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A systematic review of the techno-economic assessment of various hydrogen production methods of power generation

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Hydrogen is a low or zero-carbon energy source that is considered the most promising and potential energy carrier of the future. In this study, the energy sources, feedstocks, and various methods of hydrogen production from power generation are comparatively investigated in detail. In addition, this study presents an economic assessment to evaluate cost-effectiveness based on different economic indicators, including sensitivity analysis and uncertainty analysis. Proton exchange membrane fuel cell (PEMFCs) technology has the most potential to be developed compared to several other technologies. PEMFCs have been widely used in various fields and have advantages (i.e., start-up, zero-emissions, high power density). Among the various sources of uncertainty in the sensitivity analysis, the cost estimation method shows inflationary deviations from the proposed cost of capital. This is due to the selection process and untested technology. In addition, the cost of electricity and raw materials, as the main factors that are unpredictable.

KEYWORDS
hydrogen, energy primary source, hydrogen production technology, power generation, techno-economic assessment

Introduction

Hydrogen is a low or zero-carbon energy source that is considered the most promising and potential energy carrier of the future (Hanley et al., 2018). The current global demand for pure hydrogen is estimated to be around 70 million tons (Bourne, 2012), whereas the global hydrogen demand is expected to reach more than 300 million tons in 2050 (International Energy Agency., 2015). It has been forecasted that hydrogen will be a leading change in the global energy system toward a sustainable energy system (Staffell et al., 2019). Hydrogen can be produced from renewables, such as hydro, wind, wave, solar, biomass, and geothermal, as well as non-renewables such as coal, natural gas, and nuclear energy sources. Due to its energy carrier's nature, hydrogen offers high flexibility because it is easily converted to electricity in fuel cells for power generation, transportation, etc., (Hosseini and Wahid, 2016). In addition, hydrogen has the potential to deliver economically viable, monetarily, socially, and energy-efficient solutions to challenges related to the rising global energy demand, such as global warming (Dutta, 2014).

Power generation from renewable energy sources has been discovered and studied for decades and has been implemented on a large scale in many countries (IEA., 2016). Renewable energy is the fastest-growing source of electricity generation, and it has been predicted that its share will increase to 39% by 2050. Economic considerations are vital to evaluate the feasibility of an energy system while providing clear and cost-effective criteria. Techno-economic feasibility assessment of a particular technology considers several aspects such as technological appropriateness, economic viability, and financial incentives (Jamil et al., 2012; Rajendran and Murthy, 2019). In specific, techno-economic and sensitivity analysis of the hydrogen production methods is needed to improve the economic aspects of hydrogen. Among others will substantially impact future hydrogen production project designs and the development of innovative approaches to cut total production costs to make the fuel more affordable (Yukesh Kannah et al., 2021).

Although there have been several recent systematic reviews of the techno-economic assessment of hydrogen production, they have not principally been in the context of the techno-economic assessment of various hydrogen production methods of power generation. First (Yukesh Kannah et al., 2021), reviewed the sensitivity of various hydrogen production processes, such as (i) thermochemical conversion (e.g., pyrolysis, gasification, and steam reforming of natural gas), (ii) electrolysis water, (iii) renewable liquid reforming, and (iv) biochemical conversion. In terms of economics, steam reforming of natural gas is an economical and effective method for hydrogen production, as it has low operational (70 to 80%), feedstock (0.3 USD/kg H_2), and production (1.25 to 3.50 USD/kg H_2) costs. Second (El-Emam and Özcan, 2019), highlighted the techno-economic of hydrogen production and the environmental aspect of selected routes. The study found that geothermal, biomass, and nuclear-driven electrolysis and thermochemical technologies may replace conventional methods for hydrogen generation. Third Abe et al. (2019), viewed hydrogen as an appropriate long-term energy carrier for the economy. Solid-stage storage systems based on metal hybrids are a promising alternative to storing hydrogen in a hydrogen-powered system. Metal hybrids cannot store large quantities of hydrogen and are unable to release hydrogen at low temperatures.

Therefore, the main focus of our review discusses various hydrogen production methods, including their techno-economic aspects, sensitivity analysis, and uncertainty analysis. In addition, the current study addresses the following research question: "What are the economic performance indicators of the hydrogen energy systems for power generation?" This study aims to determine the economic performance indicators of hydrogen energy systems for power generation.

The remainder of this paper is organized as follows. Section Methods—systematic review of the literature introduces the method systematic of the literature review. Section Results presents the main results, including feedstock, hydrogen production methods, techno-economic performance, sensitivity, and uncertainty analyses. Finally, Section Discussion contains the discussion.

Methods—systematic review of the literature

The general systematic review of the literature is carried out based on the method suggested by Tranfield et al. (2003), Thürer et al. (2018) for retrieving and selecting published data sets from Scopus and the Web of Science (WoS). The primary goal is to find and choose articles that describe hydrogen production methods, power generation, and techno-economic performance indicators. The articles are gathered by conducting a thorough search of Scopus and the WoS. The selection of articles is based on the title, keywords, abstracts, highlights, and type of document. This study uses different keywords for the search, such as "economic simulation AND hydrogen OR cost energy" in Scopus and "hydrogen OR H_2 AND economic simulation OR energy cost" in the WoS. The document type is restricted to articles and reviews, excluding conference papers and books. In addition, the publication year is restricted to 2000–2020.

The selected articles are those that are relevant to the topic of this review and are grouped based on the quality of the research, that is, whether the article answers a series of questions related to the research and describes the facts based on real research scenarios. The analysis is carried out based on energy sources, feedstock, various hydrogen production processes, technique production, power generation, techno-economics in commercialization, and the economics of various hydrogen production processes. The following research questions are added based on the various researches and the analysis of articles:

- What is the source or primary energy of hydrogen production?
- What is the feedstock of hydrogen production?
- What are the types of hydrogen production methods?
- What is the technique of hydrogen conversion?
- What are the types of hydrogen production methods for power generation?
- What are the economic performance indicators of the hydrogen energy system for power generation?

The original sample of 901 articles comprises 392 articles in Scopus and 509 articles in the WoS (eight articles were removed because they were duplicates). After excluding apparently unrelated articles, that is, articles that are not related to hydrogen production and techno-economic, the number was reduced to 741 articles. The high number of unrelated articles is due to the use of the common keyword hydrogen. The articles were further reduced by 152 after screening them based on title and abstract. Finally, the total number articles that are used for the analysis is 52 (Figure 1).

Results

The review results of the techno-economic assessment of various hydrogen production are obtained from 116 case studies, which were mostly about countries in Europe (48/166) (Figures 2a,b). The country-wise distribution is as follows: Italy (8/48), Greece (8/48), Germany (8/48), Romania (8/48), Norway (5/48), France (2/48), Finland (2/48), Turkey (2/48), Spain (2/48), Switzerland (1/48), and Serbia (1/48). The country-wise distribution of the techno-economic assessment of various hydrogen production studies on Asia (42/116) is as follows: China (21/42), Iran (5/42), Thailand (5/42), Republic of Korea (3/42), Saudi Arabia (3/42), Pakistan (2/47), and UEA (2/42), and that of the American continent is 19/116, including Canada (11/19), USA (4/19), Brazil (3/19), and Mexico (1/19). However, the contribution from Australia (5/116) and Africa—represented by Morocco (2/116)—are comparatively small. The primary energy sources in Europe are dominated by photovoltaic (15/48), followed by wind (13/48), unspecified renewable energy sources (4/48), coal (2/48), biodiesel (1/48), hydropower (1/48), and unspecified sources (4/48). The primary energy sources in Asia are photovoltaic (11/42), wind (9/42), biomass (7/42), methanol (5/42), photovoltaic/wind (4/42), natural gas (2/42), as well as coal (1/42), algae nuclear energy (1/42), and renewable energy sources (1/42). Finally, the primary energy sources in Australia comprise wind (3/5) and photovoltaic (2/5), and the primary energy source in Africa is photovoltaic (2/2) (Figure 3).

Feedstock

Hydrogen is not a source of energy, but it is a pure form that functions as an energy carrier or as an industrial raw material (Ozbilen et al., 2011). Hydrogen can be combined with other materials to produce hydrogen-based fuels (Bourne, 2012). Hydrogen feedstocks can be produced from sources such as natural gas, coal, water, biomass, and fossil fuels and can be readily used in engines or turbines (Donaldson et al., 2012; Ren et al., 2013; Yao et al., 2017; Li et al., 2018; Nurdiawati et al., 2019) (Figure 4). Figure 4 reveals that water is the most widely used hydrogen feedstock in countries such as China, Canada, Italy, Brazil, the USA, and the Republic of Korea, followed by other feedstocks, such as coal, coal plus biomass (soil waste), biomass, and natural gas.

Hydrogen production methods

Hydrogen elements can be found abundantly in nature, such as freshwater, seawater, biomass, hydrogen sulfide, and fossil fuels. However, to produce hydrogen with zero or low environmental impact, it must be extracted from fossil fuels. In general, the process of extracting hydrogen from natural resources can be classified into four categories—thermal, electrical, photonic, and biochemical. Thermal and electrical energy can be produced from renewable energy (such as solar, wind, geothermal, hydro, and biomass), fossil energy, or nuclear energy. Photonic energy can be obtained from solar radiation only. Biochemical energy reserved in organic matter can be processed by microorganisms that produce hydrogen from sundry substrates, or it can be chemically transferred to thermal energy (Dincer, 2012; Dincer and Acar, 2014). Previous studies grouped all the case studies into the following four categories based on the classification of various hydrogen production methods: electrochemical, thermochemical, biochemical, and thermal-electrochemical (Dincer, 2012; Dincer and Acar, 2014).

First, the hydrogen production methods in the electrochemical category include electrolysis technologies, such as alkaline electrolyzer (AEL) and proton exchange membrane electrolyzer (PEMEL). AEL and PEMEL are mature and commercially available. AEL is the world's oldest and most widely utilized technology for large-scale systems. PEMEL are generally used for hydrogen production on a modest scale. While PEMEL offers some advantages compared to AEL, including high current densities, voltage efficiency, and quick system response when working dynamically (David et al., 2019) (Yodwong et al., 2020). Electrolysis is the process through which electricity is used to split water into its components (i.e., oxygen and hydrogen). Hydrogen production processes through nuclear-based thermochemical cycles and renewable energy base electrolysis have much lower effects on the environment than steam reforming (Ozbilen et al., 2011). Water is infiltrated into the proton exchange membrane electrolysis cell; then, hydrogen ions are absorbed by the membrane, and this recombining process forms the hydrogen molecules. Proton exchange membrane electrolyzes are considered an alternative to producing hydrogen from renewable energy sources (Silva et al., 2010). Plasma decomposition of natural gas was included in the electrochemical category. In the reviewed studies, electrochemical technology was the most extensively used method in hydrogen production, accounting for approximately 74.14% of all the case studies, followed by thermochemical technology (22.41%) and thermal-electrochemical technology (3.45%) (Figure 5a). Furthermore, electrolysis was the most frequently used method in the electrochemical category, accounting for 84%, and alkaline electrolysis accounts for 3% of all the case studies. Second, the thermochemical category includes aqueous stage reforming, auto thermal reforming, steam reforming, gasification (coal or biomass),

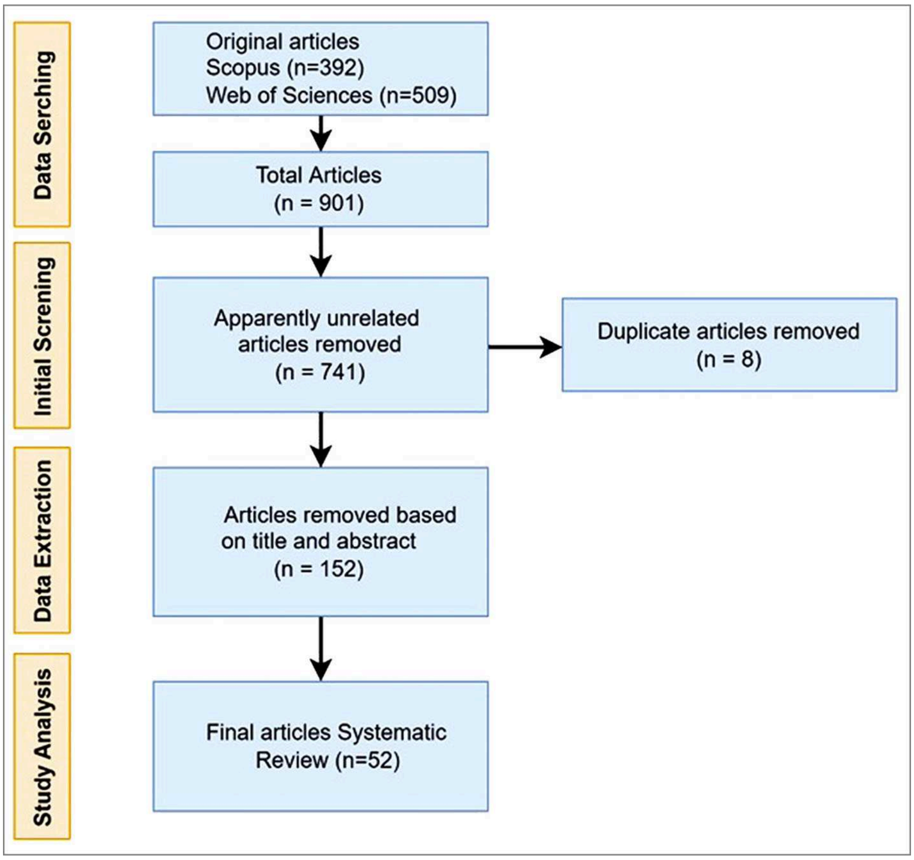

FIGURE 1
The systematic literature review process.

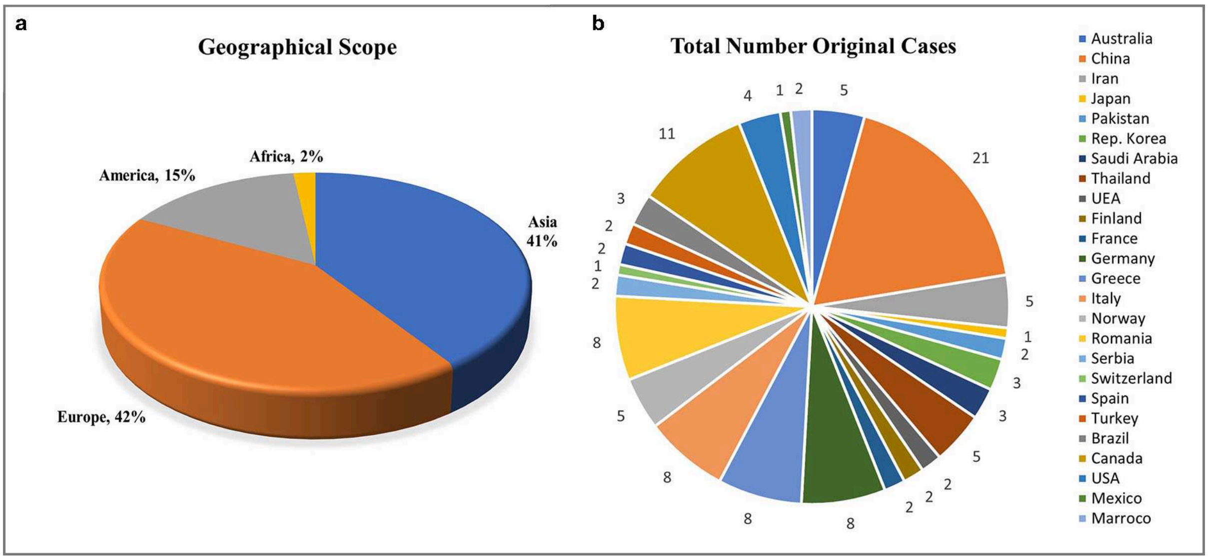

FIGURE 2
(a) Geographical scope and **(b)** the number of original case studies.

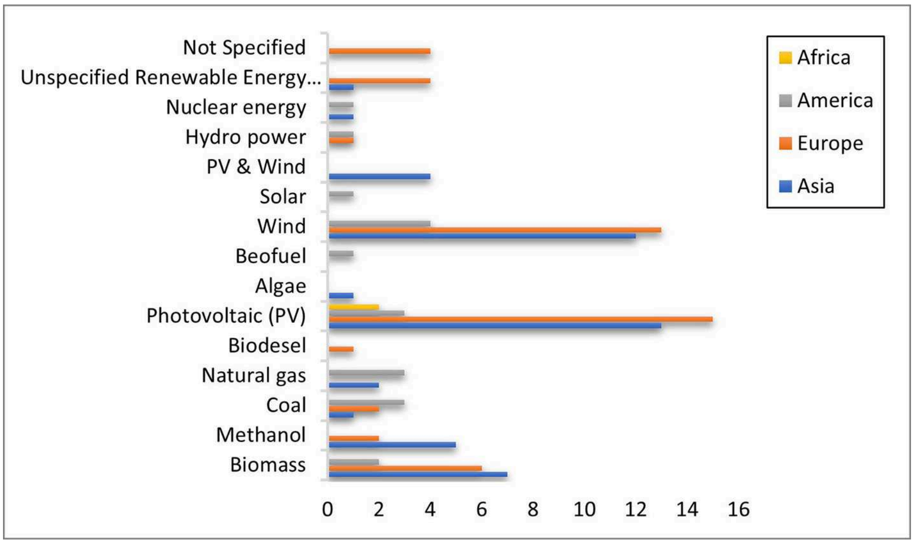

FIGURE 3
Geographical primary energy sources.

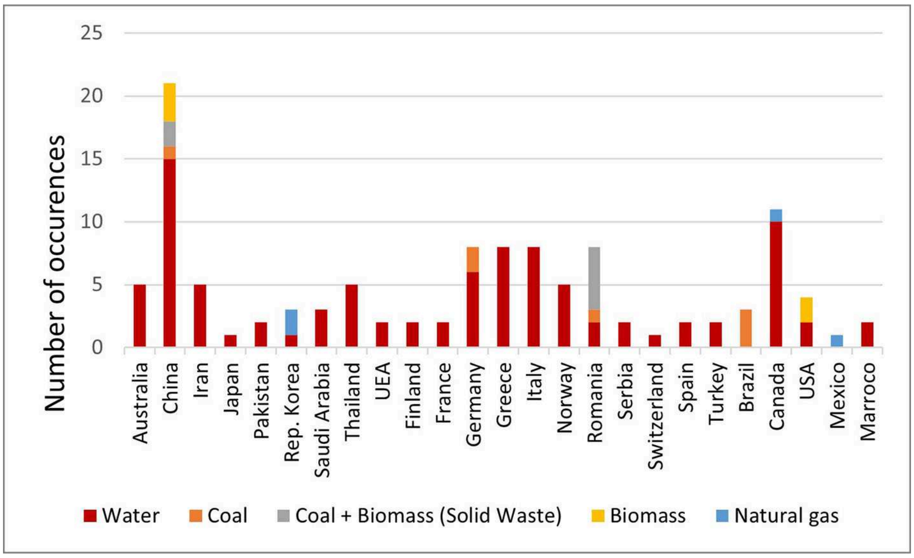

FIGURE 4
Hydrogen feedstock of various countries.

thermal cracking of fossil hydrocarbons, and water splitting. Thermochemical is the process of separating water using a heater to obtain hydrogen. The thermochemical hydrogen production process is an immature technology that must be refined over time. Gasification and reforming based on thermochemical account for 21.55 and 2.59% of all the case studies (Figure 5b). The thermochemical cycle normally does not require catalysts as a driver of chemical reactions. Chemical materials involved in the process are recycled and are the material source from which hydrogen is derived. The water-splitting thermochemical cycle is as follows: (i) it does not require hydrogen–oxygen separation membranes; (ii) it does not require overestimating thermal energy source (600–1,200 k); (iii) it does not require extra electrical energy to drive the process (Dincer, 2012). Third, the biochemical category includes fermentation and dark fermentation. The Biochemical category includes photolytic (direct water separation), photosynthetic bacteria (solar-assisted organic decomposition), dark fermentation

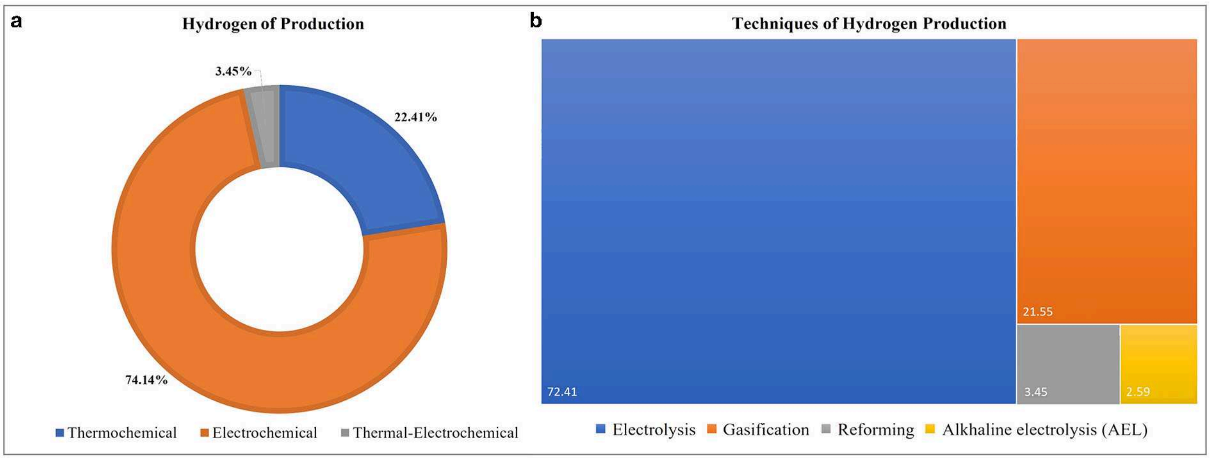

FIGURE 5
(a) Hydrogen production methods and **(b)** technique of hydrogen production.

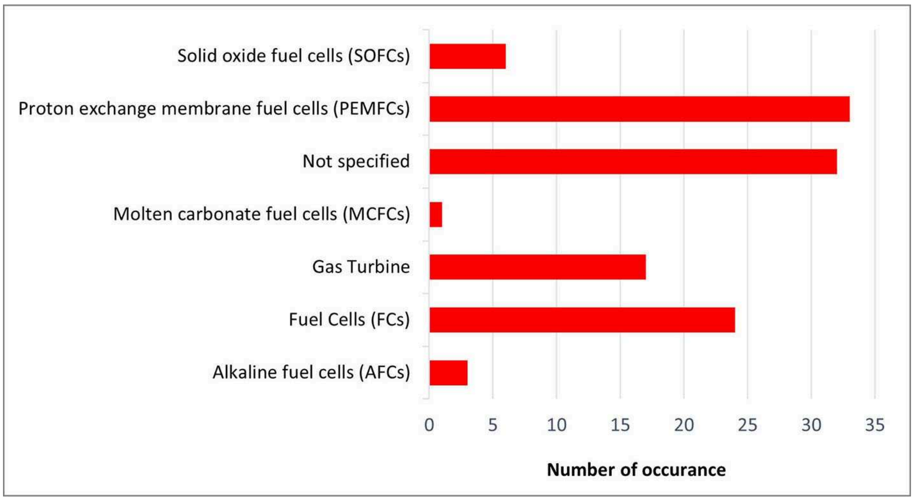

FIGURE 6
Hydrogen power generation.

(organic decomposition), and microbial-assisted electrolysis (electrical-assisted organic decomposition).

Power generation

The development of renewable energy sources (RES) is important for the sustainable growth of any nation due to the depletion of fossil fuels, the rising cost of fossil fuels worldwide, and the need to reduce emission levels. The selection and deployment of hydrogen-based power generation conversion technology are mostly governed by the electricity-requiring application. Technologies that use hydrogen as a fuel cell for power generation must provide flexible energy to ensure stability and resilience. According to the type of electrolyte used, fuel cells (FCs) can be categorized as phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), solid oxide fuel cells (SOFCs), and proton exchange membrane fuel cells (PEMFCs), molten carbonate fuel cells (MCFCs). The hydrogen that reacts with oxygen in the fuel to supply electrical energy consists of a piston engine and a gas turbine (Figure 6). A fuel cell is a device that converts the chemical energy of a fuel into electrical energy through an electrochemical reaction. Fuel cells are a flexible power generation technology with 50–60% electrical efficiency. Fuel cell stacks have a shorter technical lifetime (10.000 to 40.000 operating hours). However, compared to PEMFCs, and hydrogen is available, PEMFCs have the most potential for development (Bourne, 2012; Wang et al., 2017). Now-a-days, PEMFCs are applied extensively in numerous fields. PEMFCs provide the advantages of practically zero emissions, high power density, high efficiency, and low operating temperature compared to other fuel cell types. In addition, PEMFC providing short start and response times at the stack level appears to be the optimal technology for application drives.

Hydrogen gas turbine power generation technology is designed for large-scale power generation. Incorporating hydrogen is a potential pathway for gas turbine decarbonization by replacing natural gas with hydrogen. Each gas turbine model has a specific capability for hydrogen combustion, mainly determined by the combustion system. Gas turbine technology has three main components: a compressor, a combustion chamber, and a turbine stage. The central part of the energy is the turbine stage, which drives the compressor and gives the generator the power to run and generate electricity (Wang et al., 2021). Showed that the output of the introduction cycle is composed of a wind turbine, solar energies, and AFCs was 10.5 kW of electricity, and the electrical efficiency was 56.9%. In addition, the electrolyzer uses 9.9 kW of electricity to produce 221.3 grams of hydrogen fuel.

Techno-economic performance indicator

This section discusses the techno-economic analysis, including profitability, sensitivity, and uncertainty analysis, using various simulation results, such as Monte Carlo simulation, Aspen HYSYS (Kim et al., 2018), Aspen Plus, MATLAB, and HOMER simulation. The Aspen HYSYS simulation model is used to determine the effect of various operating conditions on the performance of the packed-bed reactor and membrane reactor (Kim et al., 2018). Moreover, it is used to determine the future risk and uncertainty in prediction (Zahid et al., 2020). Techno-economic assessment is a methodological framework for examining the technical and economic performance of a process, product, or service and includes the study of the economic impact of technology. A techno-economic assessment (TEA) is a cost-benefit comparison that considers technological and economic factors. An economic summary of hydrogen production is presented in Table 2, where each cost component is presented including capital expenditure (CAPEX), operating expenditure (OPEX), and other variables.

The CAPEX and OPEX are the main costs in a techno-economic assessment. The key issue is to minimize the CAPEX and OPEX of various hydrogen generation systems while simultaneously increasing production volume. This allows for a reduction in the cost of producing hydrogen from several energy sources. The expenditures involved with building a new facility are referred to as CAPEX. Fixed-capital investment (FCI) is the funds used to finance a facility. FCI in the first and second years is 60% and 40% of total FCI, respectively, while working capital cost is 15% of total FCI (Lee et al., 2020). Likewise, OPEX represents the various day-to-day expenses required to maintain sustainable business operations. It can also be said that they refer to the enormous costs involved in maintaining plant operations. OPEX consists of the costs of raw materials, operating labor, maintenance, and utilities. Annual expenses are considered based on items related to operating expenses and general and administrative expenses. In many cases, CAPEX values are estimated using software such as Aspen Plus or Aspen Hysys to simulate processes and perform economic analysis. The influence of plant size and capacity on CAPEX is substantial. The larger the facilities, the more the CAPEX, but the lower the production expenses. In addition, environmental influences such as integrated carbon capture and storage systems have a major impact on total production costs, resulting in an increase in CAPEX due to the use of additional equipment.

Sensitivity analysis

The main objective of the sensitivity analysis (SA) is to obtain the effect of various economic factors on the cost of a unit of hydrogen produced and determine some influential factors, including ensuring the surroundings and conditions of any operating plant after investment (Kim et al., 2018). The SA can provide information on the factor that is most sensitive and has a significant impact, including making decisions before investing. Generally, the sensitivity indicators to consider include sensitivity to capital cost, sensitivity to feedstock, and sensitivity to the internal rate of return (Khunathorncharoenwong et al., 2020; Yukesh Kannah et al., 2021). In some instances that renewables, such as wind, were used as the electricity source, several variable inputs were estimated, such as plant parameters (e.g., capacity and storage capacity), capital expenditure (CAPEX) parameters (e.g., hydrogen storage, electrolysis, and methanation), operation expenditure (OPEX) parameters (e.g., standby cost), and operating parameters (e.g., restart a level and restart time) (Rivera-Tinoco et al., 2016; Gorre et al., 2020).

The crucial parameter to perform sensitivity analysis depends on the hydrogen production process. Many studies consider capital cost, operating cost, replacement, operation & maintenance, and net present value (NPV) for process electrolysis. Other studies consider the parameters of hydrogen cost, sales price, consumption, operation expenditure, fuel, and savagery, including taxes. Reforming process parameters consist of hydrogen production costs: reactor, membrane module, compressor, pressure swing adsorption (PSA), supplement, reactants, PSA OPEX, electricity, labor, natural gas, membrane replacement, maintenance, and other costs were considered for sensitivity analysis. Finally, the gasification process only considers the NPV (Table 1).

The wind is the basic concept of SA in the application of power to gas technology to convert renewable electricity into molecular form. Electrolysis costs are reduced by 54%, and gas

TABLE 1 Summary sensitivity analysis parameter.

Article	Hydrogen production	Sensitivity analysis parameter	Key performance indicator
Gorre et al. (2020)	Electrolysis	Plant parameter, CAPEX, OPEX	-
Khunathorncharoenwong et al. (2020)	Electrolysis	Hydrogen cost, sales price, and consumption	Net present value
Hamayun et al. (2019)	Electrolysis	Operation expenditure	-
Kim et al. (2018)	Reforming	Hydrogen production cost: reactor, membrane module, compressor, pressure swing adsorption (PSA), supplement, reactants, PSA OPEX, electricity, labor, natural gas, membrane replacement, maintenance, and other costs were considered for SA	Net production cost
Rivera-Tinoco et al. (2016)	Electrolysis	Electricity price, lifespan, investment, maintenance, electrolyze, low-cost power electrolyzes, and high equipment lifespan	-
König et al. (2015)	Electrolysis	NPC: capital cost, wind power, carbon dioxide cost, Oxygen revenue, and cavern capital cost	-
Guinot et al. (2015a)	Electrolysis	Capital cost, fuel cost, operation & maintenance, interest rate, and availability factor	-
Donaldson et al. (2012)	Gasification	NPV: sunflower residue, activated carbon, and hydro price	-
Tzamalis et al. (2011)	Electrolysis	NPV: capital cost, replacement, O&M, fuel, and salvage	-
Tsatsaronis et al. (2008)	Gasification	Capital cost, cost of heat, cost of coal, and currency (current and constant)	-
Shaner et al. (2016)	Electrolysis	Capital cost, operating expenses, replacement cost, and tax	-

production costs are reduced by 40% implying a lower average price for hydrogen, thus allowing for reduced equipment costs. A reduced methanation CAPEX can reduce the amount of hydrogen that is not converted into synthetic natural gas. Thus, synthetic natural gas (SNG) production costs are more sensitive to CAPEX electrolyzed than CAPEX methanation (Gorre et al., 2020). Hydrogen price is the most sensitive parameter and is more economical in the conventional process than low-pressure steam consumption (Khunathorncharoenwong et al., 2020). A heavier load on the electrolysis section results in higher power plate CAPEX and OPEX. However, the system efficiency can impact the high cost reduction process of all systems because of the areal dependencies of most of the components (Shaner et al., 2016; Hamayun et al., 2019). When the overloaded functionality of the installed capacity is 5.0%, the cost can be reduced, leading to a capital cost reduction of 3.6%. NPC was reduced by 0.9% due to the high cost of the electricity component. The output electricity cost is highly sensitive to the efficiency of the power plant (Zahid et al., 2020). Furthermore, lesser by-product yield is substantial from an economical perspective.

An NPV is considered one of the indicators to decide the feasibility of the target technology (Lee et al., 2020). When the NPV is zero, the project is not expected to generate significant profits or losses. Therefore, a project with a positive NPV is considered profitable and acceptable, while a project with a negative NPV means that this technology needs to be developed to obtain economic gains. The NPV decreases as the price of renewable electricity or the rate of degradation increases in relation to the cost of the system. On the other hand, the internal rate of return (IRR), is the discount rate that corresponds to an NPV equal to zero. IRR is a financial risk indicator used to assess the profitability of an investment. Where IRR involves

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TABLE 2 Summary economic of hydrogen production.

References	Energy source	Technology of H2 production	H2 for power generation	Capital expenditure	Operational expenditure	Interest rate	Project lifetime (years)	H2 production capacity	Plant efficiency (%)	Electricity cost ($/kWh)	H2 cost
Lee et al. (2020)	Unspecified renewable energy	Electrolysis	Not specified	n/a	n/a	-	10	700 Nm 3 h-1	-	-	3.88–9.30
Zahid et al. (2020)	Nuclear energy	Electrolysis	PEMFCs	2,291.4 $/kW	-	4	-	266 MW	-	-	-
Schnuelle et al. (2020)	Photovoltaic (PV)	Alkaline Electrolysis	FCs	n/a	n/a	-	-	770–1,324 €/kW	-	n/a	n/a
Liu et al. (2020)	Photovoltaic, wind	Electrolysis	Gas turbine	-	2.374–2.379	-	-	-	-	-	-
Gorre et al. (2020)	Wind	Electrolysis	FCs	650 €/kWel	n/a	n/a	20	-	-	n/a	-
Khunathorncharoenwong et al. (2020)	Not specified	Electrolysis	Gas turbine, FCs	2.8–3.4 m	-	-	-	-	-	-	4.020 $/kg
Wang et al. (2019)	Not specified	Gasification	Gas turbine	n/a	n/a	-	15	-	-	-	-
Nurdiawati et al. (2019)	Algae	Gasification	PEMFCs	-	n/a	-	-	-	-	0.030 $/kg	n/a
Jiang et al. (2019)	Wind	Gasification	Not specified	n/a	n/a	-	20	-	0.47–1	-	4.34€/kg
Hamayun et al. (2019)	Photovoltaic, wind	Electrolysis	PEMFCs	21.288.900 $	7.645.920$	-	-	5 MW	n/a	-	-
Nieminen et al. (2019)	Wind	Electrolysis	PEMFCs	n/a	n/a	-	20	30 MW	-	624–625	2.90–3.40$/kg
Martínez-Salazar et al. (2019)	Natural gas	Reforming	Not specified	n/a	n/a	-	40	-	-	-	-
Jamshidi and Askarzadeh (2019)	Photovoltaic	Electrolysis	Gas turbine	-	-	-	20	-	-	-	-
Touili et al. (2018)	Photovoltaic	Electrolysis	PEMFCs, SOFCs	n/a	n/a	-	-	-	-	-	-

(Continued)

TABLE 2 (Continued)

References	Energy source	Technology of H2 production	H2 for power generation	Capital expenditure	Operational expenditure	Interest rate	Project lifetime (years)	H2 production capacity	Plant efficiency (%)	Electricity cost ($/kWh)	H2 cost
Duman and Güler (2018)	Wind	Electrolysis	PEMFCs, FCs	n/a	n/a	-	20	-	0.1694	-	-
Li et al. (2018)	Coal	Gasification	No specified	n/a	n/a	10	25	-	-	-	120 CNY/kg
Kim et al. (2018)	Natural gas	Reforming	FCs	n/a	n/a	-	-	-	-	-	n/a
Haghi et al. (2018)	Natural gas, Beofule, Wind, Solar	Electrolysis	Not specified	n/a	n/a	-	20	-	-	-	n/a
Al-Sharafi et al. (2017)	Photovoltaic, Wind	Electrolysis	Gas turbine, PEMFCs, SOFCs	2,000 $/kW	-	-	25	-	-	-	-
Aziz (2017)	Photovoltaic, Wind	Electrolysis	FCs	9,500 $	250$/year	-	15	-	-	-	-
Yao et al. (2017)	Biomass	Gasification, Reforming and Alkaline electrolysis	PEMFCs, FCs, SOFCs	n/a	n/a	-	25	-	-	-	90 kg h-1
Ye et al. (2017)	Photovoltaic, Wind	Electrolysis	PEMFCs	n/a	n/a	-	20–25	-	-	-	-
Schlachtberger et al. (2017)	Photovoltaic, Wind	Electrolysis	Not Specified	n/a	n/a	-	25–80	-	-	-	-
Walker et al. (2016)	Natural Gas	Electrolysis	Not Specified	-	n/a	-	-	-	-	n/a	-
Martin et al. (2016)	Biodiesel	Electrolysis	Not Specified	-	-	7	-	-	-	-	-
Brka et al. (2016)	Wind	Electrolysis	PEMFCs	-	-	-	25	-	-	-	-
Rivera-Tinoco et al. (2016)	Methanol	Electrolysis	PEMFCs, SOFCs	n/a	n/a	-	-	-	-	n/a	-
Rivarolo et al. (2016)	Photovoltaic, Wind	Electrolysis	Not Specified	-	-	-	-	-	-	-	-
Stojković and Bakić (2016)	Photovoltaic, Wind	Electrolysis	FCs	n/a	n/a	-	20	-	-	-	-
König et al. (2015)	Wind	Electrolysis	PEMFCs	n/a	n/a	-	-	-	-	-	-
Cormos (2015)	Not Specified	Electrolysis	PEMFCs	n/a	n/a	-	25	-	-	n/a	-

(Continued)

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TABLE 2 (Continued)

References	Energy source	Technology of H2 production	H2 for power generation	Capital expenditure	Operational expenditure	Interest rate	Project lifetime (years)	H2 production capacity	Plant efficiency (%)	Electricity cost ($/kWh)	H2 cost
Guinot et al. (2015b)	Not Specified	Electrolysis	PEMFCs	n/a	n/a	-	-	-	-	-	-
Guinot et al. (2015a)	Photovoltaic	Electrolysis	PEMFCs	n/a	n/a	-	20	-	-	n/a	-
Olateju et al. (2014)	Wind	Electrolysis	Gas turbine	n/a	n/a	-	20	563 MW	-	-	-
Sarkar and Bhattacharyya (2012)	Photovoltaic, Wind	Electrolysis	Gas turbine	n/a	n/a	-	-	-	-	n/a	-
Cormos (2014)	Biomass	Gasification	Not specified	n/a	n/a	-	-	400–425 MW	-	-	-
Shiroudi et al. (2013)	Photovoltaic	Electrolysis	PEMFCs	n/a	n/a	-	25	-	0.7	-	-
Tzamalis et al. (2013)	Wind	Electrolysis	FCs	n/a	n/a	-	-	-	-	-	-
Banerjee et al. (2013)	Biomass	Gasification	SOFCs	n/a	n/a	-	20	2,000	-	-	-
Donaldson et al. (2012)	Biomass	Gasification	Not specified	8.6 $M	n/a	0.06	-	-	-	0.12 $/kWh	-
Carapellucci and Giordano (2012)	Unspecified renewable energy	Electrolysis	PEMFCs	n/a	n/a	-	-	-	-	-	-
Shabani and Andrews (2011)	Photovoltaic	Electrolysis	FCs	n/a	-	-	20	-	-	-	-
Tzamalis et al. (2011)	Photovoltaic	Electrolysis	FCs	n/a	n/a	-	-	-	-	-	-
Tsatsaronis et al. (2008)	Coal	Gasification	AFCs	n/a	n/a	-	-	-	-	-	-
Greiner et al. (2007)	Photovoltaic	Electrolysis	GT, FCs	n/a	n/a	-	25	-	-	-	-
Zoulias and Lymberopoulos (2007)	Photovoltaic	Electrolysis	FCs	n/a	n/a	-	20	-	-	-	-
Santarelli and Macagno (2004)	Photovoltaic	Electrolysis	GR, MCFCs	n/a	-	-	-	-	-	-	-
Scherer et al. (1999)	Not specified	Electrolysis	AFCs	n/a	n/a	-	-	-	-	-	-
Shaner et al. (2016)	Photovoltaic	Electrolysis	PEMFCs	n/a	n/a	-	-	-	0.61	-	-

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comparing more than one potential project, the level of internal investment indicates the one that is most profitable, regardless of project size and technology. According to established practice, an internal rate of return (IRR) of 10% is assumed, consisting of the interest rate for own capital and credit capital. Hydrogen production costs are calculated iteratively using a plant cash flow analysis that includes total annual expenses and revenues.

Uncertainty analysis

The evaluations built on assumptions and estimates inevitability produce uncertainty in results. TEA describes uncertainty caused explicitly by errors in data input, the tension in the model itself, and the characteristic of the context in which the analysis is carried out. In the initial step of uncertainty analysis, it is always important to systematically identify the variables that generate uncertainty. The second step is determining the number of computations necessary to confirm compliance with the acceptance criteria and standard tolerance limit. In addition, TEA performs an uncertainty analysis to evaluate the parameters that most influence the project's economic performance. For example, the sensitivity parameter might vary by up to 20% relative to the baseline value (van der Spek et al., 2020). Sensitivity analysis assesses the influence of a single parameter at a time. In the meantime, a Monte Carlo simulation was conducted to examine the combined effect of numerous parameters on the economic performance of an investment. This simulation forecasts economic indicator uncertainty by randomly generating parameter values within the ranges above. In addition, the simulation examines the process's uncertainty and calculates the chance that the developed system will be profitable. Here, (Lee et al., 2020) conducted an uncertainty analysis to identify changes in the unit price of electricity and the selling price of H2 in the net present value range. The uncertainty analysis reveals that, economically, the selling price of hydrogen is more influential than renewable electricity prices, such as hydro and onshore wind energy, which is considered promising renewable power source for reducing the cost of producing hydrogen.

Discussion

This section examines the techno-economic assessment of various hydrogen productions for power generation studies included in this systematic review. Natural gas and coal are the two most crucial feedstock sources for hydrogen generation. The technology for producing hydrogen from these two feedstocks is highly developed, and there is a lot of experience operating these plants. The cost of hydrogen from various energy sources depends on the energy conversion and production costs. Most hydrogen production techniques require either thermal or electrical energy input from the energy source. Concurrently, this energy source is supplied by the energy conversion plant, representing the increase in energy's final cost. These expenses are typically the most significant contributors to the total cost of hydrogen.

Compared to other fuel cells (FCs), proton exchange membrane fuel cells (PEMFC) have become a power source for many applications and a possible option for reducing greenhouse gas emissions. PEMFCs combined with photovoltaics and batteries are now considered an excellent alternative to power generation. The application of the independent control mode can realize the optimal economical operation of the hybrid power generation system (HPGS) without a communication network. It can reduce marginal cost by up to 19.08% compared to traditional droop control. Furthermore, the cooperative control mode can achieve minimum generation costs and a difference in battery energy storage devices' charge balance state, even when the line resistance effect is quite significant (Yang et al., 2019; Okonkwo et al., 2021).

A techno-economic assessment is important now-a-days, but there are many different uncertainties in how to calculate it. The use of non-standard procedures, assumptions, and data of varying quality makes it difficult to compare the values of the literature with each other and draw rational conclusions. Several assumptions are made when calculating TEA, such as type of financing, cost and space of land acquisition, cost of raw materials, the yield of raw materials, factory life, construction time, labor costs, product costs, and utility costs. However, these assumptions do not reflect the actual reality. It affects the calculation. On the other hands, Sensitivity analysis helps determine the state and condition of each plant operating after the investment. It is more beneficial to decide before investing. The sensitivity to the cost of capital can be determined by calculating the return on investment. This is a key parameter to identify the technology running from start to finish and the return on investment at each stage of growth.

In closing, numerous researches focus on hydrogen production sources, systems, and distinct hydrogen storage alternatives. In addition, studies focusing on the social and environmental implications of the sources and systems necessary for hydrogen production are scarce. Another drawback of this study is that it concentrates on metrics that cannot be compared to others get more definitive results. Future research might include hydrogen end-use possibilities, such as various fuel cells, to improve the analysis of the long-term viability of hydrogen-based energy systems.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number (s) can be found in the article/supplementary material.

Author contributions

Z carried out the experiment with support from AK and ST. Z and AK wrote the manuscript. SM helped supervise the project. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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