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# Life cycle sustainability assessment of hydrogen from biomass gasification: A comparison with conventional hydrogen

*Antonio Valente* [a,b], *Diego Iribarren* [a,*], *Javier Dufour* [a,b]

[a] *Systems Analysis Unit, IMDEA Energy, 28935, Móstoles, Spain*

[b] *Chemical and Environmental Engineering Group, Rey Juan Carlos University, 28933, Móstoles, Spain*

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ABSTRACT

Hydrogen is a key product for a cleaner energy sector. However, the suitability of the different hydrogen production options should be checked from a life-cycle perspective. The Life Cycle Sustainability Assessment (LCSA) methodology is helpful for this purpose, allowing a thorough interpretation of a product system's performance by integrating economic, environmental and social indicators. This work presents an LCSA of renewable hydrogen from biomass gasification, and its sustainability benchmarking against conventional hydrogen from steam methane reforming. Environmental (global warming and acidification), economic (levelised cost) and social (child labour, gender wage gap, and health expenditure) life-cycle indicators are characterised and jointly interpreted. The results show that hydrogen from biomass gasification cannot yet be thoroughly considered a sustainable alternative to conventional hydrogen mainly due to economic and social concerns. However, improvement actions leading to an increase in process efficiency would significantly enhance the system's performance in each of the three sustainability dimensions.



## Introduction

Hydrogen is acknowledged as a crucial energy product towards the decarbonisation of the energy sector [1], with potential applications across different areas such as transport, residential heating, and power generation [2–4]. Moreover, numerous technological pathways –involving different feedstock and energy sources [5]– are available for the production of hydrogen. However, in order to actually contribute to establishing a cleaner and sustainable energy sector, hydrogen needs to be produced from renewable, clean and affordable feedstock and energy [6–8]. In this sense, the assessment of environmental, economic and social aspects from a life-cycle perspective is needed to thoroughly check the sustainability performance of hydrogen energy systems.

Life Cycle Sustainability Assessment (LCSA) arises as a suitable methodology when it comes to comprehensively evaluating and jointly interpreting economic, environmental and social aspects of product systems [9]. Regarding the evaluation of the environmental and economic dimensions, the use of the well-established Life Cycle Assessment [10,11] and Life Cycle Costing (LCC) [12] methodologies is commonly involved. Finally, for the evaluation

* Corresponding author.
E-mail address: diego.iribarren@imdea.org (D. Iribarren).

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of the social dimension, Social Life Cycle Assessment (SLCA) is considered the reference methodology [13,14], though less mature than LCA and LCC.

According to the scientific literature available on the life-cycle evaluation of hydrogen energy systems, the situation regarding the number of LCA, LCC and SLCA studies is significantly unbalanced, as shown in Fig. 1. A relatively high number of studies address the environmental dimension through LCA, with global warming (GWP), acidification (AP) and cumulative energy demand (CED) as the most common life-cycle environmental indicators [15]. A considerably lower number of studies assess the economic dimension from a life-cycle perspective, with capital expenses (CAPEX), operating expenses (OPEX), levelised cost of hydrogen (LCoH) and climate change-related external costs as common life-cycle economic indicators. It should be noted that less than a half of these LCC studies address renewable hydrogen production systems, and a short number of them provide a joint interpretation of environmental and economic life-cycle indicators [16–20].

Regarding SLCA, being a relatively novel area, its application to hydrogen energy systems is still very scarce. Hence, the identification of the most common social life-cycle indicators could be misleading. The few studies assessing the social dimension with an actual life-cycle perspective address hydrogen produced through alkaline water electrolysis powered by different national electricity production mixes [21,22].

Regarding LCSA, only [21] provides a complete sustainability picture by jointly interpreting environmental, economic and social life-cycle indicators. In fact, no studies providing a life-cycle sustainability benchmarking of alternative hydrogen options against conventional hydrogen were found. For the purposes of this article, “sustainability benchmarking” refers to the comparison of a set of environmental,

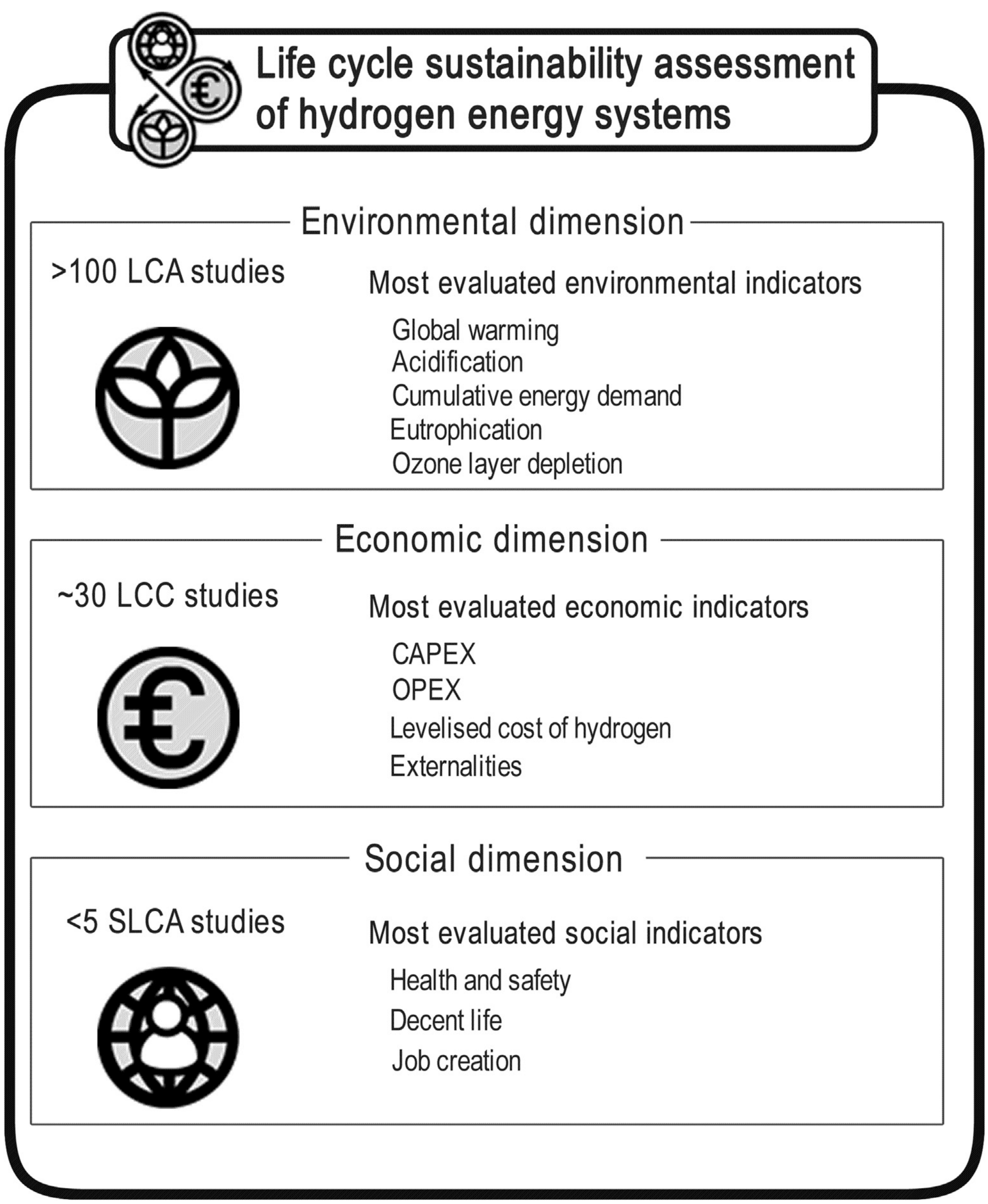


**Fig. 1 – Literature overview of life-cycle studies of hydrogen energy systems.**

economic and social life-cycle indicators of a given hydrogen option against those of a reference system (herein represented by conventional hydrogen from natural gas steam reforming).

In other studies on the sustainability assessment of hydrogen energy systems, the focus is not on the life-cycle performance but on other aspects such as plant inherent hazards [23] and multi-criteria decision analysis [24,25], applying the life-cycle concept mainly to the environmental component of the analysis. Overall, according to the state-of-the-art in hydrogen energy systems analysis, a lack of case studies addressing sustainability with an actual life-cycle perspective is acknowledged. This work contributes to filling this gap by (i) assessing the life-cycle sustainability performance of renewable hydrogen produced through biomass gasification, and (ii) robustly benchmarking such a performance against conventional hydrogen from steam methane reforming (SMR) under environmental, economic and social life-cycle indicators.

## Material and methods

To achieve the goal of a robust life-cycle sustainability benchmarking of hydrogen from biomass gasification ($BG\_H_2$) against conventional hydrogen from natural gas steam reforming ($SMR\_H_2$), both systems need to be characterised through a set of environmental, economic and social life-cycle indicators. Fig. 2 shows the methodological framework developed in this study for the LCSA of hydrogen energy systems.

The definition of the two hydrogen production systems was based on [26,27]. Fig. 3 shows the main components, processes and operating conditions for both the renewable hydrogen system (Fig. 3a) and the conventional one (Fig. 3b). The two hydrogen production plants were assumed to be located in Spain, and they involve a high daily capacity of hydrogen production (110 t and 470 t for $BG\_H_2$ and $SMR\_H_2$, respectively), 310 operating days per year, and similar total investment costs [17]. Both systems were assessed from feedstock production to hydrogen compression, and the functional unit (FU) was defined as 1 kg of hydrogen with 99.9 vol% purity at 200 bar and 25 °C [28].

When pursuing a robust benchmarking study, a significant aspect that needs to be taken into account is the mitigation of misinterpretation concerns due to inconsistent methodological choices. In this regard, for the environmental component of the analysis, libraries of harmonised life-cycle environmental indicators are available for a wide range of hydrogen options in terms of GWP [28], AP [29], and CED [30]. The use of harmonised values in comparative studies guarantees methodological consistency regarding the life-cycle impact assessment method, the general modelling approach, system boundaries, the FU, multifunctionality approaches, and the final conditions of hydrogen [28–31]. As shown in Fig. 2, GWP and AP were the environmental life-cycle indicators selected for the study due to both their relevance and their availability as harmonised indicators [28,29]. It should be noted that, due to potential duplicity concerns associated with the expected correlation between GWP and CED [30,31], the CED indicator was not included in the study.

As regards the economic dimension of the analysis, the life-cycle indicator considered was the LCoH, i.e. the ratio of the total system cost over its lifetime to the amount of hydrogen produced over the lifespan. The use of LCoH allows comparisons between technologies with different features such as capacity, size and lifespan, while including a number of economic and financial contributions to the final cost (e.g., capital costs, operating and maintenance costs, avoided costs, taxes, and incomes) [32]. For the specific systems defined in this study, the LCoH can be directly retrieved from Ref. [17]. Table 1 gathers the life-cycle environmental and economic indicators used in this study which are directly available for both $BG\_H_2$ and $SMR\_H_2$.

On the other hand, regarding the social component of the analysis, the SLCA of hydrogen energy systems is still underdeveloped. Thus, robust social life-cycle indicators for the hydrogen systems under study are not directly available. To fill this gap towards a comprehensive life-cycle sustainability benchmarking of $BG\_H_2$ against $SMR\_H_2$, the SLCA of both hydrogen energy systems was specifically undertaken in this work. Figs. 4 and 5 show the scope defined for the social assessment of $BG\_H_2$ and $SMR\_H_2$, respectively. In these figures, each process box can be understood as a separate plant involved in the supply chain of each hydrogen option. For each system, those plants with a high contribution to the system's economic [17] and environmental [26] performance were included in the scope of the social assessment. The methodological approach to the quantification of social life-cycle indicators was based on the PSILCA database [33], which acts as both a data source and an impact assessment method. Accordingly, two main terms drive the characterisation of each social indicator: (i) the hours worked at each plant $p$ per FU ($W_p$), and (ii) the risk factor for each social indicator $j$ and plant $p$ ($R_{j,p}$, expressed in medium risk hours, mrh, per working hour). Eq. (1) represents this quantification procedure:

$$S_j = \sum_{p=1}^{n} W_p \cdot R_{j,p} \tag{1}$$

where $S_j$ represents the characterisation result (in mrh per FU) for the social indicator $j$, and $n$ is the number of plants included in the system (P1–P13 for $BG\_H_2$ in Fig. 4, and P1–P14 for $SMR\_H_2$ in Fig. 5).

$W_p$ can be understood as a term of activity specific to the plant $p$, and $R_{j,p}$ as a term of intensity specific to the social indicator $j$ as well as to the country and sector associated with the plant $p$ according to the PSILCA database [33]. Regarding the activity term, two situations are distinguished: (i) direct quantification of the working hours per FU for those plants with specific inventories built in the study (i.e., P9 and P13 in Fig. 4, and P10 and P14 in Fig. 5; see Section Life-cycle inventories for social assessment), and (ii) indirect quantification of the working hours per FU for the remaining plants. For the latter, the application of Eq. (2) before Eq. (1) is required in order to convert the inventoried economic flows (see Section Life-cycle inventories for social assessment) into working hours:

$$W_p = V_p \cdot W_p^{'} \tag{2}$$

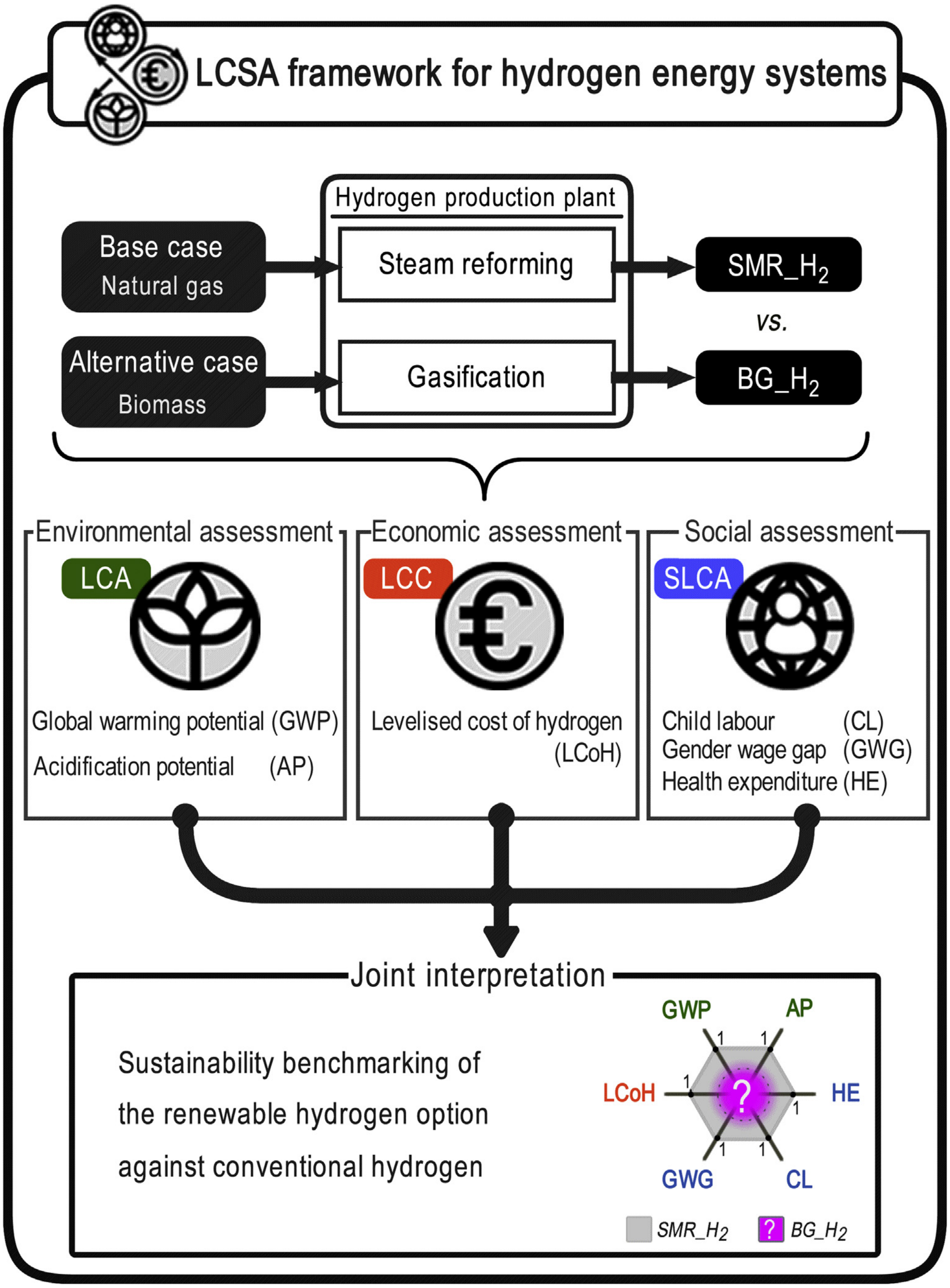


**Fig. 2 – Methodological framework for the LCSA of hydrogen energy systems.**

where $V_p$ is the economic value in USD per FU linked to the plant $p$, and $W_p^{'}$ stands for the number of working hours per USD for the plant $p$ based on the country and sector associated with this plant according to the PSILCA database [33].

As shown in Fig. 2, three social life-cycle indicators were selected. Two of them –total child labour (CL) and gender wage gap (GWG)– represent labour market dysfunctions relevant to the stakeholder category 'workers' [33]. The third one refers to health expenditure (HE) and is relevant to the stakeholder category 'society' [33]. These three indicators are among the recommended social topics in SLCA [14,34,35], and they are relevant indicators for the countries involved in the scope of the hydrogen energy systems under study (Figs. 4 and 5). Furthermore, they are strongly related to key subjects within the United Nations' Sustainable Development Goals [36]. The quantification of these three indicators was carried out in terms of medium risk hours per FU for each specific social issue. In this sense, the higher an indicator is, the worse the social performance is under the specific issue addressed. Regarding these specific social issues, child labour takes into consideration children between 7 and 14 years old involved in economic activities; gender wage gap takes into account the

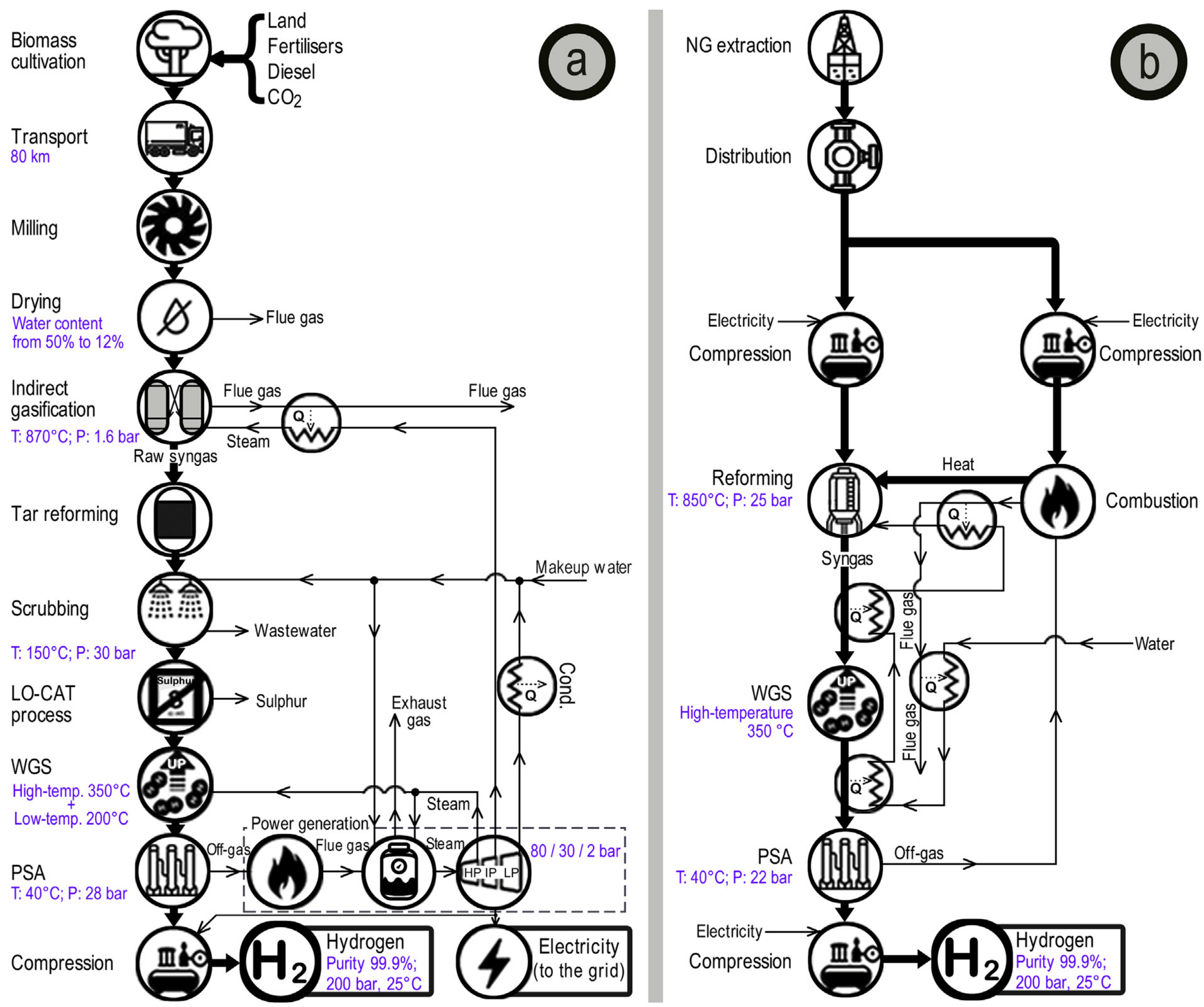


**Fig. 3 – Hydrogen production systems based on (a) biomass gasification, and (b) steam methane reforming.**

difference of salary between male and female workers on a full-time basis; and health expenditure takes into account both public and private expenditure.

## Results and discussion

### *Life-cycle inventories for social assessment*

Regarding the SLCA of BG_$H_2$ and SMR_$H_2$, and according to the scope defined in Figs. 4 and 5, specific inventories were built for the hydrogen production plants (P13 in Fig. 4 and P14 in Fig. 5) as well as for the plants providing the main feedstock (i.e., P9 –poplar cultivation– in Fig. 4, and P10 –Spanish natural gas supply– in Fig. 5). For the remaining plants, the social inventories were directly retrieved from the PSILCA database based on the specific country and sector associated with each plant [33].

Table 2 presents the life-cycle inventory of the biomass gasification plant, which was built according to literature information [17,27]. The economic flows included in this table are directly associated with PSILCA inventories, whereas the poplar mass flow is linked to the specific inventory presented in Table 3 for the biomass cultivation plant (built according to Ref. [37]). In the biomass gasification system, the net output of co-produced electricity was assumed to be sold to the Spanish grid, which is reported in Table 2 as a negative economic flow. This avoided burden approach is consistent with the choice made to address the multifunctionality associated with the BG_$H_2$ system in the environmental [28,29] and economic [17] components of the study.

Similarly, the life-cycle inventory of the conventional hydrogen production plant (Table 4) was built according to the information in Refs. [17,27]. The economic flows in Table 4 are directly linked to PSILCA inventories, while the volumetric

**Table 1 – Environmental and economic life-cycle indicators of BG_$H_2$ and SMR_$H_2$ (values per kg $H_2$).**

| Indicator | Unit | BG_$H_2$ | SMR_$H_2$ | Reference |
|---|---|---|---|---|
| GWP | kg $CO_2$ eq | 0.18 | 11.43 | [28] |
| AP | kg $SO_2$ eq | $1.45 \cdot 10^{-2}$ | $1.86 \cdot 10^{-2}$ | [29] |
| LCoH | €$_{2017}$ | 3.59 | 2.17 | [17] |

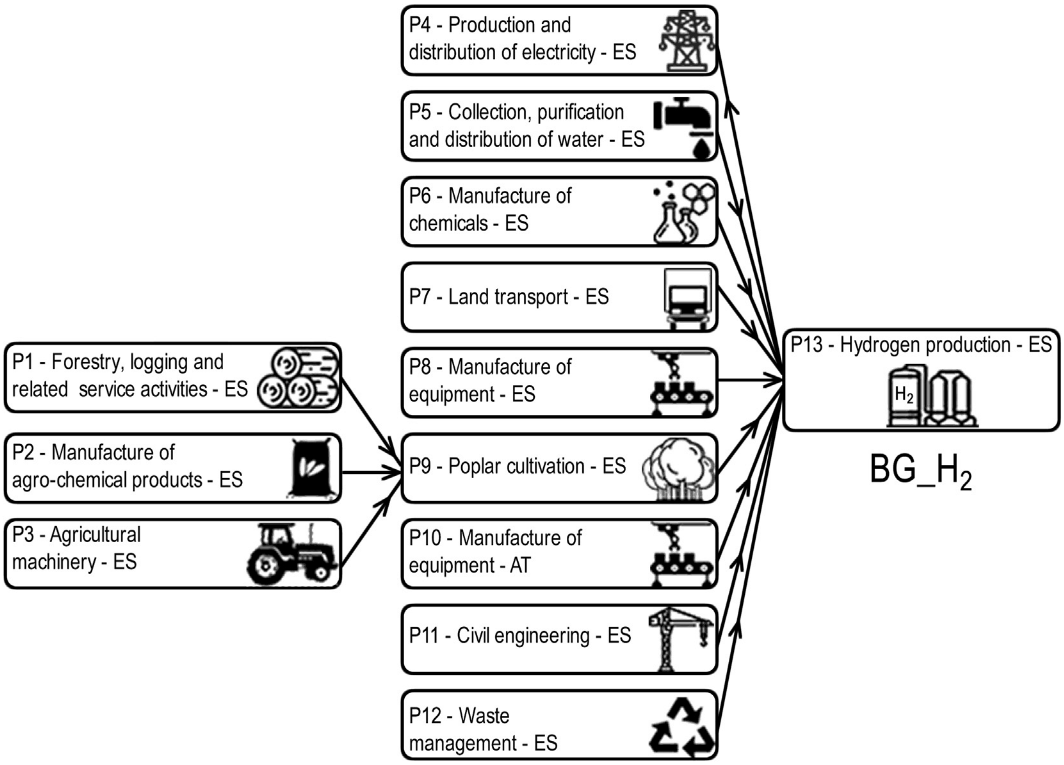


**Fig. 4 – Division of the BG_$H_2$ system into plants for the social assessment.**

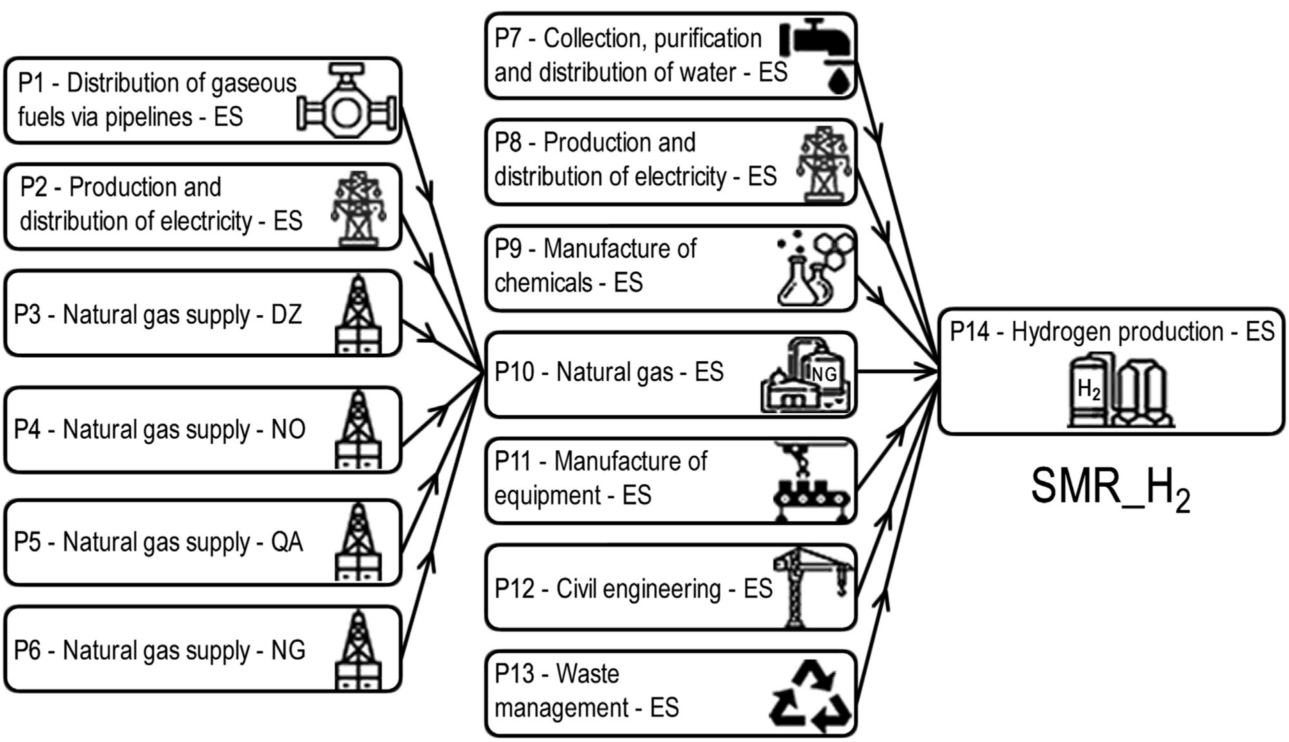


**Fig. 5 – Division of the SMR_$H_2$ system into plants for the social assessment.**

flow of natural gas is associated with the specific inventory presented in Table 5. The flows reported in Table 5 consider the Spanish natural gas grid mix according to national statistics [38,39].

The social risk factors ($R_{j,p}$) for the hydrogen plants, the poplar cultivation plant and the natural gas distributed in Spain were assumed as those of the industry “manufacture of gases”, the commodity “forestry, logging and related services

**Table 2 – Inventory data per kg of hydrogen for the social assessment of the biomass gasification plant (P13).**

| Item | Unit | Amount |
|---|---|---|
| Civil engineering (ES, P11) | $USD_{2017}$ | 0.09 |
| Collection, purification and distribution of water (ES, P5) | $USD_{2017}$ | 0.10 |
| Manufacture of chemicals and chemical products (ES, P6) | $USD_{2017}$ | 0.11 |
| Manufacture of machinery and equipment (ES, P8) | $USD_{2017}$ | 0.07 |
| Manufacture of machinery and equipment (AT, P10) | $USD_{2017}$ | 0.02 |
| Other land transport; transport via pipelines (ES, P7) | $USD_{2017}$ | 0.34 |
| Wet poplar (ES, P9) | kg | 36.28 |
| Production and distribution of electricity (ES, P4) | $USD_{2017}$ | −0.08 |
| Recycling (ES, P12) | $USD_{2017}$ | 0.06 |
| Labour (ES, P13) | h | $1.45 \cdot 10^{-3}$ |

**Table 3 – Inventory data per kg of wet poplar for the social assessment of the biomass cultivation plant (P9).**

| Item | Unit | Amount |
|---|---|---|
| Agricultural machinery (ES, P3) | $USD_{2017}$ | 0.03 |
| Forestry, logging and related service activities (ES, P1) | $USD_{2017}$ | 0.02 |
| Manufacture of pesticides and other agro-chemical products (ES, P2) | $USD_{2017}$ | 0.03 |
| Labour (ES, P9) | h | $7.50 \cdot 10^{-4}$ |

**Table 4 – Inventory data per kg of hydrogen for the social assessment of the steam reforming plant (P14).**

| Item | Unit | Amount |
|---|---|---|
| Civil engineering (ES, P12) | $USD_{2017}$ | 0.02 |
| Collection, purification and distribution of water (ES, P7) | $USD_{2017}$ | 0.04 |
| Manufacture of chemicals and chemical products (ES, P9) | $USD_{2017}$ | <0.01 |
| Manufacture of machinery and equipment (ES, P11) | $USD_{2017}$ | 0.02 |
| Natural gas (ES, P10) | $Nm^3$ | 0.33 |
| Production and distribution of electricity (ES, P8) | $USD_{2017}$ | 0.24 |
| Recycling (ES, P13) | $USD_{2017}$ | 0.01 |
| Labour (ES, P14) | h | $3.38 \cdot 10^{-4}$ |

**Table 5 – Inventory data for the social assessment of 1 $Nm^3$ of natural gas distributed in Spain (P10).**

| Item | Unit | Amount |
|---|---|---|
| Crude petroleum and natural gas (NO, P4) | $USD_{2017}$ | 0.03 |
| Electricity, gas, and water supply (DZ, P3) | $USD_{2017}$ | 0.22 |
| Electricity, gas, and water supply (NG, P6) | $USD_{2017}$ | 0.04 |
| Electricity, gas, and water supply (QA, P5) | $USD_{2017}$ | 0.04 |
| Other land transport; transport via pipelines (ES, P1) | $USD_{2017}$ | 0.10 |
| Production and distribution of electricity (ES, P2) | $USD_{2017}$ | <0.01 |
| Labour (ES, P10) | h | $2.40 \cdot 10^{-4}$ |

and activities" and the commodity "manufacture of gas, distribution of gaseous fuels", respectively (retrieved for Spain from the PSILCA database [33]). For the remaining plants, country- and sector-specific information ($R_{j,p}$ and $W_p^{'}$) is directly available in the PSILCA database [33].

However, it should be noted that the PSILCA database does not provide data for the GWG risk level of the natural gas industry of Nigeria and Algeria. Hence, for a reliable comparison between $BG\_H_2$ and $SMR\_H_2$, the GWG risk level for these countries was determined using the methodology described in Ref. [33]. In this respect, the GWG risk level refers to the ratio of the difference between the male and the female earned income to the male earned income. This was estimated for Nigeria and Algeria based on the country-specific (though not sector-specific) information reported in Ref. [40]. Accordingly, the GWG risk level of the natural gas manufacturing sector was modified from "no data" to "high risk" and "very high risk" for Nigeria and Algeria, respectively.

### *Characterisation of the social dimension*

The characterisation of the three selected social life-cycle indicators is presented in Table 6. The performance of hydrogen from biomass gasification was found to be two and three times worse than that of conventional hydrogen in terms of GWG and HE, respectively. In contrast, a favourable performance was found for the renewable hydrogen option in terms of child labour (with no CL impact for the scope considered). These findings are driven by the combination of the social profile of the country-specific sectors involved along the supply chain of each system and the number of working hours to produce the FU, which is closely linked to the technical efficiency of the processes. In this respect, despite the generally lower social risk of the countries involved in the supply chain of $BG\_H_2$, the relatively low technical efficiency of biomass gasification makes a higher amount of resources and working hours necessary [26], thus penalising the social footprint of the renewable hydrogen option in comparison with conventional hydrogen. In fact, as shown in Tables 2 and 4, the amount of working hours per FU required for $BG\_H_2$ is more than four times that for $SMR\_H_2$.

Fig. 6 shows the comparison of the social performance of both hydrogen options for the three life-cycle indicators, as well as the contribution to each social impact broken down by plant. Those plants with a relative contribution below 5% were considered within the label "rest". Regarding the CL indicator, the unfavourable performance of $SMR\_H_2$ was found to be associated with the natural gas supplied by Algeria and Nigeria to Spain. The natural gas supplied by Algeria was also

**Table 6 – Social life-cycle profile of conventional hydrogen and hydrogen from biomass gasification (values in $mrh \cdot kg^{-1}$ $H_2$).**

| Social indicator | $SMR\_H_2$ | $BG\_H_2$ |
|---|---|---|
| Child labour (CL) | 0.040 | 0 |
| Gender wage gap (GWG) | 0.309 | 0.594 |
| Health expenditure (HE) | 0.044 | 0.128 |

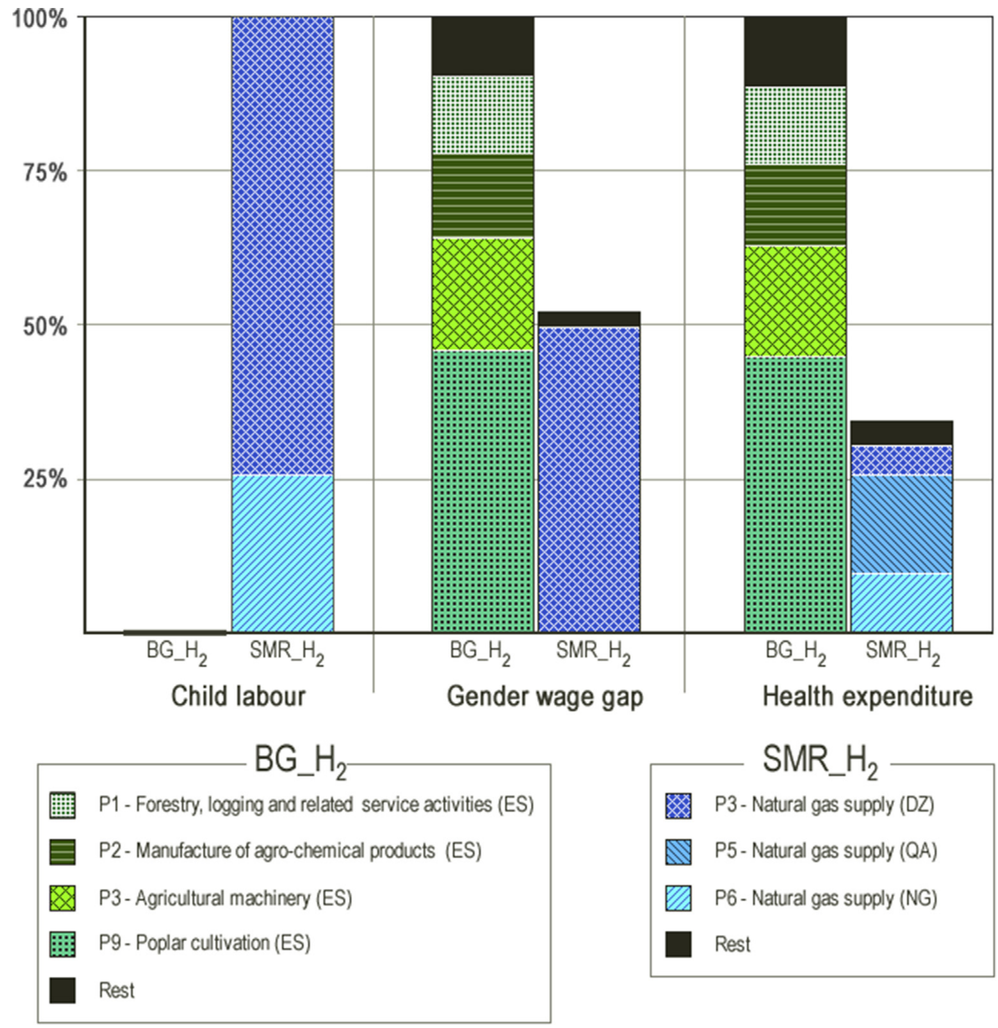


**Fig. 6 – Comparison between BG_$H_2$ and SMR_$H_2$ and plant contribution to the social impacts.**

found to dominate the GWG impact of SMR_$H_2$, while its contribution to the HE impact –though significant– was found to be lower than that of the natural gas supplied by Qatar and Nigeria. The key role of Algeria in the social performance of non-renewable hydrogen is in agreement with previous studies dealing with a different technology (hydrogen production through alkaline electrolysis powered by the Spanish grid electricity) [21,22]. The higher relevance of Algeria in two of the three social impact categories is linked to the different risk level observed for the natural gas sector in this country in terms of GWG (very high), CL (high), and HE (medium) [33]. Regarding BG_$H_2$, the poplar cultivation plant and its upstream plants were identified as the main sources of the unfavourable performance of this renewable hydrogen option in terms of both GWG and HE. Overall, regarding the identification of impact sources, the findings from the SLCA study show a high level of agreement with those from the LCA and LCC studies. In this sense, for both hydrogen energy systems, the main source of environmental, economic and social impact refers to the life-cycle stage of feedstock production.

### *Joint interpretation for sustainability assessment*

For the robust interpretation of the sustainability performance of BG_$H_2$, Fig. 7 shows the characterisation of its environmental, economic and social life-cycle indicators in relative terms with respect to the benchmark (i.e., SMR_$H_2$). In this radar chart, the points falling within the dashed hexagon indicate a better performance of BG_$H_2$ compared to SMR_$H_2$, while the points outside the hexagon indicate a worse performance of the renewable hydrogen option.

On the one hand, BG_$H_2$ outperforms SMR_$H_2$ for three out of six sustainability indicators. In particular, the renewable hydrogen option shows significantly better scores than conventional hydrogen in terms of child labour, global warming and, to a lesser extent, acidification. On the other hand, SMR_$H_2$ involves a significantly better performance than BG_$H_2$ in terms of health expenditure, gender wage gap, and levelised cost.

Overall, the results show that hydrogen from biomass gasification cannot yet be unequivocally considered a

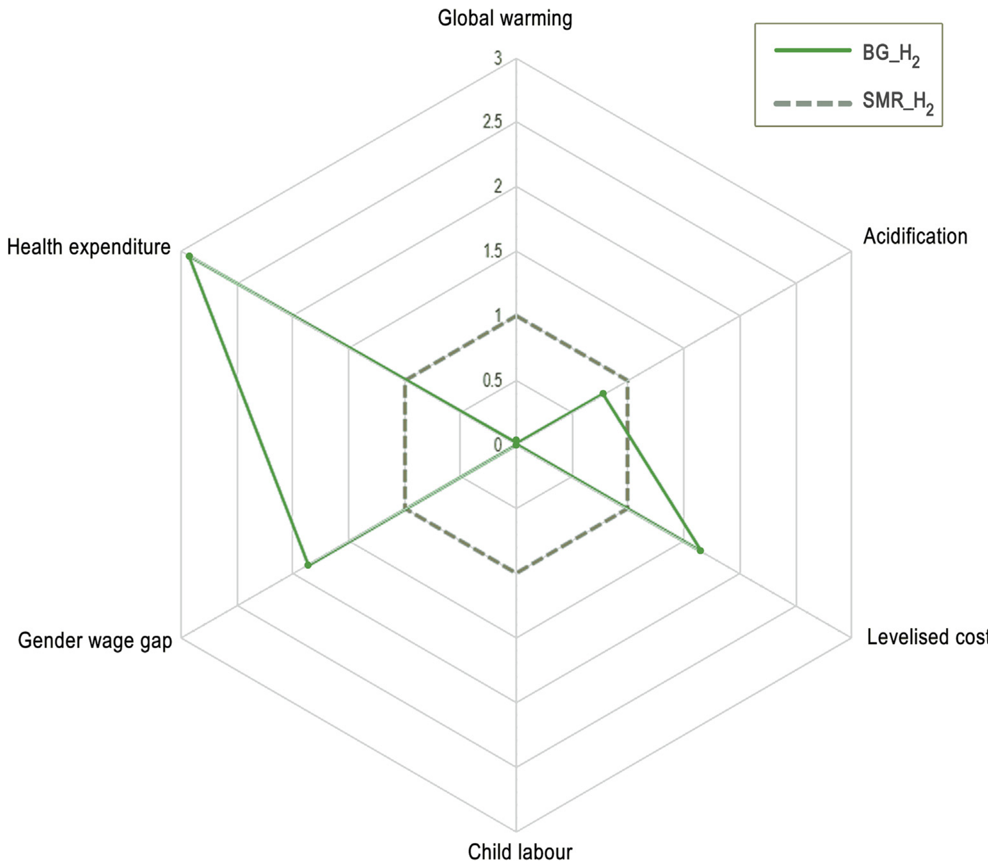


**Fig. 7 — Sustainability radar chart benchmarking the environmental, economic and social performance of hydrogen from biomass gasification against conventional hydrogen.**

sustainable alternative to conventional hydrogen mainly due to economic and social concerns. Nevertheless, improvements in the biomass gasification technology [41] —especially those leading to an increased technical efficiency and a subsequent decrease in feedstock and labour requirements— would significantly enhance the system's performance in each of the three common sustainability dimensions. In other words, technological enhancement could lead to a clear prioritisation of hydrogen from biomass gasification over conventional hydrogen from a sustainability standpoint. In this regard, it should be noted that job creation should not come at the expense of technical inefficiency.

At this point of the analysis, it should be noted that the calculation of a single sustainability score is not pursued in this study, giving preference to the joint interpretation of the selected economic, environmental and social life-cycle indicators under the umbrella of the sustainability concept. Given the lack of decision-makers in the study, potentially misleading conclusions on the suitability of hydrogen from biomass gasification are thus avoided. When a final decision is required, a tailor-made multi-criteria decision analysis including these and other sustainability indicators should be developed in accordance with the decision-makers involved (e.g., policy-makers, plant managers, and/or investors). For instance, after characterising a set of life-cycle indicators, aggregation and weighting methods could be used to provide a single sustainability index [42].

## Conclusions

The methodological framework developed in this work for the sustainability assessment of hydrogen energy systems enables the joint interpretation of the three common sustainability dimensions following a life-cycle perspective. The application of this specific LCSA framework to renewable hydrogen from biomass gasification and conventional hydrogen from natural gas reforming led to the main conclusion that the former cannot be unambiguously deemed as a sustainable hydrogen option to replace the latter. Despite significant environmental advantages, relevant economic and social concerns on hydrogen from biomass gasification are behind this conclusion. Nevertheless, technological enhancement for an increased efficiency of the biomass gasification process has a large potential to promote the role of this renewable hydrogen option as a sustainable alternative to conventional hydrogen.

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