

IEA HIA TASK 36 FINAL REPORT

LIFE CYCLE SUSTAINABILITY ASSESSMENT OF
HYDROGEN ENERGY SYSTEMS

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“Life Cycle Sustainability Assessment of Hydrogen Energy Systems”

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Executive summary

The goal of IEA HIA Task 36 was to facilitate decision-making in the hydrogen energy sector through sustainability assessment of hydrogen energy systems. Experts from 5 different countries (Spain [Operating Agent], Germany, Japan, Norway, and Italy) worked within the framework of this task. It was successfully completed in the period 2015-2017, with effective dissemination of the key results: LCA review, social acceptance, harmonization protocols, sustainability framework, and application to relevant case studies. Additionally, the collaboration with IEA HQ analysts was effective and fruitful. Addressing the challenge of developing a consistent life-cycle sustainability framework for hydrogen energy systems involves clear opportunities to enhance decision-making processes at the level of both industry and policy-makers.

1. Introduction

Comprehensive analyses are needed to evaluate the sustainability of hydrogen energy systems. Life Cycle Assessment (LCA) is a well-defined methodology to assess the environmental aspects and potential impacts associated with a product. However, when assessing the sustainability of hydrogen energy systems, further efforts are needed in order to set a solid and standardized basis that allows sound decision-making processes. Attempts to provide a general methodological framework for sustainability assessment have been based on widening the frame of discussion from the concept of environmental LCA to the Life Cycle Sustainability Assessment (LCSA) approach. A difficulty that arises is that there is not a simple, general solution to the complex problem of assessing sustainability. In particular, the singularities of a given system usually require tailor-made methodological frameworks and assumptions. Hence, concentrating efforts on the development of methodological solutions for LCSA on lower scales (e.g., at the sectoral level) is preferable. Within this context, the goal of the IEA HIA Task 36 “Life Cycle Sustainability Assessment of Hydrogen Energy Systems” was to facilitate decision-making in the hydrogen energy sector by providing a robust and comprehensive methodological framework for the sustainability assessment of hydrogen energy systems.

2. Goal and structure

The goal of Task 36 was to facilitate decision-making in the hydrogen energy sector through sustainability assessment of hydrogen energy systems. Among the specific objectives, the following ones are highlighted:

- to carry out a review of LCA studies;
- to develop an LCC (Life Cycle Costing) framework;
- to provide a robust set of social indicators for SLCA (Social Life Cycle Assessment);
- to evaluate the social acceptance of hydrogen;
- to integrate sustainability indicators into a common LCSA framework;
- to apply the methodological framework to key case studies; and
- to collaborate with IEA Headquarters (HQ) analysts and support the HIA Executive Committee in the liaison with IEA HQ.

Experts from 5 different countries (Spain [Operating Agent], Germany, Japan, Norway, and Italy) worked within the framework of IEA HIA Task 36. It essentially was a methodological and collaboration task that involved four sub-tasks as detailed in Figure 1 and Table 1.

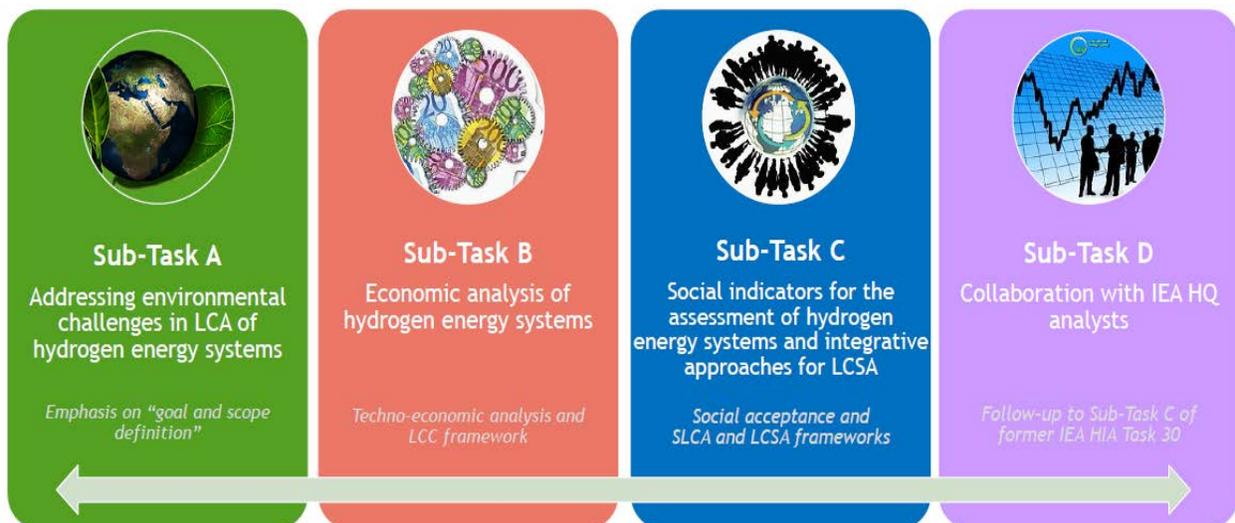


Figure 1. IEA HIA Task 36 structure.

Table 1. Description of the IEA HIA Task 36 sub-tasks.

Sub-task code	Sub-task name	Main activities
A	Addressing environmental challenges in LCA of hydrogen energy systems	<ul style="list-style-type: none"> • Literature review • Identification of the main sources of uncertainty • Recommendations on functional unit, impact assessment method, etc.
B	Economic analysis of hydrogen energy systems	<ul style="list-style-type: none"> • Literature review • Harmonization of assumptions and data • Cost evaluation and comparative analysis • Definition of LCC framework
C	Social indicators for the assessment of hydrogen energy systems and integrative approaches for LCSA	<ul style="list-style-type: none"> • Literature review of social indicators and databases • Screening of social indicators • Development of SLCA framework • Integration of LCA, LCC and SLCA into a robust LCSA framework • Evaluation of social acceptance
D	Collaboration with IEA HQ analysts	<ul style="list-style-type: none"> • Effective collaboration between HIA Task 36 experts and IEA HQ analysts

3. Sub-task A: addressing environmental challenges in LCA of hydrogen energy systems

LCA review¹

A thorough literature review of methodological choices in LCA studies of hydrogen energy systems was conducted. This review considered 97 scientific papers published until December 2015, in which 509 case studies of hydrogen energy systems were found. Based on the hydrogen production process, these case studies were classified into three technological categories: thermochemical, electrochemical, and biological (Figure 2).

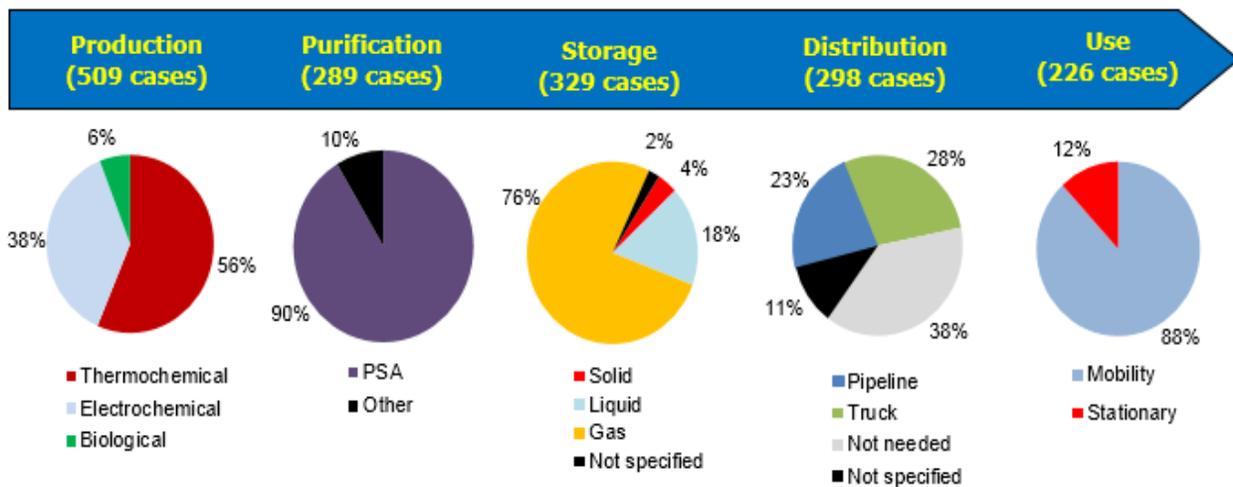


Figure 2. Technical features of the reviewed case studies according to the life-cycle stage.

Most of the hydrogen energy systems were found to define X-to-gate boundaries, while X-to-grave boundaries were found mainly for hydrogen use in mobility. The functional unit selected is often mass- or energy-based for X-to-gate studies, whereas travelled distance is typically used in X-to-grave studies. Multifunctionality was found to be mainly addressed through system expansion and, to a lesser extent, physical allocation (Figure 3).

Concerning the life cycle inventory stage, scientific literature and life-cycle databases were identified as the main data sources for both background and foreground processes. Regarding the life cycle impact assessment stage (Figure 4), the most common impact categories evaluated are global warming (i.e., carbon footprint) and energy consumption through the IPCC and VDI methods, respectively. The remaining indicators are often evaluated using the CML-family methods.

¹ Based on the publication: A. Valente, D. Iribarren, J. Dufour. "Life cycle assessment of hydrogen energy systems: a review of methodological choices". *Int. J. Life Cycle Assess.* 22; 346-363 (2017).

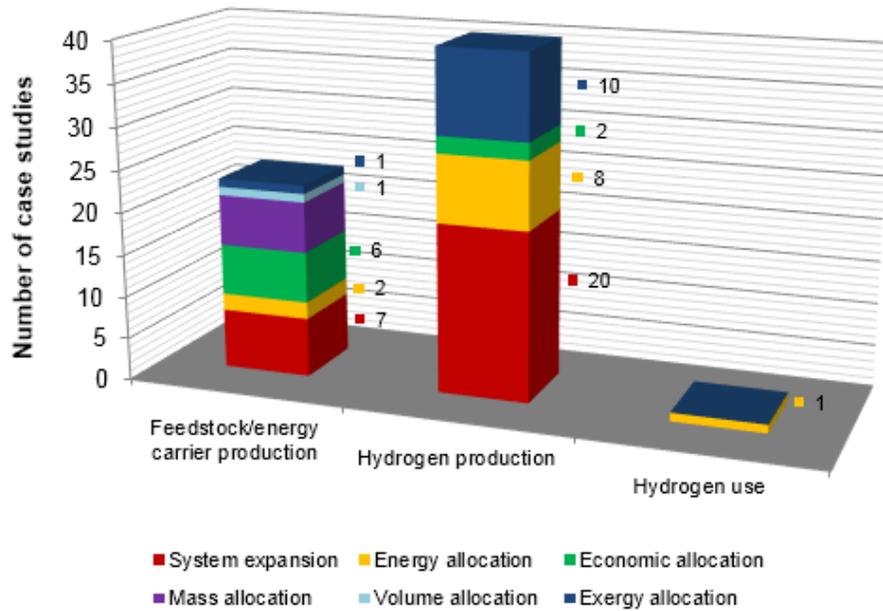


Figure 3. Choice of multifunctionality approach in LCA of hydrogen energy systems.

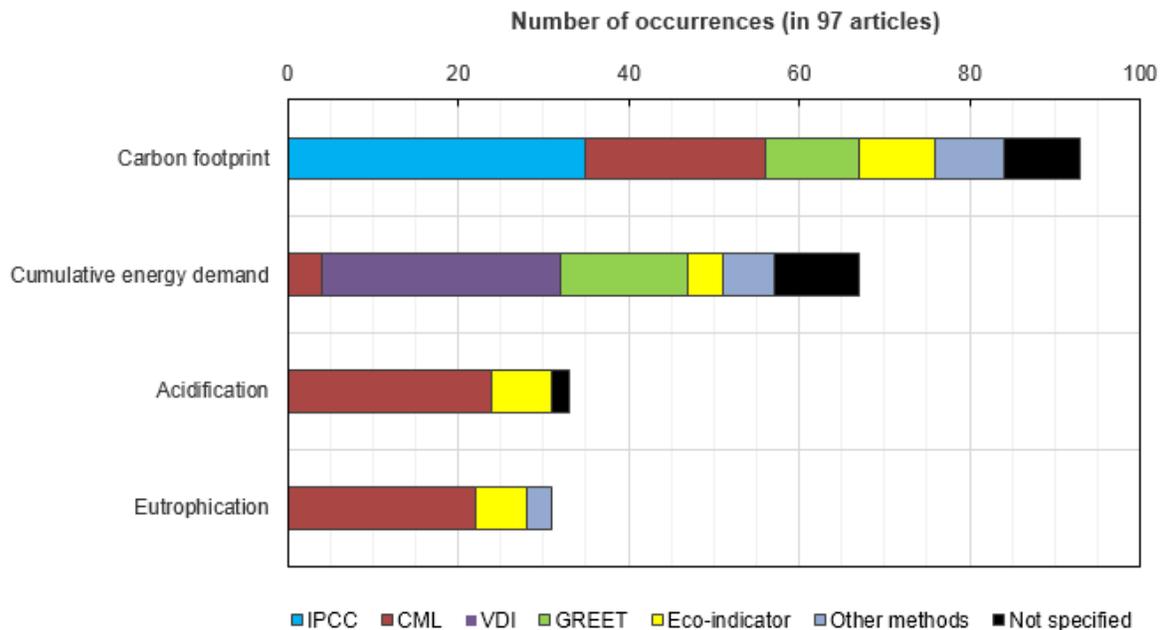


Figure 4. Choice of life-cycle indicators and impact assessment methods in LCA of hydrogen energy systems.

Overall, this review succeeded in finding relevant trends in methodological choices in LCA of hydrogen energy systems, especially regarding the frequent use of system expansion and secondary data under production-oriented attributional approaches. These trends are expected to facilitate methodological decision-making in future LCA studies of hydrogen energy systems. In particular, this review provided the basis for the definition of a methodological framework to harmonize LCA results of hydrogen energy systems.

LCA harmonization initiative²

Most of the LCA studies of hydrogen energy systems are comparative and show significant differences in terms of methodological choices. These differences significantly affect the results of the LCA studies and generally hamper their robust interpretation, especially when comparing results from different studies. Within this context, harmonization of the LCA results under a consistent methodological framework was undertaken. In particular, protocols for the harmonization of the life-cycle global warming (GWP), non-renewable cumulative energy demand (CED_{nr}), and acidification (AP) impacts of hydrogen were developed. Furthermore, these protocols were applied to conventional and renewable hydrogen based on a thorough literature survey of relevant LCA case studies.

Key methodological choices subject to harmonization included (i) attributional approach, (ii) functional unit, (iii) system boundaries, and (iv) multifunctionality approach. Figure 5 shows the general harmonized hydrogen energy system, while Figure 6 exemplifies the harmonization protocol by using the carbon footprint indicator as an example. The harmonized results were found to enhance comparative life-cycle studies by mitigating misinterpretation risk and better showing the expected relationship between indicators such as carbon footprint and non-renewable energy footprint (Figure 7).

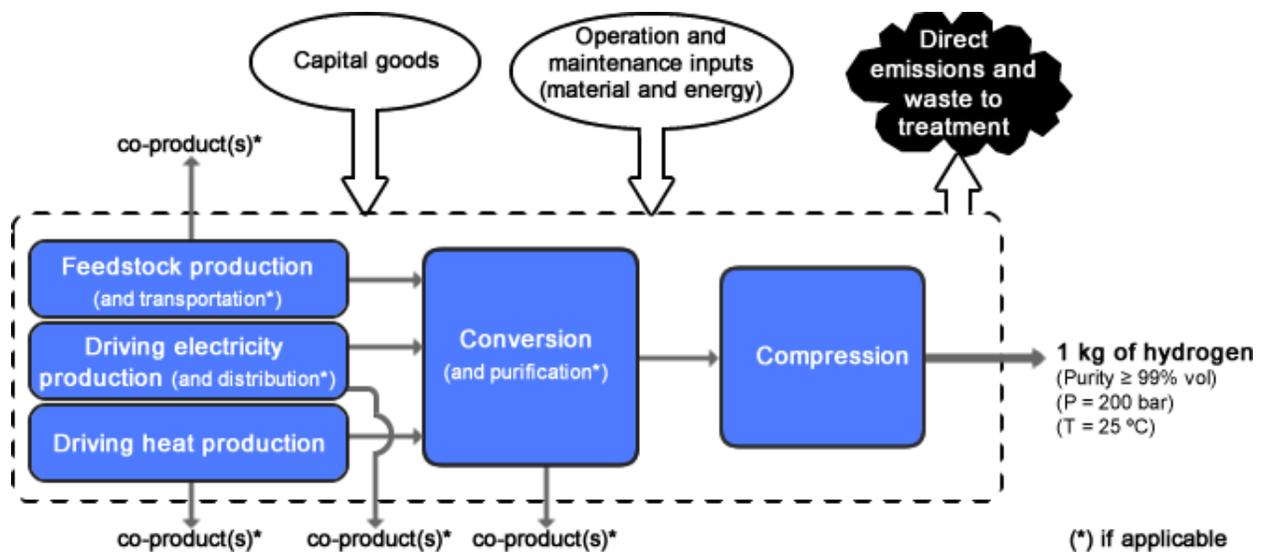


Figure 5. Harmonized hydrogen energy system.

² Based on the publications: (i) A. Valente, D. Iribarren, J. Dufour. "Harmonised life-cycle global warming impact of renewable hydrogen". *J. Clean. Prod.* 149; 762-772 (2017); (ii) A. Valente, D. Iribarren, J. Dufour. "Harmonising the cumulative energy demand of renewable hydrogen for robust comparative life-cycle studies". *J. Clean. Prod.* 175; 384-393 (2018); (iii) A. Valente, D. Iribarren, J. Dufour. "Harmonising methodological choices in life cycle assessment of hydrogen: A focus on acidification and renewable hydrogen". *Int. J. Hydrogen Energy* (DOI: 10.1016/j.ijhydene.2018.03.101); and (iv) A. Valente, D. Iribarren, J. Dufour. "Cumulative energy demand of hydrogen energy systems". In: "Energy footprints of the Energy Sector", Springer, Singapore, 2019 (DOI: 10.1007/978-981-13-2457-4_2).

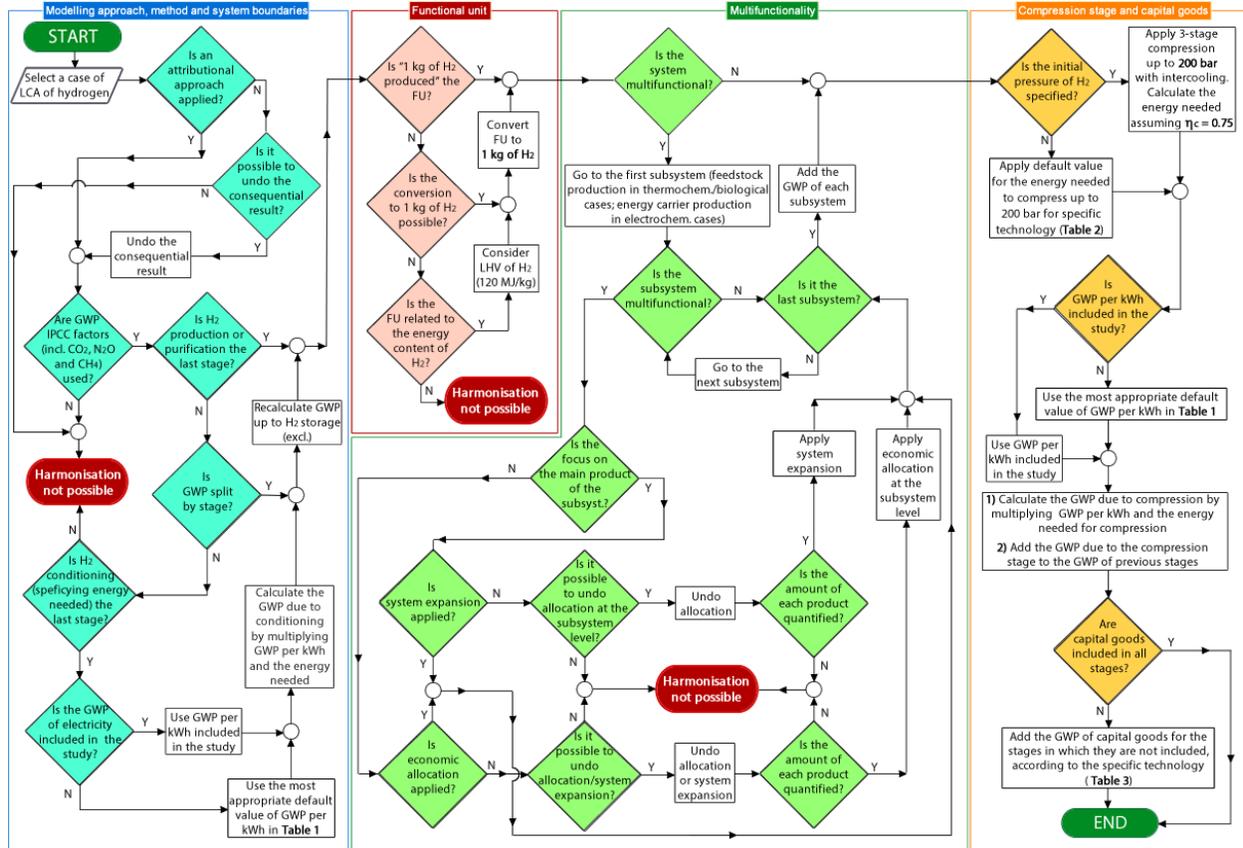


Figure 6. Example of harmonization protocol.

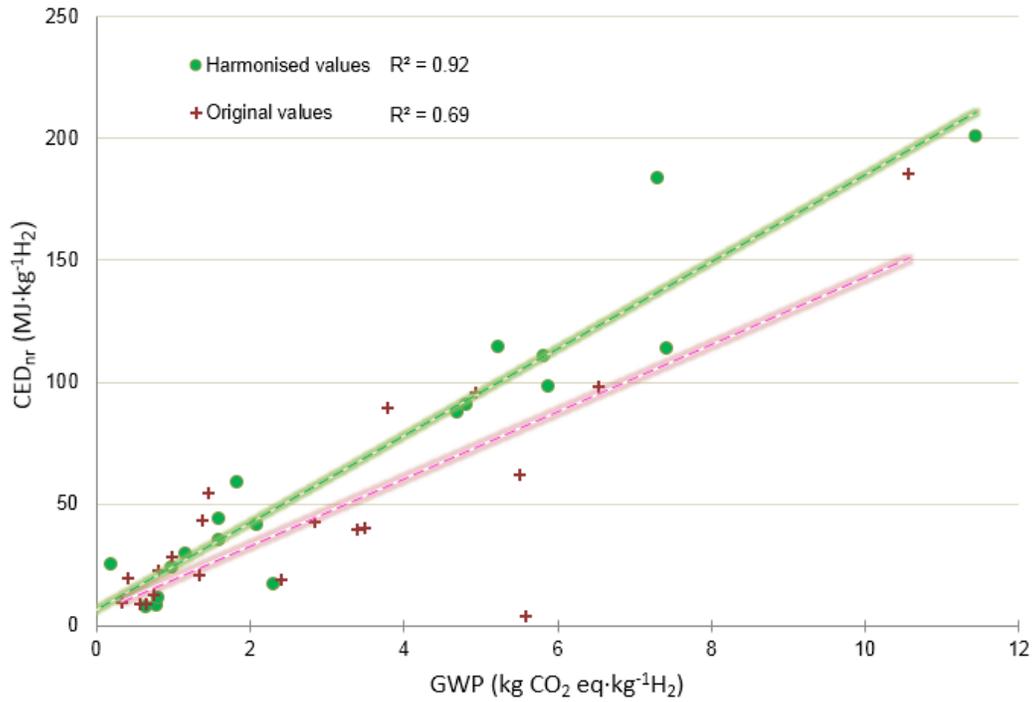


Figure 7. Relationship between GWP and CED_{nr} according to original and harmonized results.

Overall, harmonization was found to affect more significantly the thermochemical and biological hydrogen categories than the electrochemical one. Still, risk of misinterpretation was found in every technological category. The sources of potential misinterpretation were found to be usually associated with inconsistencies in terms of system boundaries (e.g., hydrogen compression) and, when applicable, multifunctionality approach.

4. Sub-task B: economic analysis of hydrogen energy systems

Life cycle costing³

Regarding the LCC of hydrogen energy systems, emphasis is laid on the use of the Levelized Cost of Hydrogen (LCoH). Two variants are considered depending on the inclusion or not of external costs. As shown in Figure 8, this has already been applied to benchmark the economic performance of hydrogen from biomass gasification (BG_H₂) against conventional hydrogen (SMR_H₂).

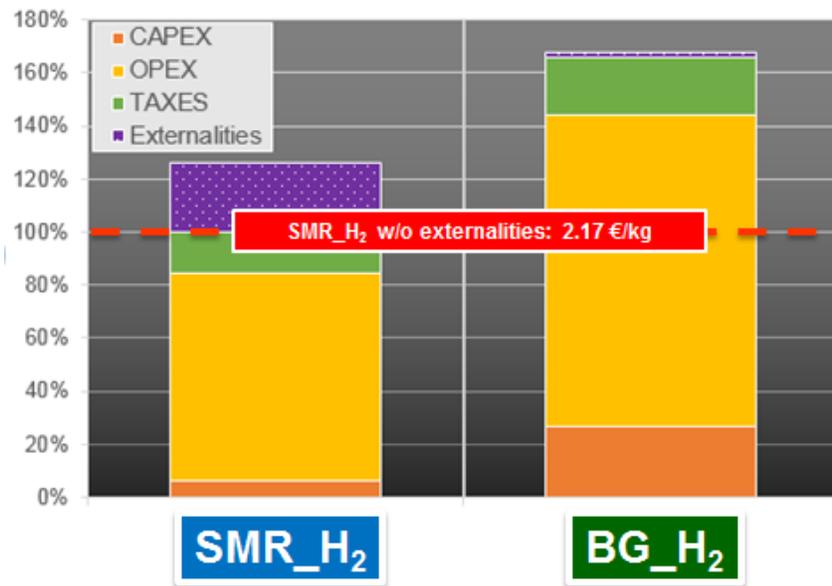


Figure 8. LCoH benchmarking.

Figure 8 also shows the breakdown of LCoH by economic component for both hydrogen options. When considering the implementation of externalities, they refer to a quantification of the public expense associated with the damaged caused by the impacts on climate change and human health. While external costs were found to affect significantly the LCoH for SMR_H₂ (near 30% increase), their influence on the LCoH for BG_H₂ was found to be almost negligible. Nevertheless, under life-cycle economic aspects, conventional hydrogen (SMR_H₂) was found to significantly outperform the assessed renewable option (BG_H₂) regardless of the inclusion or not of external costs.

³ Based on the publication: A. Valente, D. Iribarren, J.L. Gálvez-Martos, J. Dufour. "Robust eco-efficiency assessment of hydrogen from biomass gasification as an alternative to conventional hydrogen: A life-cycle study with and without external costs". *Sci. Total Environ.* 650; 1465-1475 (2019).

5. Sub-task C: social indicators for the assessment of hydrogen energy systems and integrative approaches for LCSA

SLCA and integrative LCSA framework⁴

The selection of social impact categories was based on critical concerns along the supply chain for the stakeholders ‘workers’ and ‘society’. For instance, regarding the stakeholder workers, the impact categories ‘fair salary’ and ‘total child labor’ were selected, while ‘health expenditure’ was chosen for the stakeholder society. These categories can be evaluated e.g. using the PSILCA database.

The category ‘total child labor’ involves only one indicator, whereas the categories ‘fair salary’ and ‘health expenditure’ involve more than one indicator. In this respect, ‘fair salary’ takes into account three indicators: living wage, minimum wage, and sector average wage. The category ‘health expenditure’ takes into consideration health expenditure through public, out-of-pocket, external, and total resources.

Beyond separate LCA, LCC or SLCA, the use of LCSA arises as a convenient methodological solution to thoroughly evaluate the performance of hydrogen energy systems. In this sense, previous IEA HIA Task 36 advances were used to increase the readiness level associated with the life-cycle framework for sustainability assessment of hydrogen energy systems by robustly combining harmonized life-cycle environmental (global warming, cumulative energy demand, and acidification), economic (LCoH with and without externalities) and social (fair salary, total child labor, and health expenditure) indicators.

In particular, the LCSA methodological framework shown in Figure 9 was applied for the robust comparison of two relevant hydrogen options: (i) conventional hydrogen from steam methane reforming of natural gas (SMR_H₂), and (ii) renewable hydrogen from poplar biomass gasification (BG_H₂). Overall, from a sustainability standpoint, the results show that the suitability of hydrogen from biomass gasification to replace conventional hydrogen is conditioned by the categories prioritized by the specific decision-makers (Figure 10).

⁴ Based on the conference contribution: A. Valente, D. Iribarren, J. Dufour. “Life cycle sustainability assessment of hydrogen from biomass gasification: a comparison with conventional hydrogen”. HYPOTHESIS XIII, Singapore (Singapore), 24-27 July 2018. Oral presentation and accepted article in the International Journal of Hydrogen Energy.

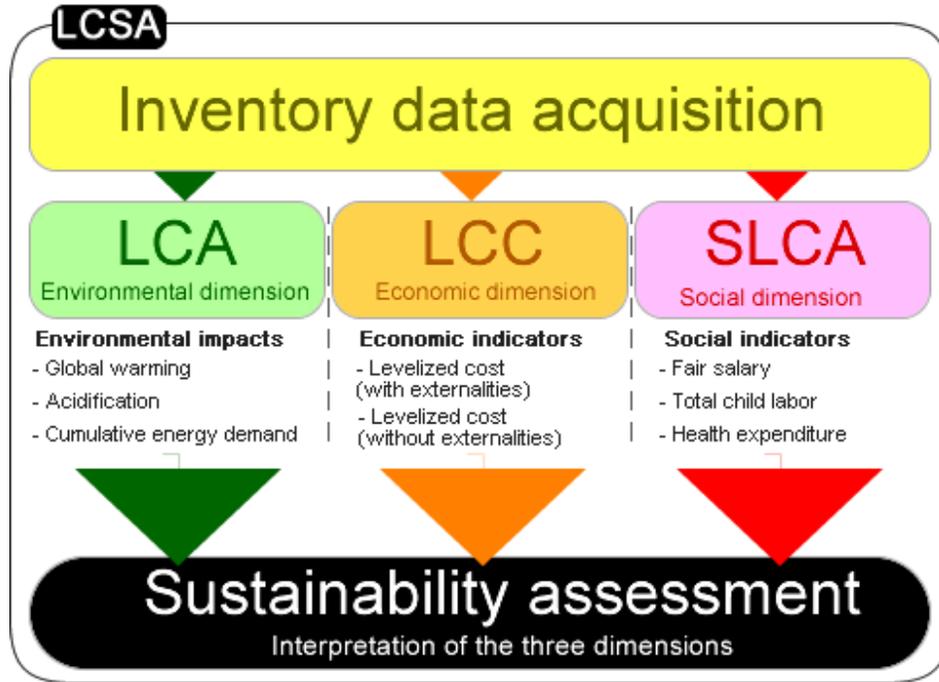


Figure 9. LCSA framework for hydrogen energy systems.

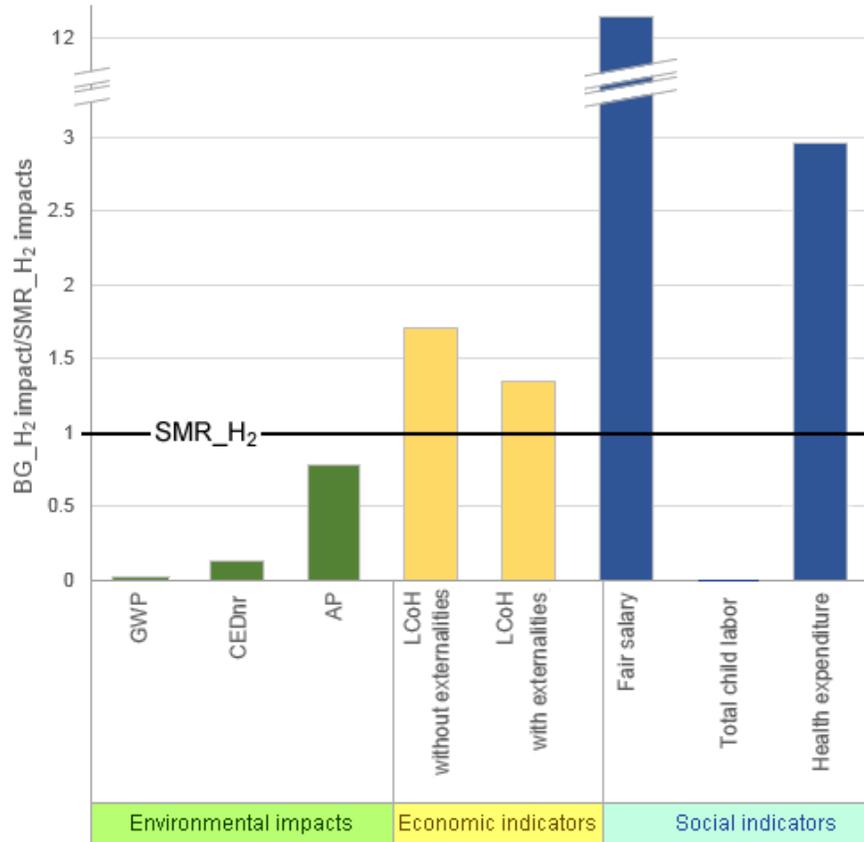


Figure 10. LCSA study of hydrogen from indirect biomass gasification vs. conventional SMR hydrogen.

Social acceptance⁵

The assessment of public perception and social acceptance of hydrogen energy systems is crucial to avoid reluctance to the deployment of hydrogen technology and infrastructure. However, the number of regional studies evaluating these aspects is scarce. In this respect, significant advances were made concerning the evaluation of the social acceptance of hydrogen energy at the national level. In particular, a complete study was conducted for Spain. Thus, the attitude of the Spanish society towards the potential role of hydrogen for transportation was assessed. With this aim, a quantitative approach was followed through the design and open electronic distribution of a survey with 12 closed-ended questions. The final size of the sample involved 1005 respondents.

The analysis of the responses provided relevant insights into three main aspects: perception of the concept ‘hydrogen’ (Figure 11), supporting attitude towards the implementation of hydrogen technologies and infrastructure (Figure 12), and determining factors for the purchase of a hydrogen vehicle. Overall, the respondents were found to be willing to accept hydrogen as a key energy carrier within the energy and transport sector. Nevertheless, further policy, industry and research efforts are required in order to overcome current obstacles hampering the success of hydrogen.

The results of this study on the social acceptance of hydrogen may be relevant not only to hydrogen stakeholders and decision-makers in Spain but also to counterparts in other regions without strong initiatives towards a well-established hydrogen economy.

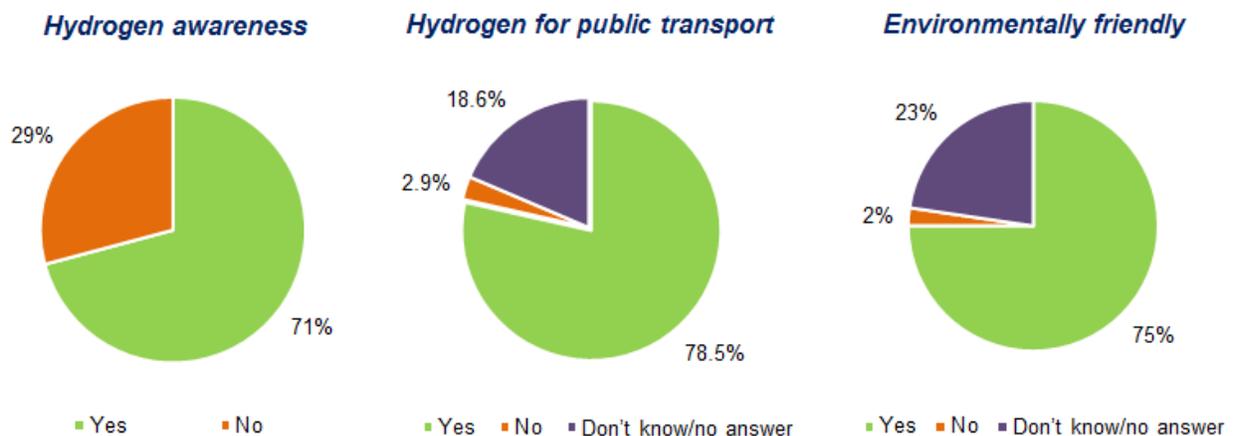
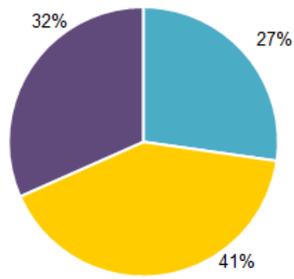


Figure 11. Results regarding hydrogen awareness and perception.

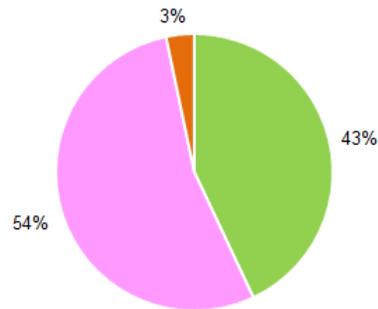
⁵ Based on the publication: D. Iribarren, M. Martín-Gamboa, J. Manzano, J. Dufour. “Assessing the social acceptance of hydrogen for transportation in Spain: An unintentional focus on target population for a potential hydrogen economy”. Int. J. Hydrogen Energy 41; 5203-5208 (2016).

Strategy for hydrogen production



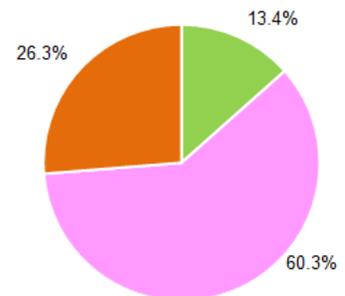
- Centralized production
- On-site production
- Don't know/no answer

Acceptance of local hydrogen stations



- Yes, regardless of proximity
- Yes, but away from residential areas
- Definitely not

Acceptance of an affordable tax



- Definitely
- Yes, but not through a new direct tax
- Definitely not

Figure 12. Results on the attitude towards hydrogen implementation.

6. Sub-task D: collaboration with IEA HQ analysts

This sub-task facilitated an effective collaboration between HIA Task 36 experts and IEA HQ analysts. In particular, the role of hydrogen in a number of IEA documents was thoroughly reviewed by the experts involved in Task 36:

- Technology Roadmap – Hydrogen and Fuel Cells (2015).
- RES-T-NEXT (2015).
- ETP (2015, 2016, and 2017).

7. Conclusions

IEA HIA Task 36 was successfully completed, with effective dissemination of the key results: LCA review, social acceptance, harmonization protocols, sustainability framework, and application to relevant case studies. Additionally, the collaboration with IEA HQ analysts was effective and fruitful. Addressing the challenge of developing a consistent life-cycle sustainability framework for hydrogen energy systems involves clear opportunities to enhance decision-making processes at the level of both industry and policy-makers.

The availability of a robust methodological framework for the assessment of hydrogen energy systems under sustainability aspects facilitates decision-making at the industry level. In addition to enable a thorough identification of specific sustainability hotspots, this methodological framework helps industry actors anticipate, check and prove the suitability of their hydrogen energy solutions according to the criteria required by current and future energy policies.

8. Appendix: separate report by Yousef M. Alshammari (IEA HIA Task 36 fellow)

Abstract

Lifecycle sustainability assessment (LCSA) has emerged a new multi-criteria decision technique to assess the long-term sustainability of energy systems by combining economic, social aspects and environmental aspect. This approach has the potential to provide a better decision making process on implementation of hydrogen energy systems and to better understand their role in the transition towards a low carbon economy. This report reviews the recent development of LCSA tools in order to address the sustainability of hydrogen energy systems. This includes a brief review of recent case studies, key environmental, economic and social indicators, and their application in the assessment of hydrogen energy systems. Greenhouse gas emissions are the key contributor to the environmental sustainability; economic aspects are indicated by capital and GDP, while the social aspects are largely influenced by the human health, safety and security. This report recommends more case studies and research work is needed to the application of LCSA to assess hydrogen systems especially in assessing the social aspects and combining them with environmental and economic aspects.

1. Introduction and Methodological Developments

Lifecycle Sustainability Analysis is a recently developed approach, first formulated by Kloepffer [1], which integrates environmental, economic and social parameters to assess the sustainability of a system or a product. According to the UNEP “Life cycle sustainability assessment (LCSA) refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle”. This new technique builds upon existing LCA methods, designed to measure environmental sustainability, in order to enable a holistic assessment of sustainability throughout the lifecycle of a product by integrating selected indicators to measure the economic and social impact. The integration of economic and social factors into the environmental analysis offers many benefits such as enabling clarifying the trade-offs between the three pillars of sustainability, enhancing the social responsibility of products, promoting awareness in value chain [2]. It also enables broadening the object of the analysis, the scope of indicators, and including a wide variety of models within the analyzed system [3].

The application of LCSA in sustainability research has gathered attention by many international organizations including the UN Global Compact, OECD Guidelines for Multinational Enterprises, ISO 26000 (Guidance on Social Responsibility) and the Global Reporting Initiative (GRI) [4]. This approach has also been considered by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry

(SETAC) as a possible approach for to integrate Triple Bottom Line aspects of sustainability into a single-dimensioned LCSA. UNEP and SETAC also cited LCSA as an important framework and should be pursued despite the little progress toward improving the methodological aspects that extend the application areas for LCSA [5].

LCSA varies from LCA whereby the goal and scope become more crucial and it requires defining the sustainability questions, as shown in Figure (1). It structures the goal and scope phase by using the identification of mechanisms as the guiding principles in addition to the adopting a holistic approach. In addition, the proposed approach consists of structuring the goal and scope phase into three main components: (i) macro-goal definition; (ii) technology map; and (iii) context description [3]. A recent LCSA methodology was proposed by Tugnoli *et al* [6] which allows for simultaneous analysis of the economic, environmental and social impact which succeeded in showing the expected sustainability impact of different routes of hydrogen production. This work will review recent advances and case studies of LCSA techniques with special focus on their application in to assess the sustainability of hydrogen energy systems.

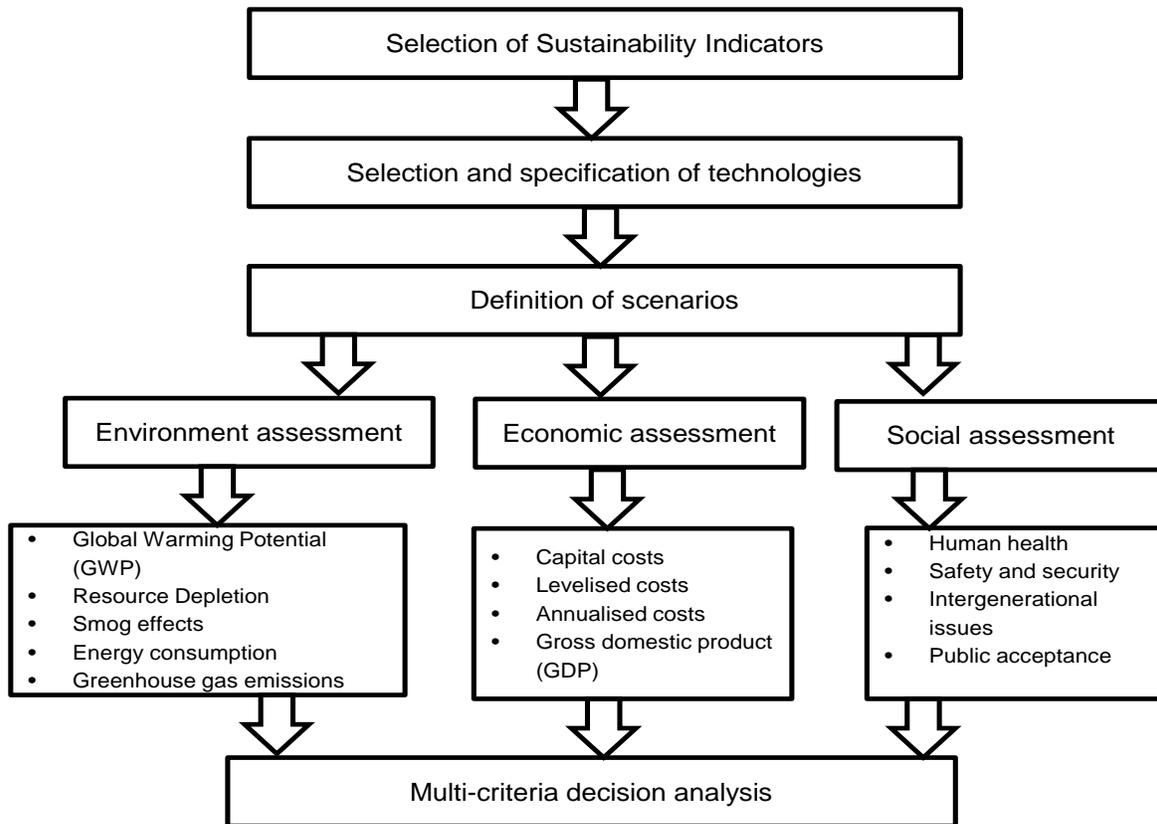


Figure 1: Model structure for goal and scope within the framework of LCSA [7]

2. Case Studies

Literature on LCSA of hydrogen systems has been scarce as the technique is relatively new. However, there have been many studies assessing the sustainability of hydrogen and other energy systems published in the literature [3, 7-22]. For example, a recent LCSA study on Hydrogen Production from Biomass was reported by Stefanova *et al* [3]. At the macro-level, this case study considers the potential for fossil-fuel dependency reduction and the sustainability of high purity hydrogen production derived from biomass gasification, when used as an alternative to fossil fuels in automotive transport. The case study examines a new technology system for the production of high-purity hydrogen from biomass gasification, to be used in fuel cells for automotive transport. The production system includes innovations regarding reactor design, as well as the materials employed. It consists of a gasifier, powered by lignocellulosic feedstock, which integrates both steam gasification, hot gas cleaning and conditioning systems in one reactor vessel. The gasifier is being coupled with water gas shift (WGS) and pressure swing adsorption (PSA) units. The high temperature and low temperature WGS reactors increase the hydrogen content of the syngas, whereas the PSA unit separates it, thus producing a pure hydrogen stream and a residual purge gas, containing the other minor gas components. One of the several sustainability questions that arise from the perspective of the public decision maker is how NO₂ air concentrations in Italy change if X% of fossil fuel is substituted by Y% of hydrogen fuels by introducing H₂-integrated production facilities along the highways or within metropolitan areas. In this case, the biomass necessary for the production of H₂ needs to be transported to the production locations, placing additional demand on transport services. Other studies [19, 20] have developed new methods to assess the key factors in influencing the sustainability of hydrogen supply chain which were found to be feasible. Tugnoli *et al* [6] presented a case study on the sustainability of hydrogen production via steam reforming processes. They showed a comparison of expected sustainability performance of selected processes, integrated reactor, membrane reactor...etc., and how to improve each option. These studies provide a basis for much further research needed to integrate social aspects with hydrogen environmental and economic sustainability.

3. Environmental, Economic and Social Indicators

LCSA indicators are a set of parameters used to assess and quantify the impact of a product throughout its lifecycle. As discussed above, in LCSA, these parameters are environmental, economic and social whereas in LCA these parameters will mainly be environmental-related. While existing LCA literature [23-37] has made use of various environmental indicators, LCC and SLCA literature focused on assessing the economic and social indicators of process systems [7-22].

3.1. Environmental Indicators:

Koroneos *et al* [29, 30] reported the LCA of different hydrogen production processes comparing the environmental impact of hydrogen production from natural gas with hydrogen production from renewable energy sources. They used the following indicators to assess the environmental impact of hydrogen generation processes. Greenhouse gases are the most concerning environmental indicators primarily because rising global concerns about climate change. Greenhouse emissions include such gases as CO₂, CH₄, N₂O and their emissions are used to assess the Global Warming Potential (GWP). The contribution of each gas to global warming varies and hence GWP is normalized on a CO₂ equivalent basis. Other environmental indicators include Energy Consumption, Land use, and Water Consumption. The environmental indicators also include the acidification emissions. This type of emissions is concerned with the release of protons into the atmosphere and it is concerned mainly with two compounds SO_x and NO_x, in addition to other compounds such ammonia, HCL, and HF. The emissions are presented as a measure of mole of H⁺ or kg of SO_x equivalent. In addition, eutrophication air emissions can be used to an indicator to assess the release of nutrients such as nitrogen and phosphorous into the water or soil. If this release is uncontrolled it may have negative impact on soil and water resources. Another environmental indicator is the winter smog indicator which quantifies the emissions of solid particulates including dust and SO₂ in order to assess the Winter Smog Potential (WSP) of product production processes.

3.2. Economic Indicators:

Lifecycle Costing (LCC) is a process for evaluation of all the costs involved in the process of manufacturing a product throughout its lifecycle including research and development costs, construction costs, operation costs, and maintenance and disposal costs [7, 38]. Compared with

the environmental indicators explained above, this analysis is useful in comparing between a range of manufacturing options in financial terms before making a decision on the investment. Examples of LCC analysis include Net Present Value (NPV), Internal Rate of Return (IRR), and Profitability Index (PI). LCC is performed at the early stage of process design which can provide a potential opportunity for cost reduction.

The indicators of LCC include Capital Expenses referred to as CAPEX and Operating Expenses OPEX [38]. The CAPEX include the direct and indirect capital costs such as equipment costs, installation, piping, building, while the indirect costs include the costs for engineering, legal expenses, contingency and contractor fees. The OPEX include the costs of such items as the labor, utilities, supplies, maintenance, insurance, plant overheads, and taxes. LCC can also include the unavailability costs which are the costs incurred as a result of loss of production. The availability analysis is useful when analyzing risks and it enables decision makers to select the optimum design with a maintenance strategy while assessing meeting the required targets. The summation of CAPEX, OPEX and unavailability costs is equal to the LCC, which makes it possible to decide on the optimum design. Furthermore, sensitivity analysis can be conducted to assess the effects of several parameters on the economic evaluation. Parameters can be technical such as design temperature, and they can also be economic such as feedstock price, CO₂ trading costs, electricity price. Sensitivity analysis is crucial to decide on the final optimum design of a process for making a product.

The Gross Domestic Product (GDP) is another important economic indicator in LCSA studies at the macro-economic level [4]. It is considered as a positive indicator as it measures the healthiness of the national economy and how this can be related to the energy system. Another crucial economic indicator is the air emission cost which includes the externality damage costs for not only greenhouse emissions but also air pollutants such as NO_x, and fine particulates [4]. These costs can be expressed in economic, environmental, or social terms. For example, emissions could result in financial penalties paid to environmental regulatory agencies. These costs can also cause environmental impact resulting from air pollution, smog effects, acid rain...etc. This can ultimately result in a social impact expressed in terms as the mortality rate, human health, property damage and various other social consequences. Finally, profits are the most key element in economic indicators of energy systems. It enables energy companies to pay taxes, recovery investments, and pay salaries of their employees [4].

3.3. Social Indicators

Social indicators reflect the social aspects associated with the implementation of energy systems in terms of its impact on society. The social impact can be expressed in many different indicators such as public acceptance, human health, employment, personal income, and government taxes. Santoyo-Castelazo *et al* [7] summarized social concerns over different types of energy systems including biomass, nuclear, hydropower, and wind technologies. The public acceptance index for such energy systems varies from technology to another depending on how it affects the end-consumer daily life. Hydrogen is an energy carrier which can be produced from different sources of energy whether they fossil fuels, nuclear or renewable sources. Hence, concerns over the food and water scarcity when implementing biomass energy will apply to hydrogen energy systems if hydrogen is produced from biomass resources. Similarly, safety and security will be an important social factor if hydrogen is produced from nuclear power. Human health is an end point social indicator, which can be quantified according to health effects produced by the environmental impact of energy systems. The social impact of human health can be quantified by such indicators as the human toxicity potential [22] which can result from the emissions of harmful gases including SO₂ and NO_x as well as solid particulates.

The social impact of energy systems may be expressed by intergenerational issues accompanied by the implementation of energy technologies. These are the issues that would have an effect on future generations including climate change, depletion of fossil fuels...etc. Another example, the long term impact arising from permanent storage of radio-active nuclear waste or captured CO₂ can present a major social challenge for energy operators in many countries [22].

4. Assessment of Hydrogen Energy Systems

The environmental aspects have been the most important factor in determining the sustainability of hydrogen energy systems. This is demonstrated by the fact that significant research work has been conducted on the environmental sustainability of hydrogen production systems, over the past decade [12, 23-31, 33, 35-37, 39-41]. For instance, Koroneos *et al* [30] showed that renewable sources of energy including wind, hydropower and solar thermal are the most environmentally benign processes for hydrogen production. They compared steam reforming of natural gas with five renewable processes for hydrogen production; solar PV, solar

thermal, wind, hydropower, and biomass using the Global Emission Model for Integrated Systems (GEMIS). The comparison was conducted by analyzing the variation of environmental factors including greenhouse emissions, acidification, eutrophication and winter smog effects. While H₂ from natural gas, 0.083 CO₂eq [kg/MJ], showed the highest greenhouse emissions, hydrogen from solar PV showed the highest impact of acidification at about SO₄eq [kg/MJ]. Similar work has also been reported by Cetinkaya *et al* [42] who analyzed the LCA of various hydrogen production processes including thermochemical water splitting with the Cu-Cl cycle which was found to be most sustainable among the processes selected. In their work, a comparison was made between steam reforming of natural gas, coal gasification, water electrolysis by wind and solar electricity and thermochemical water splitting. They focused on quantifying the global warming potential for the different options showing clearly that 1 kg of H₂ produced from fossil fuels would have the same GWP as 6 kg produced from renewable processes. Another study on the LCA of hydrogen energy systems was conducted by Bartlozzi *et al* [39] who compared the environmental sustainability of hydrogen vehicles compared with electric vehicles. They found that BEVs have a better environmental performance compared to H₂ vehicles due to the lower efficiency of H₂ fuel production. Additional work was conducted by Hajjaji *et al* [28] who compared the environmental sustainability of hydrogen production from both renewable and fossil feedstocks. They showed that biomethane reforming has the lowest impact compared with fossil methane reforming and also bioethanol reforming. While fossil methane reforming produces the highest emissions of CO₂, bioethanol reforming showed the highest impact on acidification, eutrophication, ozone layer and toxicological impact. More recently, the LCA of hydrogen production from underground coal gasification was reported by Verma and Kuma [36].

Some studies have analyzed the lifecycle sustainability aspects highlighting both the economic and social aspects of hydrogen systems combined with environmental aspects [9-11, 16, 17, 19, 20, 43-46]. For instance, McDowall and Eames [16] assessed the sustainability of six potential H₂ systems in the UK showing that CO₂ emissions are the most significant dimension in the sustainability of hydrogen systems. Furthermore, this was agreed by Tugnoli *et al* [6] who showed that the improvement of not only the reaction section, but also the separation efficiency, and energy requirement in order to enhance the sustainability of hydrogen production while investigating H₂ production from steam reforming of natural gas. In fact, the separation efficiency and energy consumption showed impact on not only the environmental aspects but also the economic aspects of H₂ production processes. Environmental indicators included global

warming, rain acidification, air toxicity, and solid waste disposal, while economic indicators included the economic impact index shown by the annual cash flow, and the societal indicators included occupational and inherent safety indices. Five different processes; Traditional with PSA, auto-thermal with PSA, internal membrane separator, external membrane with separator, and integrated reactor were compared and their score on the different sustainability dimensions were different. For example, the internal membrane reactor process showed the highest score on both the environmental impact and the economic impact while its score on the societal impact was much lower compared with external membrane process.

The study conducted by McDowall and Eames [16] considered more integrated hydrogen systems reaching to end consumers rather than focusing only on the production side analyzed by Tugnoli *et al* [6]. They analyzed six scenarios for hydrogen infrastructure in the UK within which electricity storage was found to be the most sustainable option. The study also showed that central pipeline is the most contentious infrastructure, with a strong performance for synthetic liquid fuels due to the lower barriers they offer compared with using pure hydrogen. Liquid hydrogen showed a poor sustainability performance mainly due to the social perception of nuclear power and also the low efficiency and impracticality of liquid hydrogen technology. Ubiquitous hydrogen showed a relatively high sustainability performance compared with the electricity storage and some concerns were reported regarding its feasibility. Afgan and Carvalho [47] also conducted a sustainability assessment of energy systems using a multi-criteria approach; environmental, cost and social aspects and they showed the possibility to define the consistent set of sustainability indicators to be for the evaluation of energy systems.

5. Conclusion

This report summarizes recent research work undertaken on lifecycle sustainability assessment with a special focus on their application in hydrogen energy systems. LCSA is newly developed multi-criteria analysis techniques which brings together environmental, economic, and social indicators to assess the overall sustainability of energy systems. While environmental aspects of hydrogen energy systems have been well studied, significantly less work has been conducted on the social aspects of hydrogen technologies. The social aspects can be indicated by many key indicators that directly affect human behavior in interacting with energy systems, which include human health, safety and security, and employment opportunities. These indicators may be evaluated along with key economic indicators such as capital costs, and GDP,

and environmental indicators which include the greenhouse gas emissions and energy consumption. The hydrogen production processes shows the highest impact on the environmental footprint as well as the economic aspects while their social impact is less significant. The social impact is found to be significant when potential risk is associated with hydrogen production and supply such as nuclear production of hydrogen, which poses a safety concern.

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