Received: 28 October 2024 | Revised: 7 February 2025 | Accepted: 29 April 2025 | Published online: 09 June 2025

RESEARCH ARTICLE

Green and Low-Carbon Economy
2025, Vol. 00(00) 1–15
DOI: 10.47852/bonviewGLCE52024666

The Economic-Energy-Environmental Benefits of Hydrogen Production Technologies in China

Jiamei Pei[1], Qianqian Ding[2], Lijuan Zhang[2] and Yan Xu[1,*]

[1] *School of Management Science and Engineering, Shanxi University of Finance and Economics, China*

[2] *School of Architecture and Engineering, Shanxi Technology and Business University, China*

Abstract: Energy from hydrogen is a significant means of energy conversion in China. This paper assesses and compares the economic, energy, and environmental benefits of different hydrogen production technologies in China to promote the growth of the hydrogen production sector. The findings of economic benefits reveal that (1) fossil energy hydrogen production technologies have an absolute advantage in China, and the levelized cost of hydrogen (LCOH) of coal-to-hydrogen (CTH) technology is 6.86 RMB/kg, which is more competitive. (2) The cost of electricity and the categories of electrolyzer affect the economic benefit of water electrolysis hydrogen production (WEHP). The cost of hydrogen produced from using nuclear power (NP) is the lowest (28.45 RMB/kg), while that from photovoltaic (PV) is the highest (69.1 RMB/kg). When the power sources are NP, coal power, hydropower, wind power, and PV, respectively, compared with proton exchange membrane (PEM) electrolytic hydrogen technology, the LCOH of alkaline (ALK) has decreased by 11%, 8%, 21%, 15%, and 18%, respectively, so ALK electrolytic method is more competitive than PEM. (3) Raw material cost accounts for the largest percentage, ranging from 32.3% to 79%. The findings of energy benefits show that CTH technology has the highest energy consumption among gray hydrogen technologies, which is 7.61×10^5 tce. The total energy consumption of WEHP varies with different types of electrolytic cells. The findings of the environmental benefits suggest that WEHP has the largest total carbon emissions of 4.2789×10^6 tCO_2 when the power source is coal power. Hydrogen from coal and natural gas follows. The carbon emissions of new hydrogen production technologies are generally low. Under the same power supply, the carbon emission of PEM is larger.

Keywords: green hydrogen, blue hydrogen, gray hydrogen, economic-energy-environmental benefits, China

1. Introduction

The current energy system in China is predominantly coal-based, with fossil fuels accounting for a substantial portion. As such, the task of energy transformation under the guidance and promotion of the "peak carbon and carbon-neutral" policy is both challenging and pressing. The foremost challenge facing China's energy transformation presently is energy security. Nonrenewable energy sources such as coal, oil, and natural gas have finite reserves and must be used judiciously to avoid resource depletion and potential energy supply constraints. Second, environmental concerns loom large, with China's CO_2 emissions comprising one-third of the global total. The use of fossil fuels results in various forms of environmental pollution. To address these challenges, it is crucial to identify new sources of energy that are safe, efficient, clean, and low-carbon, with the aim of replacing fossil fuels, achieving energy transformation, and promoting high-quality energy development.

Hydrogen can realize large-scale integration of renewable energy, facilitate large-scale grid stabilization, and promote cross-seasonal and cross-regional energy storage, ultimately achieving low carbonization across all sectors. As a clean, efficient, safe, and flexible energy source, hydrogen can be obtained from various primary and secondary energy sources [1], promoting the sustainable and efficient utilization of fossil fuels [2]. In addition, it boasts a high potential for storing energy across time and space and offers a broad range of application scenarios, thereby providing an important pathway for achieving low-carbon or even zero-carbon emissions in the energy, transportation, and chemical industries. Therefore, hydrogen holds a crucial role in carbon-neutral development, and its development constitutes a critical strategy for achieving low-carbon transformation within the Chinese energy system.

The hydrogen industry is characterized by a complex supply chain, encompassing production, storage, transportation, and final application stages. Among these stages, hydrogen production accounts for the largest proportion of the cost structure. Thus, the economic and market-oriented deployment of hydrogen production is pivotal to the development of the hydrogen energy industry. However, in comparison with established hydrogen-producing nations, such as Japan, the United States, and Germany, China's hydrogen production industry is still in its nascent stages, with experience gaps in production costs, capital, and policy support. Therefore, conducting a comprehensive assessment of the benefits of hydrogen production technologies assumes significant importance, as it will support the green transformation and high-quality development of China's hydrogen production industry.

***Corresponding author:** Yan Xu, School of Architecture and Engineering, Shanxi Technology and Business University, China. Email: xuyan@sxufe.edu.cn

This paper focuses on various hydrogen production technologies in China and compares their economic, energy, and environmental benefits. The contributions to this paper are as follows:

1) Considering investment costs, operation and maintenance costs, financial costs, replacement costs, tax costs, and hydrogen production volume as technical and economic parameters, a levelized cost of hydrogen (LCOH) model is constructed to evaluate the economic viability of various hydrogen production technologies, including coal-to-hydrogen (CTH), natural gas steam methane reforming (SMR), CTH coupled with carbon capture and storage (CCS), SMR coupled with CCS, and water electrolysis hydrogen production (WEHP).
2) By constructing energy efficiency and environmental benefit models, the energy consumption and carbon emissions of the 14 hydrogen production technologies are assessed separately.
3) The LCOH of each hydrogen production technology is decomposed, with a focus on analyzing the reasons for the economic differences among the technologies. This analysis aims to provide decision-making references for investors and promote the development of the hydrogen energy industry.

The remainder of the paper will be organized as follows. Section 2 shows the literature review. Section 3 elucidates the methodology. Section 4 provides the parameterization and assumptions. The results are given in Section 5. Section 6 gives the discussion. Section 7 makes the conclusions and policy implications.

2. Literature Review

Currently, a considerable number of domestic and international studies have explored the various benefits of hydrogen production technologies. At the technical level, hydrogen production technology is categorized into fossil energy hydrogen production technology and renewable energy hydrogen production technology [1].

2.1. Economic benefits

In recent years, while scholars have focused on the characteristics of hydrogen production technology, some have also investigated its economic aspects. The current research mainly concentrates on examining the economic applicability of individual hydrogen production technologies, such as CTH technology [3]. Furthermore, some scholars have explored the influencing factors of hydrogen production technology, such as fixed asset investment costs, variable costs, and internal rate of return [4, 5]. Similarly, Rezaei et al. [6] performed a quantitative analysis of hydrogen production technology, specifically evaluating the economic feasibility of utilizing wind energy to generate hydrogen in Afghanistan. Lee et al. [7] conducted an economic evaluation of WEHP and SMR technologies in terms of unit hydrogen production cost and profitability. The study determined that hydrogen production capacity was the primary factor influencing the LCOH, as confirmed through sensitivity analysis. In the pursuit of identifying the optimal path for hydrogen production technology development, existing literature has begun analyzing various hydrogen production paths [7–9]. In addition, some scholars have integrated environmental impact into their economic research. Cheng et al. [8] employed life cycle cost analysis to incorporate external costs resulting from environmental impacts and assessed the economic viability of hydrogen production from coal gasification and coal pyrolysis. At present, due to the high cost of hydrogen production from renewable energy, hindering the development of renewable energy hydrogen production technology, most scholars concentrate on the economic analysis of renewable energy hydrogen production technology [10–11]. Moreover, Guo et al. [12] systematically analyzed the costs of hydrogen production using alkaline (ALK) water electrolysis (WE) and proton exchange membrane (PEM) WE. In addition to considering economic viability, some scholars have utilized "potential" as a tool for research. Bhandari and Shah [13] analyzed the potential for hydrogen production using different power sources for solar electrolysis cells (ALK and PEM), taking the hydrogen production project in Cologne as an example.

2.2. Energy benefits

With fossil fuels being increasingly depleted, developing renewable energy sources has become an essential direction for the global energy sector. Hydrogen production technology also has the potential to offer certain energy benefits. Several scholars have conducted quantitative analyses of the carbon emissions and energy equivalents of different hydrogen production technologies from both a technological and energy efficiency perspective [14, 15]. Regarding carbon emissions, the CCS technology can be applied to hydrogen production, and in the long run, integrating hydrogen production with CCS technology presents a promising solution. However, the technology is still in its developmental stage, and the costs are relatively high, with a multitude of uncertainties that need to be addressed. Consequently, several scholars have employed innovative energy-economy-environment comprehensive evaluation models, from the perspective of general equilibrium analysis, to assess the viability of CCS technology [16]. Compared to hydrogen production from fossil fuels, scholars have directed their attention primarily toward the economic feasibility, efficiency, and development planning of hydrogen production from new energy sources. Baykara [17] demonstrated that solar-powered hydrogen production is the most environmentally and climate-friendly energy source. Wang [18] undertook a review of the current state of new energy-based hydrogen production technologies, including WP, solar power, and biomass energy, and investigated existing problems and future development directions.

2.3. Environmental benefits

As global attention toward carbon peaking and carbon neutrality intensifies, research on the environmental impact of hydrogen production technologies has also increased. Bai and Lu [19] innovatively developed an accounting method to calculate the carbon emissions of WEHP technology and clarified the accounting boundaries. Some scholars have included factors such as economic viability and hydrogen production methods in their investigation of the environmental impact. Lin [20] employed the life cycle assessment methodology to scrutinize the energy-saving and emission-reducing effects of different hydrogen production pathways for hydrogen fuel-cell vehicle. Moreover, some scholars have investigated the coupling of the CCS technology and hydrogen production technology. Al-Qahtani et al. [21] scrutinized the overall cost of five hydrogen production technologies (SMR, CTH and biomass gasification, methane pyrolysis, and renewable energy and nuclear technology electrolysis), noting that environmental externalities may constitute a significant proportion of the total cost of hydrogen gas. The study concluded that SMR coupled with CCS is the most economical hydrogen production method. At present, carbon emission accounting mainly includes the emission factor method and material method. Methods such as the material balance method and the measured method can be used in different calculation scenarios. Among them, the emission factor method is the most widely used [22].

In summary, previous studies have concentrated on the single-dimensional evaluation of hydrogen production technology. However, the analysis of hydrogen production technology from the perspectives of economy, energy, and environment is relatively limited. Therefore, this paper focuses on evaluating the economic-energy-environmental benefits of different hydrogen production technologies and systematically analyzes the economy, energy efficiency, and carbon emissions of hydrogen production technologies. The evaluation results provide a vital quantitative reference for decision makers, which is very important for supporting the development of new technologies for hydrogen production from renewable energy in China in the future and promoting the green transformation and high-quality development of the hydrogen production industry.

3. Methodology

3.1. Hydrogen production technologies

Depending on the raw material, hydrogen can be classified as gray, blue, and green hydrogen [23]. In this paper, the energy efficiency and environmental impact of gray hydrogen, blue hydrogen, and WEHP technologies are investigated. The gray hydrogen category comprises CTH, SMR, and the coal-fired power (CP) WEHP technologies. In addition, two types of electrolytic cells, namely, ALK and PEM, are used in WE to produce hydrogen. These electrolysis technologies are powered by nuclear power (NP), hydropower (HP), wind power (WP), and solar photovoltaic (PV).

3.2. Economic benefits model

The levelized cost of electricity (LCOE) serves as a metric to evaluate the economic efficiency and competitiveness of different technologies. It is widely used to quantitatively analyze the economic viability of a specific technology and to compare the competitiveness of various technologies. Specifically, LCOE represents the cost per kilowatt-hour of electricity produced over the lifetime of a power generation facility, providing an effective means to compare costs across different power generation methods. Furthermore, LCOE is determined by dividing the total costs associated with the entire life cycle of a power plant by the total electricity output, making it a valuable parameter for assessing and comparing different power generation systems [24, 25].

Correspondingly, the LCOH represents the cost associated with generating a single unit of hydrogen. It is calculated as the ratio of the present value of all expenses incurred throughout the entire life cycle of a hydrogen production project—where the net present value (NPV) is zero—to the present value of the total hydrogen output. This metric is determined by the point at which the discounted total revenue equals the discounted total costs. At this particular hydrogen cost level, the project only achieves the minimum required rate of return without generating any additional profit margin. In other words, if the market price of hydrogen matches the average production cost over the project's lifetime, investors will neither gain nor lose money on the investment. The relevant Equation (1) is presented below.

$$\sum_{n=0}^{N} \frac{Revenues_n}{(1+r)^n} = \sum_{n=0}^{N} \frac{\mathrm{Cost}_n}{(1+r)^n} \tag{1}$$

When project revenue equals the cost, that is, when the NPV is equal to zero, Equation (2) is obtained.

$$NPV = \sum_{n=0}^{N} PV = 0 \tag{2}$$

Therefore, LCOH is the hydrogen production cost when NPV equals 0, that is, when project costs and project revenues are equal. Revenues are expressed as the product of LCOH and annual hydrogen production, as shown in Equation (3).

$$\sum_{n=0}^{N} \frac{LCOH_n \times H_n}{(1+r)^n} = \sum_{n=0}^{N} \frac{\mathrm{Cost}_n}{(1+r)^n} \tag{3}$$

Assuming that the annual value of LCOH is constant, Equation (4) can be obtained.

$$COH = \left(\sum_{n=0}^{N} \frac{\mathrm{Cost}_n}{(1+r)^n} \right) \Big/ \left(\sum_{n=0}^{N} \frac{H_n}{(1+r)^n} \right) \tag{4}$$

According to Equation (4), LCOH equals the ratio of the discounted cost and the sum of the discounted hydrogen production over the entire project life cycle. LCOH can be interpreted as the value of each unit of hydrogen produced. The fulfillment of Equation (2) under this scenario implies that the project can be executed with zero profit for investors at the end of the project's life cycle. It is noteworthy that the summation should commence from n = 0, incorporating the initial investment cost in the first year of the project, which does not necessitate discounting. Alternatively, the initial cost can be spread out annually over the project's life cycle. This approach leads to Equation (5), which is derived from Equation (4) [26–28].

$$COH = \left(\sum_{n=1}^{N} \frac{CAPEX_n + OPEX_n + TAX_n + REP_n}{(1+r)^n} \right) \Big/ \left(\sum_{n=1}^{N} \frac{H_n}{(1+r)^n} \right) \tag{5}$$

Variables and factors:

Capital expenditure (CAPEX): The initial investment cost of a hydrogen production project refers to the capital input during the construction period, mainly including equipment costs, installation fees, and civil engineering costs [29].

Financial cost: The parameters involved in finance include initial capital ratio, loan term, annual interest rate, depreciation period, subsidies, and other related parameters [30].

Operational cost: The operational cost mainly refers to the operation and maintenance expenses during the operation period of the hydrogen production plant, including the cost of raw materials for hydrogen production, insurance, repair fees, personnel salaries and benefits, materials, and other fees. The compensation and benefits of the workers generated during the operation of the power plant are also included in the operating cost [31].

Tax cost: The hydrogen production project incurs several annual taxes, primarily comprising value-added tax, income tax, property tax, land use tax, urban maintenance and construction tax, and education surcharge. The taxation basis for each tax differs, necessitating determination based on the specific circumstances. Notably, the value-added tax has emerged as a preeminent tax in China. The land use tax is determined based on the area occupied, whereas self-use houses are taxed on the basis of the asset value, with a proportionate deduction. The urban maintenance and construction tax and education surcharge both adopt value-added tax as their taxation basis [27].

Replacement cost: During the operation period of the hydrogen production project using electrolysis, if the electrolytic cell reaches the end of its service life, it needs to be replaced. This cost mainly involves parameters such as the service life, cost, and replacement time of the electrolytic cell [31].

Capacity parameters and system efficiency: To effectively estimate the annual hydrogen production of the hydrogen production project during the operation period, we need to grasp important data such as the installed capacity of the hydrogen plant, annual utilization hours, and system efficiency [31].

Discount rate: The discount rate refers to the ratio at which expected future benefits or costs with a deadline are discounted to present value. It is the rate of return on assets to obtain these benefits under specific conditions. Based on this, considering the external value of funds and factors such as inflation, the concept of a discount rate is proposed [27].

3.3. Energy benefits model

In view of the energy efficiency calculation of different hydrogen production technologies, this paper only studies the consumption of the main raw materials of each technology and does not consider the energy consumption of the production process for hydrogen production equipment. In order to facilitate comparison, the energy consumption of different hydrogen production technologies is converted into coal equivalent by the method of coal equivalent coefficient.

The total energy consumption generated in the CTH process is:

$$C_{CTH} = C_{coal}R_{coal} + C_{electricity1}R_{electricity} + C_{water1}R_{water} \tag{6}$$

The total energy consumption generated in the CTH process is:

$$_{SMR} = C_{gas}R_{gas} + C_{electricity2}R_{electricity} + C_{deionized}R_{deionized} + C_{cooling}R_{cooling} \tag{7}$$

The total energy consumption generated in the process of CTH coupled with CCS is:

$$C_{coal+CCS} = C_{coal}R_{coal} + C_{electricity1}R_{electricity} + C_{water1}R_{water} \tag{8}$$

The total energy consumption generated in the process of SMR coupled with CCS is:

$$C_{gas+CCS} = C_{gas}R_{gas} + C_{electricity2}R_{electricity} + C_{deionized}R_{deionized} + C_{cooling}R_{cooling} \tag{9}$$

The total energy consumption generated in the WEHP process is:

$$C_{water\,electrolysis} = C_{electricity3}R_{electricity} + C_{nitrogen}R_{nitrogen} + C_{water2}R_{\,water} + C_{steam}R_{\,steam} \tag{10}$$

For the explanation of variables in each formula, please refer to the Table A1.

3.4. Environmental benefits model

For the evaluation of environmental benefits associated with different hydrogen production technologies, this study solely focuses on the carbon emissions generated during the hydrogen production process, while excluding the indirect carbon emissions resulting from the production of hydrogen equipment and the electricity consumption of CCS technology.

The total carbon emissions of CTH technology are:

$$E_{CTH} = I_{CTH}H \tag{11}$$

The total carbon emissions of SMR technology are:

$$E_{SMR} = I_{SMR}H \tag{12}$$

The total carbon emissions of CTH coupled with CCS technology are:

$$E_{coal+CCS} = E_{CTH} - \alpha E_{CTH} \tag{13}$$

The total carbon emissions of SMR coupled with CCS technology are:

$$E_{gas+CCS} = E_{SMR} - \alpha E_{SMR} \tag{14}$$

The total carbon emissions of WEHP technology are:

$$E_i = I_i \times E_k \times H \tag{15}$$

where E_i is the total carbon emissions of the i_{th} power source used for hydrogen production via water electrolysis, $i = 1, 2, 3, 4, 5$, representing the different power sources of coal power, NP, hydropower, wind power, and solar photovoltaic, respectively. I_i is the carbon emission intensity of the i_{th} power source used for hydrogen production from electrolysis water. E_k is the electricity consumption of the k_{th} electrolytic cell, where $k = 1, 2$, representing the ALK and PEM, respectively.

4. Parameterization and Assumptions

4.1. Assumptions

The research boundary for each hydrogen production technology is the inputs associated with the hydrogen production process, including types of hydrogen production equipment, feedstocks, and operations, with the output being hydrogen, regardless of hydrogen compression and transport. Given that the production scale of hydrogen constitutes a crucial factor influencing the cost of hydrogen production, the assumption is made that the annual production capacity for gray hydrogen, blue hydrogen, and electrolyzed water hydrogen production is 100,000 tons, in order to neutralize the impact of the production scale on LCOH.

4.2. The economic benefits

4.2.1. Gray hydrogen

This paper considers two representative gray hydrogen projects, namely, the Luoyang CTH project and the Xifeng SMR project, as benchmarks. The CTH project has a total investment of 2.4771 trillion RMB and a hydrogen production capacity of 105,000 tons per year, while the SMR project in Xifeng has a total investment of 200 million RMB and a hydrogen production capacity of 100 million m^3 per year. For facilities of varying sizes, the fixed capital investment is calculated using the formula proposed by Wang et al. [32] The cost parameters of the coal-powered WEHP technology are shown in Table 1 [31].

4.2.2. Blue hydrogen

To facilitate a more comprehensive comparison between blue hydrogen and gray hydrogen technologies, this study focuses on a hydrogen production project that utilizes the same fossil energy source for both technologies, with the addition of CCS for the blue hydrogen process. Consequently, the parameters for the CCS technology, as shown in Table 2, are the only parameters that need to be considered.

Table 1
Technical and economic parameters for WEHP project

	Unit	ALK	PEM	CP	NP	HP	WP	PV
Unit investment	RMB/kW	7000	12000					
Service life	h	75000	45000					
Electricity price	RMB/kwh			0.5	0.37	0.31	0.5	0.55
Annual running time	h	—	—	5000	7800	3800	2100	1200

Note: The expected annual operating time of the electrolytic cell is determined by the operation time of the power generation method.

Table 2
The cost parameters of CCS technology

CCS cost	Unit	Value	Data source
Capture rate	%	90	[33]
Capture cost	RMB/t	161	
Transportation cost	RMB/t·km	1.1	[31]
Sequestration cost	RMB/t	60	

4.2.3. Green hydrogen

WEHP technologies can be classified into several types based on the differences in electrolytic cells, such as ALK, PEM, and high-temperature solid oxide electrolysis cells, which are still in the experimental phase. Therefore, this study will focus on the first two methods, namely, the ALK and PEM technologies. Technical and economic parameters for hydrogen production through the electrolysis of water are presented in Table 1.

Table 3 presents the raw material cost parameters for each technology, with price data reflecting actual market prices in China.

When evaluating the LCOH of various hydrogen production technologies, it is necessary to establish consistent financial, operational, tax, and discount rate parameters, even though the technical routes may differ. In this study, a capital ratio of 20% is assumed, with the remaining funds financed by bank loans. The long-term loan interest rate, adjusted by the central bank since October 2015, is set at 4.9%, with a loan term of 20 years. The unit design operating life, depreciation period, and project residual value rate are set at 25 years, 20 years, and 5%, respectively. According to the industry standard for power generation, the hydrogen production project's internal rate of return is predetermined at 8%. The insurance premium and repair fee are expressed as rates, with values of 0.25% and 2%, respectively, of the fixed assets of the hydrogen plant per year. The project's business tax is not considered under the "VAT to VAT" policy. As a high-tech project, the state provides support, and the corporate income tax is set at 15%, while the value-added tax rate is 6.5%. The land use tax rate is established at 2 RMB per square meter [28]. The tax rate for property tax collection is regulated to be 1.2%, and the property tax deduction ratio is 30% based on relevant regulations. Additionally, urban maintenance and construction fees and education surcharges are 5% and 4%, respectively. Based on the aforementioned parameter

Table 3
Raw material cost parameters

Technology	Raw material	Consumption		Unit	Data source	Price	Unit	Data source
CTH	Coal	8.46		t/t H_2	[34]	475	RMB/t	—
	Electricity	0.66		kWh/kg H_2	[35]	0.6	RMB/kWh	[32]
	Industrial water	191.57		t/t H_2	[32]	2	RMB/t	
SMR	Natural gas	4.43		m^3/kg H_2	[34]	2.5	RMB/m^3	—
	Electricity	3.9		kWh/kg H_2	[36]	0.6	RMB/kWh	[36]
	Deionized water	14.5		kg/kg H_2		40	RMB/t	
	Cooling water	66.7		kg/kg H_2		3	RMB/t	
WEHP								
		ALK	PEM					
	Electricity	51	58	kWh/kg	[37]	Depends on the source of electricity	RMB/kWh	—
	Industrial pure water	10	10	kg/kg H_2	[7, 38]	76.2	RMB/t	[39]
	Electrolyte	1.9	0	g/kg H_2	[38]	19134.8	RMB/t	
	Steam	0.11	0	kg/kg H_2		76.2	RMB/t	
	Nitrogen	0.29	0	g/kg H_2		2121.1	RMB/t	

Table 4
Common public parameters

Cost name	Value	Cost name	Value
Capital ratio (%)	20%	Insurance rate (%)	0.25%
Loan term (years)	20	Major repair rate (%)	2%
Annual interest rate (%)	4.9%	Employee salary (CNY/year)	80000
After-tax internal rate of return (%)	8%	Welfare labor insurance coefficient (%)	60%
Service life (years)	25	Employee salary growth rate (%)	6%
Income tax (%)	15%	Urban maintenance and construction tax (%)	5%
Value-added tax (%)	6.5%	Education surcharge (%)	4%
Land use tax (RMB/square meter)	2	Property tax	1.2%

settings, Table 4 [27] provides an overview of the public parameters for the hydrogen production project.

4.3. *The energy benefits*

In this paper, when calculating the total energy consumption of different hydrogen production technologies, the consumption of main raw materials is mainly based on the raw material parameters in Table 3. The conversion coefficient of each main raw material refers to the "current conversion coefficient of commonly used energy varieties to coal equivalent," as shown in Table 5 [40].

Table 5
Reference conversion coefficients for various energy sources

Energy	Conversion coefficients (tce)
Coal (t)	0.7143
Natural gas (10000 m^3)	13.3
Electricity (10000 kWh)	1.229
Industrial Water (10000 m^3)	0.85
Deionized water (10000 m^3)	1
Cooling water (10000 m^3)	0.03
Steam (10000 m^3)	0.95
Nitrogen (10000 m^3)	0.400

Table 6
Carbon emission intensity of different hydrogen production technologies

Hydrogen production technologies	Carbon emission intensity
CTH	20 $kgCO_2/kgH_2$
SMR	9 $kgCO_2/kgH_2$
CP	839 gCO_2/kW·h
NP	10.9 gCO_2/kW·h
HP	40.6 gCO_2/kW·h
WP	8.6 gCO_2/kW·h
PV	29.2 gCO_2/kW·h

4.4. *The environmental benefits*

Carbon emission is an important parameter to evaluate the environmental benefits of different hydrogen production technologies. For the calculation of total carbon emissions of different hydrogen production technologies, this paper mainly refers to the carbon emission intensity values of different hydrogen production technologies by Wang et al. [23], as shown in Table 6.

5. Results

5.1. Economic benefits

5.1.1. Levelized cost of hydrogen production technologies

The LCOH of different hydrogen production technologies is shown in Figures 1, 2, and 3. In Figure 1, the LCOH of CTH production is 6.86 RMB/kg, and the LCOH of CTH production coupled with CCS is 14.54 RMB/kg. In Figure 2, the LCOH of SMR production is 17.95 RMB/kg, and the LCOH of SMR coupled with CCS is 26.5 RMB/kg.

In Figure 3, the LCOH of WEHP technology varies due to differences in electricity prices and utilization hours under five different power sources. The LCOH of ALK ranges from 28.45 to 69.1 RMB/kg, while that of PEM ranges from 31.79 to 84.11 RMB/kg. Among them, the LCOH of WEHP using NP as the power source is the lowest, and that using PV as the power source is the highest. When the power sources are NP, CP, HP, WP, and PV, the LCOH of ALK technology decreases by 11%, 8%, 21%, 15%, and 18%, respectively, compared to PEM electrolysis hydrogen technology. Therefore, ALK electrolysis is more competitive than PEM.

5.1.2. The cost composition of the hydrogen production technologies

Figure 4 presents the cost breakdown of CTH and SMR technologies. The internal pie chart delineates the distribution of initial investment, operation and maintenance, and tax costs, while the external pie chart depicts the proportion of primary raw materials. The cost composition of CTH technology indicates that initial investment accounts for 30% of the cost, operation and maintenance costs for 10%, raw material costs for 57%, and tax costs for 3%. Coal input is the largest contributor to raw material costs, representing 78% of the total. In contrast, the cost composition of natural gas hydrogen production indicates that initial investment accounts for 4% of the cost, operation and maintenance costs for 2%, raw material costs for 94%, and tax costs for 0%. Natural gas input is

Figure 1
LCOH of CTH and CTH coupled with CCS

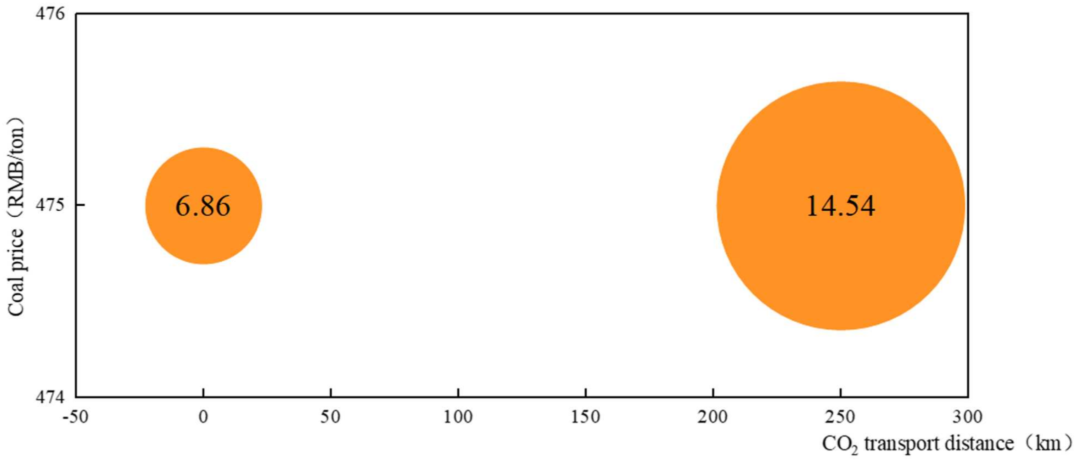


Figure 2
LCOH of SMR and SMR coupled with CCS

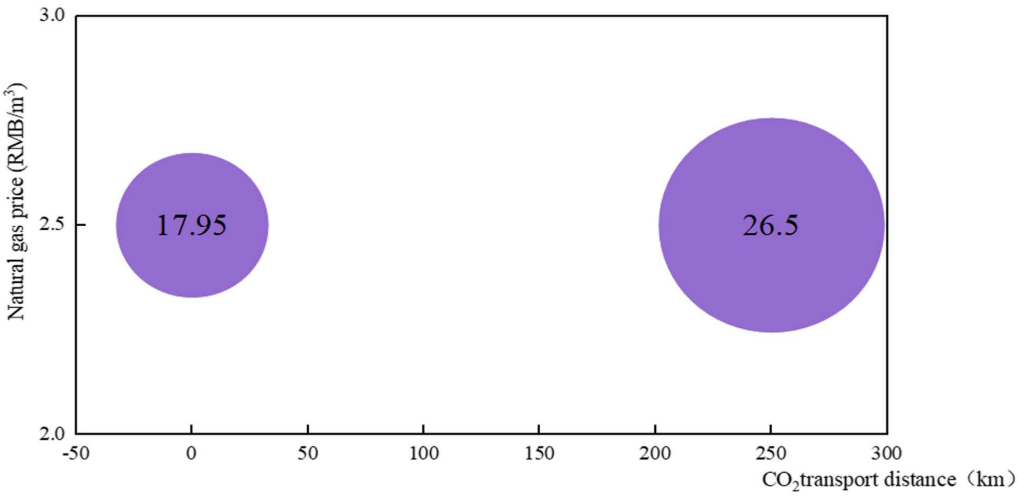
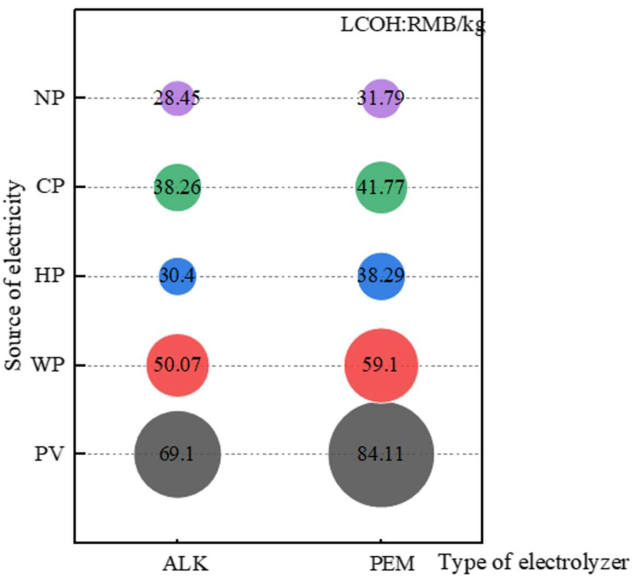


Figure 3
LCOH for hydrogen production by electrolysis of water

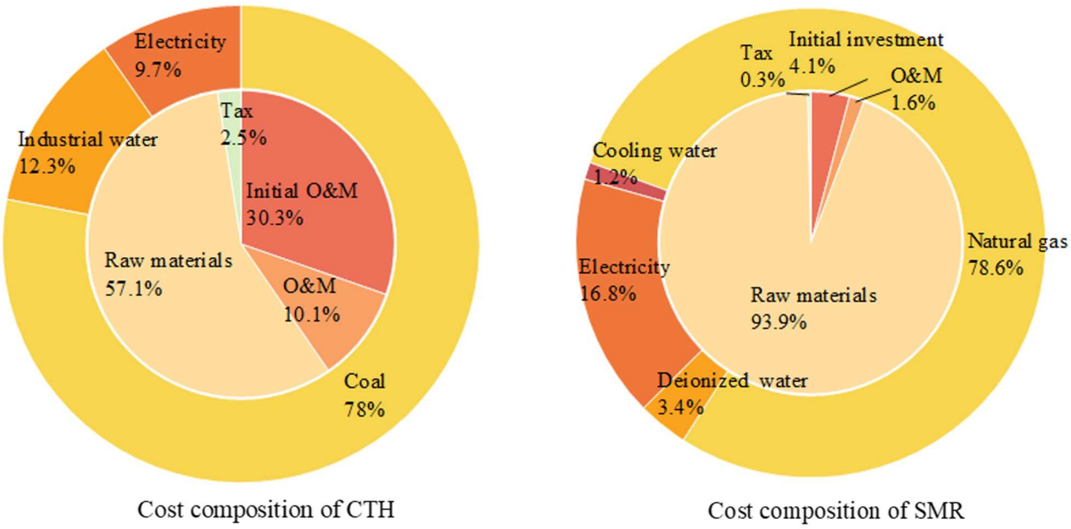


the largest contributor to raw material costs, accounting for 79% of the total, while the cost of initial investment and operation and maintenance is relatively low.

Given China's abundant coal resources and limited natural gas reserves, the cost of natural gas is higher than that of coal, rendering the raw material cost for hydrogen production from natural gas prohibitively expensive. Consequently, coal-based hydrogen production technology is more competitive. The cost composition analysis of hydrogen production from coal and natural gas indicates that the initial investment and raw material costs account for the highest proportion, ranging from 87% to 98% of the total cost. Thus, reducing the initial investment cost and improving the conversion efficiency of raw materials are crucial in significantly reducing the LCOH of gray hydrogen.

The blue hydrogen project incorporates CCS technology into the pre-existing gray hydrogen project, with its cost structure comprising the conventional hydrogen production expenses, as well as the expenses associated with CCS technology. The results of the calculation demonstrate that the initial investment cost of CCS constitutes a substantial proportion of the total initial investment cost, ranging from 78% to 92%. Additionally, the operational expenses of hydrogen production derived from fossil fuels account for a

Figure 4
Cost composition of CTH and SMR technologies



significant proportion of the total operating cost, ranging from 95% to 99%. The exorbitant initial investment cost of CCS technology serves as the primary factor contributing to the escalation of hydrogen production costs. Consequently, reducing the initial investment cost of CCS technology would notably decrease the LCOH of blue hydrogen.

Figure 5 illustrates the cost composition of hydrogen production technology by WE from different power sources, including both ALK and PEM hydrogen production technologies. The internal pie chart depicts the proportion of initial investment, operation and maintenance, taxation, and replacement costs, while the external pie chart represents the proportion of main raw materials.

The cost of WEHP is predominantly comprised of the initial investment cost and raw material cost. The former accounts for 14.6%–56.53% of the total cost, whereas the latter accounts for 32.3%–74.4%. Within the cost of raw materials, the electricity price represents over 95%. However, the proportion of electricity prices varies due to discrepancies in on-grid electricity prices and available hours of different electricity sources. HP exhibits the lowest price and availability, hence its electricity price proportion is also the lowest. Conversely, PV electricity boasts the highest price, the lowest available hours, and subsequently the highest proportion of electricity price. Therefore, reducing the initial investment cost and selecting a suitable power source would significantly enhance the competitiveness of hydrogen production from electrolyzed water.

From the perspective of hydrogen production technology, it can be observed that the LCOH for ALK technology is lower than that of PEM technology, while the initial investment cost proportion is also lower. These findings suggest that the initial investment cost of electrolysis-based hydrogen production technology is a crucial factor that affects its competitiveness. Currently, PEM technology is still in its nascent stage. However, with the advent of new low-cost electrocatalysts and the realization of self-sufficiency in key materials, the LCOH of PEM WE technology is expected to decrease further in the future. This, in turn, is expected to facilitate rapid industry expansion.

5.2. Energy benefits

The results of energy efficiency for hydrogen production technologies are presented in Table 7. Among the different types of gray hydrogen technology, the energy consumption of CTH production is notably higher than that of natural gas-based hydrogen production due to the greater heat energy required during the production process and lower energy conversion rate. In terms of green hydrogen technology, the ALK electrolyzer exhibits slightly lower hydrogen production power consumption compared to the PEM, resulting in a difference in their respective total energy consumption. As hydrogen production technology continues to develop, the maturity of the technology has gradually increased, and key core technologies have been increasingly refined. This has led to an increase in the energy conversion rate of hydrogen production devices, a decrease in the power consumption of hydrogen production, and a continuous decrease in the overall energy consumption.

5.3. Environmental benefits

The results of environmental benefits for hydrogen production technologies are presented in Table 8. The amount of hydrogen produced by different hydrogen production projects is the same, so the carbon emission intensity is the main reason for the different total carbon emissions of different technologies.

When the power source is coal-fired power, the total carbon emission of WEHP is the largest. At present, China's power structure is dominated by thermal power. Although thermal power units continue to develop in the direction of large capacity and high parameters in recent years, the carbon emission intensity of coal power is still higher than that of renewable energy and NP, and there are many factors affecting the carbon emission of coal power, including unit type, coal quality, unit capacity, etc. Among them, the higher load rate of the unit and the higher carbon oxidation rate of coal are the main reasons for the higher carbon emission intensity.

The total carbon emissions from CTH and SMR are the second. Unlike traditional fossil fuels, hydrogen only produces water when

Figure 5
Cost composition of WEHP

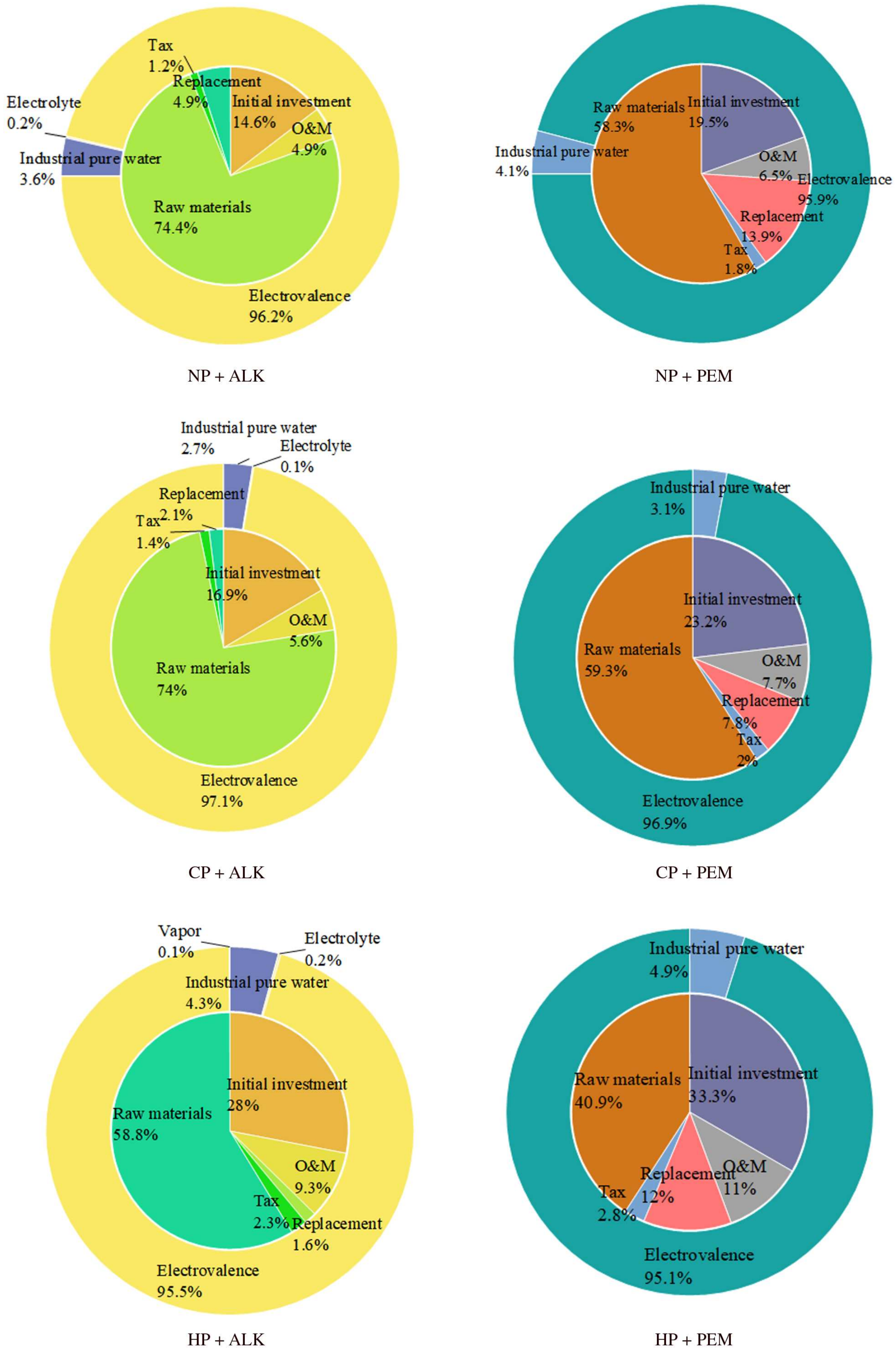


Figure 5
(Continue)

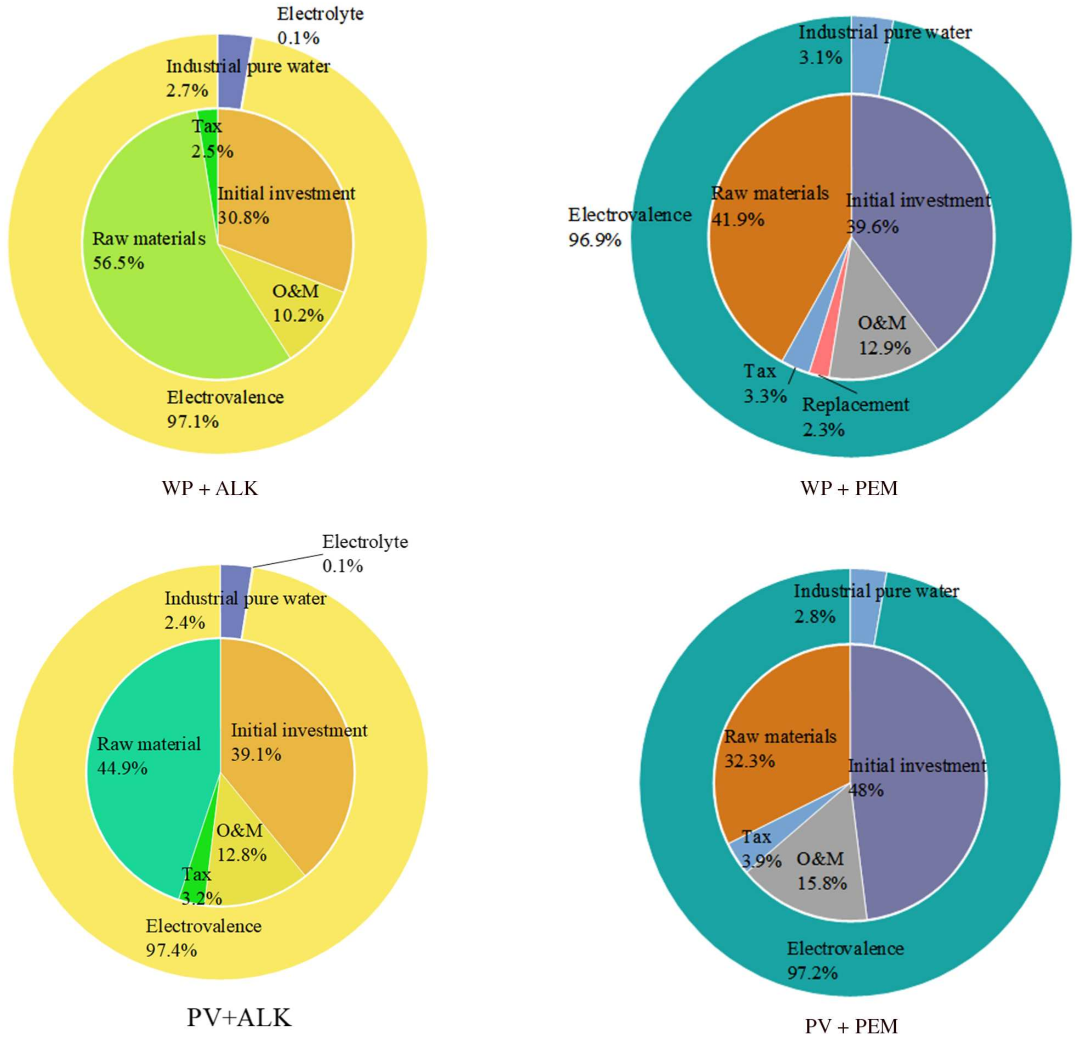


Table 7
Total energy consumption of different hydrogen production technologies

Hydrogen production technologies	Energy consumption (kgce/kg of H_2)	Total energy consumption (tce)
CTH	7.61	7.61×10^5
SMR	5.9	5.9×10^5
CTH coupled with CCS	7.61	7.61×10^5
SMR coupled with CCS	5.9	5.9×10^5
ALK	6.27	6.27×10^5
PEM	7.13	7.13×10^5

it is burned into electricity and heat without emitting greenhouse gases, which will make the carbon emission intensity of different hydrogen production technologies far lower than that of traditional power generation methods, such as the carbon emission intensity of CTH is far lower than that of coal power.

The carbon emissions from new hydrogen production technologies are generally low. Compared with traditional carbon-based energy sources, non-carbon-based energy sources such as wind energy and hydro energy basically do not produce greenhouse gases in the power generation process, and carbon emissions of renewable energy power generation mainly come from equipment production and power plant construction, so carbon emissions are lower. Carbon emission intensity is between 8 and 41 gCO_2 /kWh, with wind power being the lowest and hydropower the highest. In the process of hydrogen production by electrolytic water, the hydrogen production efficiency is different due to different electrolytic cells, resulting in slightly different total carbon emissions. The hydrogen production efficiency of PEM is slightly lower than that of ALK,

Table 8
Total carbon emissions of different hydrogen production technologies

Hydrogen production technologies	Total carbon emissions (tCO_2)
CTH	2×10^6
SMR	9×10^5
CTH coupled with CCS	2×10^5
SMR coupled with CCS	4.5×10^4
CP + ALK	4.2789×10^6
CP + PEM	4.8662×10^6
NP + ALK	5.559×10^4
NP + PEM	6.322×10^4
HP + ALK	2.0706×10^5
HP + PEM	2.3548×10^5
WP + ALK	4.386×10^4
WP + PEM	4.988×10^4
PV + ALK	1.4892×10^5
PV + PEM	1.6936×10^5

resulting in the consumption of more electricity when electrolyzing water, so when the power source is the same, the total carbon emissions of PEM electrolytic water hydrogen production technology based on green electricity is greater than that of ALK. The carbon emissions of the chemical industry after coupled with CCS are much lower than before, almost similar to new energy hydrogen production.

6. Discussion

The LCOH varies significantly across different hydrogen production technologies, with a range of 6.86–84.11 RMB/kg. The cost of gray hydrogen mainly consists of raw material costs, and its production process is simple and requires relatively small equipment and a site. As a result, gray hydrogen is currently the lowest-cost option. For hydrogen production technologies with LCOH below 20 RMB/kg, the cost composition of hydrogen production from coal and natural gas differs significantly. The cost of hydrogen production from natural gas is mainly due to the cost of natural gas, accounting for approximately 79%, while the cost of coal production is relatively higher, with a ratio of around 78%. However, the CTH path is more economical due to China's "rich coal and less gas" resource endowment, and the minimum LCOH for CTH is 6.86 RMB/kg. The second lowest-cost option is blue hydrogen, which employs CCS technology to capture greenhouse gases emitted during the hydrogen production process, thereby achieving low-emission production. However, the high initial investment cost of CCS technology increases the cost of blue hydrogen, resulting in an LCOH ranging from 10 to 30 RMB/kg, with the LCOH of CTH increasing by 7.68 RMB/kg. If a carbon tax is considered, CTH production using CCS may have an advantage. In the future, the fossil energy + CCS hydrogen production pathway is expected to become a long-term option. The highest-cost option is WEHP. Although this technology can achieve almost zero emissions during the hydrogen production process, it is constrained by technical thresholds and relatively high investment and operation costs. The LCOH for WEHP varies significantly due to differences in the cost of renewable energy power generation and equipment costs. The minimum LCOH for WEHP using NP is 28.45 RMB/kg, while the maximum LCOH for WEHP using PV is 84.11 RMB/kg. According to Figure 5, the cost composition of ALK and PEM differs under different power sources. This is because ALK has already reached the commercial application stage and is relatively mature in all aspects, while PEM is still in the research and demonstration stage. Regardless of the power source, the initial investment and operation and maintenance costs of ALK are higher than those of PEM, resulting in an LCOH of ALK that is 3.34 to 15.01 RMB/kg lower than that of PEM.

Regardless of the hydrogen production technology used, energy consumption is an unavoidable aspect of the process. However, the extent of energy consumption varies across different technologies. For instance, CTH production consumes relatively high levels of raw material heat energy, which translates to a high energy consumption of 7.61×10^5 tce. In contrast, SMR utilizes natural gas as both the raw material gas and combustion gas, eliminating the need for transportation and resulting in lower energy consumption of 5.9×10^5 tce, owing to a higher hydrogen production rate. Green hydrogen technology, on the other hand, primarily relies on electricity for the hydrogen production process using ALK and PEM technologies. This process is characterized by a low conversion rate of electric energy, resulting in relatively high energy consumption of up to 70%, second only to coal hydrogen production. In this category, the hydrogen production power consumption of the ALK electrolyzer is slightly lower than that of PEM, resulting in energy consumption of 6.27×10^5 tce and 7.13×10^5 tce, respectively.

Currently, in China, the power structure is mainly composed of thermal power, which has a relatively high carbon emission intensity. As a result, when CP is used as the power source for hydrogen production, the carbon emissions of CP + ALK and CP + PEM are the highest, at 4.2789×10^6 t CO_2 and 4.8662×10^6 t CO_2, respectively. The next highest carbon emissions are associated with gray hydrogen produced from coal and natural gas, with emissions primarily stemming from greenhouse gases produced during raw material conversion, accounting for about 70% of total emissions. The carbon emissions of gray hydrogen production are therefore relatively high, at 2×10^6 t CO_2 and 9×10^5 t CO_2. Although gray hydrogen production can be profitable, the technology requires significant nonrenewable energy consumption and high carbon emissions, making it an unsustainable option.

In comparison, the carbon emission intensity of WEHP using renewable energy is generally low. The highest carbon emission intensity is associated with HP + PEM, at 2.3548×10^5 t CO_2, and the lowest carbon emission intensity is associated with WP + ALK, at only 4.386×10^5 t CO_2. Due to the higher hydrogen production efficiency of ALK compared to PEM, Table 8 shows that regardless of the power source used for WE to produce hydrogen, the total carbon emissions of PEM are always higher than those of ALK.

Coupling CTH and SMR technologies with CCS can significantly reduce carbon emissions, to the point where emissions approach those of new energy hydrogen production. However, it will take time to reduce the cost of this technology. In the medium term, gray hydrogen coupled with CCS will likely remain the most economically viable option in China.

7. Conclusions and Policy Implications

7.1. Conclusions

After the proposal of the "double carbon" target, the need for a low-carbon energy transition has become increasingly urgent. In this context, the development of hydrogen energy is seen as a potential solution for achieving the low-carbon transition of the energy system in China. To this end, this paper employs the economic benefits model, energy efficiency model, and environmental benefits model to evaluate the economic, energy, and environmental benefits of 14 hydrogen production technologies. Based on this analysis, the study draws the following conclusions:

First, from an economic perspective, the LCOH of CTH technology is the lowest, at 6.86 RMB/kg. The abundant coal resources and scarce oil and gas resources in China lead to higher costs for natural gas than for coal, resulting in a slightly higher LCOH of SMR technology, at 17.95 RMB/kg. Fossil fuel-based hydrogen production coupled with CCS technology has a medium-level LCOH, ranging from 14.54 to 26.5 RMB/kg. The type of electrolyzer and power source are important factors affecting LCOH in electrolyzed water hydrogen production technology. The LCOH varies with different electricity prices and utilization hours. Among the power sources, NP has the smallest LCOH, while PV has the largest when electrolyzing water to produce hydrogen. When the power sources are NP, CP, HP, WP, and PV, the LCOH of ALK hydrogen production technology is 11%, 8%, 21%, 15%, and 18% lower than that of PEM, respectively. Therefore, ALK electrolysis is more cost-effective than PEM electrolysis.

Second, based on the results of cost composition for hydrogen production technologies, the cost components comprise initial investment, operating cost (including raw material cost and operation and maintenance cost), and tax cost. Notably, the initial investment cost and raw material cost make up the largest share, while taxation and operation and maintenance costs make up the smallest share. However, in contrast to other technologies, electrolysis technology for hydrogen production has a limited service life for the electrolytic cell, which necessitates consideration of replacement costs in the overall life cycle cost analysis. The replacement cost varies depending on the electrolytic cell and power source, as well as their respective service life and annual operation time. Consequently, the ratio of replacement cost for electrolysis technology differs from other hydrogen production technologies.

Third, based on the energy consumption results of various hydrogen production technologies, it can be inferred that CTH production has the highest energy consumption among gray hydrogen technologies. Additionally, hydrogen production efficiency is a critical factor influencing the energy consumption of WEHP. As the energy conversion efficiency of hydrogen production devices increases, the power consumption of hydrogen production decreases, and the total energy consumption of the process will continue to decrease accordingly.

Finally, based on the results of total carbon emissions of various hydrogen production technologies, the WEHP using CP has the highest carbon emissions, followed by CTH and SMR, while blue hydrogen has significantly higher carbon emissions. The total carbon emissions of WEHP based on renewable energy power are the lowest. The hydrogen production efficiency is a crucial factor affecting the carbon emissions of WEHP technology. The hydrogen production efficiency of the PEM is slightly lower than that of the ALK, and more electricity is consumed during WEHP. Thus, when the power source is the same, the total carbon emissions of the PEM based on green power are greater than those of the ALK.

7.2. Policy implications

Based on the development status and challenges of hydrogen production technology, this paper puts forward several policy implications to promote the sustainable development of the hydrogen energy industry.

1) Increase financial support for research and development of blue hydrogen and green hydrogen technologies

At present, the production process of gray hydrogen technology is mature, and the cost is low, and it has been widely used. However, the hydrogen production technologies of blue hydrogen and green hydrogen are in the initial stage of large-scale application and are gradually moving toward commercialization. However, it is necessary to continuously strengthen research and development and technological innovation, with the focus on achieving the goals of low cost, long life cycle, high safety, and high efficiency. Technological progress can improve the hydrogen production efficiency of the hydrogen production system, prolong the cycle life of the electrolyzer, and reduce the number of battery replacements in the whole life cycle. With the improvement in the localization of electrolyzers and hydrogen production equipment, their initial investment and replacement costs are greatly reduced, thus lowering the LCOH of hydrogen production technology. Therefore, the government should formulate relevant policies and provide financial support to serve the research and development of hydrogen production technology.

2) Provide subsidies and fiscal policies

In recent years, with the implementation of economic stimulus and support policies, China's wind power, photovoltaic, and other new energy power sources have developed rapidly, and the cost of power generation has been greatly reduced. However, the subsidies related to hydrogen energy and the lack of financial policies have led to the slow development of this industry. At present, the loan interest rate provided by China Commercial Bank for hydrogen production projects is 4.9%, and there is no special preferential loan policy. Although the tax cost accounts for a small proportion in LCOH, if the government can provide subsidies for the tax revenue of the hydrogen energy industry by learning the subsidy policies of other renewable energy power generation technologies, more social capital will enter the industry. According to the development status of hydrogen energy technology in China, the government can provide loan incentives, special fund support, value-added tax incentives, income tax credits, land taxes, investment subsidies, electricity price subsidies, and other support policies to reduce the investment costs and tax costs of hydrogen production projects.

3) Strengthen the standardization system of hydrogen energy industry

The government should promote the development of a hydrogen energy standard system and start to compile hydrogen energy standards. At present, the standardization of China's hydrogen energy industry is in its infancy, and the standard-setting work has not yet been completed. Lack of a standardized industry system leads to problems in the management of hydrogen energy projects. The government should set up an authoritative standardization committee and a working group. In the process of formulating the standard system, every application link needs to be continuously improved with the development of technology and market demand. Relevant enterprises with experience in project construction and operation should participate to make the standard system more in line with the actual situation. The establishment of a hydrogen energy standard system enables enterprises to save manpower, material resources, and financial resources and greatly reduce the capital expenditure during the construction period and the maintenance cost during the operation period of hydrogen production projects.

This paper mainly focuses on the economic-energy-environmental benefits of hydrogen production technologies, aiming at evaluating and optimizing the feasibility of hydrogen energy technology through these key indicators. However, the limitation of this paper is that external factors, such as market demand, speed of technological progress, international competition situation, and public acceptance, are not fully considered, which also have an important impact on the long-term development of the hydrogen energy industry. In order to guide the future development of the hydrogen energy industry more comprehensively, these external factors should be further included in future research to build a more complete and systematic policy framework.

Funding Support

This paper is supported by the Philosophy and Social Science Planning Program of Shanxi (2024YB085) and the Program for the Innovative Talents of Higher Education Institutions of Shanxi (PTIT). The authors would also like to acknowledge with great thanks to anonymous reviewers for their valuable comments, which largely improve the academic quality of this paper. The usual caveats apply.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Jiamei Pei: Methodology, Software, Validation, Writing – original draft. **Qianqian Ding:** Formal analysis. **Lijuan Zhang:** Visualization. **Yan Xu:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

References

[1] Dou, B., Zhang, H., Song, Y., Zhao, L., Jiang, B., He, M., ..., & Xu, Y. (2019). Hydrogen production from the thermochemical conversion of biomass: Issues and challenges. *Sustainable Energy & Fuels*, *3*(2), 314–342. https://doi.org/10.1039/C8SE00535D

[2] Banu, J. R., Kavitha, S., Kannah, R. Y., Bhosale, R. R., & Kumar, G. (2020). Industrial wastewater to biohydrogen: Possibilities towards successful biorefinery route. *Bioresource Technology*, *298*, 122378. https://doi.org/10.1016/j.biortech.2019.122378

[3] Hong, H. (2020). Méi tàn zhì qīng jīng jì shì yòng xìng fēn xī [Economic applicability analysis of coal hydrogen production]. *Energy and Energy Conservation*, *2020*(12), 4.

[4] Gan, L., & Zhu, Y. (2019). Dà xíng shuǐ diàn qǐ yè diàn jiě shuǐ zhì qīng jīng jì kě xíng xìng fēn xī [Economic feasibility analysis of hydrogen production from electrolytic water in large hydroelectric enterprises]. *Science & Technology Information*, *17*(32), 3. https://doi.org/10.16661/j.cnki.1672-3791.2019.32.022

[5] Minutillo, M., Perna, A., Forcina, A., Di Micco, S., Jannelli, E., & Jannelli, . (2021). Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario. *International Journal of Hydrogen Energy*, *46*(26), 13667–13677. https://doi.org/10.1016/j.ijhydene.2020.11.110

[6] Rezaei, M., Naghdi-Khozani, N., & Jafari, N. (2020). Wind energy utilization for hydrogen production in an underdeveloped country: An economic investigation. *Renewable Energy*, *147*, 1044–1057. https://doi.org/10.1016/j.renene.2019.09.079

[7] Lee, B., Chae, H., Choi, N. H., Moon, C., Moon, S., & Lim, H. (2017). Economic evaluation with sensitivity and profitability analysis for hydrogen production from water electrolysis in Korea. *International Journal of Hydrogen Energy*, *42*(10), 6462–6471. https://doi.org/10.1016/j.ijhydene.2016.12.153

[8] Cheng, W. J., Li, J. J., Liu, H., & Tian, Y. (2020). Analysis of life cycle cost of coal hydrogen production chain based on two technical routes. *Coal Economic Research*, *40*(3), 4–11.

[9] Kannah, R. Y., Kavitha, S., Karthikeyan, O. P., Kumar, G., Dai-Viet, N. V., & Banu, J. R. (2021). Techno-economic assessment of various hydrogen production methods–A review. *Bioresource Technology*, *319*, 124175. https://doi.org/10.1016/j.biortech.2020.124175

[10] Zhou, D. (2021). Qīng jié qīng néng de chéng běn jìng zhēng lì [Cost competitiveness of clean hydrogen energy]. *Sino-Global Energy*, *26*(8), 71. 2021

[11] Shaner, M. R., Atwater, H. A., Lewis, N. S., & McFarland, E. W. (2016). A comparative technoeconomic analysis of renewable hydrogen production using solar energy. *Energy & Environmental Science*, *9*(7), 2354–2371. https://doi.org/10.1039/C5EE02573G

[12] Guo, X., Li, X., Xu, Z., He, G., & Miao, P. (2020). Cost analysis of hydrogen production by electrolysis of renewable energy. *Energy Storage Science and Technology*, *9*(3), 688. https://doi.org/10.19799/j.cnki.2095-4239.2020.0004

[13] Bhandari, R., & Shah, R. R. (2021). Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. *Renewable Energy*, *177*, 915–931. https://doi.org/10.1016/j.renene.2021.05.149

[14] Cetinkaya, E., Dincer, I., & Naterer, G. F. (2012). Life cycle assessment of various hydrogen production methods. *International Journal of Hydrogen Energy*, *37*(3), 2071–2080. https://doi.org/10.1016/j.ijhydene.2011.10.064

[15] Dong, J., Liu, X., Xu, X., & Zhang, S. (2016). Comparative life cycle assessment of hydrogen pathways from fossil sources in China. *International Journal of Energy Research*, *40*(15), 2105–2116. https://doi.org/10.1002/er.3586

[16] Zhu, L., Duan, H. B., & Fan, Y. (2015). CO_2 mitigation potential of CCS in China–An evaluation based on an integrated assessment model. *Journal of Cleaner Production*, *103*, 934–947. https://doi.org/10.1016/j.jclepro.2014.08.079

[17] Baykara, S. Z. (2018). Hydrogen: A brief overview on its sources, production and environmental impact. *International Journal of Hydrogen Energy*, *43*(23), 10605–10614. https://doi.org/10.1016/j.ijhydene.2018.02.022

[18] Wang, M. (2019). The Status Quo and trend of producing hydrogen from new energy. *Chemical Industry*, *36*(6), 13–18. https://doi.org/10.3969/j.issn.1673-9647.2018.06.004

[19] Bai, K., & Lu, W. (2020). Diàn jiě shuǐ zhì qīng gōng yì tàn pái fàng liàng hé suàn fāng fǎ yán jiū [Study on the accounting

method of carbon emission from electrolyzed water hydrogen production process]. *Guangdong Chemical Industry*, *47*(11), 3.

[20] Lin, T. (2018). *Fuel-cycle assessment of energy consumption and environmental benefits of hydrogen fuel cell vehicles*. Master Thesis, Tsinghua University.

[21] Al-Qahtani, A., Parkinson, B., Hellgardt, K., Shah, N., & Guillen-Gosalbez, G. (2021). Uncovering the true cost of hydrogen production routes using life cycle monetisation. *Applied Energy*, *281*, 115958. https://doi.org/10.1016/j.apenergy.2020.115958

[22] Liu, H., Chen, L., Lin, Z., Dong, H., & Gao, Y. (2023). Diàn lì tàn pái fàng jì suàn fāng fǎ yán jiū [Study on calculation methods of carbon emissions from electricity]. *Electric Power System Equipment*, *2023*(2), 24–26.

[23] Wang, Y. Z., Zhou, S., Zhou, X., & Ou, X. (2021). Zhōng guó bù tóng zhì qīng fāng shì de chéng běn fēn xī [Cost analysis of different hydrogen production methods in China]. *Energy of China*, *43*(5), 29–37. https://doi.org/10.3969/j.issn.1003-2355.2021.05.005

[24] Ouyang, X., & Lin, B. (2014). Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China. *Energy Policy*, *70*, 64–73. https://doi.org/10.1016/j.enpol.2014.03.030

[25] Pan, B. B., Chen, Z. H., Jia, N. F., Li, Y. H., & Hao, Y. (2019). Research on cost accounting of photovoltaic power generation-analysis based on LCOE method. *Price Theory and Practice*, *419*(5), 138–140.

[26] Zhang, Y., & Yuan, J. (2020). Zhōng guó fēn sàn shì fēng diàn de jīng jì xìng fēn xī yǔ zhì dù zhàng ài yán jiū [Economic analysis and institutional barriers to decentralised wind power in China]. *Journal of North China Electric Power University (Social Sciences)*, *2019*(5), 14.

[27] Xu, Y., Yang, K., & Yuan, J. (2020). China's power transition under the global 1.5° C target: Preliminary feasibility study and prospect. *Environmental Science and Pollution Research*, *27*, 15113–15129. https://doi.org/10.1007/s11356-020-08085-9

[28] Yuan, J., Na, C., Xu, Y., & Zhao, C. (2016). Feed-in tariff for onshore wind power in China. *Emerging Markets Finance and Trade*, *52*(6), 1427–1437. https://doi.org/10.1080/1540496X.2016.1152797

[29] Orhan, M. F., Dincer, I., & Naterer, G. F. (2008). Cost analysis of a thermochemical Cu–Cl pilot plant for nuclear-based hydrogen production. *International Journal of Hydrogen Energy*, *33*(21), 6006–6020. https://doi.org/10.1016/j.ijhydene.2008.05.038

[30] Xu, Y., Pei, J., Yuan, J., & Zhao, G. (2022). Concentrated solar power: Technology, economy analysis, and policy implications in China. *Environmental Science and Pollution Research*, *29*, 1324–1337. https://doi.org/10.1007/s11356-021-15779-1

[31] Fan, J. L., Yu, P., Li, K., Xu, M., & Zhang, X. (2022). A levelized cost of hydrogen (LCOH) comparison of coal-to-hydrogen with CCS and water electrolysis powered by renewable energy in China. *Energy*, *242*, 123003. https://doi.org/10.1016/j.energy.2021.123003

[32] Wang, Y., Li, G., Liu, Z., Cui, P., Zhu, Z., & Yang, S. (2019). Techno-economic analysis of biomass-to-hydrogen process in comparison with coal-to-hydrogen process. *Energy*, *185*, 1063–1075. https://doi.org/10.1016/j.energy.2019.07.119

[33] Liszka, M., Malik, T., & Manfrida, G. (2012). Energy and exergy analysis of hydrogen-oriented coal gasification with CO_2 capture. *Energy*, *45*(1), 142–150. https://doi.org/10.1016/j.energy.2012.03.054

[34] Soochow Securities. (2022). Qīng néng yuán háng yè zhuān tí yán jiū ： qīng néng yuán chǎn yè liàn fēn xī [Hydrogen energy industry thematic research: Analysis of hydrogen energy industry chain]. Retrieved from: Retrieved from: https://baijiahao.baidu.com/s?id=1720994102053247975&wfr=spider&for=pc, Retrieved from

[35] Li, G., Liu, Z., Liu, T., Shan, J., Fang, Y., & Wang, Z. (2018). Techno-economic analysis of a coal to hydrogen process based on ash agglomerating fluidized bed gasification. *Energy Conversion and Management*, *164*, 552–559. https://doi.org/10.1016/j.enconman.2018.03.035

[36] Han, W. (2020). tiān rán qì zhì qīng yǔ jiā qīng zhàn hé jiàn gài shù [Overview of natural gas to hydrogen co-location with hydrogen stations]. *Chemical Enterprise Management*, *2020*(27), 2.

[37] International Renewable Energy Agency. (2018). *Hydrogen from renewable power: Technology outlook for the energy transition*. UAE: International Renewable Energy Agency.

[38] Koj, J. C., Wulf, C., Schreiber, A., & Zapp, P. (2017). Site-dependent environmental impacts of industrial hydrogen production by alkaline water electrolysis. *Energies*, *10*(7), 860. https://doi.org/10.3390/en10070860

[39] Kuckshinrichs, W., Ketelaer, T., & Koj, J. C. (2017). Economic analysis of improved alkaline water electrolysis. *Frontiers in Energy Research*, *5*, 1. https://doi.org/10.3389/fenrg.2017.00001

[40] Yueyang Statistics Bureau. (2022). Gè zhǒng néng yuán zhé biāo zhǔn méi cān kǎo xì shù [Reference coefficient of standard coal for various energy sources]. Retrieved from: http://www.yueyang.gov.cn/tjj/22771/22774/content_1983338.html

How to Cite: Pei, J., Ding, Q., Zhang, L., & Xu, Y. (2025). The Economic-Energy-Environmental Benefits of Hydrogen Production Technologies in China. *Green and Low-Carbon Economy*. https://doi.org/10.47852/bonviewGLCE52024666

Appendix

Table A1
Nomenclature

C_{coal}	the coal consumption in the CTH process	$C_{electricity1}$	the consumption of electricity in the CTH process
C_{water1}	the consumption of industrial water in the CTH process	R_{coal}	the coal equivalent coefficient of raw coal
$R_{electricity}$	the coal equivalent coefficient of electricity	R_{water}	the coal equivalent coefficient of industrial water
C_{SMR}	the total energy consumption generated in the SMR process	C_{gas}	the natural gas consumption in the SMR process
$C_{electricity2}$	the consumption of electricity in the SMR process	$C_{deionized}$	the consumption of deionized water in the SMR process
$C_{cooling}$	the consumption of cooling water in the SMR process	R_{gas}	the coal equivalent coefficient of natural gas
$R_{electricity}$	the coal equivalent coefficient of electricity	$R_{deionized}$	the coal equivalent coefficient of deionized water
$R_{cooling}$	the coal equivalent coefficient of cooling water	$C_{coal+CCS}$	the total energy consumption generated in the process of CTH coupled with CCS
$C_{gas+CCS}$	the total energy consumption generated in the process of SMR coupled with CCS	$C_{water\,electrolysis}$	the total energy consumption generated in the WEHP process
$C_{electricity3}$	the consumption of electricity in the WEHP process	$C_{nitrogen}$	the consumption of nitrogen in the WEHP process
C_{water2}	the consumption of industrial water in the WEHP process	C_{steam}	the consumption of steam water in the WEHP process
$R_{nitrogen}$	the coal equivalent coefficient of nitrogen	R_{steam}	the coal equivalent coefficient of steam water
E_{CTH}	the total carbon emissions from CTH technology	I_{CTH}	the carbon emission intensity of CTH technology
H	the total hydrogen	E_{SMR}	the total carbon emissions from SMR technology
I_{SMR}	the carbon emission intensity of SMR technology	$E_{coal+CCS}$	the total carbon emissions from CTH coupled with CCS technology
α	the CO_2 capture rate	E_{SMR}	the total carbon emissions from SMR technology
$E_{gas+CCS}$	the total carbon emissions from SMR coupled with CCS technology	E_{CTH}	the total carbon emissions from CTH technology
E_i	the total carbon emissions of the i_{th} power source used for hydrogen production from electrolysis water	I_i	the carbon emission intensity of the i_{th} power source used for hydrogen production from electrolysis water
E_k	the electricity consumption of the k_{th} electrolytic cell		