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Original Article

Hydrogen production in the light of sustainability: A comparative study on the hydrogen production technologies using the sustainability index assessment method

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ABSTRACT

Hydrogen as an environmentally friendly energy carrier has received special attention to solving uncertainty about the presence of renewable energy and its dependence on time and weather conditions. This material can be prepared from different sources and in various ways. In previous studies, fossil fuels have been used in hydrogen production, but due to several limitations, especially the limitation of the access to this material in the not-too-distant future and the great problem of greenhouse gas emissions during hydrogen production methods. New methods based on renewable and green energy sources as energy drivers of hydrogen production have been considered. In these methods, water or biomass materials are used as the raw material for hydrogen production. In this article, after a brief review of different hydrogen production methods concerning the required raw material, these methods are examined and ranked from different aspects of economic, social, environmental, and energy and exergy analysis sustainability. In the following, the current position of hydrogen production is discussed. Finally, according to the introduced methods, their advantages, and disadvantages, solar electrolysis as a method of hydrogen production on a small scale and hydrogen production by thermochemical method on a large scale are introduced as the preferred methods.

1. Introduction

Energy is one of the main factors of production. Therefore, the correct and principled implementation of energy carrier optimization programs plays an important role in ensuring the country's policies at the national and international levels [1]. Although leading to rapid economic growth in advanced industrial societies, extensive consumption of fossil fuels has led to increasing changes in the atmosphere due to the release of combustion pollutants and the increase in carbon dioxide in the atmosphere and its consequences [2]. These consequences include climate change, rising sea levels, and, ultimately, the escalation of international conflicts [3]. On the other hand, the imminent depletion of fossil resources and the prediction of rising prices are all more important than ever and the need to replace the current energy system. Therefore, using new energy sources instead of fossil fuels is inevitable. New energy systems in the future must rely on structural and fundamental changes in which non-carbon energy sources such as solar, wind, geothermal, and biomass are used [4]. Hydrogen as a clean fuel can be a good alternative to other conventional fuels and, in the future, as an energy carrier. Clean fuels have physical and chemical properties that make them cleaner than gasoline with the current structure and composition in combustion. These fuels produce fewer pollutants during combustion, while using these fuels reduces the rate of increase and accumulation of carbon dioxide that causes global warming [5]. The ease of production from water, the almost unique consumption, and the inherent environmental utility of hydrogen are features that distinguish it from other alternative fuel options [6].

Hydrogen can be used in all applications of fossil fuels. Hydrogen, in particular, complements renewable energy sources and makes them readily available to consumers anywhere, anytime [5]. Almost all renewable energy sources are not available periodically, are not portable or stored by themselves, and cannot be used as fuel, especially in transportation [3]. Although hydrogen as an energy carrier can create and improve flexibility in global energy consumption patterns, it should be noted that there is not yet a large commercial market for hydrogen as an energy carrier, and its major applications are for use in the oil industry. And

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petrochemicals and other chemical production units are restricted; The only direct use of hydrogen gas as an energy supply agent in fuel cells is produced by burning hydrogen in an electric cell [7]. Large-scale fuel cells are also considered, which are used as generators in support cases [8]. Therefore, although hydrogen is not widely used globally in commercial energy applications, it is time to find its proper place in the world energy market. Hydrogen can be produced using primary or secondary sources. Primary sources are used during the direct extraction of hydrogen from natural sources, and secondary sources decompose water into oxygen and hydrogen using energy, usually in the form of electricity. Renewable or non-renewable energy sources can provide propulsion energy in both industries [9]. Depending on the amount of access to different sources, the required technological needs, and the volume of gas required for each geographical location, the chosen method for hydrogen production will be different.

In this research, various hydrogen production methods are studied from different perspectives, and in the final section, the best possible method for hydrogen production will be selected.

2. Methodology

For assessing the sustainability domains effectively, several factors and indexes are used in this paper to show the various parameters effective in sustainability. Each factor discussed in the methodology corresponds to an index, which shows its impact on the sustainability index. The following is a summary of all indexes used.

2.1. Energy index

Energy factor refers to the energy sides of the sustainability analysis. This includes different energy-based factors, including the system's energy efficiency, storage rate, production rate, and other parameters obtained in the energy analysis processes, estimated using the first law of thermodynamics. Furthermore, this factor accounts for the energy impact of environmental friendliness or the economic effect [15].

2.2. Exergy index

The exergy factors reflect several exergy-based factors essential when analyzing the sustainability of energy systems. Using the second law of thermodynamics, exergy assessment is an integrated tool to study the quality of energy and point out where energy can be conserved further. Furthermore, the exergy efficiency is considered using the total exergy of the desired output concerning the total exergy input needed. The exergy destruction ratio is used to estimate this factor comprehensively [11,12].

2.3. Environmental friendliness index

The environmental friendliness factor is dependent on different environmental effects of different fields, including air-based, water-based, and other material impacts. The intensity of influence of the energy system on its surrounding ambient is a vital index when considering its sustainability aspect. Furthermore, this factor accounts for local impacts as well as global ones. A life cycle assessment is used by following the CML2001 process. Additionally, this factor shows the level of suitability of an energy system environmentally [9].

2.4. Economic index

The economic factor assesses the financial aspect of energy systems by further studying the benefit-cost ratio, payback time, maintenance, and operation costs, as well as the Levelized costs of electricity. Some of these factors are local and short-term, while others are more global and have a long-term effect. Studying the economic manifestations of energy systems is essential to understanding their sustainability. Therefore, this index covers an essential side of the analysis method. Additionally, the energy aspect is closely dependent on the economy, making this factor valuable and an integrated part of this analysis [8,12].

2.5. Social index

The social factor is related to the social aspects when analyzing the sustainability of energy systems. It considers job creation, which is a local and rewarding index. It also considers social awareness and social acceptance [13]. As technologies develop, societies respond differently to that technology. Also, some cultures might have certain intentions toward an energy system over another. Therefore, studying the social value behind energy systems is vital. Furthermore, the social factor measures the human health, human welfare, and social costs behind energy systems. These parameters give value for this factor as it gives precise and practical social results [16].

3. Results and discussion

The mentioned methods can be examined from different points of view. Its environmental compatibility, process efficiency, and cost of hydrogen production are some of the things that must be considered in the selection process of each method to select the final process and investment (Table 1).

3.1. Comparison of environmental effects

The negative effects of carbon dioxide on the nature of this gas are known as the main cause of greenhouse gases. Therefore, reducing carbon dioxide production is one of the notable topics in discussing future energy carriers. CO_2 emission, either in the form of waste used in another industry, or its decomposition and collection of carbon (CCS), are known as possible methods to reduce the problem of emissions [17]. In 2001, the Center for Environmental Science at the University of Leiden published the Life Cycle Assessment Operational Guide to the ISO Standards (2016) to introduce the LCA process following ISO standards. The classification of environmental impacts was done according to this practical guide. This study introduces the global warming potential (GWP) and the acid potential (AP) to explain the amount of pollution generated in the hydrogen industry. GWP (equivalent to the weight of carbon dioxide) is equivalent to a scale for releasing carbon dioxide, and AP (equivalent to the weight of sulfur dioxide) represents the discharge of sulfur dioxide from soil to water [18]. AP as a measure of the degree of acidity changes is also used. According to the environmental values reported in Figs. 1 and 2 aligned with the findings of [18], hydrogen production using fossil fuels (natural gas reforming) is the most environmentally destructive method compared to other existing methods.

According to Figs. 1 and 2, it can be seen that for hydrogen production, the hybrid thermochemical cycle method is one of the most popular methods with the environment, and in contrast to coal gasification and fossil fuel reforming, it is the most destructive method of hydrogen production.

3.2. Social cost of carbon measurement

The Social Cost of Carbon Measurement (SCC) measures the

Table 1
Parameters studied to investigate different methods of hydrogen production.

Index	factor	Description	unit
Environmental	AP	Acidification potential	gSO2/kg Hydrogen
	GWP	Global warming potential	$kgCO_2$/kg Hydrogen
	WCP	Water consumption potential	m^3 consumed
	LOP	Land-use footprint	m^2a crop-eq
	SOP	Mineral resource scarcity	kg Cu-eq
	FFP	Fossil resource scarcity	kg oil-eq
	WSF	Water Scarcity Footprint	m^3
Social	SCC	The social cost of carbon measurement	$/kg hydrogen
	PA	Public Acceptance	–
	JC	Job capacity	Person/kg hydrogen
Energy	EE	Energy efficiency	%
Exergy	EXE	Exergy efficiency	%
Economic	Cost	Production Cost	$/kg
	IRR	Internal Rate of Return	–
	PP	Payback Period	years

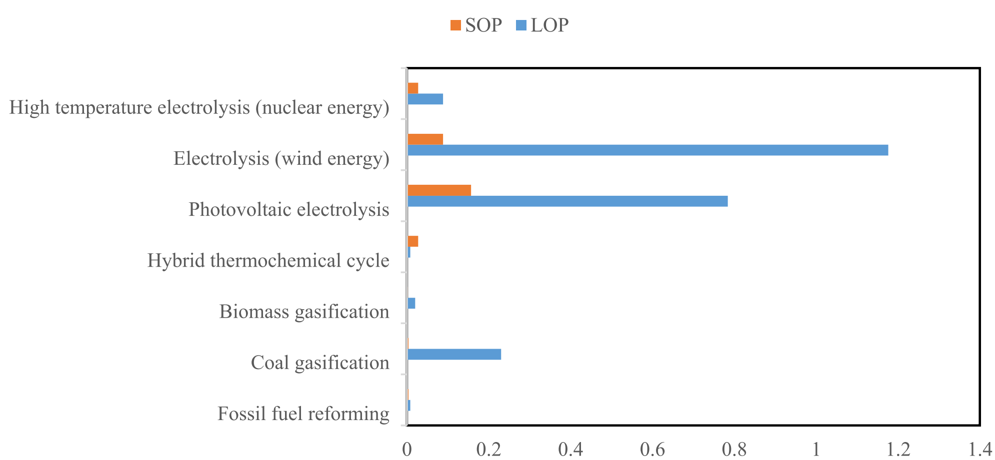

Fig. 1. Mineral resource scarcity and Land Use parameters for different methods of hydrogen production.

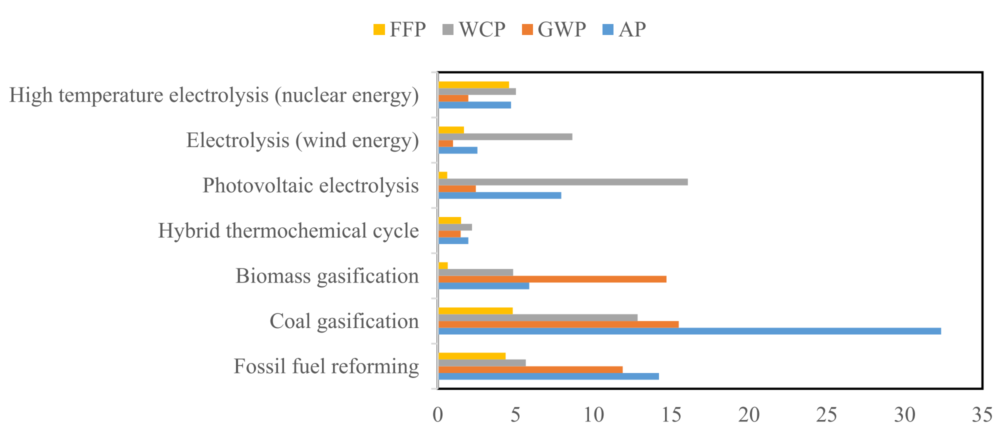

Fig. 2. Fossil resource scarcity, Water consumption potential, Global warming potential, and Acidification potential for different methods of hydrogen production.

cost of emitting a unit of carbon dioxide and resulting in environmental degradation. The Integrated Assessment Model Framework (IAM) is used to estimate this amount. It uses an economic model that shows the relationship between gas emissions and environmental temperature changes and performs these temperature changes with ultimate economic damage. In this study, the values reported in a study conducted by Dincer et al. [5] on hydrogen production methods and their associated SCC values and an average of $ 160 per ton of carbon dioxide released are reported as SCC. The values calculated in Fig. 3 show that in terms of the amount of damage caused by carbon dioxide emissions, the hybrid thermochemical cycle and other production methods use renewable energy as the least harmful process stimulus and coal gasification and natural gas reforming methods

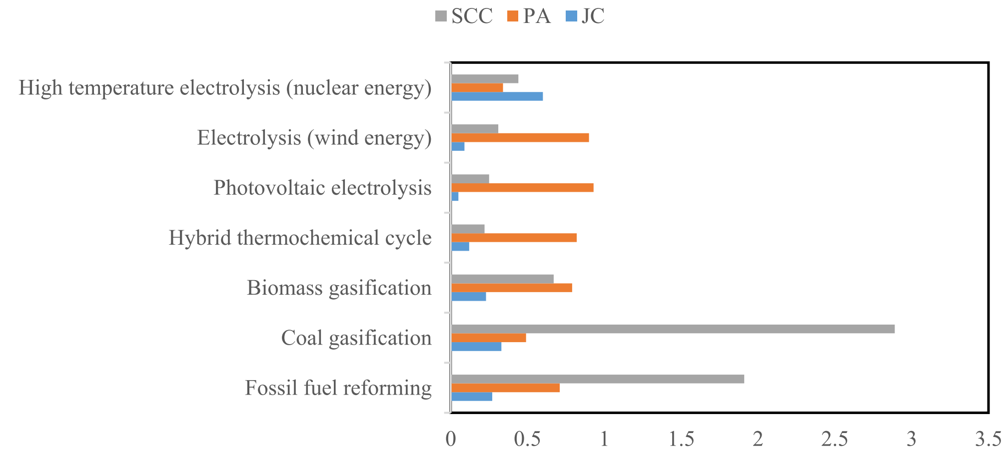

Fig. 3. Calculated social indexes for different methods of hydrogen production.

with significant differences. Attention is one of the most destructive methods. Fig. 3 shows this difference better.

3.3. Economic analysis

There are some uncertainties about the cost of hydrogen production. This amount is highly dependent on production technology development, the availability of infrastructure, and the stock price. The values presented are reported in 2016 according to a study conducted by Ref. [21]. As shown in Fig. 4, traditional methods such as natural gas reforming or coal gasification are in the best position from an economic point of view. The hybrid thermochemical cycle method is in the second place of this classification but is competitive with the previously mentioned methods. Electrolysis, with the help of solar and wind energy, has the highest cost. One of the biggest advantages of electrolysis is its ability to be used locally, so small production units are assumed to calculate the final cost. For other methods, however, the initial assumption is that production is concentrated. One of the reasons for the sharp difference between solar and wind electrolysis costs can be the final price difference between a small, large production unit and a large central production unit [19].

3.4. Energy and exergy analysis

The values presented in this section are taken from studies conducted by Dincer [3,4]. The ratio of useful output to the amount of input consumed is called efficiency. Exergy efficiency could be a more important indicator than energy efficiency as it usually gives a finer understanding of performance [5,6]. Exergy efficiency highlights those losses, and internal irreversibility is to be assessed to improve performance. Higher exergy efficiency reflects higher energy quality used in the system, making the system more sustainable, while lower exergy efficiencies reflect energy losses and irreversible internal reactions, thus low energy quality and worse sustainable score [7–10]. Furthermore, exergy analysis enables identifying energy degradation in an energy system and provides an accurate measure of the useful work utilized by the system. Therefore, the exergy efficiency indicator is useful for maximizing the benefit and efficiently using the resources. According to Fig. 5, it can be seen that the biomass gasification method is superior to other methods. On the other hand, electrolysis using solar energy shows the lowest efficiency among the methods [11,12]. Fig. 5 shows the energy efficiency distribution used in hydrogen production using different methods.

3.5. General comparison

In this section, the values listed so far are reported as normal. The values for SCC, AP, GWP, production cost, etc. for the technologies are calculated using the following equation [13,14]:

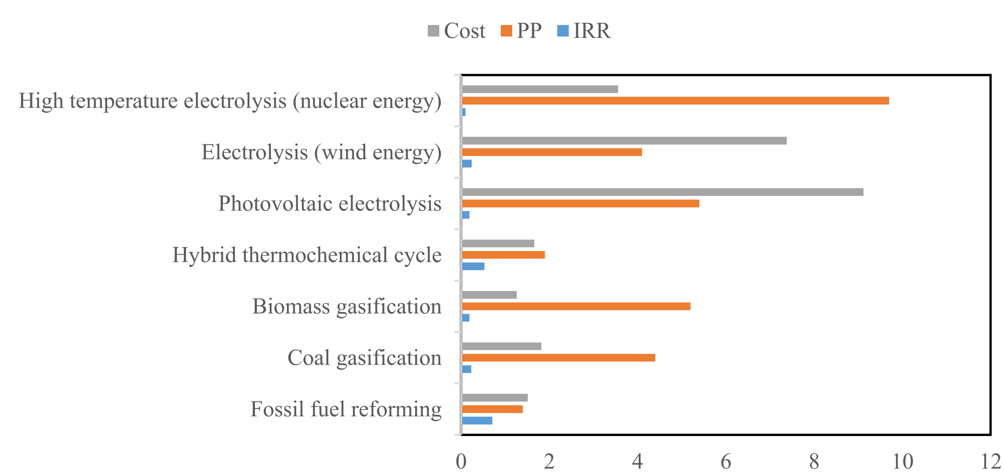

Fig. 4. Economic analysis of different hydrogen production systems.

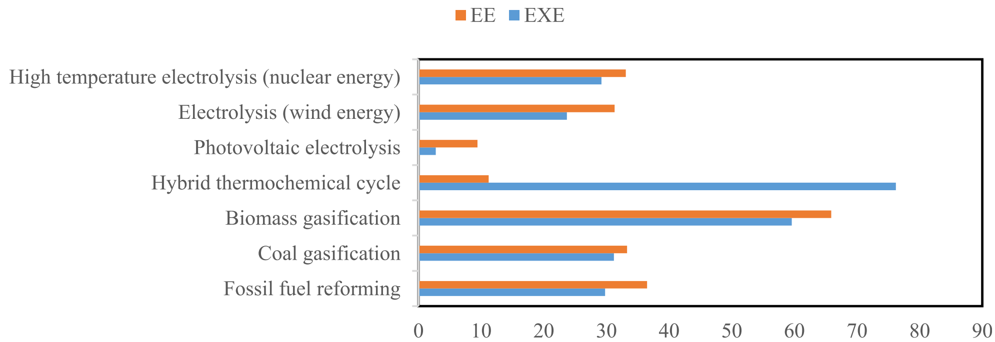

Fig. 5. Calculated exergy and energy efficiency for different methods of hydrogen production.

$$Normalized\ Value(ith) = \frac{Max - Min}{Max} \times 10 \quad (3)$$

Normalized values range from “0” to “10” (“0” indicates the worst behavior, and 10 is the ideal value). This is while the lowest cost and the lowest amount of gas emissions will be 10. For example, the coal gasification method has the highest greenhouse gas emissions for the GWP and AP components. Therefore, the normal values of GWP and AP are considered “0”. For the efficiency component, normal values are calculated based on the following formula [15,16]:

$$Normalized\ Value(ith) = Efficiency(ith) \times 10 \quad (4)$$

In this case, the normal values will still be in the range of zero to 10 (“0” is the lowest efficiency value, and “10” is the best efficiency value, i.e., 100%). Normal values of greenhouse gas emissions, cost, and efficiency are reported in Fig. 6 as a spider web diagram. The ideal hypothetical method in this classification is 10 in all components [17].

According to the presented spider diagram, the hybrid thermochemical cycle method has the highest level, and photovoltaic electrolysis has the lowest level in the diagram. These levels indicate the success of each method in estimating the desired needs for

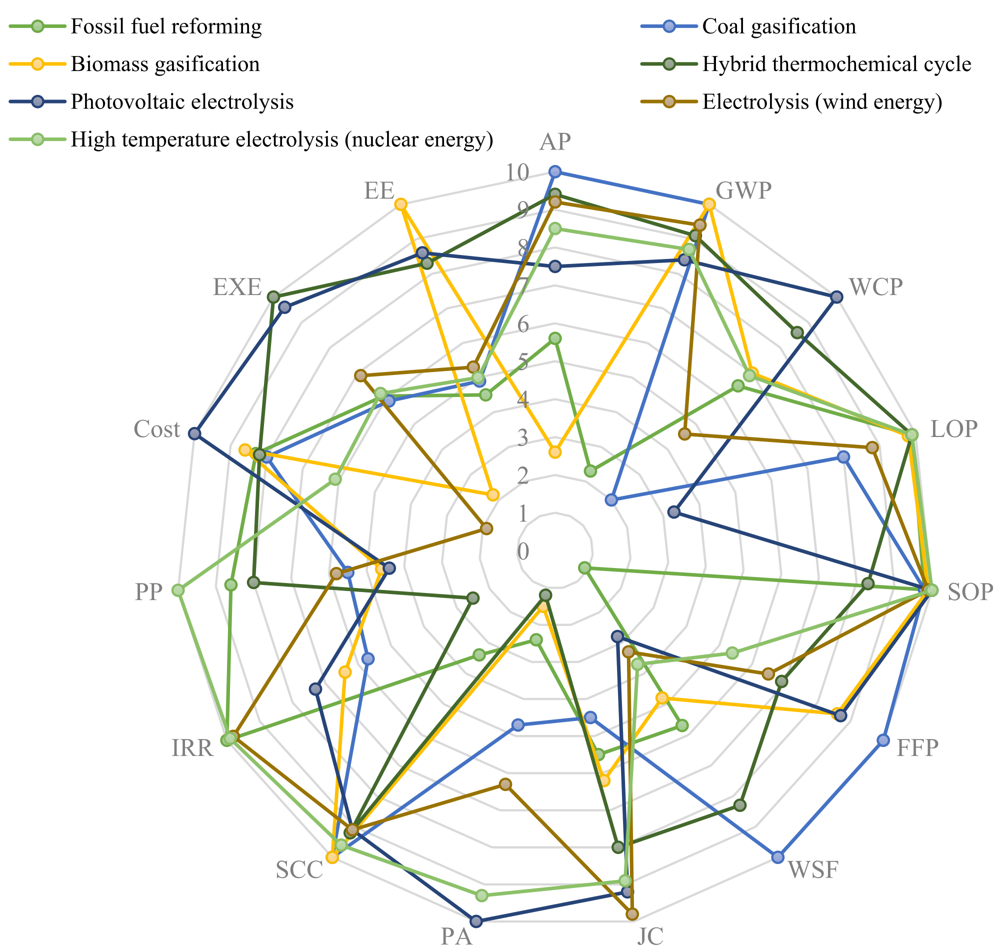

Fig. 6. Spider diagram related to the study of different parameters in different methods of hydrogen production.

selecting the preferred method of hydrogen production in the future [18,19]. Among the methods based on renewable energy, it is observed that the orientation of the surface formed in the spider diagram is more inclined towards environmental advantages. In contrast, this orientation is towards economic tendencies for methods based on fossil fuels such as fossil fuel reforming and coal gasification [20,21].

3.6. Discussion

In this paper, the alignment of each hydrogen production technology with the sustainability concept in its environmental, economic, technical, and social aspects is studied comparatively, and their feed-stock availability and potential of utilization on a Global scale are discussed [14,22]. The comparison and analysis outputs are implemented to choose suitable hydrogen production methods globally [23]. Natural gas and gasoline demand rates exceed their production rates, and the Global scale is becoming more dependent on its internal natural gas and gasoline production and losing its export opportunities [24]. Therefore, finding an alternative is vital and becomes more important each year [15,25]. Also, the hydrogen energy production methods are studied in terms of social acceptance in this paper because of the ongoing debate and social acceptance issues related to alternative energy resources on a global scale [26]. Fig. 7 summarizes the overall comparison of selected hydrogen production methods by ranking their technical, environmental, economic, and social results [16,27]. These data are illustrated in Fig. 7, which compares different technologies regarding their sustainability score [28]. The technical study of these methods is carried out based on their energy and exergy performance scores (EXE and EE), in which the results are aligned to the results of previous related papers [17,29]. The economic aspect is based on the internal rate of return, payback period, and levelized production cost ranking (IRR, PP, Cost), which aligns with the related papers' results [15,16,30]. Fig. 7 show that the hybrid thermochemical cycle gives close-to-ideal results because of its high environmental and economic evaluation rankings. And Bio-waste gasification is ranked second due to its technical, environmental, economic, and social performance, which is aligned with the results of other papers [3,18]. Photovoltaic energy-based electrolysis gives the poorest technical and financial performance. However, the social and environmental impact comparison shows that coal gasification gives the lowest rankings, and also it is sorted as the poorest option for Global scale, which seems to be the poorest in several other regions according to the results from other sources [19,20]. Steam-methane reformation has significant technical and economic advantages compared to solar and wind-based electrolysis [21]. Also, biomass gasification has good performance concerning environmental and social impact [31]. Wind-based electrolysis has a higher environmental and social performance compared to PV-based technologies [22]. Overall, the hybrid thermochemical cycle has the highest total score of the four aspects used to compare the selected methods (36.6) [32]. Immediately following the hybrid thermochemical cycle, biomass gasification gives a total score of 30.31. Steam-methane reforming gives a lower total score compared to hybrid cycle and biomass, a total score of 27.35 [23,24].

4. Conclusion

Due to the lack of continuous access to renewable energy sources such as the sun or wind, there is a need to use a clean energy carrier with high energy transfer capability and maximum accessibility. As the lightest element in nature, hydrogen, and oxygen form a water substance, covering 80% of the earth's surface. Therefore, by decomposing water into its constituent elements, hydrogen can be obtained. Also, using natural gas and biomass on the earth's surface can be extracted by performing a series of chemical reactions. Different production techniques are reported in the text, and different environmental, economic, and feasibility parameters are mentioned separately. Finally, all methods were compared visually by normalizing the values of the measured parameters and using the presented spider diagram. According to the environmental values, thermochemical methods are the most useful methods for hydrogen production, and natural gas reforming methods, and coal gasification is the most destructive method. However, natural gas reforming has the highest efficiency, and hydrogen production through electrolysis combined with thermochemical methods is in the third place of efficiency after biomass and coal gasification. From an economic point of view,

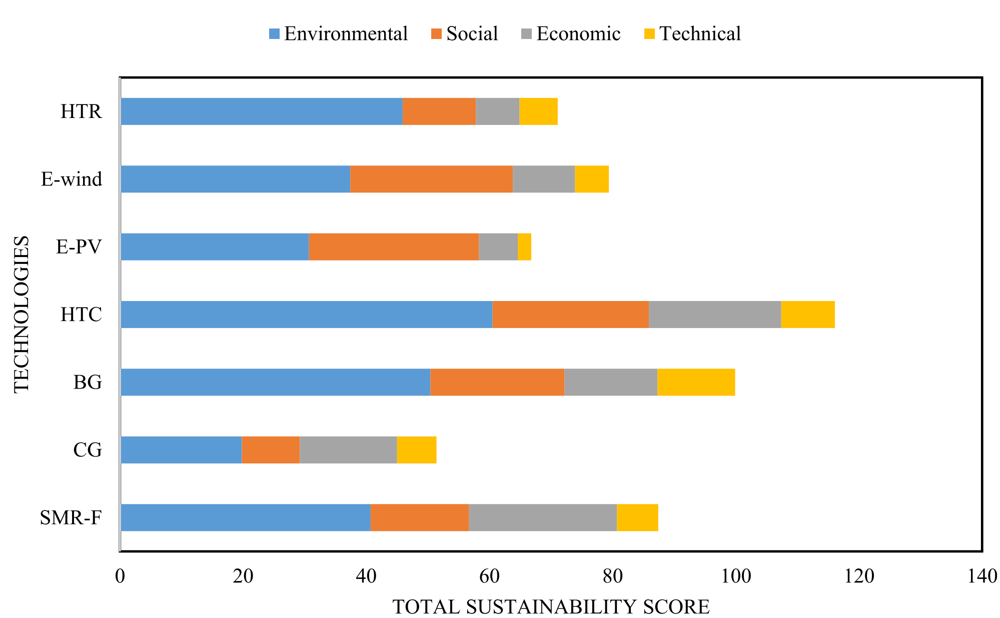

Fig. 7. Total sustainability score of the hydrogen technologies.

steam methane reforming has the lowest initial capital compared to other methods offered. At the same time, water electrolysis requires the most initial capital. Although small-scale production, especially in sparse production units (with a production capacity of fewer than 10 tons per day), the initial capital of water electrolysis is close to steam vapor reforming, which makes electrolysis competitive with reforming.

Regarding the use of renewable energy in hydrogen production, according to the information provided, if renewable energy is used to produce the electricity required for the electrolysis process, the efficiency will decrease sharply due to the low efficiency of the electricity generation process, sun or wind. Given the high speed of technological development of new energies, it is hoped that in the next ten years, in addition to a significant reduction in initial production costs, the efficiency will also increase significantly and the production of hydrogen in small mobile units by this group of energies to electrolysis is performed. Finally, it can be concluded that to produce hydrogen, and one must first determine its consumption and choose one of the mentioned methods according to the volume of hydrogen required. For the production of hydrogen in high quantities and a concentrated manner, thermochemical methods are considered a more useful method in all respects than hydrogen production through reforming. For this purpose, it is better to invest in developing production units by thermochemical method to produce future hydrogen due to the limited fossil energy and their high pollution. Also, research should be done for small and topical applications to obtain more advanced technology for photoelectrolysis at a lower cost and higher efficiency.

Declaration of competing interest

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

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