SH2E Project, 2024.

[37] J.J. Burkhardt, G.A. Heath, C.S. Turchi, Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives, Environ. Sci. Technol. 45 (2011) 2457–2464, https://doi.org/10.1021/es1033266.

[38] Clean Hydrogen Partnership, Strategic Research and Innovation Agenda 2021–2027, Clean Hydrogen Partnership, Brussels, 2022.

[39] M.B. Elbeh, A.K. Sleiti, Analysis and optimization of concentrated solar power plant for application in arid climate, Energy Sci. Eng. 9 (2021) 784–797, https://doi.org/10.1002/ese3.742.

[40] D. Yadav, R. Banerjee, Net energy and carbon footprint analysis of solar hydrogen production from the high-temperature electrolysis process, Appl. Energy 262 (2020) 114503, https://doi.org/10.1016/j.apenergy.2020.114503.

[41] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, Int. J. Life Cycle Assess. 21 (2016) 1218–1230, https://doi.org/10.1007/s11367-016-1087-8.

[42] R. Sacchi, T. Terlouw, K. Siala, A. Dirnaichner, C. Bauer, B. Cox, C. Mutel, V. Daioglou, G. Luderer, PRospective EnvironMental Impact asSEment (*premise*): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models, Renew. Sust. Energ. Rev. 160 (2022) 112311, https://doi.org/10.1016/j.rser.2022.112311.

[43] T. Aboumahboub, C. Auer, N. Bauer, L. Baumstark, C. Bertram, S. Bi, et al., REMIND - REgional Model of INvestments and Development – Version 2.1.0, Potsdam Institute for Climate Impact Research, Potsdam, 2020.

[44] S. Andreasi Bassi, F. Biganzoli, N. Ferrara, A. Amadei, A. Valente, S. Sala, F. Ardente, Updated characterisation and normalisation factors for the environmental footprint 3.1 Method, Publications Office of the European Union, Luxembourg, 2023, https://doi.org/10.2760/798894.

[45] European Commission, Commission Recommendation (EU) 2021/2279 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, European Commission, Brussels, 2021.

[46] A. Arrigoni, L. Bravo Diaz, Hydrogen Emissions from a Hydrogen Economy and their Potential Global Warming Impact, Publications Office of the European Union, Luxembourg, 2022, https://doi.org/10.2760/065589.

[47] R.G. Derwent, Global warming potential (GWP) for hydrogen: Sensitivities, uncertainties and meta-analysis, Int. J. Hydrog. Energy 48 (2023) 8328–8341, https://doi.org/10.1016/j.ijhydene.2022.11.219.

[48] N. Warwick, P. Griffiths, J. Keeble, A. Archibald, J. Pyle, K. Shine, Atmospheric Implications of Increased Hydrogen Use, Government of the United Kingdom, London, 2022.

[49] B. Steubing, D. de Koning, A. Haas, C.L. Mutel, The activity Browser — an open source LCA software building on top of the brightway framework, Softw Impacts 3 (2020) 100012, https://doi.org/10.1016/j.simpa.2019.100012.

[50] IRENA, Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi, 2022.

[51] IEA, World Energy Outlook 2022, International Energy Agency, Paris, 2022.

[52] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, S. Few, Future cost and performance of water electrolysis: an expert elicitation study, Int. J. Hydrog. Energy 42 (2017) 30470–30492, https://doi.org/10.1016/j.ijhydene.2017.10.045.

[53] K. Guerra, R. Gutiérrez-Alvarez, O.J. Guerra, P. Haro, Opportunities for low-carbon generation and storage technologies to decarbonise the future power system, Appl. Energy 336 (2023) 120828, https://doi.org/10.1016/j.apenergy.2023.120828.

[54] A. Soler, V. Gordillo, W. Lilley, P. Schmidt, W. Werner, T. Houghton, S. Dell'Orco, E-Fuels: A Technoeconomic Assessment of European Domestic Production and Imports towards 2050, Concawe, Brussels, 2022.

[55] C. Wulf, P. Zapp, A. Schonhoff, E. Bargiacchi, D. Iribarren, J. Dufour, et al., Definition of FCH-LCC Guidelines. SH2E Project, 2022.

[56] INE, Harmonised Index of Consumer Prices (HICP), Instituto Nacional de Estadística, Madrid, 2024.

[57] M. Loubert, K. Maister, C. Di Noi, L. Radwan, A. Ciroth, M. Srocka, PSILCA v3.1 a Product Social Impact Life Cycle Assessment Database – Documentation, GreenDelta, Berlin, 2023.

[58] A. Deasy-Millar, D. Fraile, M. Muron, G. Pawelec, S. Santos, O. Staudenmayer, Clean Hydrogen Monitor 2025, Hydrogen Europe, Brussels, 2025.

[59] A. Susmozas, D. Iribarren, J. Dufour, Life-cycle performance of indirect biomass gasification as a green alternative to steam methane reforming for hydrogen production, Int. J. Hydrog. Energy 38 (2013) 9961–9972, https://doi.org/10.1016/j.ijhydene.2013.06.012.

[60] A. Valente, D. Iribarren, J. Dufour, Prospective carbon footprint comparison of hydrogen options, Sci. Total Environ. 728 (2020) 138212, https://doi.org/10.1016/j.scitotenv.2020.138212.

[61] Z. Navas-Anguita, D. García-Gusano, D. Iribarren, A review of techno-economic data for road transportation fuels, Renew. Sust. Energ. Rev. 112 (2019) 11–26, https://doi.org/10.1016/j.rser.2019.05.041.

[62] D. Mullen, L. Herraiz, J. Gibbins, M. Lucquiaud, On the cost of zero carbon hydrogen: a techno-economic analysis of steam methane reforming with carbon capture and storage, Int. J. Greenh. Gas Con. 126 (2023) 103904, https://doi.org/10.1016/j.ijggc.2023.103904.

[63] V. Spallina, D. Pandolfo, A. Battistella, M.C. Romano, Annaland M. Van Sint, F. Gallucci, Techno-economic assessment of membrane assisted fluidized bed reactors for pure H_2 production with CO_2 capture, Energy Convers. Manag. 120 (2016) 257–273, https://doi.org/10.1016/j.enconman.2016.04.073.

[64] J. Gerhardt-Mörsdorf, F. Peterssen, P. Burfeind, M. Benecke, B. Bensmann, R. Hanke-Rauschenbach, C. Minke, Life cycle assessment of a 5 MW polymer exchange membrane water electrolysis plant, Adv. Energy Sustainability Res. 5 (2024) 2300135, https://doi.org/10.1002/aesr.202300135.

[65] K. de Kleijne, H. de Coninck, R. van Zelm, M.A.J. Huijbregts, S.V. Hanssen, The many greenhouse gas footprints of green hydrogen, Sustain Energy Fuels 6 (2022) 4383–4387, https://doi.org/10.1039/d2se00444e.

[66] L.Q. Luu, M. Cellura, S. Longo, F. Guarino, A comparison of the life-cycle impacts of the concentrating solar power with the product environmental footprint and ReCiPe methods, Energies 17 (2024) 4461, https://doi.org/10.3390/en17174461.

[67] IEA, The Role of Critical Minerals in Clean Energy Transitions, International Energy Agency, Paris, 2021.

[68] R.A. dos Reis, G.P. Rangel, B. Neto, Social life cycle assessment of green hydrogen production: evaluating a projected Portuguese industrial production plant, Renew. Energy 235 (2024) 121293, https://doi.org/10.1016/j.renene.2024.121293.

[69] M.B. Hannouf, T. Gates, G. Assefa, I. Gates, Advancing hydrogen sustainability in Alberta: Life cycle sustainability assessment of hydrogen production pathways, J. Clean. Prod. 530 (2025) 146850, https://doi.org/10.1016/j.jclepro.2025.146850.

[70] F. Campos-Carriedo, P. Pérez-López, J. Dufour, D. Iribarren, A parametric life cycle framework to promote sustainable-by-design product development: Application to a hydrogen production technology, J. Clean. Prod. 469 (2024) 143129, https://doi.org/10.1016/j.jclepro.2024.143129.