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ORIGINAL PAPER

Life cycle analysis and power optimization of three typical hydrogen supply chains

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Abstract

With the exhaustion of traditional fossil fuels and environmental protection pressure, clean renewable energy has become a topic of high interest. At present, three hydrogen supply chains run into the mainstream, including conventional coal-based hydrogen production (CTH), methanol-to-hydrogen production (MTH) and ammonia-to-hydrogen production (ATH). In order to comprehensively understand the impact of these three hydrogen supply chains on the environment and select the cleanest hydrogen supply scheme, the hydrogen supply chains were analyzed by CML, Eco-indicator99 method and sensitivity analysis. Besides, through sensitivity analysis to understand the contribution of each phase to the environmental impact. Thus, the optimization direction is found, and beneficial enlightenment is provided for promoting and applying hydrogen energy. The results showed that the comprehensive environmental impact of ATH was much more severe, which 2.8 and 2.4 times that of the other two supply chains. In the ATH, the environmental load of ammonia production phase is the largest, while the methanol pyrolysis phase and coal gasification phase are the main load contributors to MTH and CTH. In addition, the study also found that electricity is the most sensitive parameter. When 100% clean energy is used, the environmental impact of all three supply chains is significantly reduced. Consequently, the objective of clean creation and feasible advancement of hydrogen industry can be accomplished by changing its innovation structure as well as smart utilization of clean energy for the power age.

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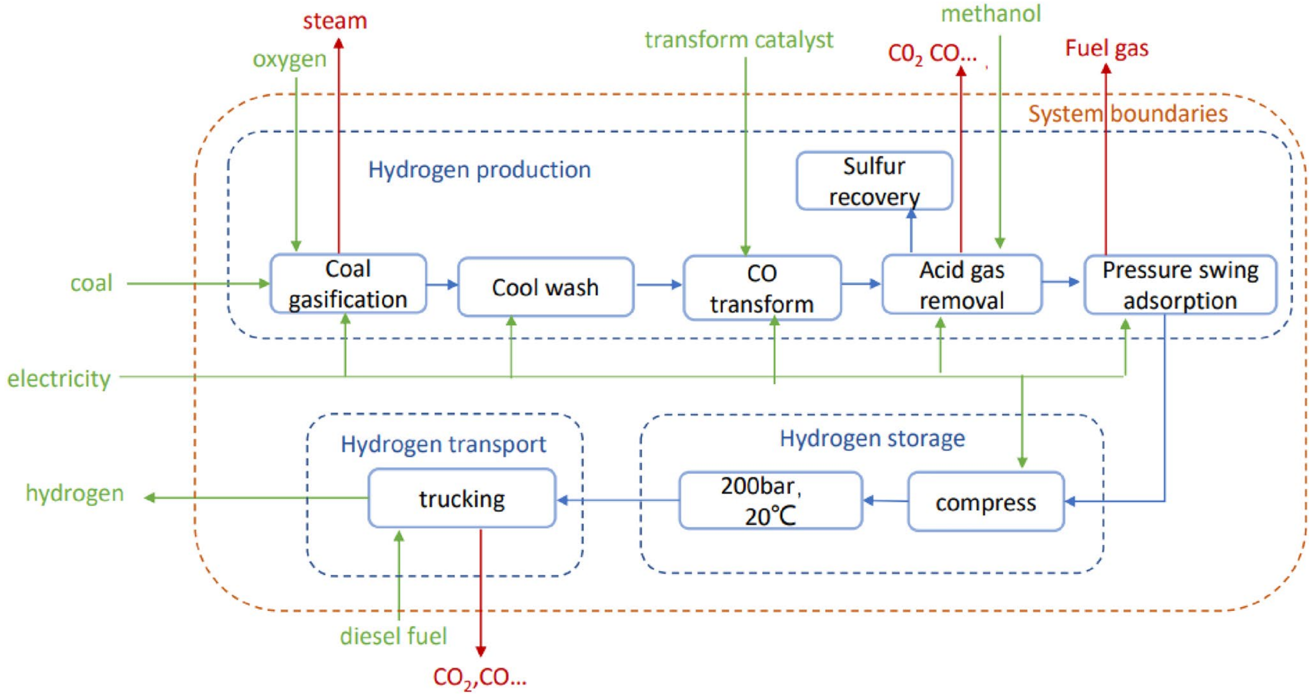
Graphical abstract

Typical hydrogen supply chain and its major environmental impact elements



Keywords Hydrogen supply chain · Life cycle assessment · Power optimization

Abbreviations

CTH	Coal-based hydrogen production
MTH	Methanol-to-hydrogen production
ATH	Ammonia-to-hydrogen production
AP	Methanol pyrolysis
CG	Coal gasification
LCI	Life cycle inventory
AP	Acidification potential
HTP	Human toxicity potential
ADP	Abiotic resource depletion potential
GWP	Global warming potential
ODP	Ozone layer depletion potential
POCP	Photochemical ozone creation potential
FWAEP	Fresh water aquatic ecotoxic potential
MAETP	Marine aquatic ecotoxicity potential
TETP	Terrestrial ecotoxicity potential
EP	Eutrophication potential
PV	Photovoltaic panel
DC	Direct current
SDGS	Sustainable development goals

Introduction

In September 2020, China put forth the objective of "carbon up to the peak" by 2030 and "carbon neutrality" by 2060 (Yang et al. 2021a). Industrial and energy structure are constantly adjusted, and renewable energy is vigorously developed. Renewable energy can not only improve environmental quality, but also bring economic benefits. Among numerous sustainable power sources, hydrogen energy has drawn wide consideration due to its high calorific worth, no environmental pollution, and abundant raw materials. Hydrogen can be directly used for combustion in internal combustion engines (Wu et al. 2021a) and can also be used as an energy carrier for fuel cells (Foorginezhad et al. 2021). In the future, zero-carbon transportation under the background of hydrogen production from renewable energy becomes possible, which is of great help to achieving carbon neutrality (Zhou et al. 2022). Countries around the world are actively preparing to build hydrogen pilot cities. For instance, South Korea intends to construct three show urban communities by 2022, where power, transportation, warming and cooling are undeniably determined by H_2 (Stangarone 2021). Europe is pushing for more innovative tasks to work on their seriousness in energy components and hydrogen innovation, and considering advancing hydrogen creation from sustainable sources. Germany, the Netherlands, Austria and Norway have put resources into huge scope electrolysis of hydrogen (Egeland-Eriksen et al. 2021; Glenk and Reichelstein 2019). Mansour Keshavarz zadeh et al. studied the adverse pollutants produced during combustion of gasoline engines fueled by a combination of methane and hydrogen. The environmental damage caused by the mixed fuel of methane and hydrogen is improved by the neural network model. (Keshavarzzadeh et al. 2023)" Japan has been pushing for a hydrogen society controlled totally by hydrogen for a long time, with the as of late finished Harumi Banner displaying a town entirely fueled by hydrogen. Toyota's Mirai and Honda's Lucidity Power device electric vehicles use hydrogen energy vehicles (Yoshizumi et al. 2021).

To meet the large-scale usage of hydrogen energy, there are emerging three typical hydrogen supply chains. Toward the finish of 2020, hydrogen production from coal delivers the biggest extent of hydrogen (62%) (Zhang 2021), which is the cheapest hydrogen supply method and equipped with the most mature technology. Methanol (CH_3OH) and Ammonia (NH_3) are the most widely used as hydrogen storage media because of their safety, high storage density and convenience in the supply chain (Mao et al. 2022). Up to now, methanol has been mainly produced by natural gas, coal, heavy oil and so on, of which natural gas to methanol accounts for more than 60% (Schorn et al. 2021). And most industrial ammonia is synthesized from nitrogen and hydrogen under high pressure, high temperature and the presence of catalyst (Yüzbaşıoğlu et al. 2021).

In the existing studies, the evaluation of the above three hydrogen supply chains mainly involved technical and economic domains. Sens (2030) assessed the economic benefits of hydrogen supply chains, which turns out that methanol is a lower cost alternative compared with ammonia and liquid organic hydrogen carrier. Fan et al. (2022) studied the equilibrium cost of hydrogen (LCOH) model, and the results demonstrated that the cost of hydrogen production from traditional coal (7.2–10.1 yuan /kg) was 57.6–129.3% lower than that of green hydrogen production. Schorn et al. (2021) compared the import costs of methanol and hydrogen based on the cost function and production model. It was found that methanol had a lower transport cost than hydrogen and could offset the additional cost of upgrading hydrogen to methanol. Ratnakar (2021) conducted an economic and efficiency evaluation of the hydrogen supply chains. The result revealed that when hydrogen is stored in the form of liquid organic matter such as ammonia or methanol, it has higher storage density and storage performance at relatively low cost, and it can be easily transported and used directly as fuel. Ding et al. (2022) indicated that methanol steam reforming hydrogen production using 6% NiO/NaF had the best hydrogen production performance, and methanol conversion rate could reach 94%. Other authors evaluated the synthesis efficiency of ammonia in the presence of Cobalt (Ronduda 2022), Mo (Fang et al. 2022) and Ru (Nishi et al. 2022) catalyst and the decomposition of ammonia under the effect of Co/NC (Li et al. 2022a), Ni/CeO_2 (Chen 2022) and $C_{O3}O_4$ (Li et al. 2022b) catalyst.

On the environmental domain, the few evaluation on the three hydrogen supply chains is mutilated, which could not conduct a comparison of different hydrogen supply chains. Sutar and Jadhav (2022) carried out an environmental impact assessment of methanol production from natural gas and found that the distillation and synthesis components were the main factors causing ecological and human toxicity. The carbon footprint (8.59–16.61CO_2eq/kg) from coal to hydrogen can be reduced by 52.34–74.59% through CO_2 capture and storage technology, but the cost will be increased by 44.59–60.84% to $1.44–2.11 kg H_2 (Li et al. 2022c). Dilshani (et al. 2022) found that in the ammonia production stage, the global warming effect caused by different catalysts was 88,036.61 ~ 125,830.55 (kgCO_2/FU) and 52,774.97 ~ 60,364.31 (kgCO_2/FU) in the hydrogen production stage. What's more, so far, we yet cannot find any efforts for comprehensive comparison on the three mainstream hydrogen supply chains from the perspective of life cycle assessment. As the world's largest hydrogen producer and consumer, it is urgent for China to conduct research on hydrogen supply.

Life cycle assessment is considered a powerful tool for quantifying the basic inputs and outputs of a product-specific system. It can assess the footprint associated with a particular product for meaningful comparisons. Since the "top-down" principle is used to analyze and design the system, this method solves the global problem first and emphasizes the consideration of specific solutions under the premise of the overall optimization of the system, which indicates its better integrity and strong systematic pertinence. In addition, multiple life cycle stages and contain various types of environmental impact assessment indicators can be covered to avoid the transfer of environmental problems between these types of impacts. It can provide environmental data support for various technical, management or policy decisions in accordance with the unified international standard (ISO14040 series), equivalent to the national standard (GB24040 series) (Larsen et al. 2022).

LCA is a common way to assess the environmental impact of a system because it has a comprehensive system view from cradle to grave and is often used in energy systems to effectively address environmental issues. Rahim Zahedi et al. studied two different processes that directly absorb carbon dioxide from the air using the life cycle assessment (LCA) method, which compensates for the environmental impact assessment that direct air carbon dioxide capture (DAC) lacks in terms of global warming (Zahedi et al. 2022a). Mohammadreza Khalili Tari et al. simulated energy consumption in buildings through LCA and considered different scenarios to optimize energy consumption and reduce environmental impact, and conducted life cycle assessments of different schemes. The result was an optimal solution: adding 30% M20 concrete by volume reduced the environmental impact by nearly 28%. (Khalili Tari et al. 2023) Zahedi et al. used the life cycle assessment method to evaluate and compare the environmental impacts of different solar cell generations in terms of resources, ecology and human health. The results show that perovskite panels have less environmental impact than polycrystalline panels and cadmium telluride panels, so they should be widely developed and applied (Zahedi et al. 2022b)."

The aim of this work is to evaluate and compare three typical hydrogen supply chains (CTH, MTH and ATH) in China from the perspective of life cycle assessment. Firstly, the environmental performance of hydrogen supply process was analyzed by integrating human health, ecosystem quality and resource indicators. Secondly the relative contribution of each phase to each type of environmental impact was calculated and compared at the same time. Finally, through sensitivity analysis, the contribution degree of each phase to the environmental impact was understood and a variety of optimization schemes were provided. Through modeling and simulation, the optimization degree of different schemes was obtained and compared.

LCA of three routes provided direction and beneficial enlightenment for the future optimization of hydrogen supply chain in environmental aspects. Simultaneously, it assisted undertakings with deciding the heading of innovation opening and strategy creators to pick hydrogen supply chain with better natural execution.

Methodology

As indicated by ISO (ISO, 2006a, b), the LCA study is generally per-shaped as four phases: (1) Goal and scope definition; (2) LCI creation; (3) Life cycle influence evaluation; (4) Interpretation of results.

Goal and scope definition of CTH, MTH and ATH

This study aims to look at the thorough environmental effects of three commonplace hydrogen supply chains (CTH, MTH and ATH). A 1000 m^3 hydrogen supply was selected as the functional unit in this study. The boundary of life cycle assessment is defined as "from cradle to gate", that is, the scope focuses on production, transportation, storage and the conversion of medium to hydrogen. This paper does not cover the application of hydrogen and waste treatment work, because the post-gate phase should be the same in all supply chains involved. In addition, all infrastructure and environmental impacts during the period of facilities will not be considered in the project. The process flowchart is drawn based on the executive reports of representative companies in the hydrogen industry chain. The system boundaries of the three hydrogen supply chains (CTH, MTH and ATH) are shown in Figs. 1, 2 and 3, respectively.

Coal-to-Hydrogen supply chain

As shown in Fig. 1, there were three parts that consisted in the CTH supply chain: hydrogen production, hydrogen storage and transportation. Hydrogen production phase adopts the most widely used domestic CG process. Coal or coal coke is first reacted with pure oxygen and vapor to obtain coal gas with H_2 and CO as the main components. Hydrogen of a certain purity is obtained through the production process of gas purification, CO conversion and H_2 purification. In the storage phase, high-pressure gaseous hydrogen storage technology (200 bar, 20 °C) is adopted, which is the main hydrogen storage technology currently applied. Since hydrogen high-pressure storage tanks can be reused for a long time, the energy consumption of this part is basically ignored. Therefore, the energy consumption in the storage phase only includes the energy consumption of compression for pressurized hydrogen. A light diesel truck is used in the hydrogen transportation phase. (S1: hydrogen production from CG, S2: hydrogen storage, S3: hydrogen transportation).

Methanol-to-Hydrogen supply chain

The supply chain of MTH includes four parts: methanol production, storage, transportation and methanol transition to the hydrogen phase. The supply chain of methanol from petroleum gas incorporates two primary phases, to be specific flammable gas extraction and handling, and the whole methanol creation (counting steam changing and syngas creation phases). As shown in Fig. 2, after desulfurizing of acidic gases, for example, SO_2, H_2S and drying out, petroleum gas is switched over entirely to syngas through steam improving interaction, in which the H/C proportion is acclimated to around 3.0. The syngas is then compacted and taken care of into a combination reactor to deliver methanol. At long last, within sight of impetuses, clean syngas is combined into rough methanol, which is then corrected in a refining unit to deliver refined methanol. Methanol can be stored in plastic or metal tanks at room temperature and pressure (1 bar, 20 °C). The transportation phase also adopts the light diesel truck transportation mode. Methanol transition to hydrogen phase includes two main phases, namely MP and pressure swing adsorption. Methanol and water fume go through the impetus at a specific temperature and tension. Under the activity of the impetus, MP response and

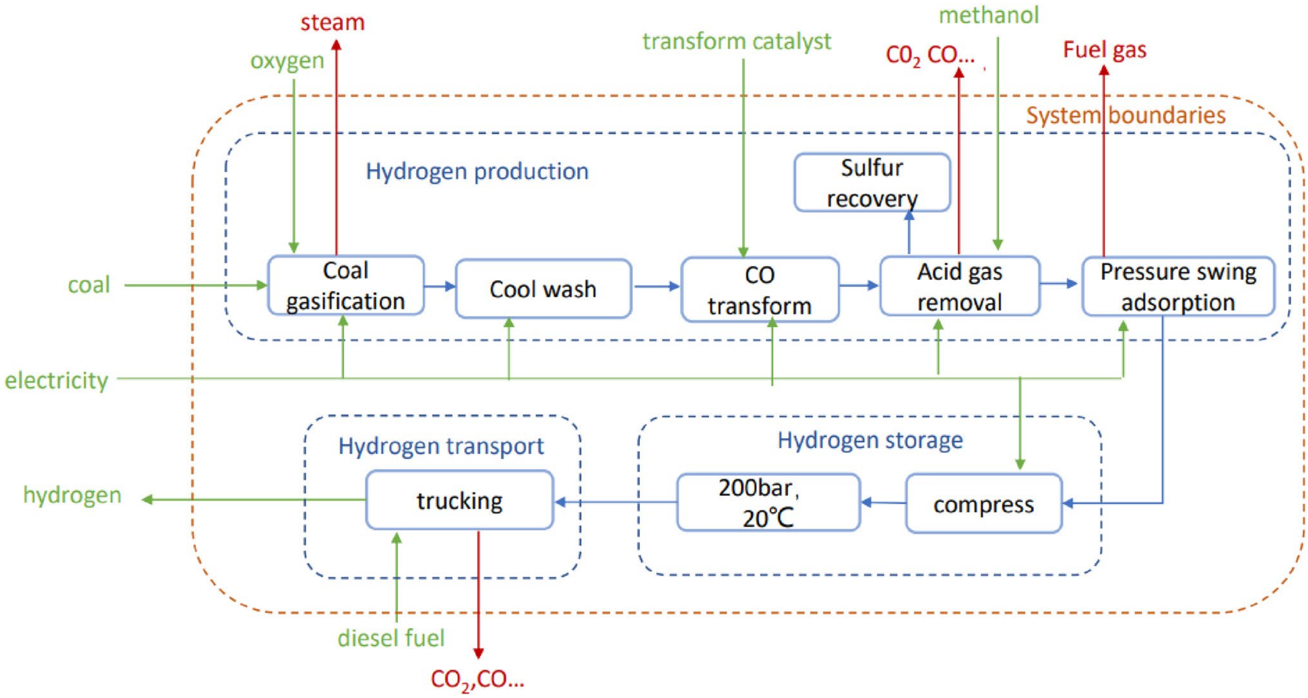


Fig. 1 Process flow of CTH supply chain

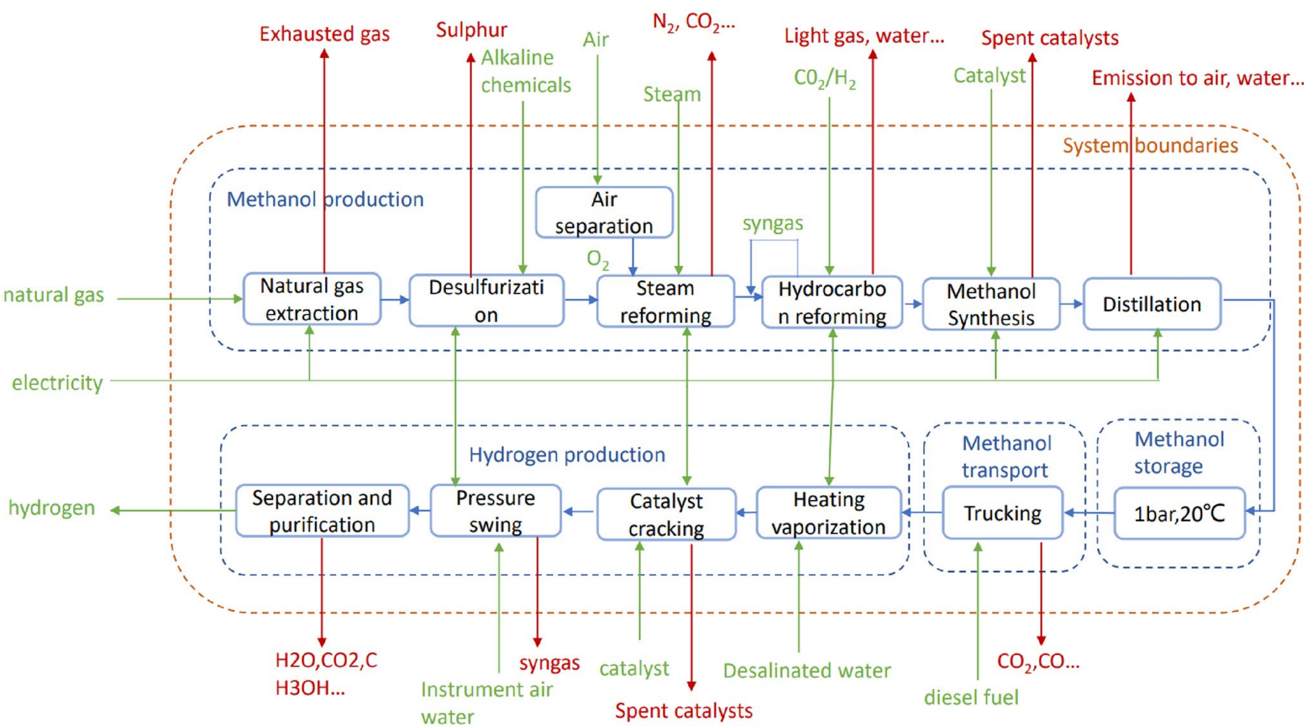


Fig. 2 Process flow of MTH supply chain

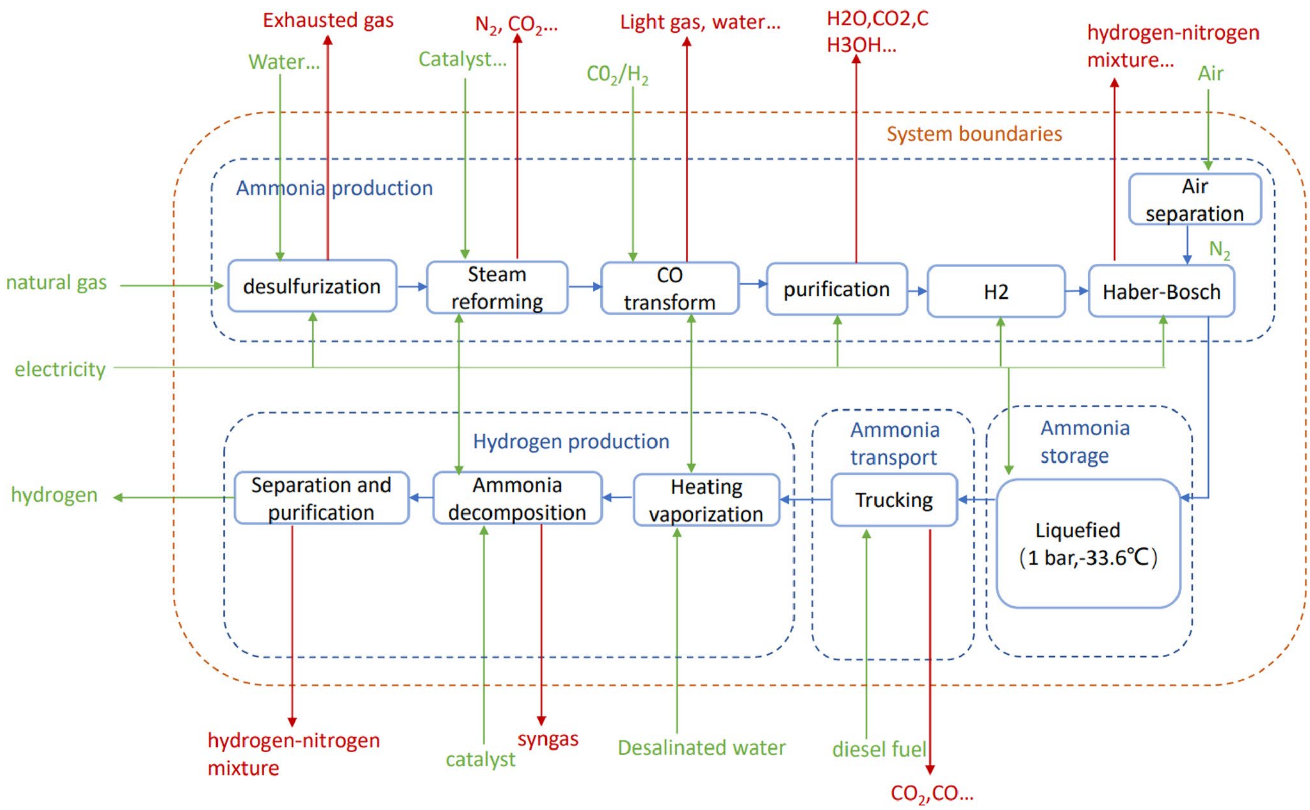


Fig. 3 Process flow of ATH supply chain

carbon monoxide change response happen, and hydrogen and carbon dioxide are created. After cooling, it is purified in a pressure swing adsorption unit, resulting in 99.995% hydrogen. (S1: natural gas processing + methanol production, S2: methanol storage, S3: methanol transportation, S4: MP).

Ammonia-to-Hydrogen supply chain

The ATH supply chain consists of four parts: ammonia production, storage, transportation and ammonia transition to hydrogen. The production of ammonia gas adopts the industrial ammonia synthesis method, which refers to the ammonia produced by the immediate blend of hydrogen and nitrogen under the activity of high tension, high temperature and impetus. Currently, most of the world's ammonia is produced by synthesis, except for a couple of results recuperated from coke broiler gas. Nitrogen, by and large, comes from the air. Hydrogen creation unrefined substances are flammable gas, naphtha, and so on. Ammonia gas is synthesized by the Haber–Bosch technique (pressurized to 32 MPa of nitrogen, hydrogen mixture, sent to the synthesis tower within the range of ~ 500 °C, through the catalyst action, synthesis reaction) after desulfurization, CO transformation, and refining. Low-temperature liquid ammonia storage (1 bar, − 33.6 °C) is used for ammonia storage. Similar to CTH, the energy consumption of tank production is basically ignored. Therefore, the energy consumption in the storage phase only includes the energy consumption of refrigeration to maintain the storage temperature of liquid ammonia. A light diesel truck is used in the ammonia transportation phase. In the presence of a catalyst, ammonia breaks down to produce a mixture of hydrogen (75%) and nitrogen (25%). The gas passes through the heat exchanger and cooler and is purified by a molecular sieve adsorption purifier to obtain high purity hydrogen. (S1: hydrogen production from natural gas + ammonia synthesis, S2: ammonia storage, S3: ammonia transportation, S4: hydrogen production from AD).

Life cycle inventory and data sources

For the cycle phases explored, all info and result data for a specific interaction, like unrefined substance utilization, energy and direct emanations, were gathered. Table 1 summarizes data sources at each phase of the life cycle of the three hydrogen storage phases. The life cycle of hydrogen storage phases for hydrogen, methanol and ammonia gas is detailed in Tables 2, 3 and 4. The data of all phases are from the existing literature. Background Data were

Table 1 Data sources

Supply chain	Phase	Data sources	Related literature
CTH	Produce	Cheng, National Energy Group (2020), Chinese Academy of Engineering (2015)	Li and Cheng 2020; B.L.C.C.E.R.I. 2020; E.C.r.I. 2015)
	Storage	Wang	YueGu 2019)
	Transport	China Transport And Transportation Yearbook (2018)	China Transportation Yearbook 2018)
MTH	Produce	National Bureau of Statistics of China (2017), Chen	China Statistical Yearbook 2017; Chen et al. 2019)
	Storage	Chen	Chen et al. 2021)
	Transport	China Transport and Transportation Yearbook (2018)	China Transportation Yearbook China 2018)
	To hydrogen	Li, Wu	Huabo and Kang Jin Tengxiang 2021; Wu et al. 2021b)
ATH	Produce	Xie, Burmistrz, Gao	Xie Xinshuo and Wei 2018; Burmistrz et al. 2016; Chisalita et al. 2020)
	Storage	Wang	YueGu 2019)
	Transport	China Transport and Transportation Yearbook (2018)	China Transportation Yearbook 2018)
	To hydrogen	Chen	Yisong et al. 2019)

Table 2 LCI of MTH

Inputs	Values	Units	Outputs	Values	Units
Natural gas processing					
Hard coal	26.5384	kg	CO_2	85.68	kg
Oil	6.7032	kg	CH_4	3.0464	kg
Iron	0.028	kg	NO_X	0.2688	kg
Natural gas	345.52	Nm^3	SO_X	0.2184	kg
Fuel natural gas	11.2616	kg	CO	0.0241	kg
			PM	0.014	kg
			Natural gas	345.52	Nm^3
Methanol production					
Natural gas	345.52	Nm^3	Methanol	0.56	t
Electricity	322.784	kwh			
Oxygen	79.52	Nm^3			
Desalinated water	2.016	t			
Fresh water	6.16	t			
Sodium Hydroxide	0.112	kg			
Trisodium phosphate	0.084	kg			
Hydrogen production					
Methanol	0.56	t	H_2	1000	Nm^3
desalinated water	0.32	t	CO_2	614.47	kg
diesel fuel	0.125	t	CO	33.79	kg
Circulating water	40	t	CH_3OH	< 100	PPM
Instrument air	100	m^3			
Electricity	90	kwh			
Steam	0.02	t			

obtained from Ecoinvent 3 database. Regarding material and energy streams, China's limited information is needed. There is no such thing as a worldwide normal in the event that the information is utilized.

Life cycle impacts assessment (LCIA) methods

The mid-point impact assessment method

The mid-point method defines the index of a medium point in the influence path, and pays attention to environmental influence factors and mechanisms. In addition, the data of various environmental impact factors can be standardized after equivalent factor conversion, and the related indexes of different environmental impact types can be calculated. There are ten main types of CML methods: AP, ADP, GWP, POCP, TETP, MAETP, EP, HTP, ODP, FAETP.

The end-point impact assessment method

Due to installation inconsistencies, environmental impacts of multiple manufacturing phases can only be compared according to certain environmental categories from the perspective of midpoint influence evaluation. Subsequently, a thorough and quantitative natural effect level is required. Impact assessment was performed from the end point of hydrogen production of 1000 Nm^3. Eco-indicator99 method is PRe company's development of Eco-Indicator95 method (Sutar and Jadhav 2022). This strategy depends on the rule of natural harm to complete ecological effect appraisal on the item life cycle. The environmental impact can be divided into three aspects: Resource, Human Health and Ecosystem Quality. The main evaluation categories and corresponding weight coefficients are shown in Table 5. The method includes the process of classification, characterization, standardization and weighting.

Table 3 LCI of CTH

Inputs	Values	Units	Outputs	Values	Units
Hard coal	682.516	kg	CO2	1468.092	kg
Oxygen	327.913	Nm^3	NOX	2.6254	kg
Natural gas	27.86	kg	SOX	1.7941	kg
Electricity	94.481	kwh	Methane	3.563	kg
Caustic soda	0.7944	kg	NMHC	0.241	kg
hydrochloric acid	0.1541	kg	PM	0.6876	kg
Methanol	0.4194	kg	H_2	1000	Nm^3
Fresh water	11.438	kg			
Transform catalyst	0.0000638	kg			
High pressure boiler feed water	844.566	kg			
Medium pressure boiler feed water	96.467	kg			
Low pressure boiler feed water	189.122	kg			

Table 4 LCI of ATH

Inputs	Values	Units	Outputs	Values	Units
Natural gas to hydrogen					
Hard coal	26.863	kg	H_2	168.738	kg
Natural gas	857.175	m^3	CO_2	533.309	kg
Petroleum	2.767	kg	CO	0.251	kg
Water	3341.012	kg	NO_X	0.6177	kg
Limestone	2.7	kg	SO_2	0.1445	kg
Iron ore	1.738	kg	CH_3OH	1.9539	kg
Iron scrap	1.89	kg	VOC	0.0189	kg
			PM	0.0594	kg
Haber–Bosch					
H_2	168.738	kg	Ammonia	600	kg
N_2	548.802	kg			
Electricity	62.49	kwh			
Water	240.426	kg			

Results

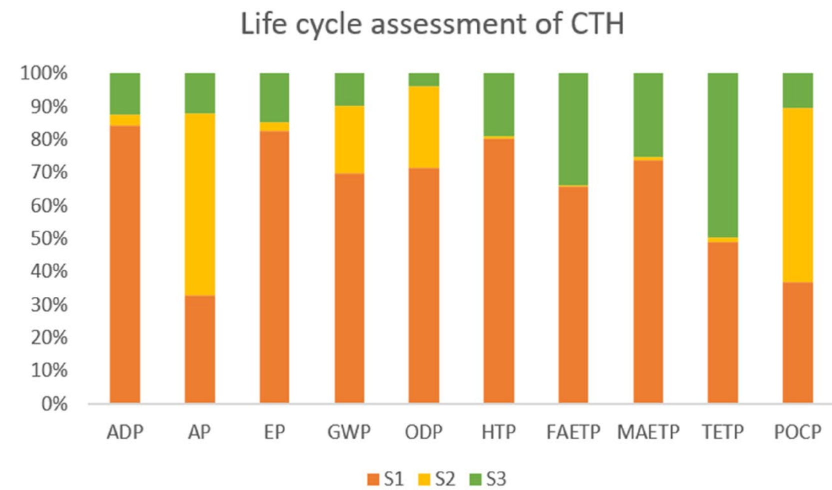
The comparison of typical hydrogen supply chains based on mid-point impacts

The total value of each environmental impact category is set as 100%, and the relative contribution of each phase to each environmental impact type can be obtained by analyzing the proportion of each phase in the life cycle of each impact type. The characteristic results of the life-cycle environmental impacts of CTH, MTH and ATH calculated based on CML are shown in Fig. 4. For ATH, the environmental impact of categories other than POCP is the greatest. As for MTH, it has the least influence except the POCP index. The influence ratios of CTH/MTH and CTH/ATH were generally in the range of 0.4–1.8 and 0.2–1.2. In terms of CTH, in the ADP category, CG has the highest consumption of fossil resources (84.1%) due to the large consumption of raw coal and the intense usage of power and steam during desulfurization and vaporization, followed by hydrogen storage (12.4%) and hydrogen transportation (3.47%). However, in the EP, FAETP,

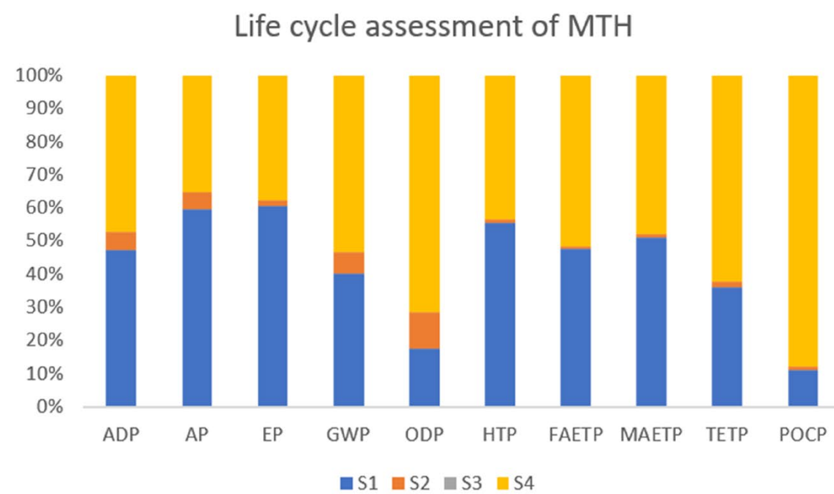
Table 5 Impact categories in Eco-indicator 99

The type of damage	Normalization factor	weight	Impact category	unit
Human health	113E-2	300	Carcinogen	DALY[a]
			Atmospheric organic pollutants	DALY
			Atmospheric inorganic pollutants	DALY
			Climatic change	DALY
			Radiation	DALY
			Destruction of the ozone layer	DALY
Ecosystem quality	1.748E-4	500	Ecotoxicity	PAF*m^2yr[b]
			Acidification/eutrophication	PDF*m^2yr[c]
Resource	1.788E-4	200	Mineral resource consumption	MJ surplus[d]
			Fossil fuel consumption	MJ surplus

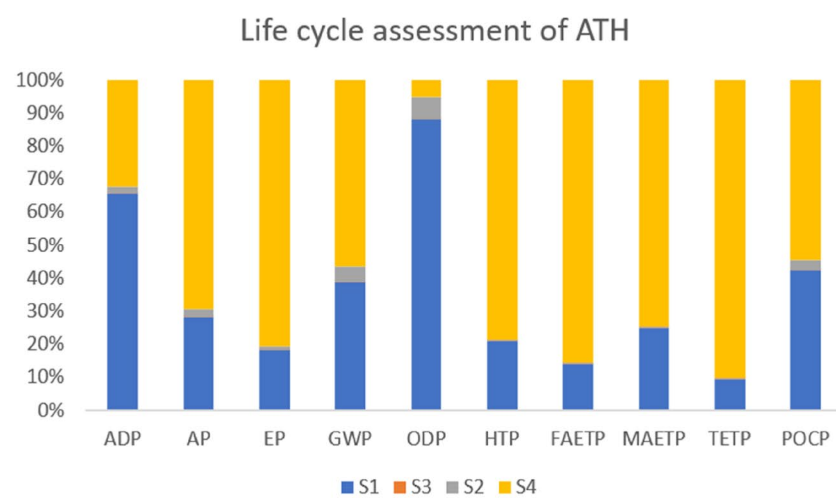
Fig. 4 Commitment of sub-phases to the LCIA of three ordinary hydrogen supply chains



(a) sub-phases to the LCIA of CTH



(b) sub-phases to the LCIA of MTH



(c) sub-phases to the LCIA of ATH

MAETP, TETP, GWP and HTP categories, over half of the ecological effect comes from the hydrogen production phase. In the AP and POCP categories, about 50 percent of the environmental impact is attributable to hydrogen transportation due to acidic gases such as sulfur dioxide in vehicle exhaust from the combustion of diesel fuel during transportation. For MTH, except for AP and EP, MP phase accounted for about 50% of the environmental impact. The reason is that the catalyst used for catalytic cracking methanol at this phase is mainly made of copper, zinc, aluminum and other metal oxides, and requires pyrolysis adsorption reaction under high temperature and high pressure. For ATH, except FOR ADP and ODP, more than 50% of other categories' environmental impacts are from the AD's hydrogen production phase. The environmental impact of hydrogen production from steam reforming of natural gas is mainly reflected in ADP and ODP, accounting for 63.5 and 83.2%, respectively.

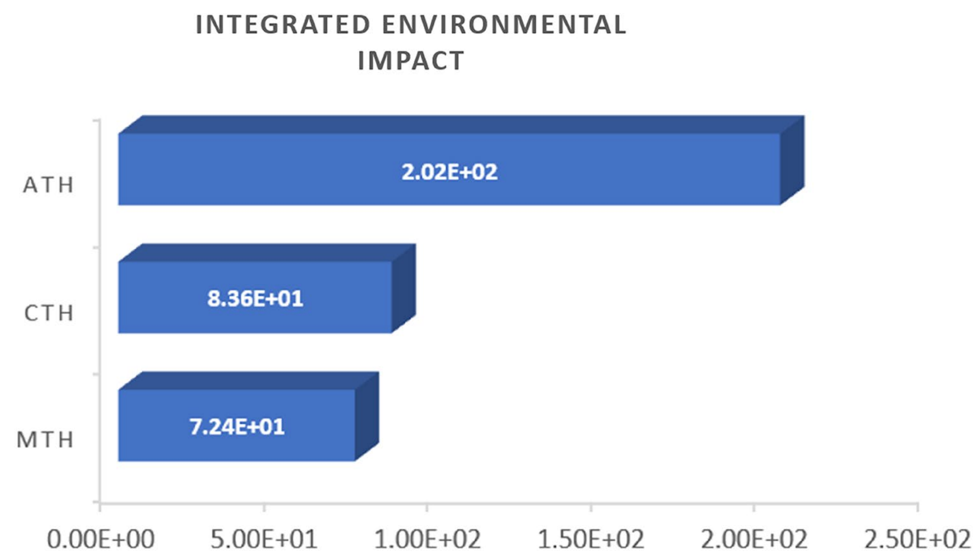


Fig. 5 The Total environmental impact of the three typical hydrogen supply chains

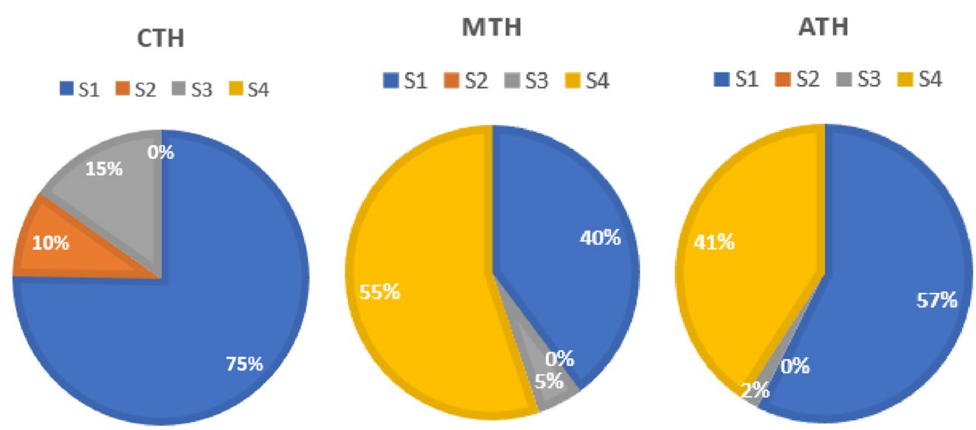


Fig. 6 Phased impact of three typical hydrogen supply chains, (a)

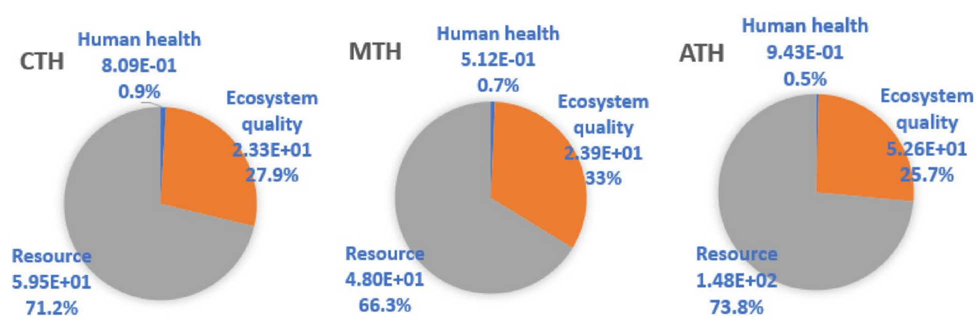
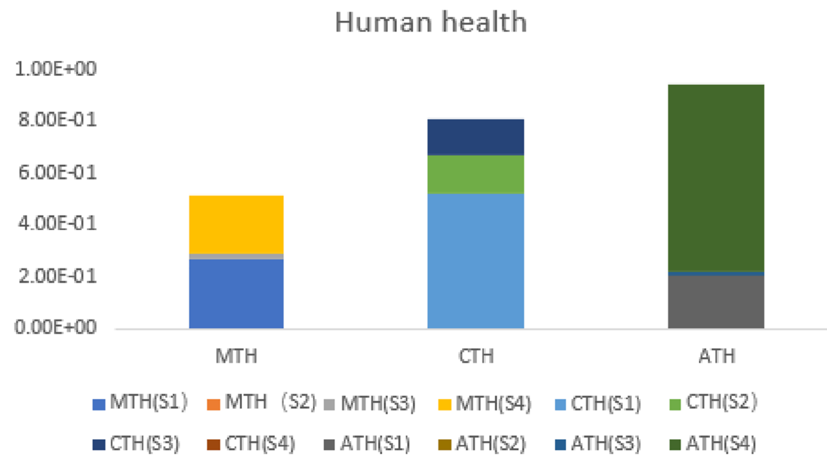
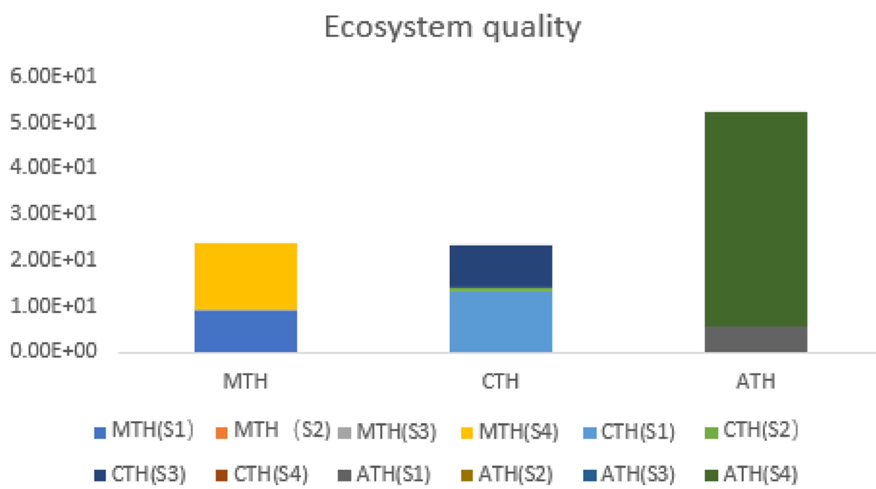


Fig. 7 The distribution of three environmental categories influence under CTH/MTH/ATH

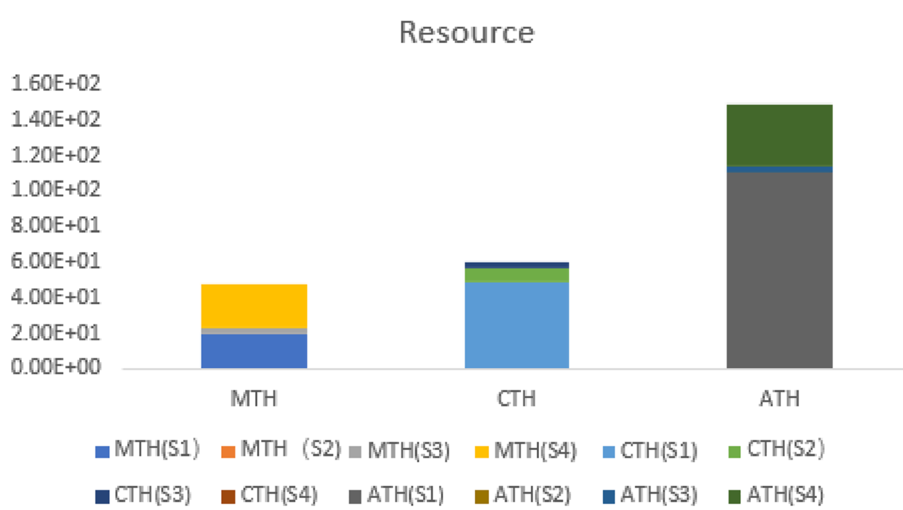
Fig. 8 Comparison of three typical hydrogen supply chains under human health/ecosystem quality/resource category



(a) Three routes’ impact in term of human health



(b) Three routes’ impact in term of ecoosystem quality



(c) Three routes’ impact in term of resource

The comparison based on end-point impact categories

The weighted results of three hydrogen storage phases under the eco-Indicator99 method (Figs. 5, 6, 7 and 8) were calculated according to the characteristic results, normalized factors and weight multiple lines, and the final environmental impact level value was obtained. It is worth noting that there is currently no widely accepted method for incorporating land use impacts into LCA studies (Commission 2021). The comprehensive influence value of ATH was the largest, almost 3 times that of MTH and 2.4 times that of CTH. The combined impact of the CTH was the second largest, 1.2 times the value of the MTH. Therefore, MTH is clearly the cleanest supply chain.

As shown in Figs. 6 and 7, the three hydrogen storage phases have the greatest impact on resource damage, which are 66.3, 71.2 and 73.8%, respectively. Fossil fuel resources account for more than 95% of the resource impact rate. However, the resource ratios of ATH/MTH and ATH/CTH are 3.1 and 2.5, respectively, which are much higher than those of other supply chains, indicating that the resource damage of CTH is much more serious than that of the other two.

For an in-depth understanding of the contributions of different sub-phases, 55% of the share in the MTH comes from the MP phase and more than 29.9% from methanol production. For CTH and ATH, the contribution to the overall impact mainly comes from the phase of hydrogen production from CG and hydrogen production from natural gas, accounting for 75 and 57%, respectively. Coal is still the primary raw material for hydrogen production because China's energy structure is more coal, less oil and less gas. In order to reduce the damage to resources at this phase, it is necessary to improve the coal conversion rate. Therefore, the CG phase assumes the main part in the ecological cordiality of the whole CTH supply chain. The evaluation results of Eco-indicator99 method place greater emphasis on the final destruction facing the "end point".

As shown in Fig. 8, the resource impact of CTH mainly comes from the production process of CG, because a large amount of coal is invested in this phase as the raw material for hydrogen production. However, the "resource" influence of MTH and ATH mainly mostly from methanol cracking to produce hydrogen and reform natural gas to hydrogen. Due to the high power consumption in the hydrogen production phase, thermal power generation is the main way of power generation in China, that is, coal and oil burning to generate electricity, so the resource consumption is large. In terms of human health, CTH and HAS are 0.8 and 0.9, respectively, while MTH's impact on human health is only 0.5, almost half of that of CTH and HAS.

If we pay attention to the impact on ecosystem quality, it can be found that the impact of MTH and CTH supply chains is about 23, while the impact of HAS on ecosystem quality is as high as 52.6, which is almost twice that of the other two supply chains. What is more noteworthy is that the ecological toxicity accounts for 49.2. The hydrogen production phase of ammonia gas accounts for about 90% of ATH, which is due to the use of nickel, manganese and other metal catalysts in the process of AD, and the high power consumption of ammonia gas at the phase of 800℃-1000℃ heating under atmospheric pressure.

Sensitivity analysis

Sensitivity analysis was directed to uncover the key elements affecting the assessment results. The information for material and energy boundaries was changed by ± 10% to decide the effect level. The parameters with the top 8 sensitivity of each supply chain were selected for analysis. If ADP, AP, HTP, and GWP are taken as average classifications, the outcomes are shown in Figs. 9, 10 and 11.

As shown in Fig. 9, the situation of MTH clearly shows that the electricity consumed in the process of reforming natural gas to methanol is the most sensitive parameter, and its sensitivity reaches ± 3.61, ± 2.12 and ± 4.17% in the influence category of AP, GWP and HTP, respectively. For the ADP category, diesel in MP is the most important factor for hydrogen production, while power utilization is the second sensitive parameter.

In terms of CTH in Fig. 10, hard coal as raw material is the main sensitive parameter affecting the category of ADP, AP, GWP and HTP, with a sensitivity range of ± 7.39, ± 1.24, ± 1.14 and ± 7.52%. Especially in ADP and HTP, it is far more than other parameters. It is worth noting that the sensitivity of AP and GWP is comparable to that of electricity used to compress hydrogen in the hydrogen storage process, because GWP and AP are greatly affected by greenhouse gases and acidic gases emitted during the thermal generation of most of China's electricity.

For the ATH in Fig. 11, the situation is similar to that of the MTH. Due to the high temperature and high-pressure requirements of AD and low ammonia conversion rate, electricity is the most sensitive parameter in the influence category of AP, GWP and HTP, with a sensitivity range of ± 6.8, ± 5.64 and ± 7.84%. In the ADP category, electricity as the second sensitive factor is ± 2.95% lower than natural gas. Therefore, according to the sensitivity analysis point of view, power, as a significant parameter of the three customary hydrogen supply chains, is the main sensitive factor influencing the ecological effect results.

* A _1 indicates the parameter A in S1 phase, and B _ 1 _1 denotes the parameter B in the first phase of S1 phase. For example, Electricity_1_2 refers to the Electricity in methanol production.

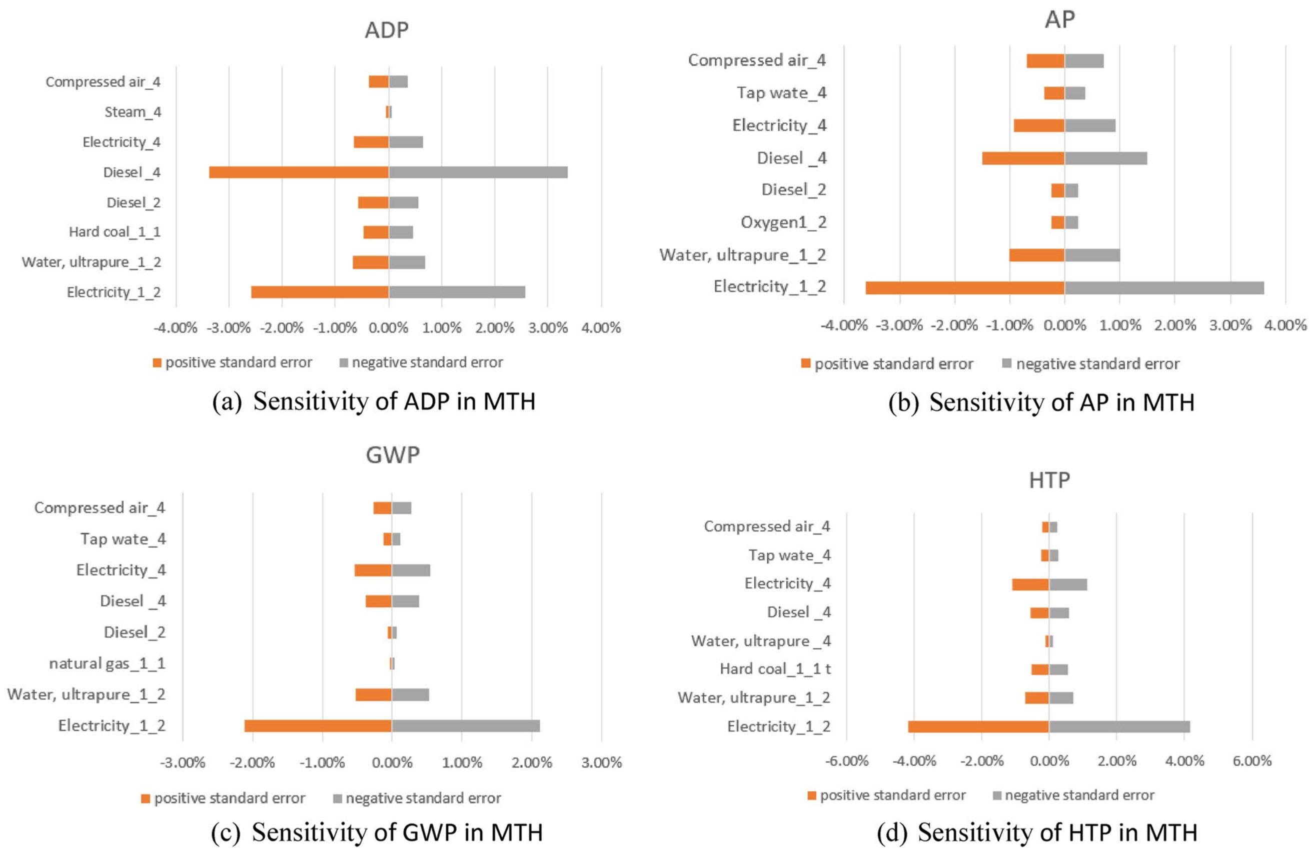


Fig. 9 Sensitivity result of MTH input parameters

* A _1 indicates the parameter A in S1 phase. For example, Hard coal_1 represents the Hard coal_1 in hydrogen production.

* A _1 indicates the parameter A in S1 phase, and B _ 1 _1 denotes the parameter B in the first phase of S1 phase. For example, Natural gas_1_1 represents the Natural gas in the Synthetic ammonia phase.

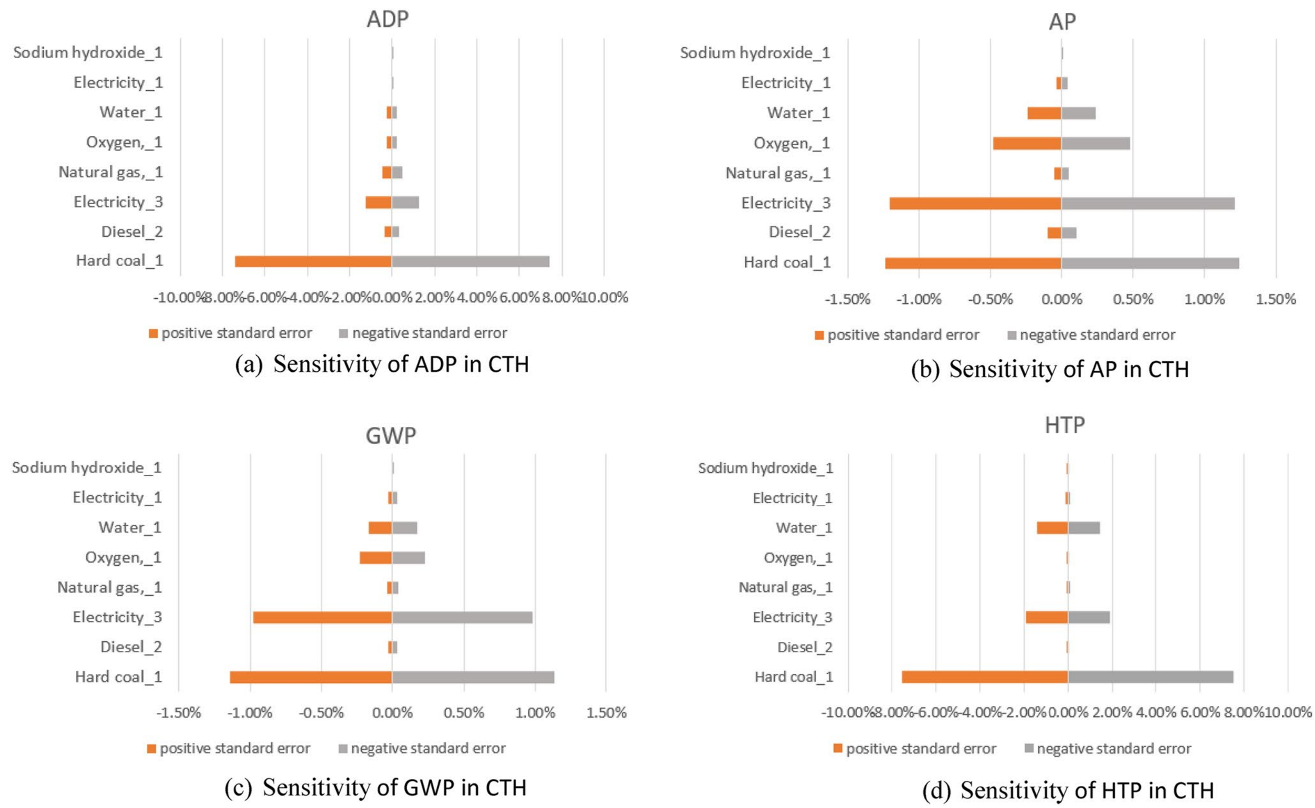
Discussion

Through clean energy optimization to mitigate the potential environmental impacts

At present, the evaluation of electricity input is mainly based on coal power, because coal combustion is still the main way to generate electricity in the short term. It is thought that as costs decrease, the share of clean energy power will be almost equal, or even higher than coal power for a long time (Li and Cheng 2020). With the increase in power generation, the electricity of the three hydrogen supply chains is optimized respectively, namely, the traditional hybrid electricity is replaced by wind power, hydropower and photovoltaic power, respectively.

In an ideal world, the mitigation potential would be clear if all electricity came from specific renewable sources. As shown in Fig. 12, the comprehensive environmental impact of the three hydrogen supply chains has a significant downward trend due to power optimization. Among them, hydroelectric power generation has the most significant optimization effect, followed by wind power generation, and photovoltaic power generation has the least optimization effect. This result is due in large part to the emission of large amounts of silicon tetrachloride and other gases, such as CO_2, and SO_2, during the production of photovoltaic panel panels, which will have a profound impact on human health.

Energy-intensive concerns are an important reason that the combined environmental impact of ATH and CTH is higher than that of MTH. For ATH, the ammonia gasification process requires 800 to 1000 °C, resulting in a large amount of electricity consumption. For CTH, the pressurization process before hydrogen storage also requires electricity. As can be seen from Fig. 13, the use of clean energy (in this case wind power, hydropower and photovoltaic) can significantly reduce its comprehensive environmental impact.



(a) Sensitivity of ADP in CTH

(b) Sensitivity of AP in CTH

(c) Sensitivity of GWP in CTH

(d) Sensitivity of HTP in CTH

Fig. 10 Sensitivity result of CTH input parameters

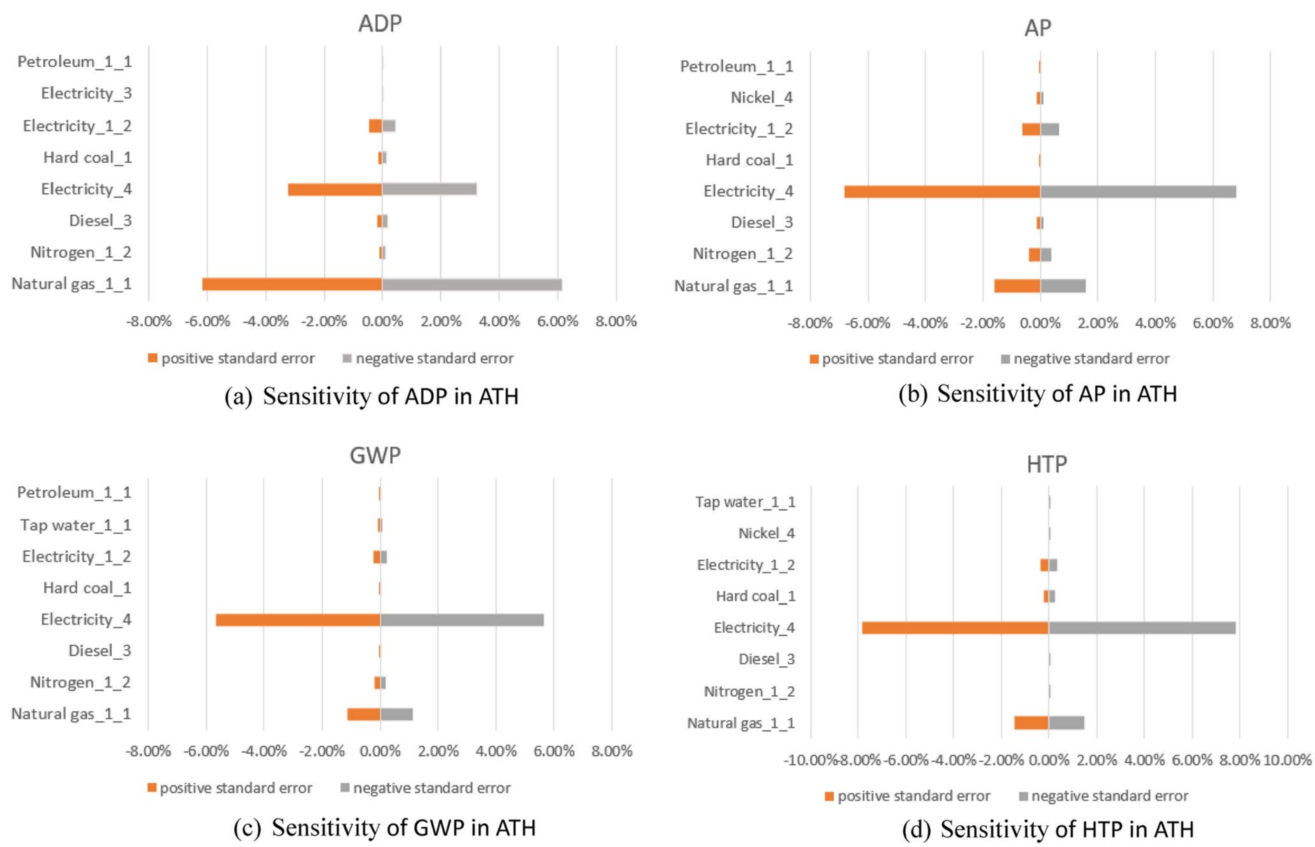
The necessity of environmental optimization in term of human health

The human health impact of CTH and ATH is 0.8 and 0.9, which is almost twice that of MTH, due to the electricity consumption of CTH and ATH during the transport phase. Therefore, the author uses wind power, hydropower and photovoltaic power generation instead of traditional thermal power generation to re-establish the hydrogen energy supply chain model. The results are shown in Fig. 13, and it is worth noting that photovoltaic and wind power have significant optimization effects in terms of human health. The human health impact values of the three supply chains were reduced by 17.4, 41.32, 75.84% and 18.36, 43.01, 79.10%, respectively.

The necessity of environmental optimization in term of eco-environmental quality

It is worth noting that using hydropower optimization in the MTH path leads to a small increase in its impact on "eco-environmental quality". The reason is that water quality and sediment, biodiversity, water resources, aquatic life and other problems generated in the development of hydropower will have a certain impact on the ecology. At the same time, the consumption of electricity in the MTH supply chain is the least, which makes the positive impact of hydropower on ecology difficult to cover its negative impact. When photovoltaic power generation is used instead of hybrid electricity, the overall optimization effect is also very significant. Among them, "ecosystem" has the largest reduction, with the reduction rates of the three hydrogen supply chains being 44.01, 27.47, and 91.49%, respectively.

The impact of CTH and MTH on the ecosystem is about 23, while the impact of ATH on the ecosystem is as high as 52.6, which is almost twice that of the other two supply chains. As can be seen from Fig. 8, 89.1% of the ecological impact in ATH comes from the S4 stage, which consumes a lot of electricity for heating, and because the experiment is based on the actual situation in China, thermal power generation is selected. The author re-established the hydrogen supply chain model by replacing traditional thermal power generation with wind power, hydropower and photovoltaic power generation. As shown in Fig. 13, ATH has the highest ecological impact reduction under the three clean energy sources. The ecological quality impact of ATH was reduced by 60.32% when modeling with wind power and 41.93% when modeling with hydropower. Notably, ATH's ecosystem quality impact was even reduced by 91.49% when modeled with photovoltaic electricity.



(a) Sensitivity of ADP in ATH
(b) Sensitivity of AP in ATH
(c) Sensitivity of GWP in ATH
(d) Sensitivity of HTP in ATH

Fig. 11 Sensitivity result of ATH input parameters

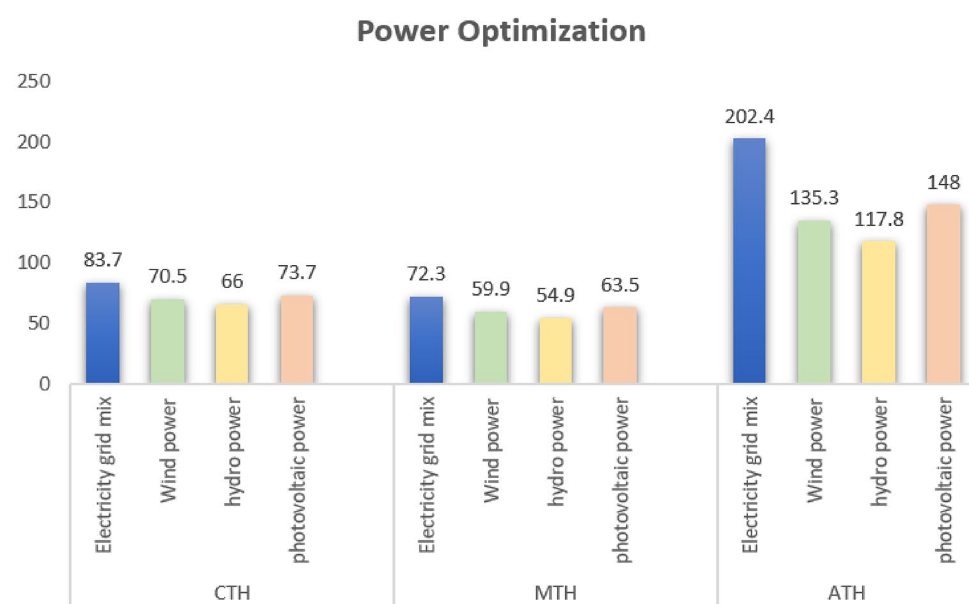


Fig. 12 Power optimization effect of three supply chains on comprehensive environmental impact

Through new production technology to mitigate the potential environmental impact

The production, transportation, storage and transformation methods selected for this study are all mainstream industrial methods. However, as production techniques have improved and optimized, cleaner technologies have emerged. Due to cost, immature technology and other reasons, these

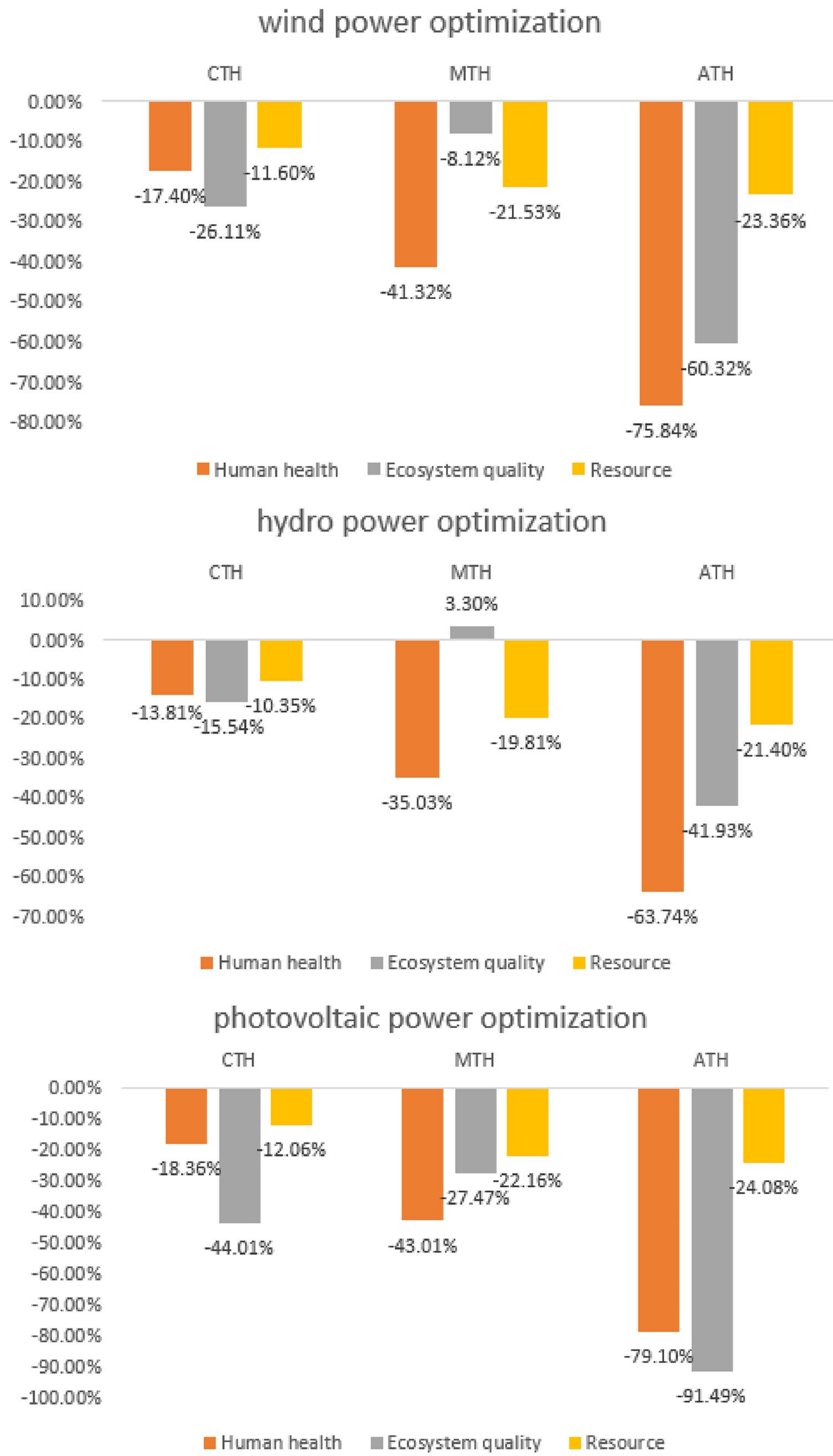


Fig. 13 Wind power, hydro power and photovoltaic power generation under different categories of optimization effect

technologies have not been put into the market for large-scale production, so this paper does not focus on the research. This section can provide directions and possibilities for enterprises to optimize the hydrogen supply chain technology.

CTH technology optimization

75% of the environmental impact of pure hydrogen technology is reflected in hydrogen production. In this study, hydrogen production from CG is the most important method of hydrogen production in China. Despite its increasingly mature technology, low cost of raw materials, and large-scale installations, it has environmental problems such as serious pollution. Palacios et al. (2022) examined different elective hydrogen creation strategies and discussed various production instruments. Luo et al. (2022) realized hydrogen production by using wind power, which can directly convert the electric energy generated through hydroelectricity. A method of using plasma to produce hydrogen from liquid benzene without producing carbon dioxide was proposed (Chung 2022). Zhong et al. (2022) examined and combined Au nanoparticles on TiO2 nanosheets as a photothermal impetus for hydrogen creation by photothermal improving of bio-based glycerol, yielding an expansion by 58%. Chung et al. (2022) fostered a mixture response framework that associated photochemical disintegration with fluid plasma, photocatalyst and electrolysis, and the last review showed that the hydrogen creation pace of the cross-breed response framework was essentially expanded. A renewable hybrid system was designed (Mehrenjani et al. 2022), which in light of sea nuclear power, sun-oriented energy and wind energy, which yield can arrive at 5.104 kg/h.

Coal is still the main raw material for hydrogen production, and the environmental impact of coal hydrogen production in CTH accounts for 75% of the entire supply chain of CTH. Therefore, it is necessary to increase the conversion rate of coal. This study provides several efficient coal conversion methods for choice. Bangwu et al. investigated hydrogen migration and redistribution in the products of copyrolysis of coal and polystyrene (PS) using reaction molecular dynamics simulations. Finally, the hydrogen content in the light tar was increased from 40.27 to 77.76% (Wu et al. 2023). Xue xd et al. proposed an efficient and clean hydrogen-electricity co-generation system based on the complementary utilization of coal and solar thermochemistry. In the end, the hydrogen output was 452.40 MW (13,582 kg/h, 28 bar) and the overall energy efficiency increased by approximately 4.91 percentage points to 49.37%. (Xue et al. 2023) Ou Guo et al. found that supercritical water gasification of coal can provide a new solution for the green transformation and upgrading of traditional coal industry. (Ou 2023) Once the above technology is mature and put into large-scale industrial production, the cleanliness of CTH can be greatly improved.

MTH technology optimization

Although MTH is the cleanest of the three supply chains, there is room for optimization in methanol production and hydrogen production from methanol. In recent years, a large number of scholars have proposed new methanol production and conversion processes that can effectively reduce the impact on the environment. Huang, Kang (Huang et al. 2022) planned a measured methanol blend framework driven by environmentally friendly power to advance the manageability of methanol creation. Eisavi, Ranjbar (Eisavi et al. 2022) proposed and broke down an original close to zero CO_2 discharge framework given the gasification of strong civil waste with a supportability record of 1.57. Adil and Rao (Adil and Rao 2022) laid out a motor model for methanol creation from syngas utilizing Aspen in addition to recreation programming, which expanded the carbon change rate by 46.97% and methanol creation by 1.21 mol/h. Kotowicz and Brzęczek (2021) acquainted three techniques with work on the proficiency of methanol creation and cleaning units: CO_2 pressure at the CCS power plant side, supplanting the choke valve with an expander, and supplanting the intensity exchanger with an ORC module.

ATH technology optimization

The overall environmental impact of the entire ATH path is greatest due to the low efficiency of the synthesis, decomposition and conversion of conventional industrial ammonia and its high environmental requirements. More green ways of making ammonia are being explored, such as ammonia nitrate synthesis, photocatalytic ammonia synthesis, electrocatalytic ammonia synthesis, plasma ammonia synthesis, cyclic ammonia synthesis, and supercritical ammonia synthesis (Li et al. 2021). The Korean national team found that the hydrogen production efficiency reached 734 LH2/kWh using a platinum catalyst of flower electrodeposition, and the green hydrogen with nearly 100% purity was successfully produced by liquid ammonia electrolysis (Yang et al. 2021b). By joining a strong corrosive-based electrochemical cell (SAEC) with a twofold anode, a few creators have accomplished a Faraday hydrogen creation productivity of 100 percent and a hydrogen creation pace of 1.48. The cycle works at much lower temperatures (250 degrees Celsius) than conventional techniques (500–600 degrees Celsius) (Lim et al. 2020). Others have studied the feasibility of small "green" ammonia plants, where renewable electricity provides hydrogen via electrolysis and nitrogen via air liquefaction to synthesize ammonia from the Haber–Bosch system. Research shows that the process reduces the power cost of synthetic ammonia plants by nearly a third (Edmonds et al. 2022). The researchers proposed four promising methods for ammonia synthesis under mild conditions: solid state, molten salt, thermochemical ring and photocatalysis. Not only do they operate at low pressures, but these pathways also offer the possibility of producing ammonia directly from H2O and N2 without the intermediate step of hydrogen production (Klaas et al. 2021).These advantages make it easier to integrate renewables.

Through recovering equipment and material to mitigate the potential environmental impact

This study is based on simapro's Ecoinvent database, which describes the decommissioning phase of plants/units in detail in the ecoinvent database Usage Guide and instructions (Treyer and Bauer 2016), The database is based on real-world significance.

Shabbani et al. investigated the application of microporous APKS and ZIF-8 adsorbents in the capture of carbon dioxide as a flue gas substitute. The purity and recovery rates of N and CO in product and waste streams were simulated and improved in the laboratory (2023). Carbon capture, storage and utilization are commonly used to reduce carbon emissions from the energy sector and limit anthropogenic climate change. At present, the main methods of CO capture are water washing, solvent absorption, membrane separation and pressure swing adsorption (Zhao et al. 2023). The environmental impact can be effectively reduced through the recycling of emissions.

Through policy support to mitigate the potential environmental impact

The government continues to introduce relevant policies and interventions to strongly support power optimization. According to policy documents such as the "14th Five-Year Plan" and the Outline of the 2035 Vision Goal "and the" 14th Five-Year Plan for Renewable Energy Development ", China has moved from top-level design to local planning (Li et al. 2023). From ensuring energy supply to low-carbon and reasonable consumption, we will build a comprehensive clean energy policy system, and put forward the goal: by 2025, the proportion of non-fossil energy consumption will reach about 20%; by 2030, the proportion of non-fossil energy consumption should reach about 25%, and the total installed capacity of wind and solar power generation should reach more than 1.2 billion kilowatts (Chen and Dagestani 2023).

In addition, other countries in the world are also actively promoting power optimization. In 2020, due to the impact of the COVID-19 pandemic, global carbon emissions will decrease by 6.03%, the largest annual decline since the industrial era. At the same time that China issued the "30·60" double carbon target, the USA, France and other developed countries issued the goal of halving carbon emissions by 2030 and peaking carbon emissions by 2050, and included investment in renewable energy investment, green transportation and other investments conducive to carbon emission reduction in the economic stimulus package, and the global carbon emission reduction ushered in a turning point (Saqib and Dincă 2023).

In particular, the Russia-Ukraine war and the global economic recession have also had a positive impact on environmental sustainability trends in energy and industrial production. Liuzehong et al. found that the Russia-Ukraine conflict exposed many drawbacks of the world energy system based on fossil energy, which will accelerate the reconstruction of the world energy pattern. The conflict has further accelerated the transition to green and low-carbon energy, promoting clean alternatives to energy production, energy consumption and electricity substitution, and energy system interconnection (Steffen and Patt 2022).

Conclusions

In this study, MTH, CTH and ATH represent three typical hydrogen supply chains in China. Through using the final production of 1000 Nm^3 hydrogen gas as the research object, the specific environmental impacts at the midpoint level and the overall impacts classified by the end point impacts were analyzed by the LCA method. The results show that MTH is the cleanest supply chain due to the advantages of high methanol conversion efficiency and easy storage at room temperature and pressure, and the hydrogen production phase of MP contributes the most to the environmental load of MTH. Hydrogen production from CG and AD are the main load contributors of CTH and ATH. Due to the high energy consumption in ammonia synthesis, decomposition and storage, and low hydrogen conversion efficiency, the overall impact of HAS on the environment is as high as 2.02E + 02, which is 2.8 and 2.4 times greater than MTH and CTH, respectively. Among the environmental impacts of MTH, CTH and ATH, the damage to resources is the greatest, accounting for 66.3, 71.2 and 73.8% of the total environmental impacts, respectively. Fossil fuel resources account for more than 95% of the resource impact rate. In terms of human health, MTH, CTH and ATH account for 0.7, 0.9 and 0.5% respectively, and MTH is almost half of CTH and ATH. If we focus on the impact on ecosystem quality, MTH, CTH and ATH account for 33, 27.9 and 25.7%, respectively. Sensitivity analysis reveals that power is the primary factor influencing the environmental effect. After 100% use of clean energy power, the ATH path with the highest power consumption has the most significant optimization effect, and the comprehensive environmental impact of wind power, hydropower and photovoltaic power is reduced by 33.15, 41.80 and 26.88%, respectively. The environmental impact of CTH and MTH paths also decreased significantly, with 15.77, 21.15, 11.95% and 17.15, 24.07, 12.17%, respectively. After power optimization, MTH is still the cleanest supply chain.

This study evaluates and improves the environmental impact of the hydrogen supply chain. The conclusion is that the use of clean energy can greatly reduce the environmental impact in the supply chain. For the hydrogen supply chain to better achieve the SDGS, it is recommended to use environmentally friendly electricity or change its technological structure. However, the current study has limitations, and some of the data are based on estimates of the overall average of the industry, which may differ slightly from actual industrial production in different regions. In addition, the social life cycle evaluation of the hydrogen supply chain is missing due to the difficulty in obtaining data, otherwise the supply chain can be evaluated more comprehensively. It is necessary to improve the relevant database.

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Author's contribution YW: writing-original draft preparation, methodology, data curation, investigation, validation, formal analysis. TJ: conceptualization, resources, supervision, writing-reviewing. QJ and XL: data curation, supervision, writing-reviewing and editing.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

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

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