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Sustainability analysis of different hydrogen production options using hesitant fuzzy AHP

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ABSTRACT

Hydrogen is seen as the key component of energy systems for a sustainable future. In the literature, there has been extensive efforts on making hydrogen energy systems more sustainable. True sustainability of such systems requires hydrogen to be produced in clean, reliable, affordable, and safe manners without harming neither the environment nor the societies. In the literature, there is a lack of studies focusing on a complete technical, environmental, social, and economic evaluation of hydrogen production systems by taking availability and reliability into account. Therefore, the primary aim of this study is to provide a comprehensive review and investigation on sustainability of hydrogen production systems, which could potentially guide researchers, policy makers, different industries, and energy market customers. The selected hydrogen production methods are grid electrolysis (electricity from fossil fuels), wind electrolysis, PV electrolysis, nuclear thermochemical water splitting cycles, solar thermochemical water splitting cycles and photoelectrochemical cells. To deal with the ambiguity and vagueness in the evaluation process, and to overcome the observed hesitancy in decision makers' preferences, a novel approach, hesitant fuzzy AHP, is used to evaluate sustainability of the selected hydrogen production methods. In the proposed model, five criteria; economic performance (initial cost and running cost), environmental performance (GHG emissions, land use, water discharge quality, and solid waste), social performance (impact on public health, employment and training opportunities, and public acceptance), technical performance (energy and exergy efficiencies, process control, and raw material input), and availability/reliability (dependence on imported resources, predictability, and scalability) are taken into account. The results show that grid electrolysis is expected to hold the key of sustainable hydrogen production in the near future while the technologies of other methods advance and their associated costs decrease.

Introduction

Increasing world population and rise in standards of living have been the two reasons behind ever growing global energy demand. So far, this demand has heavily been met by burning fossil fuels. However, their limited and nonhomogeneous reserves and concerns related to climate change and energy security have shifted the attention towards alternative energy sources and systems, such as renewables. Although they have

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tremendous advantages in terms of energy security and environmental impact, renewables are not continuous supplies of energy, therefore, they need to be stored in reliable, safe, effective, and environmentally benign ways for a sustainable future [1].

In the literature, there are many studies focusing on smart energy systems for a sustainable future, and it is widely accepted that these systems require a variety of energy storage options designed to meet different end use requirements. In traditional electricity generation and distribution systems, the challenge is to precisely adjust the supply to meet the fluctuating demand. The excess energy is usually converted to different forms other than electricity such as potential, kinetic, chemical etc. The aim of this approach is to bridge the gap between supply and demand when there is a mismatch between them [2].

Hydrogen is a promising energy storage medium with tremendous advantages such as lower transmission and storage losses compared to electricity, production from renewable and abundant resources via a wide variety of methods and technologies, and its high gravimetric energy density. As a chemical fuel, hydrogen can easily be integrated to existing fuel distribution and utilization network with minimal adjustments. In addition, hydrogen can be used in fuel cells or internal combustion engines to generate electricity with minimal or zero environmentally harmful emissions. In order to be considered as truly sustainable manners, hydrogen must be produced from clean, affordable, reliable and abundant resources in energy and cost efficient and environmentally and socially benign manners [3].

In the literature, there is an increasing amount of studies on sustainability analysis of hydrogen production systems. Dincer and Acar [2] have introduced the critical perspectives of innovation specifically for hydrogen production under a new concept (so-called: 18S concept), covering source, system, service, scope, staff, scale-up, safety, scheme, sector, solution, stakeholder, standardization, subsidy, stimulation, structure, strategy, support and sustainability. They have discussed and highlighted the importance of these specific conceptual items on sustainable hydrogen production. The authors also have comparatively assessed some innovative hydrogen production methods by using a ranking method based on the 18S concept. Their results have showed that renewable sources, particularly hydro, geothermal and solar show a unique potential to support sustainable hydrogen production. The authors also have pointed out that the production methods supporting heat recovery (such as thermal production methods) and the photonic based options show better performance in terms of emissions, cost, and efficiency.

Aasadnia and Mehrpooya [4] have reviewed the sustainability of large-scale liquid hydrogen production methods and approaches. In their study, the authors have introduced a novel classification of hydrogen liquefaction systems in terms of heat exchange and expansion process methods. The authors have also highlighted the importance of using renewable resources in hydrogen liquefaction plants. In addition, the authors have reviewed hybrid conceptual hydrogen liquefaction plants which integrate renewable resources to conventional plants for better sustainability. In addition to renewability of resources, the authors have considered the operational costs and system efficiencies of hydrogen production processes. The authors' sustainability analysis has also covered specific energy consumption (SEC) and exergy efficiency of hydrogen liquefiers is discussed. The authors have concluded that SEC reduction of hydrogen liquefaction is not expected to be rapid in the near future, the authors have pointed that this amount is expected to remain within the range of 5–8 kWh/kg LH_2. Overall, the authors have included energy and exergy efficiencies, renewability of resources, and operational costs when assessing the sustainability of liquid hydrogen production and concluded that further analysis should be done for a more comprehensive analysis, especially considering environmental impacts of hydrogen production methods.

Nikolaidis and Poullikkas [5] have conducted a comparative overview of 14 different hydrogen production processes in order to assess their sustainability. The authors have considered production costs and rates, system efficiencies, scalability, and investment costs while assessing the sustainability of conventional and new hydrogen production methods. The authors have concluded that thermochemical pyrolysis and gasification are economically viable approaches providing the highest potential to become competitive on a large scale in the near future while conventional methods retain their dominant role with costs in the range of 1.34–2.27 USD/kg. The authors have also pointed out that biological methods appear to be promising pathways, but further research studies are needed to improve their production rates, while the low conversion efficiencies in combination with the high investment costs are the key restrictions for water-splitting technologies to compete with conventional methods. However, the authors have concluded that further development of these technologies along with significant innovations concerning hydrogen storage, transportation and utilization, could decrease dependence on fossil fuel imports and green hydrogen can dominate over the traditional energy resources. In their study, environmental and social impacts and technical criteria (such as availability) have not been considered for sustainable hydrogen production. In a similar study, the authors have concluded that the key to sustainable hydrogen production is to integrate storage, transportation and utilization with renewable based hydrogen production [6].

With the increasing renewable resource integration to our energy mix, there has been growing attention on alternative hydrogen production methods other than fossil fuel powered option. Fereidooni et al. [7] have conducted a comprehensive evaluation of hydrogen production from photovoltaic power stations. The authors have presented the viability of PV based electrolysis options for sustainable hydrogen production. The authors investigated the production capacity, running cost, and overall system energy efficiency as sustainability criteria. Their results have showed that PV electrolysis is a sustainable alternative to produce hydrogen in both small and large scales.

When produced from renewable and sustainable sources, hydrogen becomes a promising green energy carrier for clean development. Hosseini and Wahid [8] have given an overview of the state-of-the-art hydrogen production technologies using renewable and sustainable energy resources. The authors have taken overall system energy efficiency and production cost into account and concluded that solar and wind powered hydrogen production has a potential to become sustainable options when their prices decrease with developments in their technologies. The authors have discussed that solar and wind powered systems have essentially zero greenhouse gas emissions and left other environmental and technical sustainability criteria to future studies.

Fukuzumi et al. [9] have investigated the sustainability of thermal and photocatalytic production of hydrogen with earth-abundant metal complexes. The authors have developed abundant and reliable catalysts for sustainable solar and thermal based hydrogen production. The authors have accomplished eliminating the dependence on precious and high cost Pt catalysts in renewable hydrogen production systems. As a result, they have reported reduced hydrogen production costs and enhanced efficiencies with systems which could enhance energy security for different regions around the world. The authors' study has expanded the sustainability criteria used by previous researchers by including abundancy in addition to efficiency and cost. However, the true environmental impact of these systems has not been studied yet.

Singh et al. [10] have investigated the role of hydrogen as a sustainable fuel for future of the transport sector. The authors have presented the recent developments in the field of production, storage, transport and delivery of hydrogen along with environmental and safety aspects of its use as an energy carrier. The authors have concluded that renewable sources should be used for hydrogen production to make it completely sustainable. In their study, it is also mentioned that for a successful "hydrogen economy" in the near future, the technical and economic challenges associated with hydrogen must be addressed quickly. Even though the authors have pointed out the challenges very well, their study has not covered environmental, social, and technical availability criteria.

Vincent and Bessarabov [11] have reviewed low cost hydrogen production by anion exchange membrane electrolysis for a sustainable future. The authors have provided a summary of important research that has been carried out on membranes, electrocatalysts, and ionomers used in electrolyzers, and the performance of such electrolyzers. The authors have aimed to identify gaps and future research directions in water electrolysis. The authors have stated that water electrolysis is still a developing technology; therefore, for commercially viable hydrogen production, requires further investigation and improvements are needed, especially on efficiency enhancement, membrane stability, robustness, ease of handling, and cost reduction. Despite the fact that the authors have covered some technical, economic, and safety aspects of sustainability, this study does not cover environmental and social aspects which are mentioned in future directions.

Ahmed et al. [12] have investigated the role of hydrogen as a transport fuel for a sustainable future. The authors have discussed a framework based on macroeconomic issues considering several feasible options for a sustainable future. The authors have stated the importance of renewable energy choices for sustainable growth. In addition, the authors have discussed that while the benefits of prioritizing a modern emission-free future transport system are great, often issues raised regarding how a national economy can deliberate and implement such policy options become contentious. Here, it should be noted that the authors have defined the sustainability framework based on three dimensions: energetic (efficiency), economic (production cost), and environmental (CO_2 emissions). Similar studies have taken the same criteria into account for hydrogen use in sustainable aviation [13] and road transportation [14] sectors and highlighted the importance of renewables in hydrogen production. Further investigation is needed for a better sustainability analysis including other energetic, economic, environmental, social, and availability criteria.

The main motivation behind this study is the need to provide a comprehensive review and investigation on sustainability of hydrogen production systems, which could potentially guide researchers, policy makers, different industries, and energy market customers. In the literature, there is a lack of studies focusing on a complete technical, environmental, social, and economic evaluation of hydrogen production systems by taking availability and reliability into account. Therefore, in this study, the primary goal is to conduct a performance investigation of some key hydrogen production systems, which are grid electrolysis (electricity from fossil fuels), wind electrolysis, PV electrolysis, nuclear thermochemical water splitting cycles, solar thermochemical water splitting cycles, and photoelectrochemical cells. To do so, a hierarchical decision model is built based on literature review and interviews with experts on the field. The model consists of five main and seventeen sub-criteria such as economic performance (initial and running cost), environmental performance (GHG emissions, land use, water discharge quality, and solid waste), social performance (impact on public health, employment and training opportunities, and public acceptance), technical performance (energy and exergy efficiencies, process control, and raw material input), and availability/reliability (dependence on imported resources, predictability, and scalability). To define the weights of main and sub-criteria, experts are provided with a questionnaire having pairwise comparisons. To handle the observed hesitancy of the experts about assigning exact values for comparisons in the evaluations, hesitant fuzzy AHP is used. In the end, several recommendations and future directions are provided for the quality and end use enhancement of hydrogen production methods.

The study is organized as follows: Section Hydrogen production methods gives the details about hydrogen production methods and MCDM tools used in hydrogen production. Section Research methodology presents the research methodology including HFS and HFAHP. Section Proposed model presents the structure of the hierarchical decision model for hydrogen production option selection, the calculation of the importance weights of the criteria of the proposed model and the results of the sensitivity analysis. Finally, Section Conclusions concludes the research results and gives directions for future research.

Hydrogen production methods

In this study, the sustainability aspects of six different hydrogen production methods are investigated which can be classified based on their primary energy sources as shown in Fig. 1.

In this section, the options presented in Fig. 1 are discussed in detail. It should be noted that all electrical energy-based hydrogen production options essentially use the same electrolyzer technology with different energy resources: fossil fuels, wind, or solar. In this study, grid electrolysis is also used as fossil fuel electrolysis as the grid electricity is assumed to be generated from fossil fuels. In addition, when conducting the sustainability assessment, grid electrolysis is assumed to be developed in an area with already existing access to grid electricity from fossil fuels. On the other hand, in the other options, the infrastructure needs to be developed first as well (e.g., wind turbine or PV panel installation or thermochemical facility building, etc.).

Electrical energy based hydrogen production options

Electrical energy is a form of energy resulting from the flow of electric charge. It can be harnessed from a variety of primary energy sources: biomass, geothermal, hydro, nuclear, ocean, solar, and wind. In this study, electrolysis is the only electrical energy-based hydrogen production method.

In electrical energy-based hydrogen production processes, hydrogen and oxygen are produced from water and electricity in an electrolyzer. Electrolyzers have a wide range of applications. They can support small-scale appliances and distributed hydrogen production. On the other hand, larger electrolyzers are capable of producing hydrogen in centralized facilities. In order to produce hydrogen in an environmentally benign way via electrolysis, electricity should come from low or zero carbon resources. Electrolyzers also vary based on their operating temperatures. At lower operating temperatures, electrolysis has lower efficiencies but these electrolyzers have simpler designs and there are fewer problems due to corrosion and heat losses. These systems are commercially available in some hydrogen fueling stations. High-temperature electrolyzers operate at temperatures mostly above 750 °C, therefore these systems require higher quality

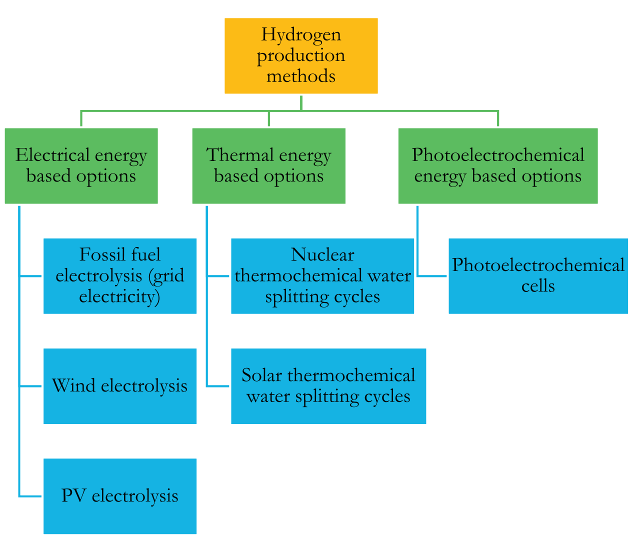

Fig. 1 – Classification of elected hydrogen production methods.

heat which is generally provided by nuclear and concentrated solar power plants. High-temperature electrolyzers have higher efficiencies compared to the low-temperature alternatives. There is increasing demand to clean electricity-based electrolysis due to the global efforts to minimize greenhouse gas emissions especially after Kyoto Protocol and Paris Agreement.

Electrolyzers are categorized based on their electrolytes. The type of electrolyte used in an electrolyzer defines the anode (oxidation) and cathode (reduction) reactions. The anode reaction is also identified as oxygen-evolving reaction while the cathode reaction is called as hydrogen evolving reaction. Three of the most common electrolyzers are (i) alkaline electrolyzers (AEL), (ii) polymer electrode membrane or proton exchange membrane electrolyzers (PEMEL), and (iii) solid oxide electrolyzers (SOEL).

Grid electrolysis

In grid electrolysis, the electrolyzer is connected to an already existing electricity network. This option seems to be the cheapest and quickest way during the transition to a successful hydrogen economy. However, with this option, it is not possible to produce hydrogen in remote and/or rural regions with no access to reliable electricity. In addition, even though electrolysis itself emits no environmentally harmful gases, this option indirectly has negative environmental impacts as the contributor of increasing fossil fuel combustion for electricity production.

In the literature, there is a wide variety of studies focusing on different aspects of grid electrolysis such as energy storage and grid balancing [15]. Grid electrolysis-based hydrogen production is currently seen as the most convenient option during transition to hydrogen fueled vehicles (e.g., fuel cell vehicles) [16,17]. Further information on grid electrolysis and the its future on sustainable hydrogen production can be found in Refs. [18–20].

Wind electrolysis

The basics of wind electrolysis is very similar to grid electrolysis with one difference: in wind electrolysis, the electrolyzer is connected to the electricity provided by wind turbines. Wind electrolysis is a viable approach to producing greener hydrogen, holding promise to better utilize locally available renewable energy sources [21]. A wind electrolysis system can reduce greenhouse gas emissions while integrating larger percentages of renewable energy into the electric grid [22]. To enable a greater penetration of renewable energy resources, hydrogen production from wind electrolysis must be cost competitive [23]. For instance, as a vehicle fuel, this means competing with gasoline or other vehicle fuels; as energy storage for the grid, this means being cost competitive with other grid electricity technologies [24]. Hydrogen could be produced for 4 USD/kg or less at some high wind class sites [20]. However, a bigger issue is the capacity factor, which needs to be 44% or better along with relatively high wind speeds [25]. Along with low production costs, however, delivery and storage costs will also factor into the final cost of hydrogen, which calls for investigating a wider range of wind class sites, where geographical elements such as distance from end use should also be considered [26].

PV electrolysis

The sustainable nature of solar electricity along with its associated large resource potential and falling costs have motivated a rapid increase in the deployment of utility scale solar electricity generation plants in recent years [27]. As the installed capacity of photovoltaics (PVs) continues to grow, cost-effective technologies for solar energy storage will be critical to mitigate the intermittency of the solar resource and to maintain stability of the electrical grid [28]. Hydrogen generation via solar water splitting represents a promising solution to these challenges, as hydrogen can be stored, transported and consumed without generating harmful byproducts [29]. However, the cost of hydrogen produced by electrolysis is still significantly higher than that produced by fossil fuels [30]. The U.S. Department of Energy has calculated the hydrogen threshold cost to be 2.00–4.00 USD per gallon of gasoline equivalent, whereas the most up-to-date reported hydrogen production cost via electrolysis is 3.2–6.6 USD per gallon of gasoline equivalent [31].

Thermal energy based hydrogen production options

Thermal energy refers to the energy contained within a system that is responsible for its temperature and heat is the flow of thermal energy. Thermolysis, thermochemical water splitting, biomass gasification, and biofuel reforming are some examples of thermal based hydrogen production methods. Biomass, geothermal, nuclear, ocean, and solar are some of the sustainable primary energy sources for thermal hydrogen production.

Research on thermochemical cycles mainly focus on using solar or nuclear primary heat input. Numerous thermochemical cycles have been proposed in the past and checked against factors such as: corrosion problems, cost analysis, heat transfer, material stability, maximum temperature, processing scheme, reaction kinetics, and separation of substances, side reactions, thermodynamics, thermal efficiency and toxicity. Some have sufficiently progressed to be experimentally demonstrated and have already proven their scientific and practical feasibility. All cycles however, have design challenges and none has actually been implemented on a commercial scale.

Nuclear thermochemical water splitting cycles

As long as it can provide electricity and process heat, any type of nuclear reactor can be used for the production of hydrogen [32]. Besides high temperature electrolysis, another promising candidate to produce large amounts of hydrogen by high temperature water-splitting is thermochemical process. The most straightforward method of water splitting would be a one-step direct thermal decomposition. However, this would require temperatures higher than 2500 °C for reasonable quantities, which is industrially not feasible. Therefore, multi-step processes are being considered [33].

A thermochemical cycle is a process consisting of a series of thermally driven chemical reactions where water is decomposed into hydrogen and oxygen at moderate temperatures. Supporting intermediate chemical compounds, which are regenerated and recycled internally and remain completely in the system, are used in a sequence of chemical and physical processes. The only input to the cycle is water and high temperature heat. Therefore, these cycles are potentially more efficient than low temperature electrolysis and could significantly reduce production costs [34].

Solar thermochemical water splitting cycles

Thermochemical hydrogen production has been under study at one level or another for many years. Most recently, renewable sources of thermal energy, like solar and nuclear reactor sources, have been emphasized. Nuclear power represents a high energy density source that is restricted in operating temperature range because of the materials of construction needed to contain nuclear material. Solar power represents a low energy density source that can attain far higher temperatures through solar concentration, but is still restricted in operating temperature because of materials of construction needed to contain the thermochemical reaction. Nevertheless, feasible operating temperatures for a solar cycle are much higher than those for a nuclear cycle. As a consequence, the inventory of possible solar powered thermochemical reactions to produce hydrogen from water is quite large [35].

A simple two-step thermochemical water-splitting reaction to produce hydrogen generally requires very high temperature heat for endothermic metal oxide reduction to release oxygen, and a lower temperature exothermic reaction of water with the metal, increasing the oxidation state of the metal and releasing hydrogen. In most two-step cycles of this sort, the reduction temperature exceeds the vaporization temperature of the metal and this class is called the Volatile Metal Oxide class. Several two-step metal oxide cycles have been investigated in which mixed oxides, usually ferrite compounds, undergo reduction and oxidation without volatilization and these and other non-volatile multi-step reactions were assigned to a Non-Volatile Metal Oxide class. All of the reactions in these two classes rely on very high temperatures (>1400 °C) [36,37].

Thermal reduction of some more complex chemicals can be achieved at lower temperatures because the oxygen bonds are weaker than for simple metal oxides. An intermediate reaction is necessary to release hydrogen and another reaction (sometimes more than one) is required to restore the oxidation state of the initial compound. Lower temperature cycles either employ intermediates for oxidation, complicating the cycle chemistry, or use electrolysis to release hydrogen and restore the original oxidation state of the cycle. A sulfuric acid cycle is one of very few low temperature pure thermochemical cycles that operate at a moderate temperature (~850 °C), but it is a multi-step cycle with an intermediate compound required to close the cycle. Another sulfuric acid cycle is simplified to a two-step cycle by using an electrolytic step to close the cycle [38].

Photoelectrochemical energy based hydrogen production options

A photoelectrochemical hydrogen production cell (PEC) essentially contains one or two photoelectrodes (i.e., photoanode and photocathode). In a PEC, there is at least one semiconductor electrode. The photonic energy is absorbed by the photoelectrode(s) in a PEC. PV cells and PEC semiconductor electrodes have analogous operating mechanisms. In both systems, electron–hole pairs are produced by the photons with energies higher than the band gap of the photoactive surface. Such electron–hole pairs are used to either reduce or oxidize water. A PEC can use the solar spectrum more efficiently compared with photocatalysis and PV electrolysis because it combines water electrolysis and photocatalysis in one single element [39]. Because PECs do not have a need for additional power supplies, they are more compact, which is one of the major advantages of these systems. There are many kinds of photosensitive semiconductors investigated in the literature. The most promising option so far is TiO_2 [40]. In addition to TiO_2, several other semiconductors have been studied, such as ZnO, Fe_2O_3, $BiVO_4$ and WO_3 [41]. Metal nitrides and phosphides (i.e., Ta_3N_5 and GaP), metal oxynitrides (i.e., TaON) and n-type and p-type silicon have also been investigated in the open literature [42].

MCDM tools used in decisions related to hydrogen production methods

Since many decisions related with hydrogen production concern multi-dimensional criteria, Multi Criteria Decision Making (MCDM) tools are utilized in the relevant literature. Ren and Toniolo [43] have proposed a methodology including the improved decision making trial and evaluation laboratory (DEMATEL) and interval evaluation based on distance from average solution (EDAS) to order the pathways of hydrogen production. The alternatives of pathways have been categorized into 4 groups: coal gasification, stream reforming of methane, biomass gasification, and wind turbine electrolysis. As a result of the analysis, biomass gasification has been noticed as the best option among these alternatives. On the other hand, the coal gasification has been found as the least sustainable option. In order to reveal the effect of changings of the weights on the decision, a sensitivity analysis has also been conducted. Yu [44] has utilized interval-valued intuitionistic fuzzy set theory to select the best hydrogen production technology among three basic alternatives: nuclear based high temperature electrolysis technology, electrolysis of water technology by hydropower, and coal gasification technology. In the proposed methodology, three main criteria such as economic performance, social performance, and the support degree of government policies have been taken into account. Nuclear based high temperature electrolysis technology has been considered as the best alternative. On the other hand, coal gasification technology has been found as the least satisfactory option. Ren et al. [45] have presented a novel fuzzy multi-actor MCDM method to order the biomass-based technologies for hydrogen production. Four main criteria (economic, environmental, technological, and social-political) have been taken into consideration with their fifteen subcriteria. By evaluating these criteria, the best biomass-based technology has been selected among four alternatives: pyrolysis, conventional gasification, supercritical water gasification, and fermentative hydrogen production. Conventional gasification has been found as the best technology and fermentative hydrogen production has been considered as the least desirable one. Pilavachi et al. [46] have utilized Analytic Hierarchy Process (AHP) to select the best hydrogen production process among seven alternatives: steam methane reforming, partial oxidation of hydrocarbons, coal gasification, biomass gasification, the combination of photovoltaics and electrolysis, the combination of wind power and electrolysis, and the combination of hydropower and electrolysis. The evaluation has been performed by taking into consideration following criteria: CO_2 emissions, operation and maintenance costs, capital cost, feedstock cost, and hydrogen production cost. The results have indicated that the processes which are integrating renewable energy sources are the most satisfactory options. Afgan et al. [47] have presented a sustainability index based multi criteria evaluation process for hydrogen systems in which performance, environment, market, and social factors have been considered. The hydrogen energy system options have been categorized into four parts: feedstock, electrical energy, H_2 production, and H_2 utilization.

Although MCDM methods are well studied in hydrogen production study field, there are not any studies which utilize a novel approach to deal with the vagueness in the decisions of the experts. Because hydrogen production option evaluation concerns opinions of the experts which have high potential to carry hesitancy when scoring the criteria and the alternatives, Hesitant Fuzzy Sets (HFS) should be utilized to overcome this problem.

Research methodology

In this section, the research methodology behind the sustainability evaluation of hydrogen production processes is explained in detail. This section has two parts: first, hesitant fuzzy sets are introduced and then hesitant fuzzy analytic hierarchy process (HFAHP) is introduced.

Hesitant fuzzy sets

Ordinary fuzzy sets are utilized to handle uncertainties and vagueness in the opinions of the decision makers [48]. However, for the problems involving contradictions in the opinions of the decision makers when scoring the criteria and the alternatives, an evolved fuzzy set which is strong enough to deal with the subjective conflictions is required to use. In practice, it is very common that decision makers cannot assign an exact linguistic variable reflecting their ideas if the problem has high uncertainty. For such kind of problems, a novel fuzzy sets named hesitant fuzzy set (HFS) introduced by Torra and Narukawa [49] and Torra [50] is required to be utilized. After HFS has been introduced, Rodriguez et al. [51] have proposed hesitant fuzzy linguistic terms sets (HFLTS) to let experts define their expressions which hesitate among several terms. Then, the assessments of experts are aggregated by ordered weighted averaging (OWA) operator. OWA operator could have been used here as well, as recommended in Öztayşi et al. [52], however, it has two important drawbacks:

i. The decision makers are forced to limit the deviation among their preferences with two.
ii. When there are more than two decision makers, which usually is the case, since the method uses only the range of

different preferences, and does not interested in how many decision makers preferred each evaluation point within the range, if the majority of the decision makers has a similar preference which is different from the minority, this majority does not have a higher influence on the final decision.

Given those drawbacks, it could be concluded that fuzzy envelopes approach and the usage of OWA operator can be used perfectly in individual evaluations, and in compromised decision making in groups where mild contradictions are faced. However, its usage in its current form can give misleading results in aggregate decision making.

To handle the hesitancies, researchers have begun to attach more importance on HFS in a wide range of business study fields. Recently, project portfolio selection procedure [53] has been developed with the help of HFS. On the other hand, in some researches, HFS has been combined with other traditional MCDM techniques. For instance, Choquet integral approach has been integrated with HFS to handle soil erosion [54] and ELECTRE method has been combined with HFS to select the best maintenance agency [55]. Although HFS has been well studied in industrial sectors, the number of studies in the energy sector is very limited. Yuan et al. [56] and Çoban and Onar [57] have benefited from HFS approach for the selection of the best renewable energy option. Xiao et al. [58] have proposed a HFS based methodology for renewable energy project selection.

Hesitant fuzzy analytic hierarchy process (HFAHP)

Analytic Hierarchy Process (AHP) is one of the most commonly used MCDM method, and it is performed by conducting pairwise comparisons between main criteria, sub-criteria and alternatives. The performance of pairwise comparisons' matrices in which the decision makers make scoring, are also measured by checking the consistencies. In many cases, because the decision makers have vagueness in their minds, fuzzy expressions are found as more desirable to make evaluation. On the other hand, if the decision makers have contradiction, in other words, if they tend to use such expressions for scoring: "Between 6 and 8", rather than scoring the comparison with an exact value such as "7", it is necessary to use hesitant fuzzy AHP (HFAHP). A HFAHP procedure which is depending on Buckley's theory can be summarized in twelve phases as following:

Step 1) A hierarchical model consisting of five main and seventeen sub-criteria, and six alternatives is constructed.

Step 2) As in an ordinary AHP procedure; criteria, sub-criteria and alternatives are evaluated using pair wise comparisons based on linguistic terms in Table 1. Different from a classical fuzzy AHP approach, decision makers are let to choose an interval of linguistic terms whenever necessary to fully express their preferences. However, in order to be able to use OWA operator, they are asked to limit the maximum range of each interval by two.

Step 3) The fuzzy envelopes approach [59] is used to end up with trapezoidal fuzzy numbers representing overall individual preferences. Firstly, the fuzzy envelopes for the decisions of the experts are formed. The lowest scale is s_0 the highest scale is $s_{g,}$ and the evaluations are varying between two term; s_i to $s_{j.}$ Therefore, it can be mathematically denoted as $s_0 \le s_i < s_j \le s_{g.}$ To proceed with the fuzzy envelopes approach, OWA operator of dimension n is used which can be calculated by using Equation (1).

$$\text{OWA}\,(a_1,\ a_2, \ldots,\ a_n) = \sum_{j=1}^{n} w_j b_j \tag{1}$$

where b_j is the largest of the aggregated arguments $a_1, a_2, \ldots, a_n$ and $W = (w_1,\ w_2,\ \ldots,\ w_n)^T$ is the associated weighting vector where $\sum_{i=1}^{n} w_i = 1$.

The values of a, b, c, and d constituting the trapezoidal fuzzy number Ñ (i.e., Ñ= (a, b, c, d)), can be found by using Equations (2)–(5):

$$a = min\left\{a_L^i,\ a_M^i,\ a_M^{i+1}, \ldots, a_M^j, a_R^j\right\} = a_L^i \tag{2}$$

$$d = max\left\{a_L^i,\ a_M^i,\ a_M^{i+1}, \ldots, a_M^j, a_R^j\right\} = a_R^j \tag{3}$$

$$c = \left\{\begin{array}{c} a_M^i, if\ \ i+1=j \\ \text{OWA}_{w^2\left(a_{m,}^j \ldots, a_m^{(i+j)/2}\right)}\ ,if\ \ i{+}j\ is\ even \\ \text{OWA}_{w^2\left(a_{m,}^j \ldots, a_m^{(i+j+1)/2}\right)},if\ \ i{+}j\ is\ odd \end{array}\right\} \tag{4}$$

$$c = \left\{\begin{array}{c} a_M^{i+1}, if\ \ i+1=j \\ \text{OWA}_{w^2\left(a_{m,}^j a_{m,}^{j-1} \ldots, a_m^{(i+j)/2}\right)}\ ,if\ \ i{+}j\ is\ even \\ \text{OWA}_{w^2\left(a_{m,}^j a_{m,}^{j-1} \ldots, a_m^{(i+j+1)/2}\right)},if\ \ i{+}j\ is\ odd \end{array}\right\} \tag{5}$$

Table 1 – Linguistic scales for hesitant FAHP [53].

Rank	Linguistic Term	Abbreviation	Triangular Fuzzy Number
10	Absolutely High Importance	AHI	7,9,9
9	Very High Importance	VHI	5,7,9
8	Essentially High Importance	ESHI	3,5,7
7	Weakly High Importance	WHI	1,3,5
6	Equally High Importance	EHI	1,1,3
5	Exactly Equal	EE	1,1,1
4	Equally Low Importance	ELI	0.33,1,1
3	Weakly Low Importance	WLI	0.2,0.33,1
2	Essentially Low Importance	ESLI	0.14,0.2,0.33
1	Very Low Importance	VLI	0.11,0.14,0.2
0	Absolutely Low Importance	ALI	0.11,0.11,0.14

Assuming that α is in the unit interval [0, 1], first ($W^1 = (w_1^1, w_2^1, \ldots, w_n^1)$) and second ($W^2 = (w_1^2, w_2^2, \ldots, w_n^2)$) types of weights are specified by using α [60] as in Equations (6) and (7), respectively.

$$w_1^1 = \alpha_2,\ w_2^1 = \alpha_2(1-\alpha_2), \ldots,\ w_n^1 = \alpha_2(1-\alpha_2)^{n-2} \tag{6}$$

$$w_1^2 == \alpha_1^{n-1},\ \ w_2^2 = (1-\alpha_1)\alpha_1^{n-2}, \ldots,\ w_n^2 = 1-\alpha_1, \mathrm{w} \tag{7}$$

where $\alpha_1 = \frac{g-(j-i)}{g-1}$ and $\alpha_2 = \frac{(j-i)-1}{g-1}$ (g is the top rank number of evaluation scores (in this study, the top rank number from Table 1 is 10), j is the rank of highest evaluation and i is the rank of lowest evaluation).

Step 4) The finalized individual pair wise comparison matrix of expert k, $\tilde{A}^k$, is prepared as a result of Step 3 where $\tilde{a}_{ij} = (a_{ij_l}, a_{ij_{m1}}, a_{ij_{m2}}, a_{ij_u})$ as shown in Equation (8):

$$\tilde{A}^k = \begin{bmatrix} 1 & \cdots & \tilde{a}_{ln} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{nl} & \cdots & 1 \end{bmatrix} \tag{8}$$

The reciprocal values are calculated as shown in Equation (9).

$$\tilde{a}_{ji} = \left(\frac{1}{a_{ij_u}}, \frac{1}{a_{ij_{m2}}}, \frac{1}{a_{ij_{m1}}}, \frac{1}{a_{ij_l}}\right) \tag{9}$$

Step 5) The aggregate decision matrices should be formed only if the individual preferences are consistent. Defuzzifying the matrices to calculate the consistency is a widely preferred method [61,62]. Given the trapezoidal fuzzy number $\tilde{d} = (l, m_1, m_2, u)$, the crisp number ($\mu_{\tilde{d}}$) can be calculated by using Equation (10).

$$\mu_{\tilde{d}} = \frac{l + 2m_1 + 2m_2 + u}{6} \tag{10}$$

Equations (11) and (12) can then be used to calculate consistency ratio (CR);

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{11}$$

$$CR = \frac{CI}{RI} \tag{12}$$

where CI refers to the consistency index, λ_{max} symbolizes the largest eigenvector of the matrix, n is the number of criteria, and RI is the random index that differs for each n. If the CR value is lower than 0.1, it can be accepted as satisfactory and the result is found as consistent [63].

If any of the matrices are inconsistent, the experts are asked to revise the corresponding pairwise comparisons until the required consistency is reached.

Step 6) As the consistency is established in every matrix, individual matrices are aggregated using geometric means, and the aggregate matrix $\tilde{C}$ in Equation (13) is formed

$$\tilde{C} = \begin{bmatrix} 1 & \cdots & \tilde{c}_{xy} \\ \vdots & \ddots & \vdots \\ \tilde{c}_{yx} & \cdots & 1 \end{bmatrix} \tag{13}$$

such as

$$\tilde{c}_{ij} = \sqrt[n]{\prod_{k=1}^{n} \tilde{a}_{ij}^k} \tag{14}$$

where k represents the individual experts, and n is the total number of these experts.

Step 7) After reaching the aggregate matrices, each row's geometric mean ($\tilde{r}_i$) is calculated by using Equation (15).

$$\tilde{r}_i = (\tilde{c}_{i1} \otimes \tilde{c}_{i2} \ldots \otimes \tilde{c}_{in})^{1/n} \tag{15}$$

Step 8) The fuzzy weights ($\tilde{w}_i$) for criteria, subcriteria, and alternatives are calculated by using Equation (16). To decrease the deviation in the weights, it is assumed that $\tilde{r}_l \oplus \tilde{r}_2 \ldots \oplus \tilde{r}_n$ is the maximum parameter of ALI (shown in Table 1, it is 9) [52].

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \ldots \oplus \tilde{r}_n)^{-1} \tag{16}$$

Step 9) All the fuzzy numbers found are defuzzified by using Equation (17).

$$D = \frac{c_l + 2c_{m1} + 2c_{m2} + c_u}{6} \tag{17}$$

Step 10) The defuzzified weights are then normalized to obtain the local weights of the criteria. To calculate the global weights of the sub-criteria, their local weights are multiplied with the weight of the main-criteria they belong.

Step 11) Previous steps are rerun for each matrix formed for each alternative to calculate the preference score of alternative i (S_i). The final fuzzy scores can be retrieved by using Equation (18).

$$S_i = \sum_{j=1}^{n} w_j s_{ij},\ \forall i \tag{18}$$

where w_j is the global weight of criterion j and s_{ij} is the score of alternative criterion i with respect to j. By ranking the defuzzified values, the best alternative is obtained.

Proposed model

In this section, the detailed structure of the proposed model is provided along with the explanation of each criterion and its corresponding weight. Then, the selection process is explained with the results and their discussion. In the end, the sensitivity analysis is given.

Structure of the proposed model

Finding different resources is one way to address the increasing global energy demand. However, these resources should be handled more efficiently in order to get more outputs from the same amount of energy consumption. In the long term, scientific and technical developments might allow substitution of traditional fuels with new fuels and clean energy systems. For this to happen, the new resource or alternative energy system must perform at least as efficiently as the traditional ones. It is also expected for alternative and clean energy systems to have fewer negative environmental effects, for example GHG emissions and health and safety risks.

Sustainable hydrogen production is critically necessary to tackle the energy and environmental challenges in a clean, efficient, effective, reliable and affordable way, and address the crucial requirements for implementation. Sustainable hydrogen production options are expected to have enhanced (i) efficiencies, (ii) resource utilization, (iii) affordability, (iv) environmental protection, (v) energy security, and (vi) system design and performance analysis. The selected sustainable hydrogen production criteria are presented in Fig. 2. The hierarchical model for hydrogen production option selection can be seen in Fig. 3.

In this study, better economic, environmental, social, and technical performance and availability/reliability criteria are considered as sustainability indicators. Initial and running costs are considered as indicators of economic performance. GHG emissions, land use, water discharge quality, and solid waste generation are the environmental performance indicators. Social performance of hydrogen production systems is comparatively assessed based on their impact on public health, employment and training opportunities, and public acceptance. Within technical performance category, energy and exergy efficiencies, process control, and raw material input are the performance parameters. Last, the availability/reliability of selected hydrogen production methods are compared to each other based on their dependence on imported resources, predictability, and scalability. For comparison purposes, when considering economic, environmental, social, and technical performances, the production amounts of all selected methods are assumed to be equal (such as GHG emissions per kg hydrogen production).

Initial cost include the costs of the design and construction of all components of a hydrogen production process. Here, it should be noted that in grid electricity based electrolysis, the costs of construction of the power plant and the grid are not included in the initial cost. But in wind and PV electrolysis, nuclear and solar thermochemical, and photoelectrochemical methods, all components are considered in the initial cost which makes these alternatives more expensive than grid electrolysis. Running cost covers the operation and maintenance costs of the selected hydrogen production methods. Running costs include costs of labor, material and energy resources, and maintenance for proper operation.

In environmental impact category, impact to air, land, and water are considered for a better understanding of the true damage on the environment. Greenhouse gas emissions, land use, water discharge quality, and solid waste generation are the criteria used to evaluate the environmental performance of hydrogen production systems. Gases that trap heat in the atmosphere are called greenhouse gases which are namely CO_2, CH_4, N_2O, and fluorinated gases. Land use is the land requirement for the hydrogen production system and its auxiliary components. Water discharge quality indicates how polluting the liquid discharge from selected hydrogen production methods are. Here it should be noted that not only contaminants and impurities but also discharge temperature is considered when evaluating wastewater quality. Last, solid waste generation of the selected methods are compared. In grid electrolysis, the impact on the environment during the construction of power plant is not considered.

Impact on public health can be caused directly or indirectly by the selected methods. In this study both direct and indirect impacts are considered. Employment opportunities indicate the new jobs introduced while training opportunities show new skill sets and know-how addition to the existing workforce. Public acceptance is also taken into account as a social performance criterion because the successful integration of hydrogen into the existing energy mix requires acceptance by greater audiences.

Energy efficiency is a measure of how well energy is conserved while exergy efficiency focuses on the conservation of “the quality of energy”. Exergy is used to quantify the maximum useful work which can be extracted from a source or system. Therefore, exergy efficiency is absolutely necessary to truly investigate a system's technical performance. Process control means how effectively the process input parameters can be monitored, controlled, and adjusted as the output requirements or environmental conditions change. And raw material input is a measure of the quantity, quality, cost, and abundance of the raw material input requirements of a process. For instance, a process requiring precious and rare

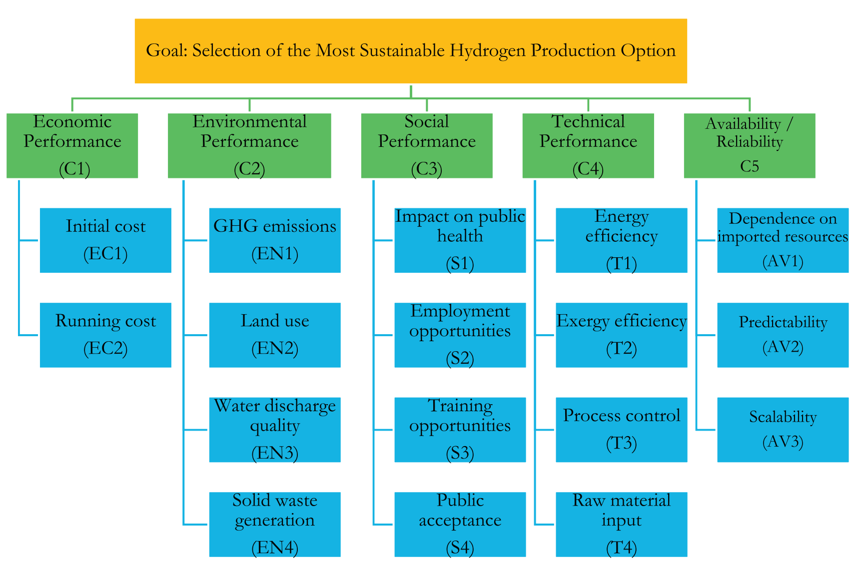

Fig. 2 – Sustainable hydrogen production criteria.

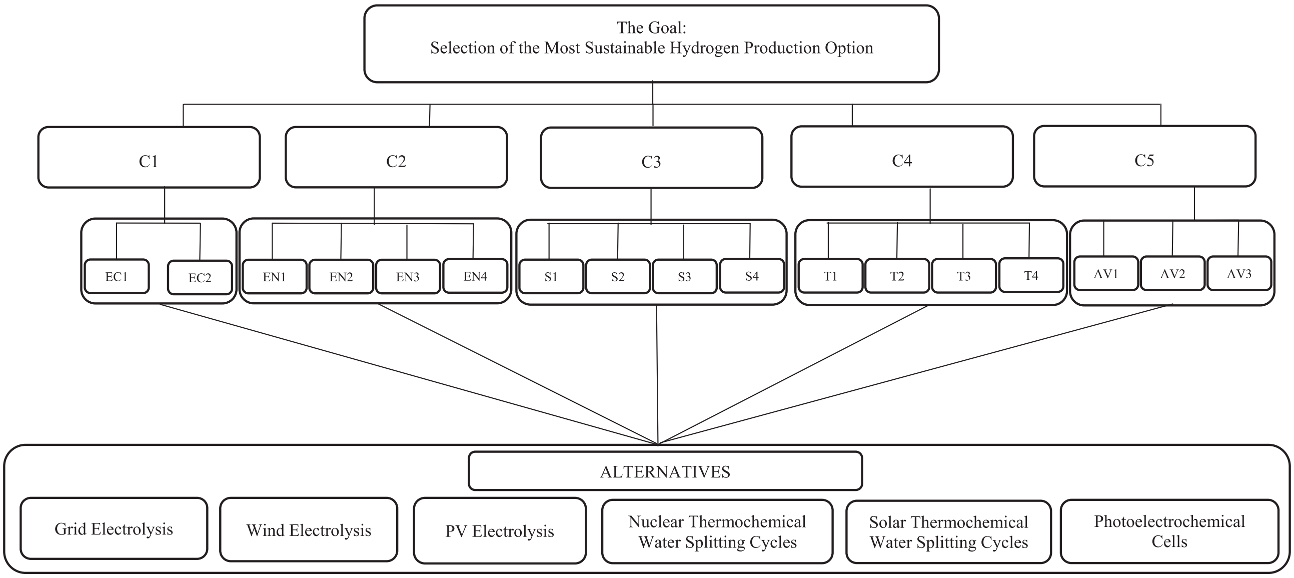

Fig. 3 – The proposed model for hydrogen production selection decision.

elements would be considered to have low performance based on this criteria.

Lastly, in availability/reliability criteria, dependence on imported resources, predictability, and scalability are considered. It has been widely accepted that a truly sustainable system must rely on locally available and abundant resources instead of imports for better energy security. Predictability could include the variations in the input (e.g., predicting the speed of wind in the future), or predicting the output quality and quantity with designated process parameters. Scalability of a system is an indicator of how well it would be adjusted to different regions, users, output amounts, etc. For instance, it would be more challenging to change the scale of a nuclear power plant while PV panels could be used for both single housing units and large scale power plants which makes them highly scalable.

Criteria weights

Three experts from hydrogen production industry have scored the criteria and sub-criteria by using pairwise comparisons. All experts have had different experiences and backgrounds from academic and business environments of energy industry. In order to perform HFAHP, it is necessary to have evaluation scores with a maximum of 2 differences between their values. For example, if an expert gives the score such as “Between 2 and 5”, it is unacceptable; because the difference between “2” and “5” equals to “3”. Therefore, the evaluation process is required to be iterated until the difference is lower than or equal to 2.

First of all, five main criteria (economic performance (C1), environmental performance (C2), social performance (C3), technical performance (C4) and availability/reliability (C5)) are evaluated by each expert and individual matrices are aggregated by using geometric means (as mentioned at Step 6). The consistency ratio is computed as 0.09, 0.0004 and 0.007 for expert 1, expert 2, and expert 3 respectively. These values are acceptable according to Saaty's rules [63]. Tables 2–4 indicate the fuzzy envelops of the main criteria evaluations of all experts.

After aggregating the matrices, OWA operator is applied to the fuzzy envelops for computing trapezoidal fuzzy sets which are shown as (a, b, c, d). For example, in Table 5, the fuzzy envelope of C1 and C2, which is clarified as “Between WLI and ELI” by all experts is found as (0.2, 0.33, 1, 1). Firstly, it is necessary to calculate α_1 and α_2 by the help of the formula given at Step 3. g which is the top rank number equals to 10; i which is the rank of lowest evaluation (WLI) equals to 3 and j which is the rank of highest evaluation (ELI) equals to 4. Then;

$$\alpha_1 = \frac{10-(4-3)}{10-1} = 1$$

$$\alpha_2 = \frac{(4-3)-1}{10-1} = 0$$

Since a $= a_L^i$ and d $= a_R^j$; a $= 0.2$ (minimum value of WLI shown as 0.2, 0.33, 1) and d $= 1$ (maximum value of ELI shown as 0.33, 1, 1).

If *if* $i+1 = j$; then $b = a_M^i$. In our case, $i+1 = j$; therefore b $= 0.33$.

If *if* $i+1 = j$; then $c = a_M^{i+1}$. In our case, $i+1 = j$; therefore c $= 1$.

So, (a, b, c, d) for the fuzzy envelope of C1 and C2 equals to (0.2, 0.33, 1, 1).

Further, geometric means are calculated for the trapezoidal fuzzy sets. First row is computed as following:

$$a_g = (1*0.2*0.58*0.3*0.34)^{1/5} = 0.414$$

$$b_g = (1*0.33*1*0.40*0.48)^{1/5} = 0.578$$

$$c_g = (1*1*2.08*0.48*1)^{1/5} = 1$$

$$d_g = (1*1*2.92*1*1.71)^{1/5} = 1.37$$

Table 2 – Fuzzy envelops of the main criteria evaluation of expert 1.

	C1	C2	C3	C4	C5
C1	EE	Between WLI and ELI	WHI	WLI	WLI
C2		EE	ESHI	Between EHI and WHI	Between VLI and ESLI
C3			EE	Between VLI and ESLI	VLI
C4				EE	Between ELI and EE
C5					EE

Table 3 – Fuzzy envelops of the main criteria evaluation of expert 2.

	C1	C2	C3	C4	C5
C1	EE	Between WLI and ELI	Between WLI and ELI	Between ESLI and WLI	Between EHI and WHI
C2		EE	EE	Between WLI and ELI	Between WHI and ESHI
C3			EE	Between WLI and ELI	Between WHI and ESHI
C4				EE	Between ESHI and VHI
C5					EE

Table 4 – Fuzzy envelops of the main criteria evaluation of expert 3.

	C1	C2	C3	C4	C5
C1	EE	Between WLI and ELI	Between EHI and WHI	EE	Between WLI and ELI
C2		EE	Between WHI and ESHI	Between EHI and WHI	EE
C3			EE	Between WLI and ELI	Between ESLI and WLI
C4				EE	Between WLI and ELI
C5					EE

Table 5 – Trapezoidal fuzzy sets of main criteria.

	C1	C2	C3	C4	C5
C1	(1,1,1,1)	(0.2,0.33,1,1)	(0.58,1,2.08,2.92)	(0.30,0.40,0.48,1)	(0.34,0.48,1,1.71)
C2	(1,1,3,5)	(1,1,1,1)	(1.44,2.46,2.92,3.65)	(0.58,0.69,2.08,2.92)	(0.48,0.75,1,1.32)
C3	(0.34,0.48,1,1.71)	(0.27,0.34,0.40,0.69)	(1,1,1,1)	(0.16,0.25,0.58,0.69)	(0.25,0.44,0.62,1.11)
C4	(1,2.08,2.46,3.27)	(0.34,0.48,1.44,1.71)	(1.44,1.71,3.97,6.08)	(1,1,1,1)	(0.58,1.18,1.91,2.08)
C5	(0.58,1,2.08,2.92)	(0.75,1,1.32,2.08)	(0.89,1.61,2.26,3.98)	(0.48,0.52,0.84,3.98)	(1,1,1,1)

For normalization, all values are divided by 9 which is the highest score in the linguistic scale table.

$$a_w = 0.414/9 = 0.046$$

$$b_w = 0.578/9 = 0.064$$

$$c_w = 1/9 = 0.111$$

$$d_w = 1.37/9 = 0.153$$

Table 6 shows the trapezoidal fuzzy weights of main criteria. The crisp weights are also obtained by defuzzifying the fuzzy numbers as shown in Step 9 (see Table 7).

When main criteria evaluation results of all three international experts are taken into account, it is seen that (Table 7) technical performance criteria has the highest importance, immediately followed by environmental performance criteria. Third important performance criteria is technical. Based on the common view of our international experts, social performance criteria has the lowest importance, followed by economic performance criteria. The agreement between our experts state that technical performance (especially exergy efficiency) is key to sustainable hydrogen production. Exergetically efficient hydrogen production means that the process is using its resources less wastefully, which eventually lowers the process cost and environmental impact. This is why environmental impact has the second highest importance: sustainability requires effective and clean technologies. Close to these two criteria, availability and reliability state that using domestic and reliable resources is very important. When all of these criteria are met, costs are expected to go down as new technologies evolve and production sizes increase, and as a result, social performance improves as well. In a similar study, Thengane et al. [64] have compared GHG and waste generation, energy efficiency, raw material input, and scalability and highlighted the importance of technical performance. However, in their study, economic and social performances have not been taken into account.

The same steps are applied for all sub-criteria. First of all, economic performance (C1) taken into account. The sub-criteria of economic aspects (initial cost (EC1), running cost (EC2)) are evaluated by each expert and the individual evaluations are aggregated by the help of geometric means. Because there are only two sub-criteria, the consistency is not needed

Table 6 – Trapezoidal fuzzy weights of main criteria.

Main Criteria	Trapezoidal Fuzzy Weights
C1	(0.05,0.06,0.11,0.15)
C2	(0.09,0.12,0.2,0.26)
C3	(0.04,0.05,0.08,0.11)
C4	(0.09,0.13,0.21,0.26)
C5	(0.08,0.11,0.15,0.28)

Table 7 – Crisp values of the weights of main criteria.

Main Criteria	Crisp Weights
C1	0.140
C2	0.257
C3	0.106
C4	0.267
C5	0.228

to measure [63]. Tables 8–10 indicate the fuzzy envelops of the economic performance sub-criteria evaluations of experts. The aggregated trapezoidal fuzzy sets of economic performance sub-criteria and the crisp values of the weights of economic performance sub-criteria are also given at Table 11 and Table 12 respectively.

Previous steps are conducted for other sub-criteria and the crisp weights are obtained by defuzzifying the fuzzy numbers. The weights of main criteria and global weights of all sub-criteria can be seen at Table 13.

Table 13 shows that running cost is given higher weight than the initial cost within economic performance criteria. Our experts have stated that in the long run, having low running cost becomes more important than having low initial cost. Environmental performance criteria comparison shows that GHG emissions is assigned the highest weight and land use is given the lowest weight. With the introduction of new rules and regulations after Kyoto Protocol and Paris

Table 8 – Fuzzy envelops of the economic performance sub-criteria evaluation of expert 1.

	EC1	EC2
EC1	EE	Between VLI and ESLI
EC2		EE

Table 9 – Fuzzy envelops of the economic performance sub-criteria evaluation of expert 2.

	EC1	EC2
EC1	EE	ESHI
EC2		EE

Table 10 – Fuzzy envelops of the economic performance sub-criteria evaluation of expert 3.

	EC1	EC2
EC1	EE	Between WLI and ELI
EC2		EE

Table 11 – Aggregated trapezoidal fuzzy sets of economic performance sub-criteria.

	EC1	EC2
EC1	(1,1,1,1)	(0.41,0.62,1,1.33)
EC2	(0.75,1,1.61,2.47)	(1,1,1,1)

Table 12 – Crisp values of the weights of economic performance sub-criteria.

Economic Performance Sub-criteria	Crisp Weights
EC1	0.43
EC2	0.56

Agreement, reduction of GHG emissions has become the priority for many "clean technologies". Our experts also agree that first step of lowering environmental impact should be addressing GHG emissions. Water discharge quality also has high importance, since wastewater and polluted waters are significant threats to the environment (e.g., ecosystem damage, biodiversity loss, health issues, etc.). Solid waste is relatively easier to manage and handle, therefore it has the second lowest importance. Land use, although it is important, when compared to the impact on the air and water quality, has the lowest importance. Within social performance criteria, impact on public health has the highest importance and public acceptance has the lowest. Our experts have stated that sustainable hydrogen production should not threated human health, which should be a priority. They have stated that it is desired to have training opportunities which would enhance the know-how. They have stated that having skilled jobs with training opportunities is more important than the number of jobs. Which is why employment opportunities has the second lowest importance. Our experts expect public acceptance as a later step with lower importance. Technical performance comparison indicates that exergy efficiency is the most important sub-criteria while raw material input is assigned the lowest weight. A truly sustainable process must use its resources effectively with minimal waste of "useful work" which requires high exergy efficiency, which is the reason behind the results. Energy efficiency has high importance as well, followed by process control. With better process control options, supply and the process rates can be adjusted based on the fluctuating demand and supply, as well as changing market conditions. Predictability is given the highest and scalability has the lowest weight among the availability/reliability criteria. Predictability states that when a process is highly predictable, it becomes possible to anticipate the process outputs based on changing environmental and process parameters. Next important criteria is dependence on imported resources, as sustainability states that using locally available resources should be preferred.

Hydrogen production option selection

The fuzzy envelops for six alternatives (electrolysis (electricity from fossil fuels) (A1), wind electrolysis (A2), PV electrolysis (A3), nuclear thermochemical water splitting cycles (A4), solar thermochemical water splitting cycles (A5),

Table 13 – Weights of main and sub-criteria.

Main criteria	Weights of main criteria	Sub-criteria	Global weights of sub-criteria
Economic Performance (C1)	0.140	Initial cost (EC1)	0.061
		Running cost (EC2)	0.078
Environmental Performance (C2)	0.257	GHG emissions (EN1)	0.115
		Land use (EN2)	0.023
		Water discharge quality (EN3)	0.073
		Solid waste generation (EN4)	0.044
Social Performance (C3)	0.106	Impact on public health (S1)	0.056
		Employment opportunities (S2)	0.018
		Training opportunities (S3)	0.024
		Public acceptance (S4)	0.007
Technical Performance (C4)	0.267	Energy efficiency (T1)	0.048
		Exergy efficiency (T2)	0.151
		Process control (T3)	0.038
		Raw material input (T4)	0.029
Availability/Reliability (C5)	0.228	Dependence on imported resources (AV1)	0.072
		Predictability (AV2)	0.092
		Scalability (AV3)	0.063

photoelectrochemical cells (A6)) in terms of sub-criteria are obtained according to evaluations of the experts. As an example, the fuzzy envelops of all experts for evaluation of initial cost (EC1) are given at Table 14.

OWA operator is applied to the fuzzy envelops of experts individually for computing trapezoidal fuzzy sets. As an example, in Table 14, for Expert 3, the fuzzy envelope of A3 and A6 which has 2 differences between the edges of the ranges is clarified as "Between ELI and EHI". And it equals to (0.33, 1, 1, 3). Similar computation is made to find α_1 and α_2. Then;

$$\alpha_1 = \frac{10-(6-4)}{10-1} = 0.88$$

$$\alpha_2 = \frac{(6-4)-1}{10-1} = 0.11$$

Since a $= a_L^i$ and d $= a_R^j$; a = 0.33 (minimum value of ELI shown as 0.33, 1, 1) and d = 3 (maximum value of EHI shown as 1, 1, 3).

If $i+j$ is even, then $b = OWA_{w^2\,(a_{m,}^{j}\,\ldots,a_{m}^{(i+j)/2}\,)}$. In our case, $i+j =$ 10; therefore

$$b = \alpha_2{*}1 + \alpha_1{*}1 = 0.88{*}1 + 0.11{*}1 = 1$$

If $i+j$ is even, then $c = OWA_{w^2\,(a_{m,}^{j}\,a_{m,}^{j-1}\,\ldots,a_{m}^{(i+j)/2}\,)}$, therefore

$$c = 2{*}1 - 1 = 1$$

So, (a, b, c, d) for the fuzzy envelope of A3 and A6 in terms of initial cost evaluation of Expert 3 equals to (0.33, 1, 1, 3).

As the next step, geometric means are calculated for the trapezoidal fuzzy sets. Then, for normalization, all values are divided by 9 which is the highest score in the linguistic scale table. After obtaining the trapezoidal fuzzy weights of sub-criteria from all experts, the aggregation is made by using geometric means. Similar steps are followed and the crisp values of weights of main criteria, sub-criteria and alternatives in terms of criteria are obtained (as seen at Table 15).

To conclude the proposed process, it is necessary to multiply the sub-criteria weights of alternatives with obtained criteria weights. Then, the obtained values of each alternative are multiplied with the weights of criteria. The final weights of alternatives are given at Table 16.

Table 16 shows the overall comparison of sustainability of the selected hydrogen production methods. When all criteria are taken into account, grid electrolysis is seen as the most sustainable option, followed by photoelectrochemical cells and wind electrolysis. On the other hand, nuclear water splitting cycles is seen as the least sustainable, followed by PV electrolysis and solar thermochemical water splitting cycles. The main reason behind high sustainability of grid electrolysis is the fact that our experts considered the power plant and grid connection are already existing in this method, which lowers the initial cost and land use significantly. In addition, grid electrolysis is already mature and well established, as a result, this method has higher energy and exergy efficiencies, better process control and predictability, and wider public acceptance which are significant benefits while transitioning to a hydrogen economy. However, in the long term there are several problems associated with grid (fossil electricity based) electrolysis, such as high GHG emissions and negative impact on public health. Compared to other selected methods, grid electrolysis has less training opportunities since its technology is very well developed and mature. Among the selected methods, nuclear thermochemical water splitting cycles has several challenges such as costs associated with the risk and control of nuclear, land requirement for the nuclear facility, water discharge quality issues, and solid waste hazard risk. Furthermore, public acceptance of nuclear energy is very low especially because of some serious nuclear power plant accidents: Fukushima Daiichi nuclear disaster (2011), Chernobyl disaster (1986), Three Mile Island accident (1979), and the SL-1 accident (1961). Nuclear is often seen as a "clean" alternative to fossil fuel based energy systems due to its zero GHG emissions. However, for a truly sustainable future, renewable energy sources are to be selected, as agreed on by our experts.

In this study, wind electrolysis, PV electrolysis, and solar thermochemical water splitting cycles are selected as renewable based hydrogen production methods. These

Table 14 – Fuzzy envelops of all experts for evaluation of initial cost (EC1).

	A1	A2	A3	A4	A5	A6
Expert 1						
A1	EE	Between VHI and AHI	Between VHI and AHI	Between VHI and AHI	Between VHI and AHI	Between VHI and AHI
A2		EE	Between EHI and WHI	Between WLI and ELI	Between ESLI and WLI	Between WHI and ESHI
A3			EE	Between ESLI and WLI	Between VLI and ESLI	Between EHI and WHI
A4				EE	Between WLI and ELI	Between ESHI and VHI
A5					EE	Between VHI and AHI
A6						EE
Expert 2						
A1	EE	Between VHI and AHI	Between EHI and WHI	Between ESHI and VHI	Between WHI and ESHI	Between EHI and WHI
A2		EE	Between VLI and ESLI	Between WLI and ELI	Between ESLI and WLI	Between VLI and ESLI
A3			EE	Between WHI and ESHI	Between EHI and WHI	EE
A4				EE	Between WLI and ELI	Between ESLI and WLI
A5					EE	Between WLI and ELI
A6						EE
Expert 3						
A1	EE	AHI	Between WHI and ESHI	Between VHI and AHI	Between ESHI and VHI	Between WHI and ESHI
A2		EE	Between ALI and VLI	Between ESLI and WLI	Between VLI and ESLI	Between ALI and VLI
A3			EE	Between WHI and VHI	Between WHI and ESHI	Between ELI and EHI
A4				EE	Between ESLI and WLI	Between VLI and ESLI
A5					EE	Between ESLI and WLI
A6						EE

Table 15 – Local and global weights of hydrogen production options in terms of sub-criteria.

Main criteria (Weights)	Sub criteria	Global weights of sub-criteria	Crisp Local Weights of Alternatives						Crisp Global Weights of Alternatives					
			A_1	A_2	A_3	A_4	A_5	A_6	A_1	A_2	A_3	A_4	A_5	A_6
C1 (0.140)	EC1	0.438	0.476	0.045	0.136	0.080	0.143	0.119	0.208	0.020	0.060	0.035	0.063	0.052
	EC2	0.562	0.046	0.288	0.202	0.100	0.160	0.204	0.026	0.162	0.114	0.056	0.090	0.115
C2 (0.257)	EN1	0.449	0.045	0.273	0.209	0.092	0.158	0.223	0.020	0.123	0.094	0.041	0.071	0.100
	EN2	0.093	0.103	0.118	0.220	0.029	0.094	0.436	0.010	0.011	0.020	0.003	0.009	0.040
	EN3	0.284	0.091	0.221	0.213	0.064	0.138	0.273	0.026	0.063	0.061	0.018	0.039	0.078
	EN4	0.174	0.053	0.271	0.212	0.071	0.159	0.234	0.009	0.047	0.037	0.012	0.028	0.041
C3 (0.106)	S1	0.530	0.049	0.262	0.213	0.077	0.165	0.234	0.026	0.139	0.113	0.041	0.088	0.124
	S2	0.170	0.253	0.095	0.097	0.347	0.147	0.061	0.043	0.016	0.017	0.059	0.025	0.010
	S3	0.230	0.050	0.193	0.188	0.175	0.160	0.234	0.012	0.044	0.043	0.040	0.037	0.054
	S4	0.070	0.373	0.112	0.137	0.062	0.175	0.141	0.026	0.008	0.010	0.004	0.012	0.010
C4 (0.267)	T1	0.181	0.363	0.080	0.075	0.198	0.194	0.090	0.066	0.015	0.013	0.036	0.035	0.016
	T2	0.565	0.406	0.075	0.062	0.199	0.182	0.077	0.230	0.042	0.035	0.112	0.103	0.043
	T3	0.144	0.374	0.107	0.095	0.170	0.093	0.160	0.054	0.015	0.014	0.024	0.013	0.023
	T4	0.110	0.088	0.182	0.182	0.045	0.224	0.278	0.010	0.020	0.020	0.005	0.025	0.031
C5 (0.228)	AV1	0.316	0.051	0.226	0.226	0.043	0.226	0.226	0.016	0.072	0.072	0.014	0.072	0.072
	AV2	0.405	0.292	0.086	0.148	0.050	0.142	0.282	0.118	0.035	0.060	0.020	0.057	0.114
	AV3	0.279	0.373	0.062	0.064	0.373	0.064	0.064	0.104	0.017	0.018	0.104	0.018	0.018

Table 16 – Final scores of alternatives.

Alternatives	Weights
A_1	0.211
A_2	0.163
A_3	0.154
A_4	0.126
A_5	0.157
A_6	0.188

options have similar performances such as lower running costs and reduced negative impact on the environment. Renewable based hydrogen production methods, especially photoelectrochemical cells, have high social performance and they rely on locally available sources which are great advantages. Most of the renewable based technologies are still in research and development stage and not commercialized in large scales. As a result, they either have lower efficiencies or high initial costs which hinder their economic and technical performance. These challenges, however, are expected to be addressed as renewable technologies evolve with advancements in material sciences and introduction of novel technologies. Therefore, it is commonly accepted to use grid (fossil based) electricity for hydrogen production as a sustainable strategy. Transition to hydrogen economy can be initiated by grid electrolysis as the cleaner and novel technologies (such as photoelectrochemical cells) evolve to become more efficient, affordable, and reliable hydrogen production systems of the future.

Sensitivity analysis

Sensitivity analysis is a vital final piece for many quantitative decision models used to assess the stability of the calculated optimal solution given changing criteria weights. To apply the analysis, the criteria weights are changed one at a time from 0 to 1 by 0.1, while the weights of the rest of the criteria are kept proportionally the same. Fig. 4 parts a, b, c, d, and e illustrate the sensitivity analysis results for economic performance, environmental performance, social performance, technical performance, and availability/reliability, respectively.

As can be seen from Fig. 4 (a) and (e), although the sequence of the following alternatives are changing as the criterion weights are increased, the final decisions (i.e. the preferred hydrogen production options) remain the same. It means that the decision is not sensitive to changes in the criteria weights of economic performance and availability/reliability. Therefore, no matter how the individual criterion weight changes for economic performance and availability/reliability, A1 remains the best alternative.

In part (b) of Fig. 4, it can be seen that a decrease in the criterion weight of the environmental performance from its

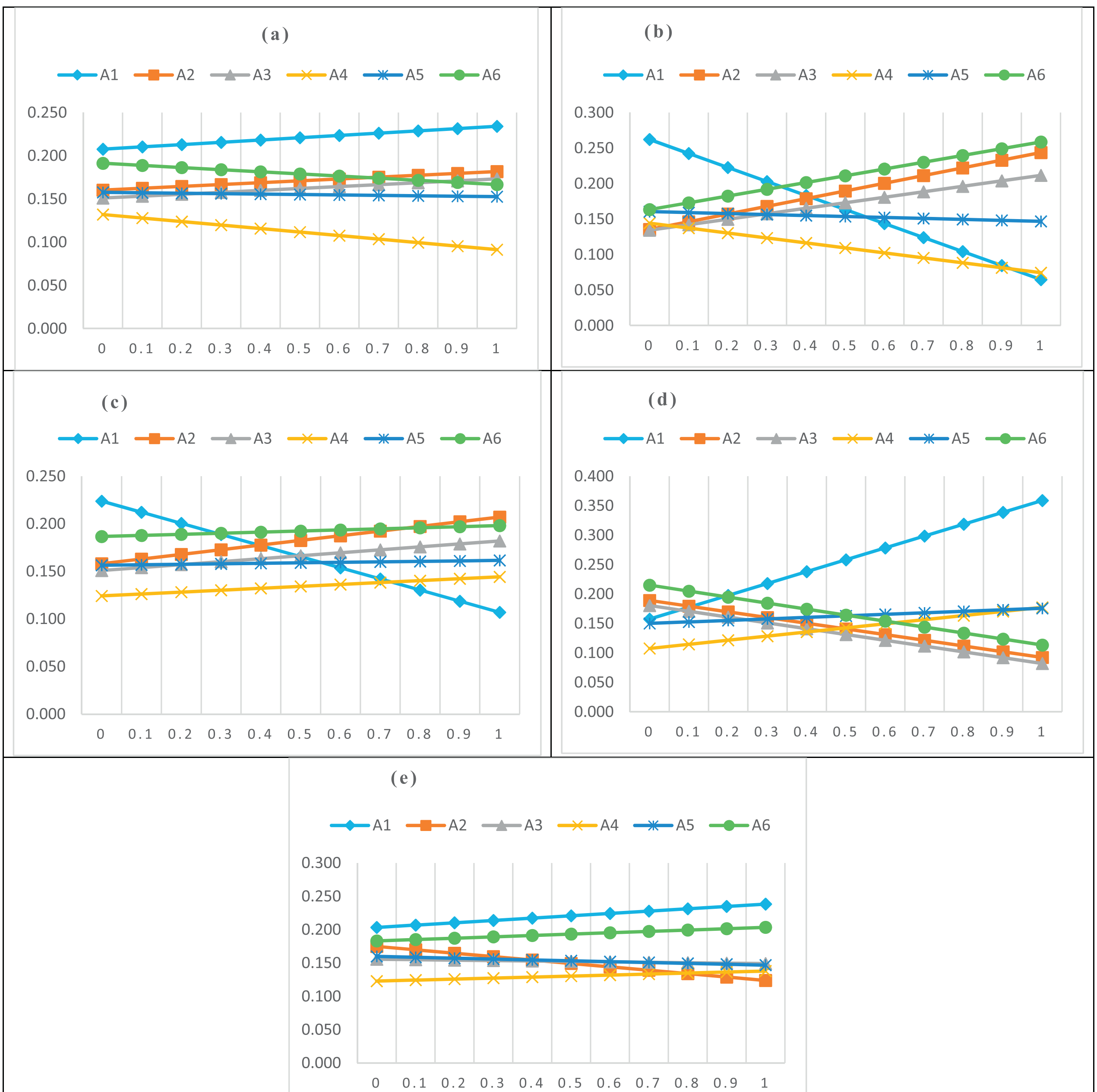

Fig. 4 – Sensitivity analysis of (a) economic performance, (b) environmental performance, (c) social performance, (d) technical performance, and (e) availability/reliability criteria with respect to different weights.

actual value of 0.257 does not affect the position of the best alternative, A1. However, as the criterion weight of the environmental performance is increased to approach 0.35, it is observed that A1 leaves the lead to A6.

In part (c) of Fig. 4, it can be concluded that the decrease in the criterion weight of social performance does not change the selected alternative, A1. However, as the weight is increased above 0.30, the rank of A1 starts to decrease, and A6 becomes the most preferred option for a while. After the weight reaches to 0.8, the overall ranking of the alternatives becomes A2, A6, A3, A5, A4 and A1. It means that the selected alternative changes again, and the new one is A2. It is also interesting to see the initial leader of the list, A1, in the last position.

In part (d) of Fig. 4, it can be concluded that if the weight of technical performance is below 0.2, A6 is the preferred option. However, as the weight is increased above 0.2, A1 becomes the selection, and the distance between preference levels of A1 and all other alternatives increases constantly, making the choice a very clear one.

Conclusions

In this study, hesitant fuzzy AHP is used to evaluate the sustainability of different hydrogen production methods by taking environmental, economic, social, technical, and availability/reliability criteria into account. The selected hydrogen production methods are grid electrolysis (electricity from fossil fuels), wind electrolysis, PV electrolysis, nuclear thermochemical water splitting cycles, photoelectrochemical cells, and solar thermochemical water splitting cycles. Initial cost and running cost are the economic performance criteria. In environmental performance evaluation, GHG emissions, land use, water discharge quality, and solid waste generation are considered. Social performance evaluation criteria include impact on public health, employment opportunities, training opportunities, and public acceptance. Technical performance criteria are: energy efficiency, exergy efficiency, process control, and raw material input. And last but not least, dependence on imported resources, predictability, and scalability are the availability/reliability criteria. The key results of this study can be summarized and concluded as.

- Among the selected main categories, technical performance is given the highest importance, followed by environmental performance. On the other hand, social performance has the lowest weight on sustainability of hydrogen production, compared to the other selected performance criteria.
- Running cost is given higher weight than the initial cost within economic performance criteria.
- Environmental performance criteria comparison shows that GHG emissions is assigned the highest weight and land use is given the lowest weight.
- Within social performance criteria, impact on public health has the highest importance and public acceptance has the lowest.
- Technical performance comparison indicates that exergy efficiency is the most important sub-criteria while raw material input is assigned the lowest weight.
- Predictability is given the highest and scalability has the lowest weight among the availability/reliability criteria.
- When all criteria are taken into account to evaluate and compare the sustainability of selected hydrogen production options, grid electrolysis is seen as the most sustainable option, followed by solar thermochemical water splitting cycles and wind electrolysis. On the other hand, nuclear water splitting cycles is seen as the least sustainable, followed by PV electrolysis and photoelectrochemical cells.

Nomenclature

AEL	Alkaline electrolyzer
AHI	Absolutely high importance
AHP	Analytic hierarchy process
AHI	Absolutely high importance
ALI	Absolutely low importance
DEMATEL	Decision making trial and evaluation laboratory
EDAS	Evaluation based on distance from average solution
EE	Exactly equal
EHI	Equally high importance
ELI	Equally low importance
ELECTRE	Elimination and choice expressing reality
ESHI	Essentially high importance
ESLI	Essentially low importance
GHG	Greenhouse gas
HFAHP	Hesitant fuzzy analytic hierarchy process
HFLTS	Hesitant fuzzy linguistic terms sets
HFS	Hesitant fuzzy sets
LH_2	Liquid hydrogen
MCDM	Multi criteria decision making
OWA	Ordered weighted averaging
PEC	Photoelectrochemical cell
PEMEL	Polymer electrode (or proton exchange) membrane electrolyzer
PV	Photovoltaics
SEC	Specific energy consumption
SOE	Solid oxide electrolyzer
VHI	Very high importance
VLI	Very low importance
WHI	Weakly high importance
WLI	Weakly low importance

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