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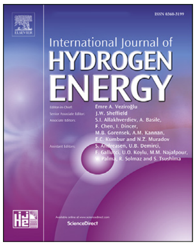

Life cycle assessment of three types of hydrogen production methods using solar energy

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HIGHLIGHTS

- Photothermal technology coupling hydrogen production by S–I cycle has the lowest environmental impact.
- Optimal heat source for PEM water electrolysis is photovoltaic power generation.
- Reducing the pollution in the construction of plant can reduce the pollution of the whole hydrogen production system.
- Increasing the lifetime of the system can reduce the environmental impact of hydrogen production.

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ABSTRACT

A comprehensive life cycle assessment (LCA) is carried out for three methods of hydrogen production by solar energy: hydrogen production by PEM water electrolysis coupling photothermal power generation, hydrogen production by PEM water electrolysis coupling photovoltaic power generation, and hydrogen production by thermochemical water splitting method using S–I cycle coupling solar photothermal technology. The assessment also contains an evaluation of four environmental factors which are global warming potential, acidification potential, ozone depletion potential, and nutrient enrichment potential. After conducting a quantitative analysis of all three methods with environmental factors being considered, a conclusion has been drawn: The global warming potential and the acidification potential of the thermochemical water splitting by S–I cycle coupling solar photothermal technology are 1.02 kg CO_2-eq and 6.56E-3 kg SO_2-eq. And this method has significant advantages in the environmental impact of the whole ecosystem.

Introduction

With the increasing global attention to global warming, climate change, energy security and ecological environment protection, developing renewable energy system has become a major strategic for global energy transformation. Hydrogen is a promising energy source that can be produced through renewable energy such as hydro power, wind power and solar power etc. As an energy carrier, hydrogen has the advantages of high efficiency, cleanness, safety, and sustainability, and is considered as the '21st Century Energy'. Hydrogen has become a research hotspot to expand the usage and promotion of renewable energy, either incorporated into the existing natural gas pipeline network, or through methanation reaction with CO_2 to provide gas, or through fuel cell to generate power.

Hydrogen energy is a secondary energy, which needs to consume primary energy for preparation. Therefore, the development of green and efficient hydrogen production technology coupled with renewable energy is needed for the

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large-scale utilization of hydrogen energy. As ideal renewable energy, solar energy has the characteristics of clean and inexhaustible. Using solar energy to produce hydrogen can greatly reduce the greenhouse gas emissions and produce ‘Green Hydrogen'.

Previous studies reported that LCA (Life Cycle Assessment) can be a good evaluation method to analyze different hydrogen production process. Cetinkaya et al. [1] reported five different hydrogen production methods and presented an example of a hydrogen filling station. The carbon dioxide equivalent emission and energy equivalent of each method are quantified and compared. The results showed that in terms of carbon dioxide equivalent emissions, the Cu–Cl cycle's thermochemical water splitting method was superior to other methods, followed by wind and solar electrolysis. In terms of hydrogen production capacity, compared with renewable energy methods, natural gas steam reforming, coal gasification and Cu–Cl cycle methods have advantages in thermochemical decomposition of water.

Lattin et al. [2] proposed an LCA for thermochemical water splitting using a nuclear reactor's sulfur-iodine cycle. This life cycle assessment studied the impact of the combination of advanced nuclear power plants and hydrogen production plants on the environment, focusing on quantifying the carbon dioxide emission per kilogram of hydrogen. The results showed that the GWP of the system is 2500 g carbon dioxide equivalent (CO_2-eq) per kilogram of hydrogen. The global warming potential (GWP) of the system is about 1/6 of that of steam reforming of natural gas for hydrogen production.

The research team composed of Burmistrz et al. [3] from AGH University of science and technology is committed to the overall benefit research of the actual hydrogen production project. The team compared the impact of shell and Texaco/Ge coal gasification hydrogen production processes with the idea of life cycle assessment, and comprehensively evaluated the specific benefits of coal gasification hydrogen production process. In general, coal gasification hydrogen production technology has high energy consumption and is not friendly to the environment. In the coal gasification hydrogen production system, the use of carbon dioxide capture equipment can greatly reduce the direct emission of carbon dioxide and have a positive impact on the environmental protection benefits of the system.

Space and Mann [4] of the National Renewable Energy Laboratory (NREL) of the United States have long been engaged in the research on the life cycle assessment of methane steam reforming hydrogen production system. Their research ideas and relevant data have been used for reference and quoted by many research teams, and the research results are authoritative and representative. The study establishes the life cycle process from natural gas exploitation and transportation to hydrogen production in hydrogen production plant, traces the detailed list sources of material consumption and energy consumption in various links, and constructs a complete system boundary. The evaluation results show that the energy consumption and greenhouse gas emission in the operation link of hydrogen production plant account for 87.1% and 74.8% of the total life cycle of the system respectively, it is the main influencing link of the whole system.

Solli et al. [5]from Norwegian University of science and technology has been engaged in the research of life cycle assessment project for a long time. The team uses Deontief matrix model to conduct life cycle assessment and analysis of sulfur iodine cycle hydrogen production system for nuclear heating, and has established relevant inventory data from uranium mining to hydrogen production process. The results show that the life cycle greenhouse gas emission equivalent of sulfur iodine cycle hydrogen production system for nuclear heating is 412 g CO_2/kgH_2. The construction and operation process of nuclear power system is the leading factor causing greenhouse gas emission.

Siddiqui [6] conducted a comparative life cycle assessment from well to pump for the hydrogen production routes of water electrolysis, biomass gasification, coal gasification, methane steam reforming and hydrogen production from ethanol and methanol. The CML 2001 impact assessment method is used for assessment and comparison. For the hydrogen production route through water electrolysis mixed with electric power in the United States, relatively high life-cycle carbon dioxide and sulfur dioxide emissions are determined, which are 27.3 kg/kgH_2 and 50.0 g/kgH_2 respectively.

Lubis [7] carried out a life cycle assessment of nuclear hydrogen production by thermochemical decomposition of water. The copper chlorine thermochemical cycle is considered, and the environmental impact of nuclear power plants and thermochemical power plants is evaluated. The construction of nuclear power plants and hydrogen power plants has a significant contribution to the overall environmental impact. The operation of hydrogen production plant has much less impact on the environment. Changes in the inventory of materials or chemicals required for thermochemical plants will not significantly affect the overall impact. The improvement analysis suggests the development of more sustainable processes, especially in the construction of nuclear power plants and hydrogen production plants.

Blumberga [8] carried out a life cycle assessment to compare different biological hydrogen production methods using different photosynthetic methods, and identify the environmental “hot spots” of the whole process. The results show that using bio hydrogen power generation has more environmental benefits than using fossil fuel power generation. If a cycling photobiological hydrogen production from green algae with forced sulfur deprivation is used instead, the analysis provides quantification of CO_2 to avoid fossil fuel emissions. If coal is an alternative energy source for power production, it can be proved that the highest level of this quantity is about 25.5 tCO_2/year.

Acar and Dincer [9] conducted a comparative environmental impact assessment of possible hydrogen production methods for renewable and non-renewable resources, with particular emphasis on their application in Turkey. The results show that compared with other traditional methods, the thermochemical decomposition water with Cu–Cl and S–I cycle is more environmentally friendly in discharge. The choice of wind energy, solar energy and high-temperature electrolysis also provides environmental protection. The overall ranking shows that the thermochemical water splitting method using S–I and Cu–Cl cycle are the main candidates which are hopeful to produce hydrogen in an environmentally friendly manner.

Zhao et al. [10] conducted a detailed quantitative assessment of the environmental impact of three commercial H_2O electrolysis technologies, including solid oxide electrolysis cell (SOEC), polymer electrolyte membrane electrolysis cell (PEM), and alkaline electrolysis cell (AEL). In terms of GWP, the influence of PEM is 16 times that of SOEC and about 15 times that of AEC.

Reiter et al. [11] studied the system boundary characteristics and inventory data of hydrogen production from photovoltaic power generation used GABI 5 to model the material and energy balance, and evaluated the main parameters affecting GWP and primary energy demand. The results showed that hydrogen production from renewable energy sources such as wind power or photovoltaic power generation has great potential to reduce GWP and primary energy demand.

The objective of this study is to conduct a comprehensive LCA analysis for three different type of solar energy hydrogen production methods, i.e., PEM water electrolysis coupling photovoltaic power, PEM water electrolysis coupling photothermal power, and thermochemical water splitting method using S–I cycle coupling solar photothermal power. The best hydrogen production way coupled with solar energy will be discussed by comparing the four major environmental factors: GWP, acidification potential (AP), ozone depletion potential (ODP), and Eutrophication Potential (EP).

Hydrogen production methods

The system boundary of hydrogen production methods compared in this paper is shown in Fig. 1. Solar power generation methods are mainly divided into photovoltaic power generation and photothermal power generation. Photovoltaic power generation refers to the semiconductor interface photovoltaic effect, through solar cells directly converting solar energy into electricity. Photovoltaic power generation has the characteristics of less regional impact, safety, and reliability.

Photothermal power generation refers to the use of large-scale arrays or grooved mirrors to collect solar light and provide steam through heat exchanger devices to promote steam turbines' operation and power generation. Photothermal power generation can store some amount of heat by molten salt or chemical reaction etc., which greatly reduces the instability of power generation caused by uneven illumination.

Hydrogen production by water electrolysis

At present, the mainstream technologies for hydrogen production using water electrolysis include alkaline water electrolysis (AEL), proton exchange membrane electrolysis (PEM) [12], and solid oxide electrolysis cells (SOEC) [13]. AEL has been a most mature commercial technology currently, but low efficiency and bad load matching ability with renewable energy's fluctuation. At the same time, due to its electrolyte using KOH, long-term usage usually can cause corrode and equipment damage. PEM technology has just emerged in recent years. With gradual maturity of the technology, it has a trend to catch up with the AEL technology and become the most attractive one in hydrogen production market especially coupling with renewable energy. Therefore, PEM was selected as the hydrogen production method in this study.

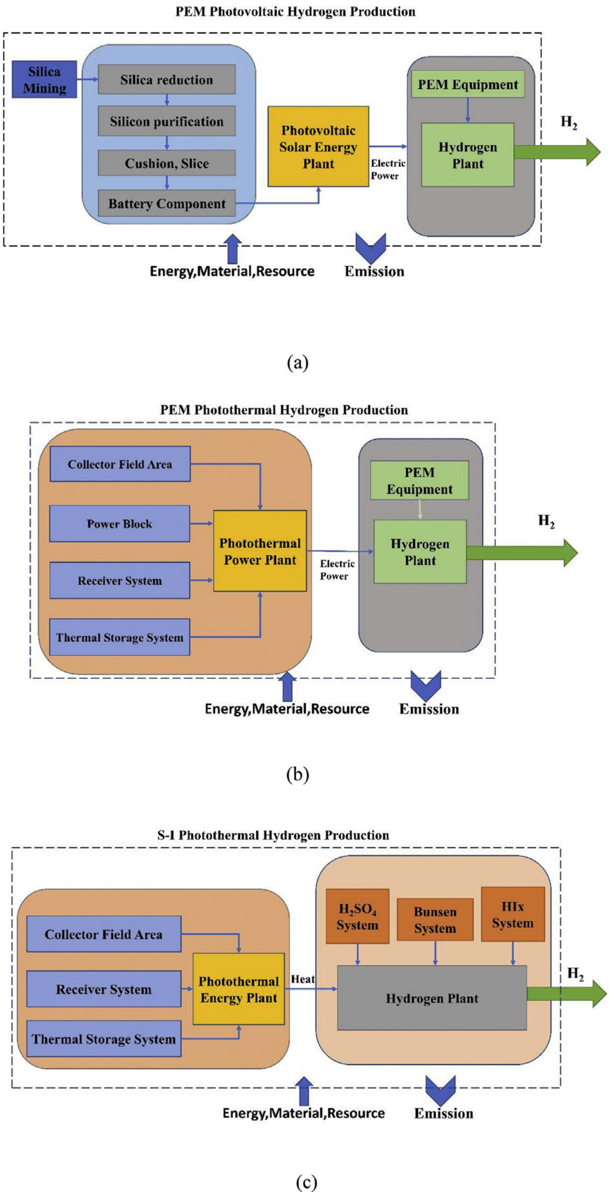

Fig. 1 – System boundary of different hydrogen production methods using solar energy. (a) PEM photovoltaic hydrogen production; (b) PEM photothermal hydrogen production; (c) SI photothermal hydrogen production.

The basic principle of the PEM water electrolysis reaction is shown in Fig. 2. The electrolytic cell is filled with strictly purified pure water, and the electrolytic cell can be divided into a cathode chamber and an anode chamber with a proton exchange membrane separated, the electrodes are placed in the two chamber respectively [14]. At a certain voltage, the current passes through the two poles, with H_2 generated by cathode and oxygen generated by anode.

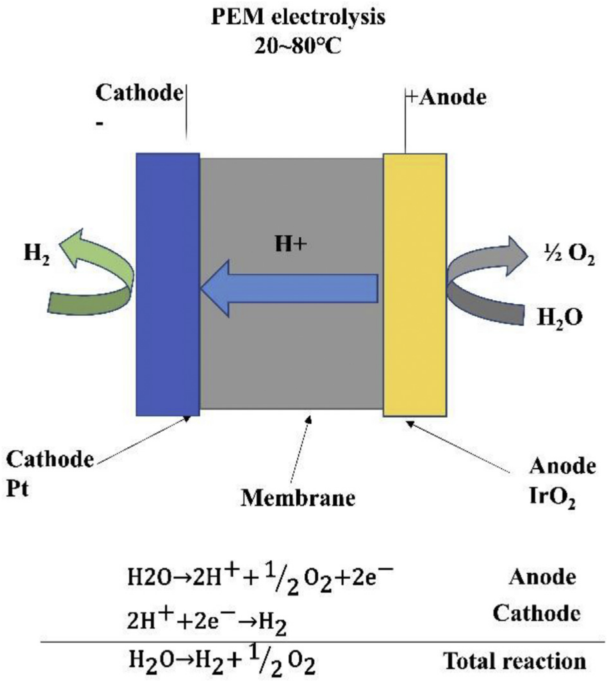

Fig. 2 – Schematic diagram of PEM electrolysis water.

Hydrogen production by thermochemical cycles

The concept of thermochemical water splitting was first proposed by Funk et al. [15]. The earliest idea was to introduce mediator substances to split raw water into hydrogen and oxygen. In the 1970s, General Atomics (GA) [16] studied 25 thermochemical processes and finally selected two best thermochemical water splitting processes: UT-3 cycle and sulfur iodine (S–I) cycle. Because the S–I cycle has more advantages in hydrogen production efficiency, this paper chooses the S–I cycle as the hydrogen production method.

The basic principle of thermochemical water splitting by the S–I cycle is shown in Fig. 3. The cycle splits water into hydrogen and oxygen through three closed-loop chemical reactions. Sulfuric acid and hydroiodic acid are generated through the Bunsen reaction. Due to the presence of excess iodine, sulfuric acid and hydroiodic acid are spontaneously separated from liquid to liquid, forming the upper sulfuric acid phase and lower hydroiodic acid phase. Two-phase solutions are purified and concentrated, and then enter the decomposition process. Sulfuric acid is decomposed into O_2, SO_2, and H_2O at 1073–1173 K. At 473–973 K, hydroiodic acid is decomposed into H_2 and I_2. Except for the products O_2 and H_2, the rest is recycled again to achieve pollution-free hydrogen production.

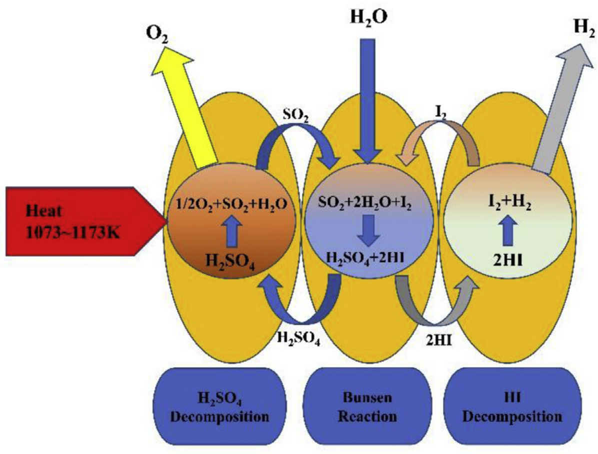

Fig. 3 – Principle diagram of thermochemical water splitting by S–I cycle for hydrogen production.

Life cycle assessment methods

Criteria of life cycle assessment

The Center for Environmental Sciences of Leiden University (CML) released an 'ISO standard operating guide' in 2001, which includes a set of impact categories, characterization methods, and factors for the inventory of substances used in the LCA impact assessment phase (considering natural resources and emissions to nature). Guinee et al. [17] explained each environmental impact and each environmental impact category. The influence categories used in this study are as follows:

- Acidification potential (AP): AP is the deposition of acidified pollutants on soil, groundwater, surface water, biological organisms, ecosystems, and materials, measured in kg SO_2-eq. The main contributors to this category are SO_2, NO_x, and NH_x. The natural environment, man-made environment, human health, and natural resources are the protected areas of AP with significant indigenous influence.
- Eutrophication Potential (EP): Eutrophication includes all potential effects of excess nutrients (mainly nitrogen and phosphorus). The enrichment of nutrients may lead to adverse changes in species composition and an increase in biomass in aquatic and terrestrial ecosystems. Nitrogen and phosphorus and other emissions that cause similar effects are classified as eutrophication impact categories. The unit of EP is kg PO_4-eq.
- Global Warming Potential (GWP): GWP is the effect of human emissions on radiative forcing (e.g. thermal radiation absorption) and is measured in kilograms of carbon dioxide equivalent. Global warming that causes climate change may affect ecosystems and human health. Most greenhouse gas emissions enhance radiative forcing, thereby increasing the Earth's surface temperature ('greenhouse effect').
- Ozone Depletion Potential (ODP): Ozone depletion is due to ozone depletion emissions resulting in stratospheric ozone layer thinning. Due to this thinning, most of the solar UV-B radiation reaches the Earth's surface, which has potentially harmful effects on human and animal health, terrestrial and aquatic ecosystems, biochemical cycles, and materials. Thus, ODP (in kg R11-eq) has an impact on four protected areas: human health, natural environment, man-made environment, and natural resources.

PEM coupled with photovoltaic power for hydrogen production

To keep the contrast parameters consistent, the setting of PEM electrolysis equipment and hydrogen production plant is the same as 3.1. At present, most of the installed capacity of PV power stations in China is around 10 MW. Therefore, the energy supply of the studied photovoltaic grid power station used here is 10 MW. The photovoltaic power generation system boundary includes polysilicon production, photovoltaic cell module production, and power plant construction. The solar cells are multi-use crystalline silicon solar cells in the current market. Since the cost price of a polycrystalline silicon battery is lower than that of a single-crystal silicon battery, polycrystalline silicon battery components are finally adopted to reduce the project cost. Referring to Dunhuang photovoltaic grid-connected power station in Gansu, China, the specific annual average grid-connected power and annual average utilization hours are shown in Table 1 [18]. The life cycle of the photovoltaic power station is set to be 30 years, during which a total of 50.97 million kWh can be generated. Later this method denoted as PEM + PV.

As shown in Fig. 1, the production process of photovoltaic modules includes silica reduction, silicon purification, and ingot slicing process, and finally assembled into photovoltaic cell components. The input and output lists for PV (photovoltaic) module production are from the [19].

In addition to the production of photovoltaic modules, the main materials consumed in the construction of power plants are concrete and steel. The input list of photovoltaic power plant construction is shown in Table 2.

PEM coupled with photothermal power for hydrogen production

Reference to the Large Hydrogen Plant in Guyuan, a city in Hebei, China, the PEM electrolyzer equipment studied in this paper has the power consumption of 5 MW, with capacity of 90 kg/h H_2, efficiency of 60%. The annual output of the equipment is 17.52 MNm^3 H_2. Considering the coupling between the electrolyzer and solar energy, the equipment is assumed to operate for 10 h per day, and the life of the entire hydrogen production plant is 30 years. For the full operation state, the energy consumption of the whole system is 54.81 kWh/kg H_2.

The cathode of the PEM electrolysis device is sprayed on the carbon brazing plate with platinum-based metal, and the anode is sprayed with iridium oxide [20]. The membrane material is Nafion material from DuPont, which is obtained by Dr. Walther Grot to improve Teflon material. It is the most popular membrane material for PEM. The overall structure of the electrolysis device is composed of chamber structure and skeleton structure. Apart from the membrane and electrode, most of the chamber structures are constructed by stainless steel. The skeleton part is constructed by resin, stainless steel, and chloroprene rubber [21].

Table 1 – Average annual grid electricity and annual utilization hours.

Item	Amount	Unit
Average annual solar radiation	1782	$kW \cdot h \cdot m^{-2}$
Average annual utilization hours	1691	h
Installation capacity	10049.6	kWp
Average annual grid electricity	1699	Million kWh

Table 2 – Consumption List of the construction of 10 MW Photovoltaic Power Station.

Input	Amount	Unit
Aerated Concrete	7.36E7	kg
Stainless Steel	7.26E3	kg

The detailed input list is shown in Table 3 and Table 4. Table 1 is the construction input of the whole PEM electrolytic water hydrogen plant for each 1 kg hydrogen production. Table 2 shows the input of the PEM electrolysis device during operation for each 1 kg hydrogen production.

The energy supply of the whole system is solar photothermal power generation. Photothermal power generation uses 20 MW centralized solar tower power generation technology. Photothermal power plants include five modules, namely collector module, receiver module, heat storage module, and steam power generation module. Because it is difficult to obtain the construction data of 20 MW solar tower power station, all the construction data used in this paper are from the Ecoinvent database. Due to the hydrogen production from electrolytic water does not require large-scale electricity, large installed capacity power plants are not considered in our study. The data set is scaled for the modeling of a 440 MW power plant from South Africa [22]. The design of a 20 MW power plant is represented by linear and nonlinear equations with specific parameters [23]. Later this method denoted as PEM + PT.

S–I cycle coupled with photothermal for hydrogen production

The hydrogen production capacity of the thermochemical water splitting by the S–I cycle hydrogen plant calculated in this paper is 200 tons of hydrogen per day [24], and the life of the hydrogen plant is set 30 years. Ozbilen estimated the input materials of thermochemical water splitting by Cu–Cl cycle hydrogen plant [25]. Since the main difference in thermochemical hydrogen production lies in the operation process, it is assumed that the construction materials of the thermochemical water splitting by the S–I cycle hydrogen plant are similar. In addition to the basic plant construction, other main construction materials are from the Bunsen reactor, sulfuric

Table 3 – Consumption list of the construction of PEM hydrogen production plant (1 kg H_2).

Input	Unit	Amount
Concrete	kg	0.00619
Aluminum	kg	0.000111
Copper	kg	0.000331
Polycarbonate Compound	kg	0.000111
Steel	kg	0.0074

Table 4 – Consumption list of the operation of PEM electrolysis water (1 kg H_2).

Input	Unit	Amount
Activated Carbon	kg	9.94E-6
Aluminum	kg	2.98E-5
Copper	kg	4.97E-6
Electricity	KWh	60
Iridium	kg	8.3E-7
Platinum	kg	8E-8
Stainless Steel	kg	0.000111
Titanium	kg	0.000583
Water	kg	9
Nafion™	kg	1.76E-5

acid and HI_x distillation columns, purification towers, and reactors, and the construction of various pipelines. For each 1 kg hydrogen production, the list of all construction materials for the hydrogen plant is shown in Table 5. Later this method denoted as S–I + PT.

The main reactions for hydrogen production from thermochemical water splitting by S–I cycle and the respective required temperatures are shown below:

$$I_2 + SO_2 + 2H_2O \xrightarrow{\sim 393K} H_2SO_4 + 2HI \tag{1}$$

$$H_2SO_4 \xrightarrow{\sim 1073K} \frac{1}{2}O_2 + SO_2 + H_2O \tag{2}$$

$$2HI \xrightarrow{\sim 723K} H_2 + I_2 \tag{3}$$

The heat required in the reaction process comes from solar heat. To reduce the operation cost, we reduce the step of heat conversion into electricity in the photothermal power station. The heat in the heat storage module is directly used as the energy source of hydrogen production in the S–I cycle. The other components of the photothermal power station are unchanged. The heat value of the whole system comes from the process simulation by Aspen Plus [26].

Only water is consumed during the whole reaction process, but considering that a certain amount of iodine will deposit and adhere to the pipe wall during the actual operation, we consider the iodine loss during the operation of hydrogen production from the thermochemical water splitting by the S–I cycle. For every 1 kg H_2 produced, the consumption list of sulfur-iodine cycle hydrogen production is shown in Table 6.

Table 5 – Consumption list of the construction of thermochemical water splitting by S–I cycle hydrogen (1 kg H_2).

Input	Unit	Amount
Aluminum	kg	0.0223
Copper	kg	0.312
Lead	kg	0.0505
PVC	kg	0.173
Spruce log	kg	3.8
Steel	kg	10.2
Concrete	kg	40.1
Titanium	kg	0.0148

Table 6 – Consumption list of the operation of hydrogen plant by thermochemical water splitting by S–I cycle (1 kg H_2).

Input	Unit	Amount
Aluminum	kg	8.6E-8
Copper	kg	7.14E-7
Lead	kg	1.95E-7
PVC	kg	6.68E-7
Steel	kg	2.62E-6
Titanium	kg	5.74E-9
Water	kg	0.000714
Iodine	kg	5.03E-5
Thermal energy	MJ	184

Result and discussion

Environmental impacts of different hydrogen production methods

The environmental impacts of the three hydrogen production methods are studied, and the results of CML 2001 impact categories (GWP, AP, EP, ODP) are given. To ensure the comparability of the results, all impact categories are calculated based on the 30-year service life of the equipment aimed at producing 1 kg hydrogen. The calculation results are shown in Fig. 4.

As a whole, the environmental impacts of PEM + PV and PEM + PT are higher than that of S–I + PT. In terms of GWP, PEM + PV is little higher than PEM + PT. PEM + PV and PEM + PT are 9.37 kg CO_2-eq and 8.67 kg CO_2-eq, respectively, which are 9 times and 8 times higher than that of S–I + PT. The GWP of S–I + PT is only 1.02 kg CO_2-eq. Unlike GWP, the AP and EP of PEM + PT are slightly higher than that of PEM + PV, and they are both 10 times higher than S–I + PT. For ODP, PEM + PV is 3.19E-11 kg R11-eq, much higher than PEM + PT and S–I + PT, which is 100 times and 100 times higher than PEM + PT and S–I + PT. All in all, no matter what kind of environmental factors, S–I + PT has more advantages than PEM + PV/PT. On the one hand, the energy consumption of hydrogen production from electrolytic water is higher than that from thermochemical water splitting by the S–I cycle. On the other hand, whether it is solar photovoltaic or photothermal, there is a process of light to electricity or heat to electricity, but S–I + PT can directly use the energy of heat, avoiding the step of steam turbine power generation, greatly reducing the impact on the environment.

In terms of hydrogen production from PEM electrolysis water, the hydrogen production from electrolysis water using photothermal power generation is lower than that using photovoltaic power generation in GWP, while slightly higher than that using photovoltaic power generation in AP and EP. It is worth noting that the ODP of hydrogen production from electrolysis water using photothermal power generation is two orders of magnitude lower than that using photovoltaic power generation. If only considering the influence of GWP, the photothermal power generation technology is preferred in coupling with PEM hydrogen production.

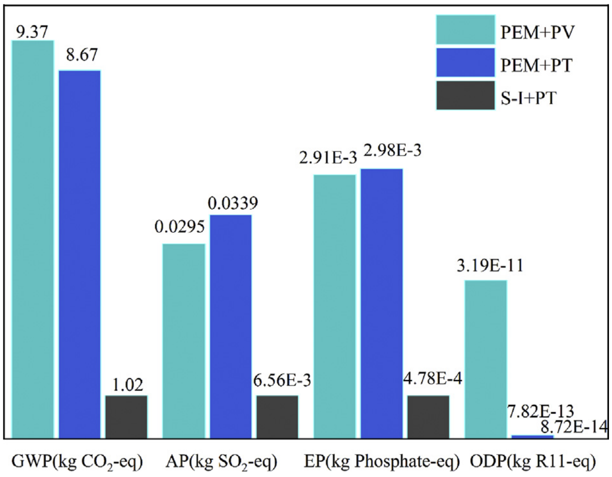

Fig. 4 – Environmental impact of different hydrogen production methods.

Proportion of environmental impact in each hydrogen production methods

To better understand the contribution of each step to the environmental impact in different hydrogen production methods, the environmental impact weights of the four main steps in the hydrogen production process, i.e. the construction of solar power plants, the operation of solar power plants, the construction of hydrogen plants and the operation of hydrogen plants, are analyzed.

Fig. 5 shows the proportion of environmental impact in each step of PEM + PV. It can be seen that in the four environmental impacts, the equivalent percentage of the construction of solar photovoltaic power station is the highest, followed by the construction of PEM electrolytic hydrogen plant. The environmental impact of solar photovoltaic power operation is almost 0% and the impact of PEM hydrogen production plant operation is only 1%. It can be concluded that all the environmental impacts in the process of PEM + PV are from the construction process of power plants and hydrogen production plants. Therefore, selecting materials with low environmental emission for plant construction can effectively reduce the environmental impact of the overall system.

Fig. 6 shows the proportion of environmental impacts in each step of PEM + PT. As shown in the figure, the construction of solar thermal power plants contributes most to the environmental impact. In terms of GWP, AP, EP, and ODP, the construction of solar thermal power plants accounts for 73%, 82%, 82%, and 95%, respectively. The second major impact constructing a PEM electrolytic water hydrogen plant, whose equivalent proportion of GWP is 22%, AP is 15%, EP is 14% and ODP is 4%. Unlike photovoltaic power stations, the operation of photothermal power stations will also have a certain impact on the environment. The proportion of GWP is 4%, AP is 2%, EP is 3%, and ODP is 1%. The environmental impact of this part is mainly due to the use of molten salt in the heat storage system and the production and recovery of this part will have a certain impact on the environment. In order to effectively reduce the environmental emission during the operation of the power plant, the recovery and low pollution treatment of the molten salt heat storage system can be added, so as to reduce the pollution of molten salt to the environment. The operation of PEM water electrolysis hydrogen plant has little impact on the environment.

The environmental impact of each step of S–I + PT is shown in Fig. 7. In terms of GWP, the construction of photothermal power plants accounted for 77%, S–I hydrogen production plants accounted for 21%, and the operation of photothermal power plants accounted for 2%. It can be seen that the main source of GWP is still the construction of power

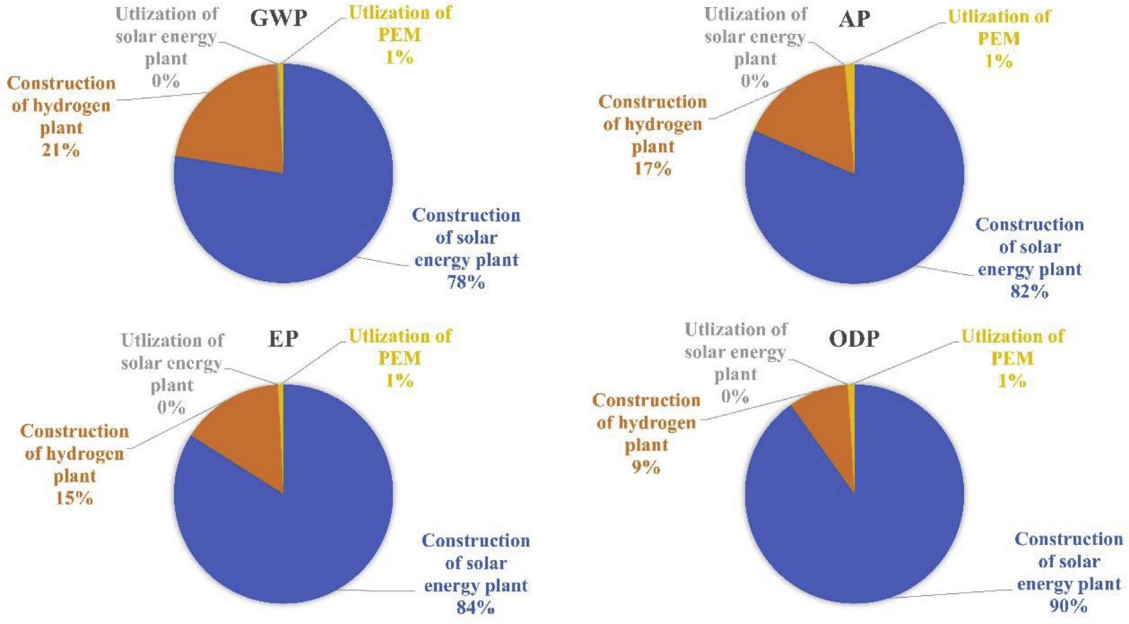

Fig. 5 – Contribution of each step to the environmental impact in PEM + PV.

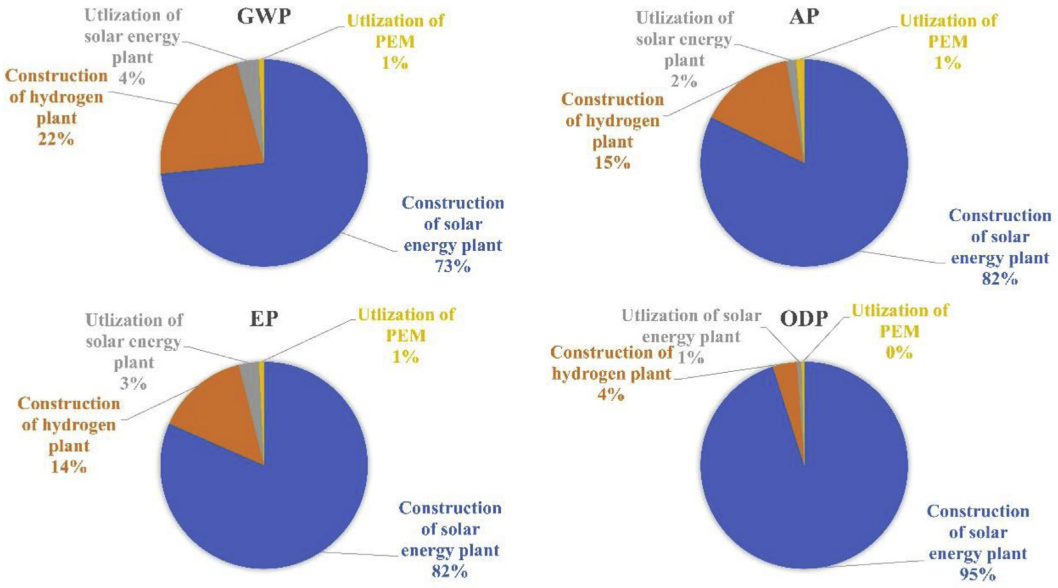

Fig. 6 – Contribution of each step to the environmental impact in PEM + PT.

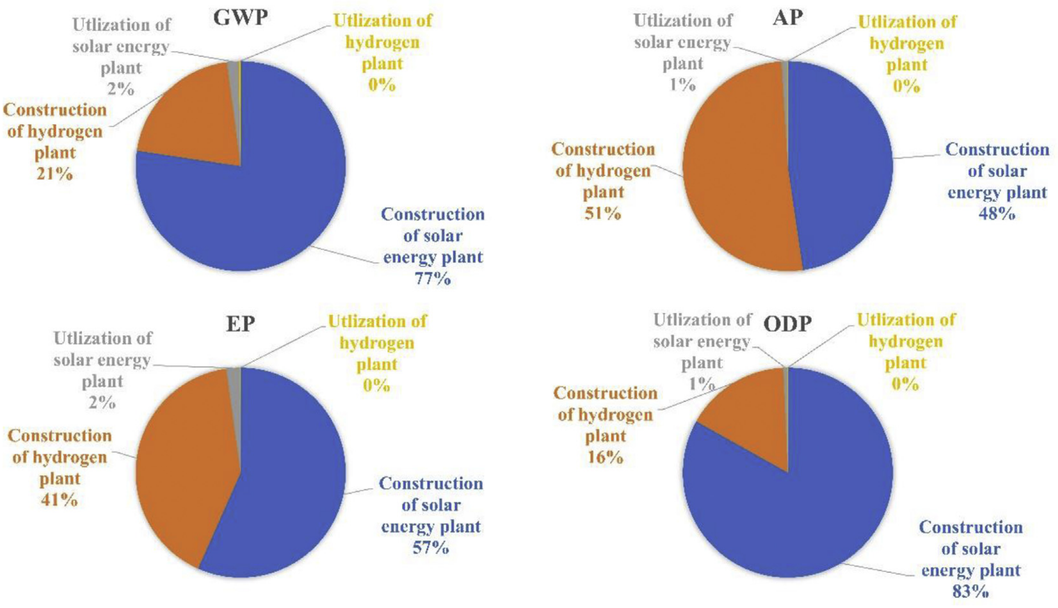

Fig. 7 – Contribution of each step to the environmental impact in S–I + PT.

plants and hydrogen plants, and the GWP generated during operation is very small. In terms of AP, the construction of photothermal power plant accounts for 48%, while the proportion of the construction of the S–I hydrogen production plant is slightly higher accounting for 51%. The impact during operation can be ignored. In terms of EP, the construction of photothermal power plants accounts for 57%, the construction of hydrogen plants accounts for 41%, and the operation of power plants accounts for 2%. In terms of ODP, the most important influence is the construction process of photothermal power plants, accounting for 83%, while the construction of hydrogen plants only accounts for 16%. There is almost no ODP influence in the operation of power plants and hydrogen plants.

Effect of lifetime to the environmental impacts

In the previous section, the environmental impact equivalent proportions of different steps in hydrogen production were analyzed. In this section, the change of environmental impact with the lifetime of the entire hydrogen production system will be further studied with the lifetime of the system changing from 30 years to 60 years.

Fig. 8 shows the changes of GWP under different lifetimes of each hydrogen production system. Within the calculation range, the lowest GWP of PEM + PV is 4.63 kg CO_2–eq at the lifetime of 60 years, and the highest GWP is 9.37 kg CO_2–eq at the lifetime of 30 years. During the lifetime from 30 to 60 years, the GWP of PEM + PT and S–I + PT change from 8.67 kg

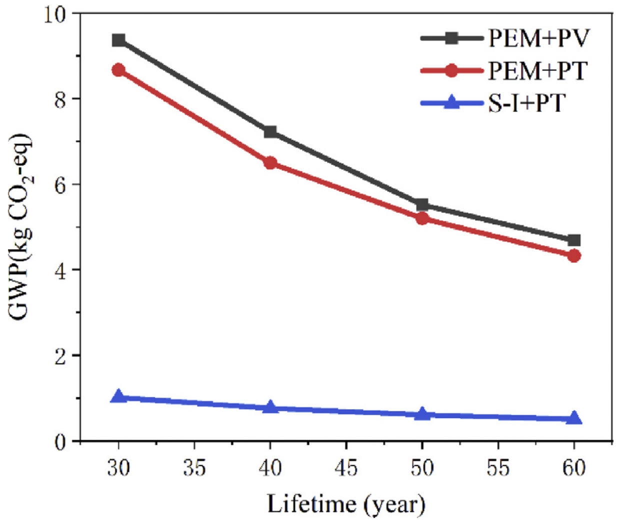

Fig. 8 – Variation of GWP (per kg H_2 production) with the lifetime of the system.

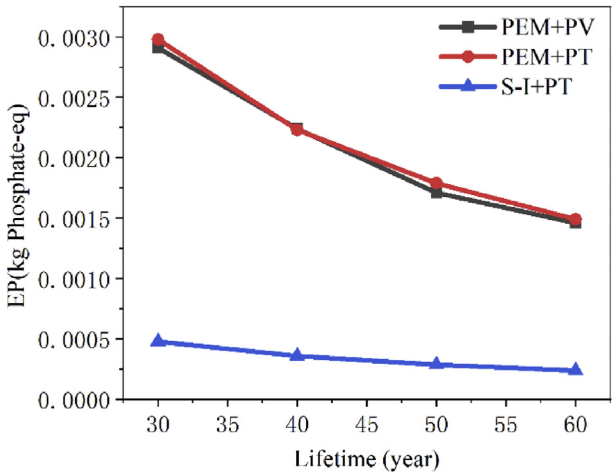

Fig. 10 – Variation of EP (per kg H_2 production) with lifetime of the system.

CO_2–eq to 4.33 kg CO_2–eq and from 1.02 kg CO_2–eq to 0.511 kg CO_2–eq, respectively. It can be clearly seen that with the increase of lifetime, the GWP of per 1 kg hydrogen production will decrease, and the amplitudes of variation of PEM + PV, PEM + PT, and S–I + PT are similar, which are around 50%. The results show that with the increase of life time, the GWP of unit hydrogen production will be effectively reduced, but in terms of the reduction amount, the reduction amount of the S–I + PT with low environmental impact is not much.

Fig. 9 shows the changes of AP in different hydrogen production systems with different lifetimes. When the system lifetime changes from 30 years to 60 years, the AP of PEM + PV decreases from 0.0295 kg SO_2-eq to 0.0147 kg SO_2-eq, the AP of PEM + PT decreases from 0.0339 kg SO_2-eq to 0.0169 kg SO_2-eq, while the AP of S–I + PT decreases from 6.56E-3 kg SO_2-eq to 3.28E-3 kg SO_2-eq. It can be seen that as the lifetime increases, the AP for producing 1 kg of hydrogen will also decrease. The amplitudes of variation of PEM + PV, PEM + PT, and S–I + PT are all-around 50%. However, the quantities of PEM + PV and PEM + PT variation are 0.145 kg SO_2–eq and 0.147 kg SO_2–eq, while the quantity of S–I + PT is 0.000239 kg SO_2-eq.

Fig. 10 shows the change of EP under different lifetimes of different hydrogen production systems. In the system lifetime of 30 years, 40 years, 50 years, and 60 years, the EP of PEM + PV is 2.91E-3 kg Phosphate-eq, 2.24E-3 kg Phosphate-eq, 1.71E-3 kg Phosphate-eq, 1.46E-3 kg Phosphate-eq. The EP of PEM + PT is 2.98E-3 kg Phosphate-eq, 2.23E-3 kg Phosphate-eq, 1.79E-3 kg Phosphate-eq, 1.49E-3 kg Phosphate-eq. The EP of S–I + PT is 4.78E-4 kg Phosphate-eq, 3.59E-4 kg Phosphate-eq, 2.87E-4 kg Phosphate-eq, 2.39E-4 kg Phosphate-eq. The EP of PEM + PV and PEM + PT is similar, and the quantity of variation decreases significantly with the increase of lifetime. The quantity of variation of the EP of S–I + PT has little change. However, the amplitudes of variation of PEM + PV, PEM + PT, and S–I + PT are similar, with a value of about 50%.

Fig. 11 shows the changes of ODP under different lifetimes of different hydrogen production systems. When the system lifetime changes from 30 years to 60 years, the ODP of PEM + PV decreases from 3.19E–11 kg R11-eq to 1.6E–11 kg R11–eq, and the quantity of variation is 1.59E-11 kg R11-eq

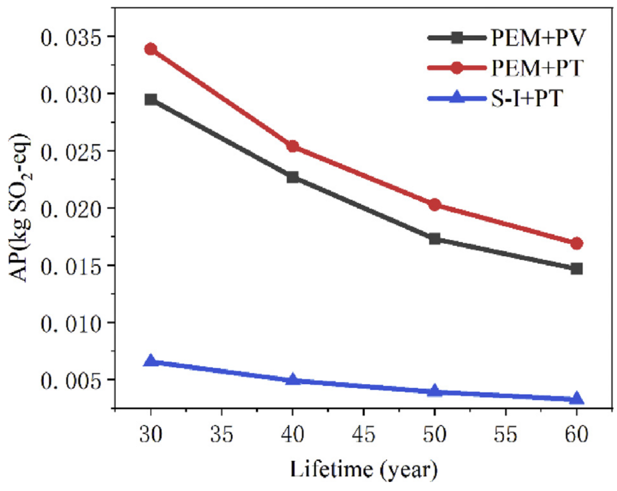

Fig. 9 – Variation of AP (per kg H_2 production) with lifetime of the system.

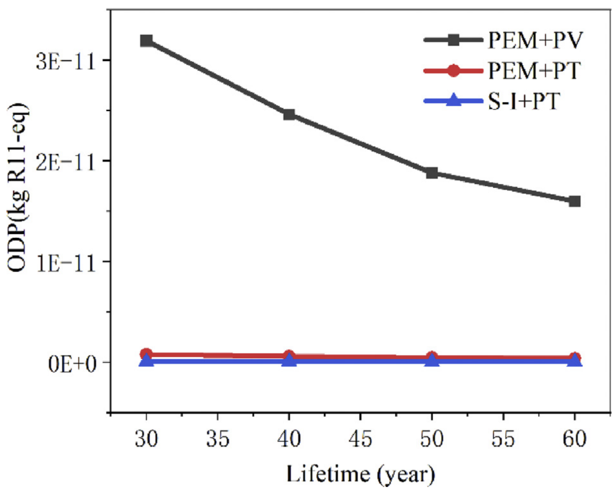

Fig. 11 – Variation of ODP (per kg H_2 production) with lifetime of the system.

The ODP of PEM + PT decreased from 7.82E-13 kg R11-eq to 3.91E-13 kg R11-eq. The ODP of S–I + PT decreased from 8.72E-14 kg R11-eq to 4.36E-14 kg R11-eq. It can be seen that with the increase of lifetime, the ODP of production of 1 kg of hydrogen will be reduced, even if the amplitudes of variation are all 50%, the quantity of variation of PEM + PV is more than that of PEM + PT and S–I + PT.

Conclusion

In this study, the life cycle assessment is carried out for hydrogen production by solar photovoltaic power generation coupled with PEM electrolysis water, solar photothermal power generation coupled with PEM electrolysis water, and solar photothermal coupling with thermochemical water splitting by S–I cycle. Four environmental impacts (GWP, AP, EP, ODP) of each method are quantified. The proportion of environmental impact in each step of each method and the change of environmental impact with lifetimes are studied and analyzed. The research conclusions of this paper are as follows:

- From the respect of the environmental impact of the whole system, solar photothermal coupling thermochemical water splitting by S–I cycle for hydrogen production has the lowest GWP, AP, EP, ODP. Therefore, S–I + PT has the best environmental impact than PEM + PT/PV. The environmental impact of solar photothermal power generation coupled with PEM water electrolysis is smaller than that of solar photovoltaic power generation coupled with PEM water electrolysis.
- During the solar photovoltaic power generation and solar thermal power generation coupled PEM water electrolysis process, the main environmental impact comes from the construction of solar power plant and PEM water electrolysis plant. In the process of solar photothermal coupling thermochemical water splitting by S–I cycle for hydrogen production, in terms of AP, the construction of hydrogen production plant is the main influence, followed by the construction of solar photothermal power plant, while GWP, EP, and ODP mainly come from the construction process of the solar thermal power plant. No matter which hydrogen production method, reducing the environmental pollution emission in the process of plant construction can greatly reduce the environmental impact of the whole hydrogen production system.
- Increasing the lifetime of the system can effectively reduce the environmental impact of the process of hydrogen production. This amount emission reduction is more obvious in hydrogen production methods with high environmental impact.

Declaration of competing interest

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

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