Front. Eng. Manag. 2023, 10(4): 672–694
https://doi.org/10.1007/s42524-022-0245-x

RESEARCH ARTICLE

Xingmei LI, Xiaoyan LV, Wenzuo ZHANG, Chuanbo XU

Can energy storage make off-grid photovoltaic hydrogen production system more economical?

Abstract Under the ambitious goal of carbon neutralization, photovoltaic (PV)-driven electrolytic hydrogen (PVEH) production is emerging as a promising approach to reduce carbon emission. Considering the intermittence and variability of PV power generation, the deployment of battery energy storage can smoothen the power output. However, the investment cost of battery energy storage is pertinent to non-negligible expenses. Thus, the installation of energy-storage equipment in a PVEH system is a complex trade-off problem. The primary goals of this study are to compare the engineering economics of PVEH systems with and without energy storage, and to explore time nodes when the cost of the former scenario can compete with the latter by factoring the technology learning curve. The levelized cost of hydrogen (LCOH) is a widely used economic indicator. Represented by seven areas in seven regions of China, results show that the LCOH with and without energy storage is approximately 22.23 and 20.59 yuan/kg in 2020, respectively. In addition, as technology costs drop, the LCOH of a PVEH system with energy storage will be less than that without energy storage in 2030.

Keywords hydrogen, off-grid photovoltaic, energy storage, LCOH, engineering economics

Received Jun. 8, 2022; revised Aug. 21, 2022; accepted Sep. 19, 2022

Xingmei LI, Xiaoyan LV, Wenzuo ZHANG, Chuanbo XU (✉)
School of Economics and Management, North China Electric Power University, Beijing 102206, China; Beijing Key Laboratory of New Energy and Low-Carbon Development, North China Electric Power University, Beijing 102206, China
E-mail: chuanbo_xu@ncepu.edu.cn

This research is supported by the National Natural Science Foundation of China (Grant No. 71772060), the State Key Laboratory of Power System Operation and Control (Grant No. SKLD22KM16), the Social Science Foundation of Beijing (Grant No. 22JCC092), and the Fundamental Research Funds for the Central Universities (Grant Nos. 2021MS022 and 2021PT013).

1 Introduction

Hydrogen (H_2), as a clean fuel, will become a game changer in the global energy industry (Bae and Cho, 2010; Hart et al., 2014; Yukesh Kannah et al., 2021). Hydrogen is predicted to play a key role in shifting the global energy system (GES) toward a sustainable energy system (SES) by 2050 (Khouya, 2020). Hydrogen can be produced from renewable or non-renewable energy (Giddey et al., 2015). Currently, hydrogen production from non-renewable energy occupies a dominant position, of which 62% is derived from coal gasification, and 19% stems from steam methane reforming (SMR). Contrastingly, hydrogen production through the electrolysis of water from renewable energy accounts for only 1%, which is far behind the former (Rezaei et al., 2019). However, non-renewable energy, such as coal and natural gas (NG), is truly exacerbating environmental pollution when converted into hydrogen, threatening to increase CO_2 levels in the atmosphere (Bae and Cho, 2010; Longden et al., 2022; Yang et al., 2022). Owing to these circumstances, more stringent environmental protection policies have been introduced internationally to reduce the consumption of non-renewable energy (Lockley and von Hippel, 2021), which will shift the gray hydrogen produced from non-renewable energy toward green hydrogen from renewable energy electrolyzed water.

Renewable energy, as the most promising way to replace fossil energy for hydrogen production (Rahmouni et al., 2017), has inherent intermittency and volatility (Ziegler et al., 2019). Furthermore, with the escalation of variable renewable energy sources, balancing the power supply system becomes difficult, thereby exacerbating the curtailment rate (Chi and Yu, 2018; Squadrito et al., 2021). For this reason, the incompatibility between supply and demand characteristics impedes the promotion of renewables; thus, tailored energy management is imperative (Zhang and Wei, 2020). Energy storage, as one of the methods to solve such problems, is being vigorously developed (Zhou et al., 2022).

Various policies have been successively issued by the Chinese government since 2021 to promote the advancement of energy storage. For example, Guidance on Accelerating the Development of New Energy Storage issued in July 2021 emphasizes that the transformation of new energy storage from the initial commercial stage to large-scale development will be realized, and the installed scale of the new energy storage will reach more than 30 GW by 2025; in addition, by 2030, the comprehensive market-oriented development of new energy storage will be realized (National Development and Reform Commission and National Energy Administration, 2021). Further, in response to the country's call to fully address the intermittency and volatility of renewable energy, many provinces have clearly issued documents that 5%–20% of energy storage devices must be configured according to the installed capacity of renewable energy (Table 1). Configuring energy storage when hydrogen is produced by electrolyzing water with renewable energy is inevitable.

Geothermal energy, hydro energy, biomass energy, wind energy, and solar energy are the five representative renewable energy sources. However, the utilization of geothermal energy is limited by the geographical environment (National Energy Administration, 2016), and hydropower poses the risk of damaging biodiversity. In addition, when biomass energy is burned, it may release into the atmosphere, which can harm the environment. Compared with the above three types of renewable energy, wind and solar energy have fewer restrictions, less impact on the ecosystem, and high cleanliness. Based on this, the state emphasized that comprehensively promoting the large-scale and high-quality development of wind power and solar power and the development and utilization of biomass energy, geothermal energy, and other energy sources according to local conditions are necessary (State-owned Assets Supervision and Administration Commission of the State Council, 2021). Compared with wind energy, solar energy has broad development prospects (Zhao et al., 2019; Zhou et al.,

Table 1 Requirements for planning and allocation proportion of new energy supporting energy storage in some provinces/cities

Province/City	Energy storage scale	Configuration proportion requirement
Hebei	-	10%
Shanxi	Pilot, 500 MW–1 GW	5%–20%
Liaoning	-	10%–15%
Jilin	-	10% for some existing projects
Jiangsu	-	Encourage allocation according to a certain proportion
Zhejiang	1 GW by 2024	Encourage allocation according to a certain proportion
Anhui	1.2 GW by 2024	10%, 1 h
Fujian	Pilot, 300 MW	10%
Jiangxi	-	10%, 1 h
Shandong	4.5 GW by 2025	10%, 2 h
Henan	-	10%, 2 h
Hubei	2021 new energy supporting, 500 MW	10%
Hunan	4 GW by 2025	10%–20%, 2 h
Guangdong	2 GW by 2025	-
Hainan	-	10%
Guizhou	-	10%
Yunnan	-	Encourage the allocation and storage of wind and solar
Shaanxi	-	10%–20%, 2 h
Gansu	Stock + newly added, preliminary 866 MW	5%–20%, 2 h
Qinghai	-	10%, 2 h
Inner Mongolia	5 GW by 2025	15%, 2 h/4 h
Guangxi	-	5%–10%, 2 h
Tibet	Pilot, 220 MW	-
Ningxia	-	10%, 2 h
Xinjiang	770 MW by 2023	10%–15%, 2 h
Tianjin	2021–2022, 526 MW	10%–15%

2021). Solar energy has a higher energy density, almost no geographical restrictions, and longer term, which make it widely used in photothermal, power generation, photochemical, and fuel oil applications (Feng et al., 2022). Therefore, corresponding to the rapid development of solar energy, this study uses solar energy to produce hydrogen and studies the economy of a photovoltaic (PV)-driven electrolytic hydrogen (PVEH) production system equipped with energy storage.

Although the introduction of energy storage makes the PVEH system operate more smoothly, the cost of configuring energy storage is high, thereby making many enterprises flinch. On the one hand, when the electricity generated by the PV panel is greater than the rated power of the electrolyzer, the energy storage system will store excess electricity. On the other hand, the stored electricity will be released as supplementary electricity for the hydrogen production. This increases the operation time of the electrolyzer, significantly increasing the amount of hydrogen produced. However, the introduction of an energy storage system will bring additional construction, operation, and maintenance costs, which cannot be underappreciated (National Energy Administration, 2021). Therefore, when the cost of a PVEH system with energy storage becomes lower than that of a PVEH system without energy storage, it is a problem worthy of in-depth study.

Based on this, the primary goals of this study are to compare the economy of off-grid PVEH systems with and without energy storage, and to explore the time node when the cost of the PVEH system with energy storage can compete with the latter by factoring the technology learning curve. The levelized cost of hydrogen (LCOH), which is calculated by determining the ratio of the total discounted costs for the life of the system to the total discounted hydrogen production, is a widely used economic indicator (Kong et al., 2021). The structural diagram of the PVEH system with energy storage is shown in Fig. 1. In addition, according to the different expectations for the future, this study will set three scenarios, namely pessimism, neutrality, and optimism, through different values of technical learning rate and calculate the LCOH of the PVEH system with and without energy storage from 2020 to 2060 under these three scenarios to obtain the time node when the LCOH of the PVEH system with energy storage is lower than that of the PVEH system without energy storage. In addition, this study compares the LCOH of a PVEH system with non-renewable energy hydrogen production methods, such as NG, NG carbon capture, utilization and storage (CCUS), coal, and coal CCUS, to further explore the economy of PVEH systems with energy storage.

In addition, as mentioned above, the main purpose of this study is to compare the economy of the PVEH system with energy storage with that without energy storage to explore the time node when the economy of the former is better than that of the latter. The contributions of this study are as follows.

(1) The economy of PV hydrogen production with energy storage is evaluated. Many studies have overlooked whether the addition of energy storage devices to PV hydrogen production systems is a trade-off issue, because whether the increased hydrogen production due to the introduction of energy storage devices can compensate for the huge investment costs caused by this requires

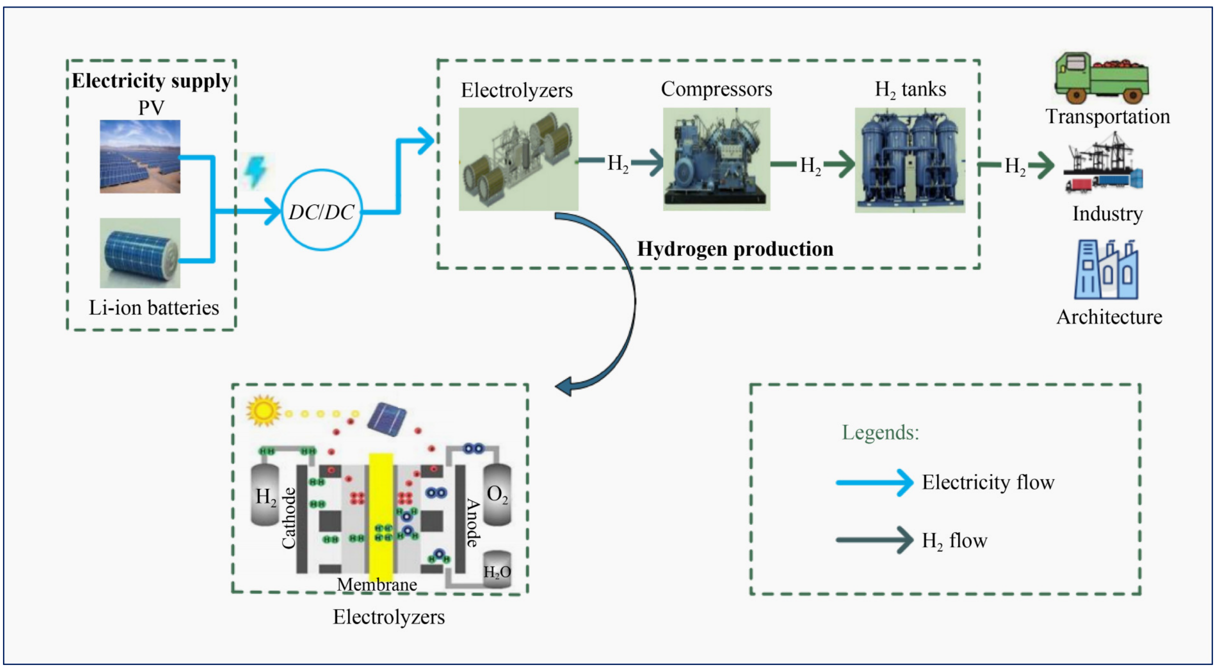


Fig. 1 Structure diagram of off-grid PV/battery/hydrogen system.

further research. Therefore, the LCOH indicator is used in this study to comprehensively compare the economics of PV hydrogen production systems with and without energy storage.

(2) The time nodes at which PV hydrogen production with energy storage can compete with PV hydrogen production without energy storage are provided. To comply with the goal of achieving carbon neutralization in 2060, this study takes 2020 to 2060 as the research interval. According to the different technical learning rates of power plants, the three scenarios of pessimism, neutrality, and optimism are given in this study to explore the time point at which the PV hydrogen production system with energy storage can compete with the PV hydrogen production system without energy storage under the effect of the technical learning rate.

(3) Discussions on the time point at which the economy of PV hydrogen production system with energy storage can compete with that of NG, NG CCUS, coal, and coal CCUS hydrogen production are carried out, and pressure tests on the impact of changes in the efficiency of electrolyzers and energy storage batteries on LCOH are performed to provide suggestions for the development of hydrogen energy in the future.

The remainder of this paper is organized as follows. Section 2 presents a comprehensive review of the relevant literature. Section 3 describes the power functions of the system components and provides an operational strategy for a PV/hydrogen/Li-ion energy storage system. Section 4 introduces the calculation of the LCOH under three situations. Section 5 presents a case study that verifies the effectiveness of the proposed framework. Finally, Section 6 concludes the study.

2 Literature review

Technical and economic analyses are equivalent to economic analysis, and the techno-economic problem of hydrogen production from renewable energy has been rolling out among scholars of different sectors in recent years. The commonly applied techno-economic research methods in the literature can be classified into techno-economic optimization and techno-economic assessment. Numerous studies have documented the development of these fields, and several representative studies are presented below.

2.1 Techno-economic optimization

To address this issue, scholars have mainly adopted the HOMER software and algorithms for techno-economic optimization. For example, Bernal-Agustín and Dufo-López (2010) considered the optimal configuration of the system when the net present value (NPV) of the wind energy hydrogen production system is equal to 0 in the grid-connected state and allows excess electricity to be sold to the grid at a variable price. Furthermore, Sanchez et al. (2014) carried out a techno-economical optimization of a stand-alone wind-PV-hydrogen power system in the southeastern region of Mexico to minimize the total cost, and a particle swarm optimizer (PSO) was used to solve the problem. Finally, the minimum, average, and maximum numbers of wind turbines, PV panels, and electrolyzers were obtained. As an improvement of previous work, Kong et al. (2021) proposed the PSO-CROA (chemical reaction optimization algorithm), which aims to maximize the profit of the system and is subject to the limitations imposed by environmental benefits and government subsidies, as required to obtain the optimal configuration of the system. Moreover, technical and economic models were established by Holl et al. (2017) to ascertain the optimal system, in which the technical model mainly emanated from nine thermodynamics and fluid mechanics equations, and NPV was selected as the target of the economic model. Furthermore, Abdin and Mérida (2019) considered nine different renewable energies (mainly wind and PV) for hydrogen production systems and their combinations and used HOMER to simulate the optimal combination and size of system components to minimize the cost of energy (COE). Pan et al. (2020) established a bi-level programming model that minimizes the total cost of the wind/PV hybrid power hydrogen generation system in the upper layer and the LCOH in the lower layer to obtain the optimal capacity allocation under eight scenarios. In addition, Chen et al. (2021) investigated the optimal configuration of a hydrogen production system from electrolytic water for renewable energy power generation using hydrogen as an energy carrier to mitigate the variability of renewable sources.

However, most of the above-mentioned studies mainly dealt with the optimal capacity configuration of renewable energy hydrogen production systems, and economic indicators only serve as a measure to obtain the optimal capacity allocation without in-depth evaluation and comparison of specific economic indicators of renewable energy hydrogen production systems to determine whether a hydrogen production method is economically viable. To this end, more scholars have used various economic analysis methods to evaluate the economy of renewable energy hydrogen generation systems.

2.2 Techno-economic assessment

Nematollahi et al. (2019) estimated the potential of solar energy and wind energy in selected provinces, and the most economical location and method of hydrogen production were obtained. Menanteau et al. (2011) examined the techno-economy of water electrolysis for hydrogen production by wind power generation in an alkaline electrolyzer. LCOH was calculated when the installed capacity changed in the range of 10–200 MW from 2020 to 2030.

In addition, Yates et al. (2020) divided the input parameter values into nominal, maximum, and minimum values to obtain the possible distribution of the LCOH of the PVEH system through Monte Carlo simulation and provided the five factors that most affected the LCOH through regression analysis. Khouya (2020) simulated the hydrogen production efficiency of wind power and PV plants with different installed capacities. The results showed that the hydrogen production efficiency of wind power plants and PV plants was 66% and 62%, respectively, and the LCOH decreased with an increase in the installed capacity of PV and wind power plants. Accordingly, Bhandari and Shah (2021) identified the economy of hydrogen production when PV is combined with an alkaline electrolyzer and proton exchange membrane (PEM) electrolyzer under off-grid and grid-connected conditions, respectively. The results showed that grid-connected PV and alkaline electrolysis (AE) were the most economical methods to produce hydrogen. Moreover, Rezaei et al. (2019) captured the LCOH, and the results revealed that the LCOH ranged from 1.375 to 1.95 dollor/kg. Besides, in Al-Qahtani et al. (2021), by including monetized values of environmental impacts on human health, ecosystem quality, and LCOH, an estimation of the "real" total cost of hydrogen was obtained to rank the alternative technologies transparently. Additionally, Shah (2020) applied fuzzy Delphi, fuzzy analytical hierarchy process (FAHP), and environmental data envelopment analysis (DEA) to evaluate the economy of hydrogen production from six renewable energy sources.

Nevertheless, renewable energy is intermittent and variable, whereas few of the studies above have considered, as we do, the economy of PVEH in the context of energy storage system. In areas pertinent to serious solar power curtailment, excess power can be stored using an energy storage battery to ensure a smooth power output, which prolongs the working life of the electrolyzer and improves its working efficiency. However, the transition from a conventional hydrogen production system to an energy-storage-based hydrogen production system is prohibitively expensive for the construction, operation, and maintenance of the energy storage system. It is noteworthy to highlight the fact that, in concert with the progress in technology in recent years, the cost of energy storage systems continues to decrease. Therefore, for practical purposes, this study presumes that the PVEH is off-grid and the capacity of the energy storage system is fixed to analyze the economy of the PVEH system equipped with energy storage.

Hence, the main gaps filled in this article are discussed as follows.

(1) In contrast to Olateju and Kumar (2016), Rezaei et al. (2021), and Squadrito et al. (2021), who ignored the economy of the PVEH system with energy storage (mainly used to smooth power output and improve the working life and efficiency of the electrolyzer), pessimistic, neutral, and optimistic scenarios are considered in this study based on the value-setting of unit investment cost. Under the three scenarios, the LCOH of the PVEH system with and without energy storage were calculated to weigh the economy of the system with energy storage.

(2) As an extension of the work of Fan et al. (2019) and Timilsina (2021), who only compared the economics of renewable energy and traditional energy equipped with carbon capture and storage (CCS) in hydrogen production, this study provides the time node when a PVEH system with energy storage is more economical than not adding energy storage, and when it can compete with NG, NG CCUS, coal, and coal CCUS hydrogen production systems.

3 Description of the PV hydrogen production system

The components included in this system are the PV panel, Li-ion energy-storage battery unit, and electrolyzer. This study considers hydrogen production by off-grid PVEH, and the electricity generated by the PV is only used for hydrogen production. When the power generated by the PV exceeds the rated power of the electrolyzer and the excess power does not exceed the available storage capacity of the Li-ion battery, the excess power is stored in the Li-ion battery. Otherwise, if the excess power exceeds the remaining capacity of the Li-ion battery, the stored power can only reach the maximum capacity of the Li-ion battery, and the rest of the power is abandoned. Conversely, if the electricity generated by the PV is less than the rated power of the electrolyzer, the Li-ion battery begins to release the stored power as a supplement to the power used for hydrogen production. The operating strategy of the proposed PVEH system with energy storage is shown in Fig. 2.

3.1 PV output

A PV system is a power system designed to capture usable solar power through PVs. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from direct current (DC) to alternating current (AC), and mounting, cabling, and other electrical accessories to set up a working system. The power output function of the PV panels considering the influence of temperature is calculated as follows (Xu et al., 2020):

$$P_{pv,t} = P_{STC} \cdot f_{pv} \cdot \frac{G(t)}{G_{STC}} \cdot (1 + \alpha_P \cdot (T_c(t) - T_{c,STC})), \quad (1)$$

where $P_{pv,t}$ denotes the output power of the PV panel at time t; P_{STC} signifies the rated power of the PV panel

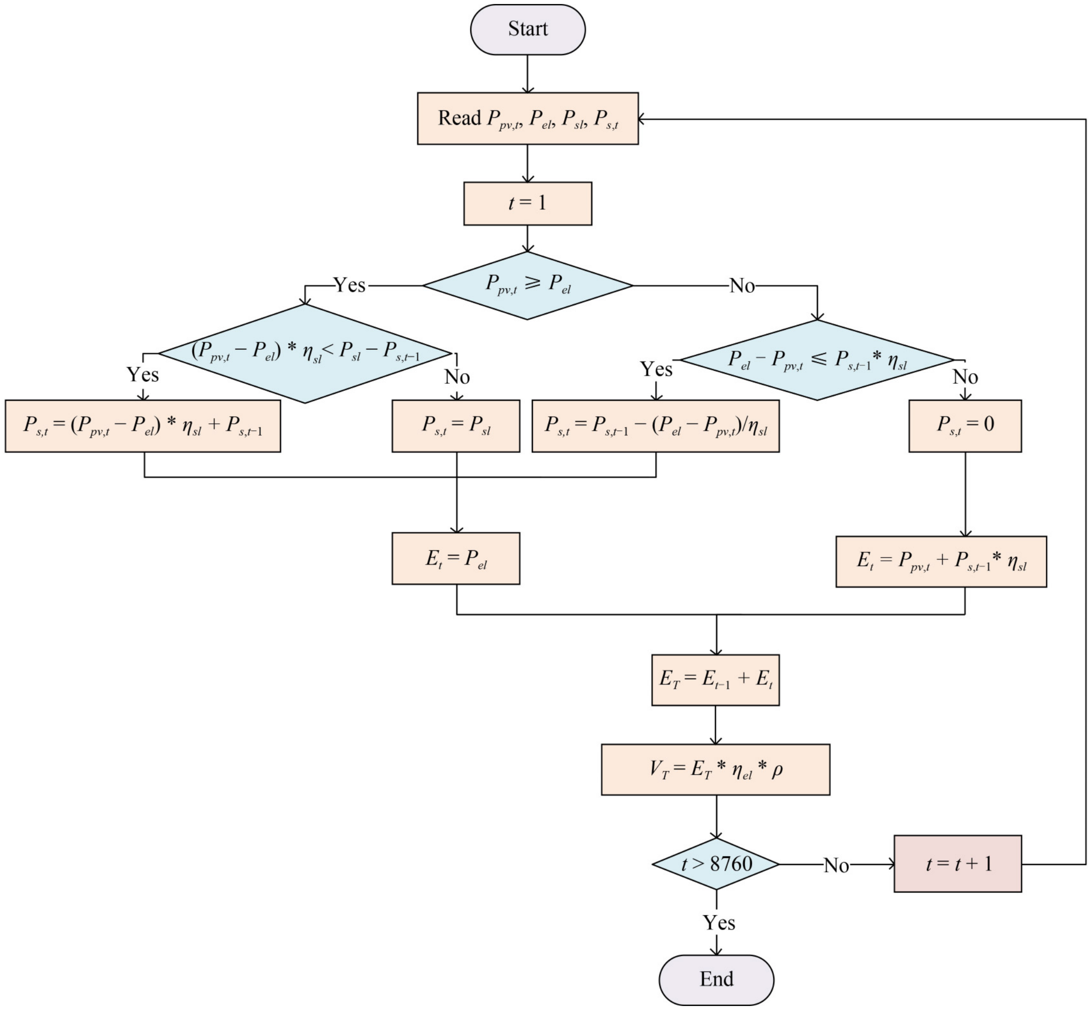


Fig. 2 Operating strategy of the proposed PVEH system with energy storage.

under standard test condition (STC); $G(t)$ indicates the actual solar radiation intensity on the PV panel at time t, whereas G_{STC} refers to the solar radiation intensity at the STC; f_{pv} refers to the PV de-rating factor due to the changing effect of the temperature and dust on the panels; and α_p is the temperature coefficient of power. Moreover, $T_c(t)$ and $T_{c,STC}$ are the real-time and STC PV panel temperatures, respectively.

The PV panel temperatures $T_c(t)$ can be determined as follows:

$$T_c(t) = T_{\partial e}(t) + 0.0256 \cdot G(t), \tag{2}$$

where $T_{\partial e}(t)$ is the actual ambient temperature and 0.0256 is the illumination temperature coefficient.

The relative parameters of the PV panels are listed in Table 2.

Table 2 Parameters of the PV panel

Parameter	Value
Rated capacity (P_{STC})	500 kW
Solar radiation intensity at the STC (G_{STC})	1 kW/m^2
PV de-rating factor (f_{pv})	80%
Temperature coefficient of power (α_P)	−0.005
STC of the PV panel temperatures ($T_{c,STC}$)	25°C

3.2 Hydrogen production system

Hydrogen energy production systems include electrolyzers and compressors. Additionally, the electrolyzer unit uses electricity to electrolyze water into hydrogen and oxygen. Currently, three mainstream electrolysis technologies can be used: AE, solid oxide electrolysis (SOE), and PEM electrolysis. This study uses AE technology because its development is the most mature and commercialized, and its cost is lower than that of the two other technologies (Saba et al., 2018). Here, let ρ be the amount of hydrogen produced per kWh of electricity. Ideally, its value should be 0.034 kg/kWh. However, owing to the efficiency of the electrolyzer, this value cannot be fully achieved. In this study, the charging efficiency of the electrolyzer η_{el} is 70%, the rated power of Li-ion battery P_{sl} is presumed to be 150 MW, and the overall energy storage efficiency

η_{sl} is 85%. Subsequently, the formulas for hydrogen production calculation in year Y under different scenarios are proposed as follows.

(1) Without Li-ion energy storage system

In this situation, given that no energy storage battery exists, power generation for hydrogen production can be obtained by comparing the output power of the PV panel at time t with the rated power of the electrolyzer. Therefore, two situations must be considered.

Case 1: $P_{pv,t} \leqslant P_{el}$, then the amount of electricity used to produce hydrogen at time t is determined by Eq. (3):

$$E_t = P_{pv,t}, \tag{3}$$

where P_{el} denotes the rated power of the electrolyzer. That is, if the output power of the PV panel at time t is less than the rated power of the electrolyzer, then all the power generated by the PV panel can be used to produce hydrogen. Thus, at time t, the power that can be used to produce hydrogen, E_t, is the output power of PV panels $P_{pv,t}$.

Case 2: $P_{pv,t} > P_{el}$, then the amount of electricity used to produce hydrogen at time t is computed using Eq. (4):

$$E_t = P_{el}. \tag{4}$$

In this case, given that no energy storage device exists, the maximum power used for hydrogen production at time t is only the rated power of the electrolyzer, whereas the excess power is abandoned.

In summary, the total power generation E_Y for hydrogen production in year Y, calculated as 8760 h, is presented as follows:

$$E_Y = \sum_{t=1}^{8760} E_t. \tag{5}$$

Then, the total hydrogen production V_Y in year Y (expressed in kilograms) is given by:

$$V_Y = E_Y \cdot \eta_{el} \cdot \rho. \tag{6}$$

(2) With Li-ion energy storage system

More complicated than in the case without energy storage, it is necessary to compare the output power of the PV panel at time t with the rated power of the electrolyzer to determine the charging and discharging states of the Li-ion battery and obtain the actual power consumption for hydrogen production when energy storage is available.

Case 1: $P_{pv,t} > P_{el}$. At this juncture, the electricity generated by the PV system is greater than the rated power of the electrolyzer. Thus, the Li-ion battery will store excess power. At time t, the power stored in the Li-ion battery $P_{s,t}$ can be expressed as follows:

$$\begin{cases} P_{s,t} = (P_{pv,t} - P_{el}) \cdot \eta_{sl} + P_{s,t-1}, \text{ if } (P_{pv,t} - P_{el}) \cdot \eta_{sl} < P_{sl} - P_{s,t-1} \\ P_{s,t} = P_{sl}, \text{ if } (P_{pv,t} - P_{el}) \cdot \eta_{sl} \geqslant P_{sl} - P_{s,t-1} \end{cases}. \tag{7}$$

Accordingly, the amount of electricity used to produce hydrogen at time t is given by Eq. (8):

$$E_t = P_{el}. \tag{8}$$

Case 2: $P_{pv,t} = P_{el}$. In this case, the electricity generated by the PV is equal to the rated power of the electrolyzer. To this end, Li-ion batteries neither store nor release electricity.

Thus, the electricity stored by the Li-ion battery at time t is expressed as:

$$P_{s,t} = P_{s,t-1}. \tag{9}$$

Similarly, the power generation used for hydrogen production can be derived using Eq. (10):

$$E_t = P_{pv,t}. \tag{10}$$

Case 3: $P_{pv,t} < P_{el}$. In this case, the power stored in the Li-ion battery is released, which plays an important role in increasing the amount of hydrogen production. The power stored by the Li-ion battery and the amount of electricity used to produce hydrogen at time t can be expressed as follows:

$$\begin{cases} P_{s,t} = P_{s,t-1} - \dfrac{P_{el} - P_{pv,t}}{\eta_{sl}}, \ E_t = P_{el}, \text{ if } P_{el} - P_{pv,t} < P_{s,t-1} \cdot \eta_{sl} \\ P_{s,t} = 0, \ E_t = P_{pv,t} + P_{s,t-1} \cdot \eta_{sl}, \text{ if } P_{el} - P_{pv,t} \geqslant P_{s,t-1} \cdot \eta_{sl} \end{cases}. \tag{11}$$

Therefore, for Li-ion energy storage, the total annual electricity generation used for hydrogen production can be derived as follows:

$$E_Y = \sum_{t=1}^{8760} E_t. \tag{12}$$

Furthermore, the mass of hydrogen, which could be obtained in year Y, is determined by Eq. (13):

$$V_Y = E_Y \cdot \eta_{el} \cdot \rho. \tag{13}$$

4 Calculation of economic indicators

LCOH is mainly used to evaluate the cost of hydrogen production in the system. Therefore, this study uses the LCOH to evaluate the economy of a PVEH system with accurate and comprehensive energy storage.

4.1 Levelized cost of hydrogen (LCOH)

In this regard, the key factor in the economic aspect of a renewable hydrogen production system is the LCOH, which is the cost incurred to gain 1 kg of hydrogen during the lifetime of the hydrogen production system. The cost of hydrogen production considers not only the initial investment due to plant construction but also the annual operating cost and interest throughout the life cycle, as well as the final residual value. The formula for calculating LCOH is as follows:

$$LCOH = \frac{C_I - \frac{S_R}{(1+i)^{TY}} + \sum_{Y=1}^{TY} \frac{A_Y + B_Y}{(1+i)^Y}}{\sum_{Y=1}^{TY} \frac{V_Y}{(1+i)^Y}}, \tag{14}$$

where C_I represents the initial investment cost. The initial investment is mainly used for the purchase of land, equipment, and plant construction, which comprises the initial investment of power, electrolytic, and energy storage plants. With the advancement of technology, the initial investments continue to decline and follow the learning curve. i represents the benchmark discount rate, which is often the benchmark discount rate of the power industry (usually 8%), and $(1+i)$ represents the discounting cost and hydrogen production capacity. In addition, β_i (i = 1, 2, 3) denotes the learning rate of the power, electrolytic, and energy storage plants, and the initial investment C_I can be expressed by Eq. (15):

$$C_I = C_0 e^{-\beta_i Y}, \tag{15}$$

where C_0 is the initial investment cost in the base year. Moreover, S_R implies the residual value of fixed assets at the end of the life cycle, which comprises three parts: The residual values of the power, electrolysis, and energy storage plants. TY represents the last year of the life cycle. A_Y signifies the annual operation and maintenance (O&M) costs, which mainly include annual maintenance costs, wages and welfare, material costs, and insurance costs. Similarly, it is mainly composed of three parts: The O&M costs of the power, electrolysis, and energy storage plants. B_Y includes the annual interest expenses of power, electrolysis, and energy storage plants.

4.2 General analytical framework for off-grid PV/battery/hydrogen system

To evaluate the economy of a PVEH system with energy storage more accurately, this section presents an analysis framework for an off-grid PVEH system with energy storage.

Step I. Identification of feasible location

Above all, according to the radiation intensity of sunlight, we identify Nanjing in Jiangsu, Foshan in Guangdong, Hohhot in Inner Mongolia, Wuhan in Hubei, Xichang in Sichuan, Haixi in Qinghai, and Harbin in Heilongjiang as the representative areas of seven regions in China (East, South, North, Central, Southwest, Northwest, Northeast China, respectively) to compare the economy of the system with and without energy storage.

Step II. Calculate the annual hydrogen production

First, according to the collected information about light and ambient temperature, the output power at time t is calculated. Second, by comparing it with the rated power of the electrolyzer and the power stored by the energy storage battery at time t, the total annual hydrogen production with and without energy storage is calculated, respectively.

Step III. Result analysis and display

First, pessimistic, neutral, and optimistic scenarios are considered in this study based on the value-setting of the unit investment cost related to the different learning rates of power plants. Under the three scenarios, the LCOH of the PVEH system with and without energy storage are calculated according to the hydrogen production amount obtained in Step II. Second, taking the neutral scenario as an example, the LCOH of seven areas is compared. Finally, the influence of energy storage on the PVEH system is analyzed.

Step IV. Discussion and sensitivity analysis

First, we further analyze the economy of the PVEH system with and without energy storage by calculating the NPV and internal rate of return (IRR). Second, we compare the economy of the PVEH system with that of NG, NG CCUS, coal, and coal CCUS hydrogen production systems and provide the time node at which the PVEH system with energy storage can compete with the above four hydrogen production methods. Finally, we discuss the impact of the respective and simultaneous efficiency changes of the electrolyzer and Li-ion battery on the LCOH as required to observe the changing trend of the LCOH, so as to provide suggestions for the development of the PVEH hydrogen production system.

5 Case study

5.1 Background

The proposed PV/hydrogen/energy storage system is applied to Nanjing (Jiangsu), Foshan (Guangdong), Hohhot (Inner Mongolia), Wuhan (Hubei), Xichang (Sichuan), Haixi (Qinghai), and Harbin (Heilongjiang). These are the central areas in the geographical locations of the seven regions of China. Thus, the illumination intensity is relatively dense.

Based on the hourly (8760 h) solar radiation density $G(t)$ and real ambient temperature $T_{\partial e}(t)$ in 2020 obtained from the local meteorological bureau, the hourly PV output of the seven locations in 2020 is illustrated in Fig. A1 in Appendix A. To proceed with the study, the relevant parameters of investment and cost of power plants, electrolysis plants, and energy storage plants are depicted in Tables B1, B2, and B3 in Appendix B, respectively, which were used to calculate the LCOH with and without the Li-ion energy storage system.

5.2 Results

Before providing the formal results, taking Haixi, Qinghai as an example, this study makes the corresponding unit investment costs pertinent to the power plants, electrolytic plants, and energy storage plants in 2020 change in the range of [−20%, 20%], as required to observe the changes in the LCOH with and without energy storage and ascertain the factor that has a significant impact on LCOH. The variations in the LCOH with and without energy storage, subsequent to the changes in the unit cost of power plants, electrolytic plants, and energy storage plants, are shown in Fig. 3.

Figure 3(a) shows that in concert with the unit cost of the power plant escalating from −20% to 20%, the LCOH grows significantly from 17.68 to nearly 23.01 yuan/kg, which increases 5.33 yuan/kg, a rise of nearly 30.15%. Contrastingly, when the unit investment cost of the electrolytic plant changes, LCOH only grows from 19.27 to 21.41 yuan/kg, which increases 2.14 yuan/kg, a raise of 11.12%. Incidentally, without energy storage, the change in the unit cost of an energy storage plant has no impact on LCOH. In conclusion, this figure puts in evidence the relative weight of each contribution, highlighting that small variation of the unit cost of the power plant creates significant variation in the LCOH without energy storage.

Drawing some parallels with Fig. 3(a), Fig. 3(b) shows that insofar as energy storage, subsequent to the unit cost of the power plant grows from −20% to 20%, the LCOH escalates from 19.51 to nearly 24.45 yuan/kg accordingly, which increases 4.94 yuan/kg, a rise of nearly 25.32%. As for unit cost changes in the electrolytic plant, LCOH increases from 20.99 to 22.97 yuan/kg, an increase of 1.98 yuan/kg or approximately 9.43%. Of the energy storage plant, in concert with the change of its unit cost, LCOH increases from 21.46 to 22.50 yuan/kg, an increase of 1.04 yuan/kg, or nearly 4.85%.

As alluded to earlier, it is conspicuous that the unit cost of the power plant is the most salient factor affecting LCOH, irrespective of whether energy storage is added, whereas electrolytic plants and energy storage plants have minor impacts on LCOH. However, owing to the uncertainty of technology, national policy, and market, it is difficult to accurately predict the change in the learning rate of power plants in the future. Therefore, according to the different learning rates of power plants, this study is divided into three scenarios (pessimistic, neutral, and optimistic) to explore the economy of PV hydrogen production technology with energy storage. Moreover, to comply with the goal of achieving carbon neutrality by 2060, the changes in LCOH from 2020 to 2060 concerned with the different learning rates of power plants are investigated under pessimistic, neutral, and optimistic scenarios.

5.2.1 Calculation results of LCOH in three scenarios

(1) LCOH of the pessimistic scenario

In a pessimistic scenario, the learning rate of the power plant is assumed to be 0.02, namely, $\beta_1 = 0.02$, whereas the learning rate of the electrolytic plant is 0.15, that is, $\beta_2 = 0.15$, and the learning rate of the energy storage plant is 0.3, that is, $\beta_3 = 0.3$, which implies that we are pessimistic about the future and do not deem there will be much room for progress in the technology of the power plant in the future, which will contribute to the prominent reduction of the unit investment cost. As specified above, under the pessimistic scenario, the trends of the LCOH with and without energy storage in the seven areas are shown in Table 3.

Table 3 shows that in 2020, the value of LCOH with energy storage in the seven areas fluctuated around 22 yuan/kg, which was greater than the value of LCOH without energy storage, which fluctuated around 21 yuan/kg. However, in concert with the further progress of the technology, LCOH with and without energy storage drops sharply, and 2030 is a key time node when the LCOH with energy storage will be more competitive than the LCOH without energy storage, with values of

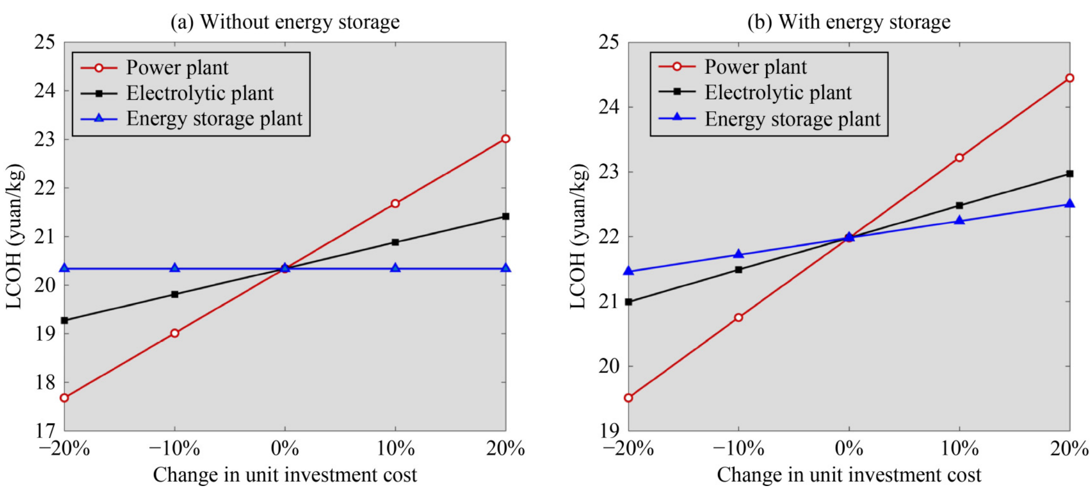


Fig. 3 Change of LCOH with unit investment cost.

Table 3 LCOH with and without energy storage in the pessimistic scenario

Area	Whether there is energy storage	LCOH under the pessimistic scenario (yuan/kg)				
		2020	2030	2040	2050	2060
Nanjing	×	20.78	14.11	11.16	9.30	7.90
	√	22.43	13.76	10.90	9.17	7.87
Foshan	×	20.84	14.14	11.17	9.31	7.91
	√	22.48	13.78	10.91	9.18	7.89
Hohhot	×	20.59	13.95	11.02	9.17	7.78
	√	22.23	13.60	10.76	9.04	7.76
Wuhan	×	20.39	13.81	10.90	9.07	7.69
	√	22.02	13.47	10.65	8.95	7.67
Xichang	×	20.42	13.82	10.91	9.07	7.70
	√	22.06	13.48	10.66	8.95	7.68
Haixi	×	20.34	13.77	10.86	9.03	7.66
	√	21.98	13.43	10.61	8.91	7.64
Harbin	×	20.62	13.96	11.02	9.16	7.77
	√	22.25	13.60	10.75	9.03	7.74

Table 4 LCOH with and without energy storage in the neutral scenario

Area	Whether there is energy storage	LCOH under the neutral scenario (yuan/kg)				
		2020	2030	2040	2050	2060
Nanjing	×	20.78	12.56	8.80	6.60	5.15
	√	22.43	12.32	8.71	6.67	5.33
Foshan	×	20.84	12.59	8.81	6.61	5.16
	√	22.48	12.34	8.73	6.68	5.33
Hohhot	×	20.59	12.42	8.67	6.49	5.05
	√	22.23	12.18	8.59	6.56	5.23
Wuhan	×	20.39	12.29	8.58	6.41	4.98
	√	22.02	12.06	8.50	6.49	5.16
Xichang	×	20.42	12.30	8.58	6.41	4.98
	√	22.06	12.07	8.50	6.49	5.16
Haixi	×	20.34	12.25	8.54	6.38	4.95
	√	21.98	12.02	8.46	6.45	5.14
Harbin	×	20.62	12.42	8.66	6.47	5.03
	√	22.25	12.17	8.58	6.54	5.20

approximately 13.60 and 14.11 yuan/kg, respectively. Likewise, the LCOH with energy storage is significantly smaller than the LCOH without energy storage before 2050. Since then, an interesting phenomenon has occurred. LCOH with energy storage gradually approaches LCOH without energy storage. By 2050, the LCOH with and without energy storage will be approximately 9.06 and 9.13 yuan/kg, respectively, with a difference of only about 0.07 yuan/kg. Further, by 2060, LCOH without energy storage is almost close to LCOH with energy storage, with values of about 7.66 and 7.64 yuan/kg, respectively. The main factors driving the change in LCOH include the maturity of energy storage technology, and the decline rate of unit investment cost of energy storage plant presents a marginal decreasing effect. Therefore, the decline of LCOH with energy storage gradually slows down and gradually becomes consistent with that of LCOH without energy storage.

(2) LCOH of the neutral scenario

Different from the pessimistic scenario, in the neutral scenario, we set the learning rate of the power plant to 0.035, that is, $\beta_1 = 0.035$, whereas the learning rates of the electrolytic plant and energy storage plant remain unchanged, namely, $\beta_2 = 0.15$ and $\beta_3 = 0.3$. This scenario implies that we hold a neutral attitude toward the future technological progress of the power plant. In other words, the technology of the power plant will progress in the future, but not significantly. The changes in LCOH in the seven areas are outlined in Table 4.

Table 4 shows that in 2020, the LCOH with energy storage is higher than that without energy storage. However, in synchronization with the advancement of technology, LCOH with and without energy storage continue to decline, and 2030 is a key time node when LCOH with energy storage will be more competitive than LCOH without energy storage, with values of 12.18 and 12.42 yuan/kg, respectively. Compared with the pessimistic scenario of 2030, the values of LCOH with and without energy storage have decreased significantly. Differently, in the neutral scenario, the improvement of the learning rate of the power plant makes the LCOH with energy storage begin to be greater than that without energy storage in 2050, with values of 6.49 and 6.41 yuan/kg, respectively. In addition, by 2060, the LCOH with and without energy storage will be 5.16 and 4.89 yuan/kg, respectively.

(3) LCOH of the optimistic scenario

In this scenario, we set the learning rate of the power plant to 0.05, that is, $\beta_1 = 0.05$, whereas the learning rates of the electrolytic plant and energy storage plant are identical to upfront, namely, $\beta_2 = 0.15$ and $\beta_3 = 0.3$. To this end, the changes in the LCOH with and without energy storage are listed in Table 5.

Table 5 shows that 2030 is a key time node when LCOH with energy storage will be more competitive than LCOH without energy storage with values of 10.95 and 11.09 yuan/kg, respectively. Different from the neutral scenario, as early as 2040, the LCOH with energy storage began to be higher than that without energy storage, with values of about 6.97 and 6.92 yuan/kg, respectively. By 2060, the LCOH with and without energy storage will be 3.93 and 3.64 yuan/kg, respectively.

(4) Comparison of the LCOH in the three scenarios

By comparing the results under the pessimistic, neutral, and optimistic scenarios, the LCOH of the PVEH system with energy storage will be less than that without energy

Table 5 LCOH with and without energy storage in the optimistic scenario

Area	Whether there is energy storage	LCOH under the optimistic scenario (yuan/kg)				
		2020	2030	2040	2050	2060
Nanjing	×	20.78	11.23	7.05	4.88	3.64
	√	22.43	11.09	7.10	5.08	3.93
Foshan	×	20.84	11.25	7.06	4.88	3.64
	√	22.48	11.11	7.11	5.08	3.93
Hohhot	×	20.59	11.09	6.94	4.78	3.55
	√	22.23	10.95	6.99	4.98	3.84
Wuhan	×	20.39	10.97	6.86	4.71	3.49
	√	22.02	10.84	6.91	4.92	3.79
Xichang	×	20.42	10.98	6.86	4.72	3.49
	√	22.06	10.85	6.91	4.92	3.79
Haixi	×	20.34	10.94	6.83	4.69	3.47
	√	21.98	10.80	6.87	4.89	3.76
Harbin	×	20.62	11.09	6.92	4.75	3.52
	√	22.25	10.95	6.97	4.95	3.81

storage by 2030. The difference is that, first, the reduction rate of LCOH in the optimistic scenario is greater than that in the neutral scenario because of the difference in learning rate, and the reduction rate of LCOH in the neutral scenario is greater than that in the pessimistic scenario, thereby making the LCOH of the PVEH system in the optimistic scenario less than that in the neutral scenario and the LCOH in the neutral scenario less than that in the pessimistic scenario in the same year. Second, with the maturity of the technology market, the decline rate of the unit investment cost of energy storage presents a marginal decline effect: The larger the learning rate, the sooner the unit investment cost of energy storage reaches the mature level, whereas hydrogen production increases because the energy storage remains unchanged, thereby enabling the LCOH of the PVEH system with energy storage to reach the mature level as the learning rate increases. Therefore, in the pessimistic scenario, the LCOH with energy storage is always smaller than that without energy storage. In the neutral scenario, the LCOH with energy storage begins to be larger than that without energy storage from 2050, whereas in the optimistic scenario, the time is advanced to 2040.

5.2.2 Comparison of LCOH in the seven areas

To clearly show the change trend of the LCOH with and without energy storage in the seven areas, this section will take the neutral scenario as an example to compare the LCOH with and without energy storage in the seven areas from 2020 to 2030. The results are shown in Fig. 4.

Figure 4 shows that with the increase in hydrogen production, the cost of hydrogen production in different areas will vary greatly. In addition, the LCOH of Foshan in Guangdong is the highest, whereas that of Haixi in Qinghai is the lowest, regardless of whether energy storage is available. The LCOH of the five other areas from high to low is Nanjing (Jiangsu), Harbin (Heilongjiang), Hohhot (Inner Mongolia), Xichang (Sichuan), and Wuhan (Hubei).

5.2.3 Influence analysis of energy storage on PVEH system

In this section, we analyze the role of energy storage in the PVEH system from three aspects: The initial investment cost of energy storage, output of energy storage, and increased hydrogen production after adding energy storage.

(1) Initial investment cost of energy storage when adding energy storage is more economical

The discussion above shows that under pessimistic,

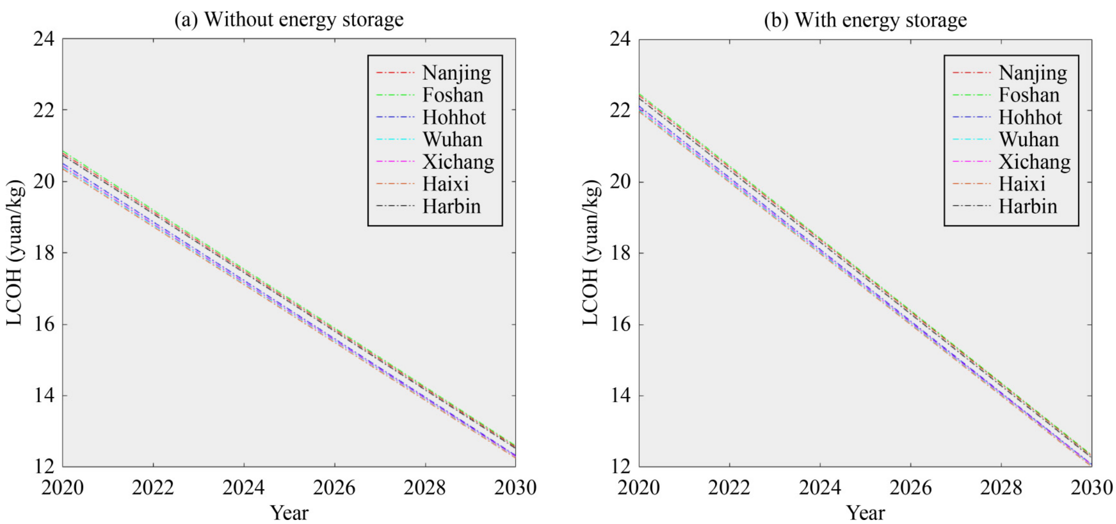


Fig. 4 LCOH without and with energy storage in the seven areas.

neutral, or optimistic scenarios, the LCOH of the PVEH system with energy storage in 2030 will be smaller than that of the system without energy storage. Therefore, the neutral scenario is taken as an example to observe the change in the initial investment cost of energy storage from 2020 to 2030 when making the PVEH system with energy storage more economical (Table 6).

Table 6 shows that the initial investment cost of 150 kW energy storage in seven areas in 2020 is about 1.8×10^8 yuan. At this time, the PVEH system with energy storage does not have a competitive advantage. In 2030, when the initial investment cost of energy storage is reduced to 8.9×10^6 yuan, the PVEH system with energy storage began to be competitive with the PVEH system without energy storage.

(2) Energy storage output after adding energy storage

Take Foshan, Guangdong with the highest LCOH and Haixi, Qinghai with the lowest LCOH among the seven areas as examples to observe the output of the energy storage battery in 168 h a week.

As shown in Fig. 5, the outputs of the energy storage battery in Foshan, Guangdong, and Haixi, Qinghai are also similar because the PV output is relatively stable and the power of the electrolyzer is 100 MW. They start charging at approximately 8:00 am every day. The remaining power after meeting the rated power of the electrolyzer can fully charge the 150 MW energy storage battery because of sufficient sunlight. However, owing to the weak sunlight intensity after approximately 7:00 pm, the energy storage battery begins to discharge. The main differences between the outputs of the energy storage batteries in the two areas are that the discharge time of the energy storage batteries in Foshan is approximately 2 h earlier than that in Haixi, and the discharge point of the energy storage batteries in Foshan is slightly smaller than that in Haixi.

(3) Increased hydrogen production after adding energy storage

Taking Haixi, Qinghai as an example, we observe increased hydrogen production within one week after adding energy storage. The results are shown in Fig. 6.

As can be seen from Fig. 6, corresponding to the time when the energy storage battery is discharged in Fig. 5, the hydrogen produced by the electric power discharged from the energy storage at this time is increased compared to that without energy storage. Figure 6 also shows that the energy storage battery releases power for hydrogen production between approximately 7:00 pm and 8:00 pm every day. Compared with the case without energy storage, hydrogen can be increased by approximately 2774.4 kg per day after adding energy storage.

Table 6 Initial investment cost of energy storage

Area	Initial investment cost of energy storage (yuan)	
	2020	2030
Nanjing	180003600	8961852
Foshan	180003050	8961822
Hohhot	180001502	8961747
Wuhan	180001010	8959622
Xichang	180001307	8961547
Haixi	180000000	8958622
Harbin	180002100	8960822

5.3 Discussion

Next, we will further analyze the economy of the PVEH hydrogen production system from three aspects: 1) calculation of NPV and IRR economic indicators, 2) comparison with traditional hydrogen production methods, and 3) effect of efficiency change in electrolyzers and energy storage batteries on the economy of a PVEH system with energy storage.

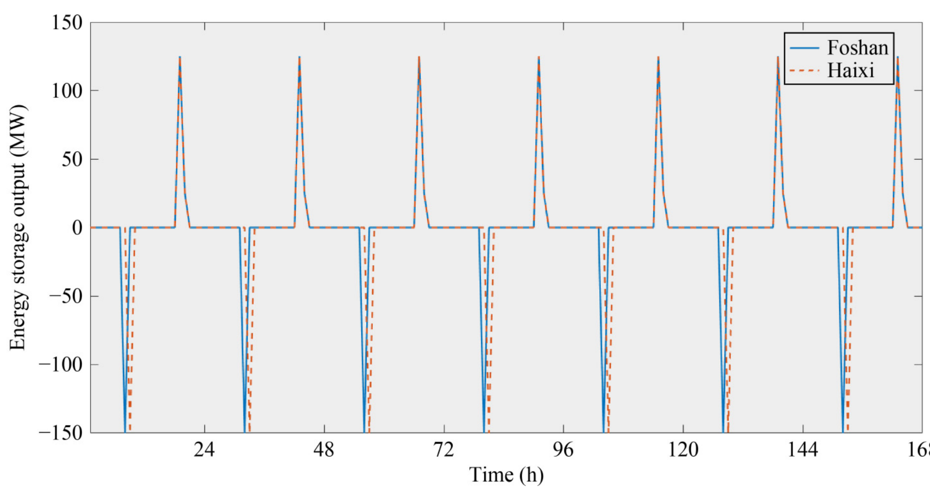


Fig. 5 Output of energy storage battery: A negative value indicates discharging whereas a positive value indicates charging.

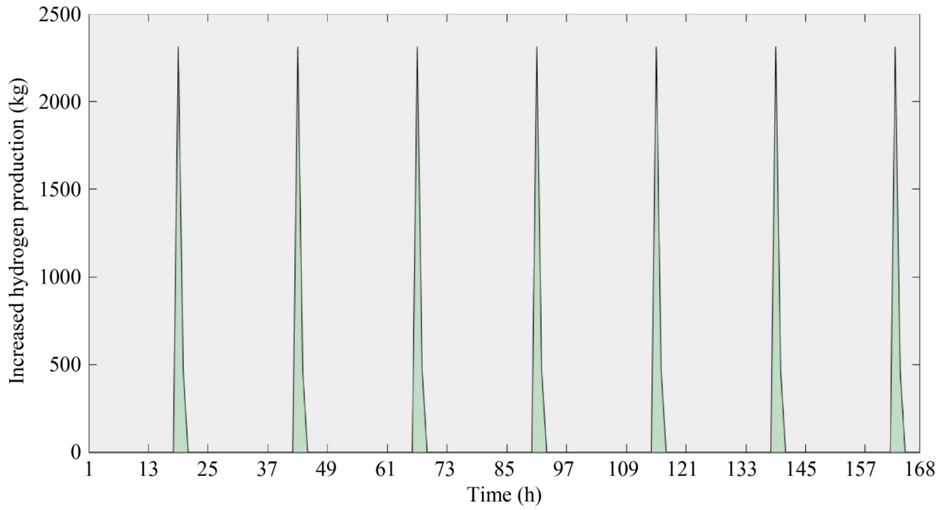


Fig. 6 Increased hydrogen production after adding energy storage.

5.3.1 Calculation of NPV and IRR

LCOH is mainly used to evaluate the cost of hydrogen production in the system. However, this does not reflect project profitability. Although NPV can compensate for the LCOH defect, it cannot reflect the efficiency of unit investment in project investment. On the contrary, the IRR is an important indicator for investigating the use efficiency of project funds. Therefore, this section comprehensively reflects the economy of the PVEH system by calculating NPV and IRR. The specific calculation formula is as follows:

$$NPV = -C_I + \frac{S_R}{(1+i)^{TY}} + \sum_{Y=1}^{TY} \frac{C_{A,Y} - A_Y}{(1+i)^Y}, \tag{16}$$

where $C_{A,Y}$ implies the annual cash inflow, which mainly refers to the profit from the sale of hydrogen, and can be calculated using the following formula:

$$C_{A,Y} = V_Y \cdot \gamma, \tag{17}$$

where γ represents the market price per kilogram of hydrogen, which usually takes a value of 30.64 yuan/kg according to reference (Bhandari and Shah, 2021).

Notably, if $NPV = 0$, then the IRR can be obtained by using Eq. (18):

$$0 = -C_I + \frac{S_R}{(1+IRR)^{TY}} + \sum_{Y=1}^{TY} \frac{C_{A,Y} - A_Y}{(1+IRR)^Y}. \tag{18}$$

The changes in NPV and IRR in the seven areas from 2020 to 2060 are shown in Fig. 7.

Figure 7(a) presents that around 2030, the NPV of the system with energy storage in the seven areas will be greater than that of the system without energy storage. The NPV of the seven areas after adding energy storage from large to small is: Harbin, Haixi, Wuhan, Xichang, Hohhot, Nanjing, and Foshan. Similarly, Fig. 7(b) depicts that, also around 2030, the IRR of the system with energy storage in the seven areas is greater than that of the system without energy storage, and the IRR of the seven areas is relatively close, with only about 1% difference of a certain year. After adding energy storage, the IRR of the seven areas from large to small is: Harbin, Haixi, Wuhan, Xichang, Hohhot, Nanjing, and Foshan (among them, the IRRs of Wuhan and Xichang are the same, and the IRRs of Nanjing and Foshan are the same).

5.3.2 Economic comparison with traditional fossil fuels

(1) Consider different hydrogen production methods

Next, the economy of the PVEH with energy storage under the three scenarios is further explored by comparing the economy of this system with that of NG, NG CCUS, coal, and coal CCUS. The LCOH of NG, NG CCUS, coal, and coal CCUS hydrogen production systems in 2020 and 2060, respectively, are shown in Fig. 8.

Figure 8 shows that the LCOH of three hydrogen production methods have showed an increasing trend from 2020 to 2060, except that the LCOH of coal CCUS showed a slight downward trend from 2020 to 2060. Therefore, if the change in the LCOH of the PVEH system with and without energy storage is compared with the LCOH of the four traditional hydrogen production modes in 2020, then the latest time nodes for the PVEH system with and without energy storage to compete with the traditional hydrogen production modes in the pessimistic, neutral, and optimistic scenarios are presented as follows.

Under the pessimistic scenario, Fig. 8 shows that in 2020, the LCOH of NG, NG CCUS, coal, and coal CCUS are 9.25, 13.22, 7.27, and 9.05 yuan/kg, respectively; whereas the LCOH of PVEH system without and with energy storage is 21 and 22 yuan/kg, respectively. Therefore, adopting a PVEH system for hydrogen production

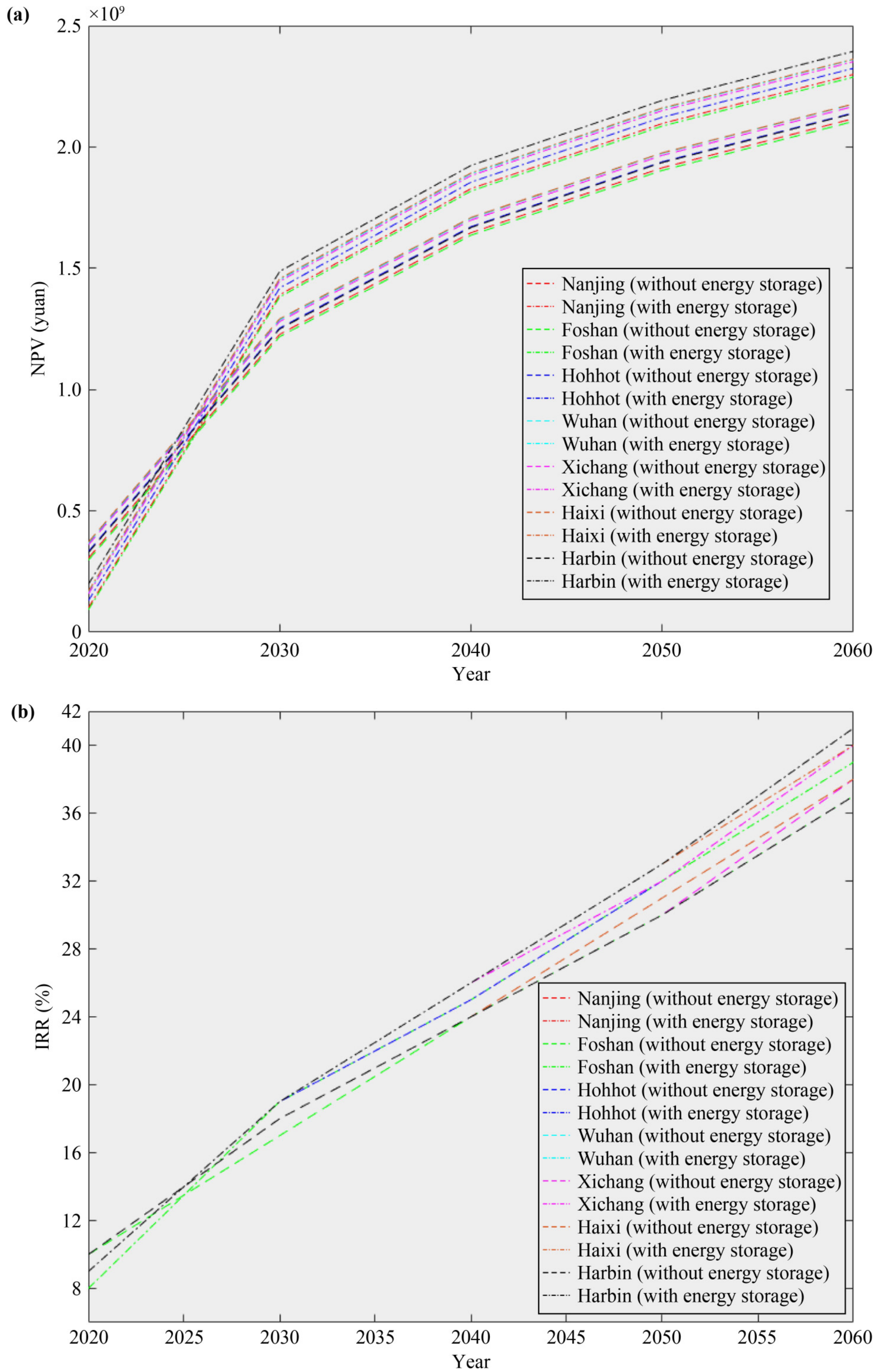


Fig. 7 NPV and IRR in the seven areas.

in 2020 does not have the advantage competing with the four traditional hydrogen production methods. From 2035, the PVEH systems with and without energy storage can compete with the NG CCUS system. By 2050, PVEH systems with and without energy storage can compete with NG and coal CCUS hydrogen production systems. Furthermore, due to the scarcity of fossil resources, the LCOH of the PVEH system with and without energy storage since 2060 is about 7.66 and 7.64 yuan/kg, respectively, which can compete with the four traditional hydrogen production methods, with values of 21.15, 14.54, 21.15, and 8.59 yuan/kg, respectively.

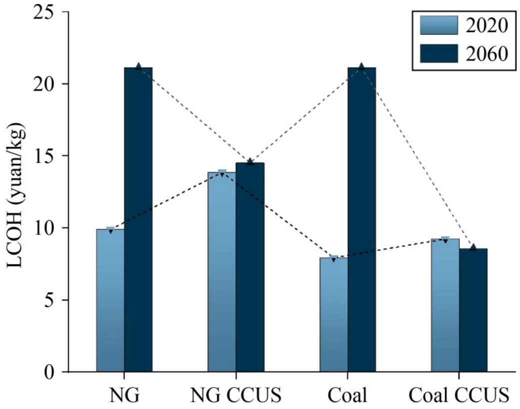


Fig. 8 LCOH with different hydrogen production methods in 2020 and 2060, respectively.

Under the neutral scenario, the LCOH of the PVEH system without and with energy storage is 20.50 and 22.05 yuan/kg, respectively, which still cannot compete with NG, NG CCUS, coal, and coal CCUS in 2020. From 2030, the PVEH systems with and without energy storage can compete with the NG CCUS system, which is five years earlier than the pessimistic scenario. From 2040, PVEH systems with and without energy storage can compete with NG and coal CCUS hydrogen production systems, which is 10 years earlier than the pessimistic scenario. From 2050, PVEH systems with and without energy storage can compete with the four traditional hydrogen production methods, which is 10 years earlier than that of the pessimistic scenario.

Under the optimistic scenario, PVEH systems with and without energy storage cannot compete with traditional hydrogen production methods in 2020. Similar to the neutral scenario, from 2030, the PVEH systems with and without energy storage can compete with the NG CCUS system. The difference is that, from 2040, which is 10 years earlier than the neutral scenario, the PVEH system with and without energy storage can compete with the four traditional hydrogen production modes.

(2) Consider the carbon trading market

Incidentally, if the carbon trading market is considered, the LCOH of various hydrogen production methods after adding the carbon trading cost according to the current carbon price of 40 yuan/ton are shown in Table 7.

If the carbon trading market is considered, then the PVEH systems with and without energy storage can compete with the NG CCUS system in a pessimistic scenario from 2035. By 2050, PVEH systems with and without energy storage can compete with NG, NG CCUS, and coal CCUS hydrogen production systems. Under the neutral scenario, from 2040, PVEH systems with and without energy storage can compete with the four traditional hydrogen production methods. Under the optimistic scenario, this time could be advanced to 2035.

Table 7 CO_2 emissions of H_2 production and LCOH

H_2 production pathway	CO_2 emission (kg CO_2eq/kg H_2)	LCOH (yuan/kg)
NG	12.40	10.40
NG CCUS	4.30	14.05
Coal	19.14	8.70
Coal CCUS	1.80	9.32

(3) Consider state subsidies

Incidentally, in 2020, the transportation cost of hydrogen in China was estimated to be 13–15 yuan/kg. If the transportation process of hydrogen is considered, the LCOH of the PVEH system with and without energy storage in the pessimistic scenario will be 37 and 35.60 yuan/kg, respectively. Meanwhile, the current price of hydrogen acceptable to users is approximately 35 yuan/kg. At present, a subsidy of 0.6–2 yuan/kg needs to be provided by the state in 2020 to support the development of hydrogen energy. However, in neutral and optimistic situations, the government is not required to provide subsidies.

5.3.3 Effect of component efficiency change on LCOH

(1) Influence of electrolyzer efficiency change on the LCOH

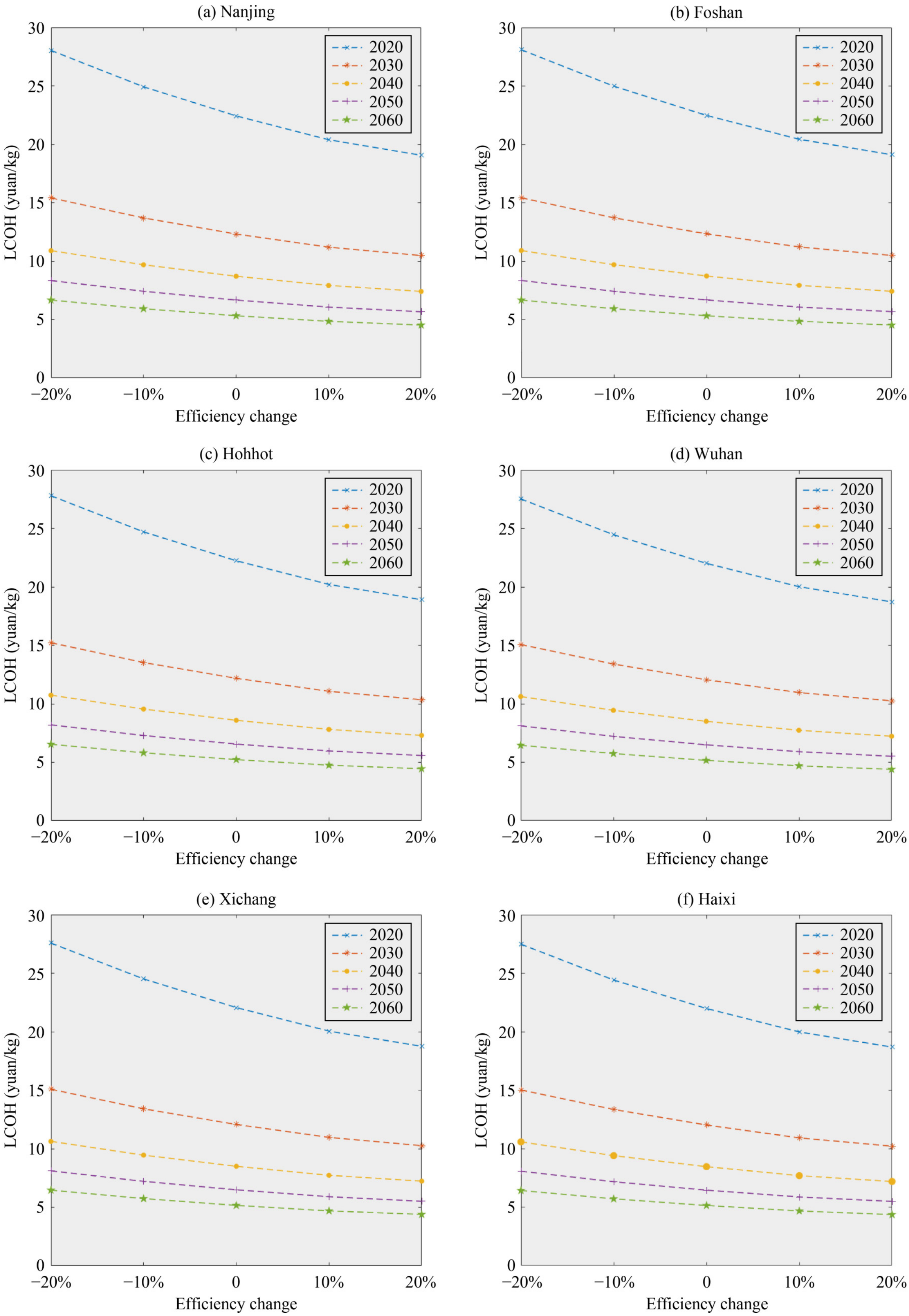
First, taking the neutral scenario as an example, we explore the changes in the LCOH of PVEH system with energy storage in seven areas synchronously with the efficiency of the electrolyzer ranging within [−20%, 20%], whereas the efficiency of the Li-ion battery remains unchanged. The results are shown in Fig. 9.

Figure 9 depicts that with the continuous increase in the efficiency of the electrolyzer, LCOH undergoes a trend of decline in each year. Further, by 2040, when the efficiency of the electrolyzer increases by 10%, the PVEH system with and without energy storage can compete with NG, NG CCUS, coal, and coal CCUS. Originally, this time will be 2050. The reason is that the amount of hydrogen production increases with the efficiency of the electrolyzer. Thus, the unit hydrogen production cost decreases under the same investment cost.

(2) Effect of efficiency change of Li-ion batteries on LCOH

Second, we investigate the variations in LCOH of PVEH system with energy storage when the efficiency of the Li-ion battery ranges from [−20%, 20%], whereas the efficiency of the electrolyzer remains unchanged. The results are shown in Fig. 10.

Figure 10 shows that unlike the effect of the change in the electrolyzer efficiency on LCOH, along with the escalation of Li-ion battery efficiency, the downward trend of the LCOH curve in each year is relatively flat, that is, LCOH only decreases slightly, which also indicates that the increase in Li-ion battery efficiency has modest effect on LCOH.


(a) Nanjing
(b) Foshan
(c) Hohhot
(d) Wuhan
(e) Xichang
(f) Haixi
LCOH (yuan/kg)
Efficiency change
−20%
−10%
0
10%
20%
0
5
10
15
20
25
30
2020
2030
2040
2050
2060

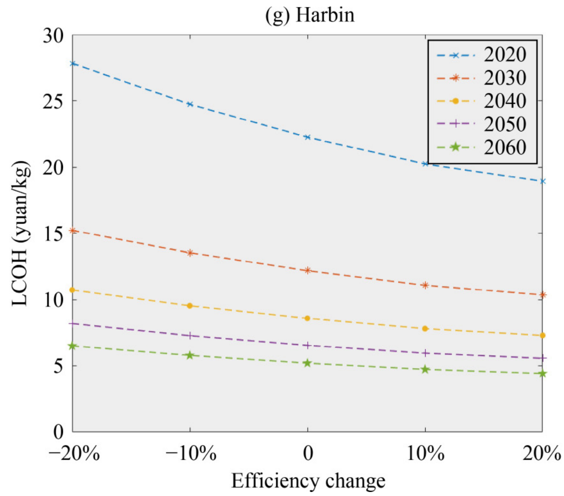
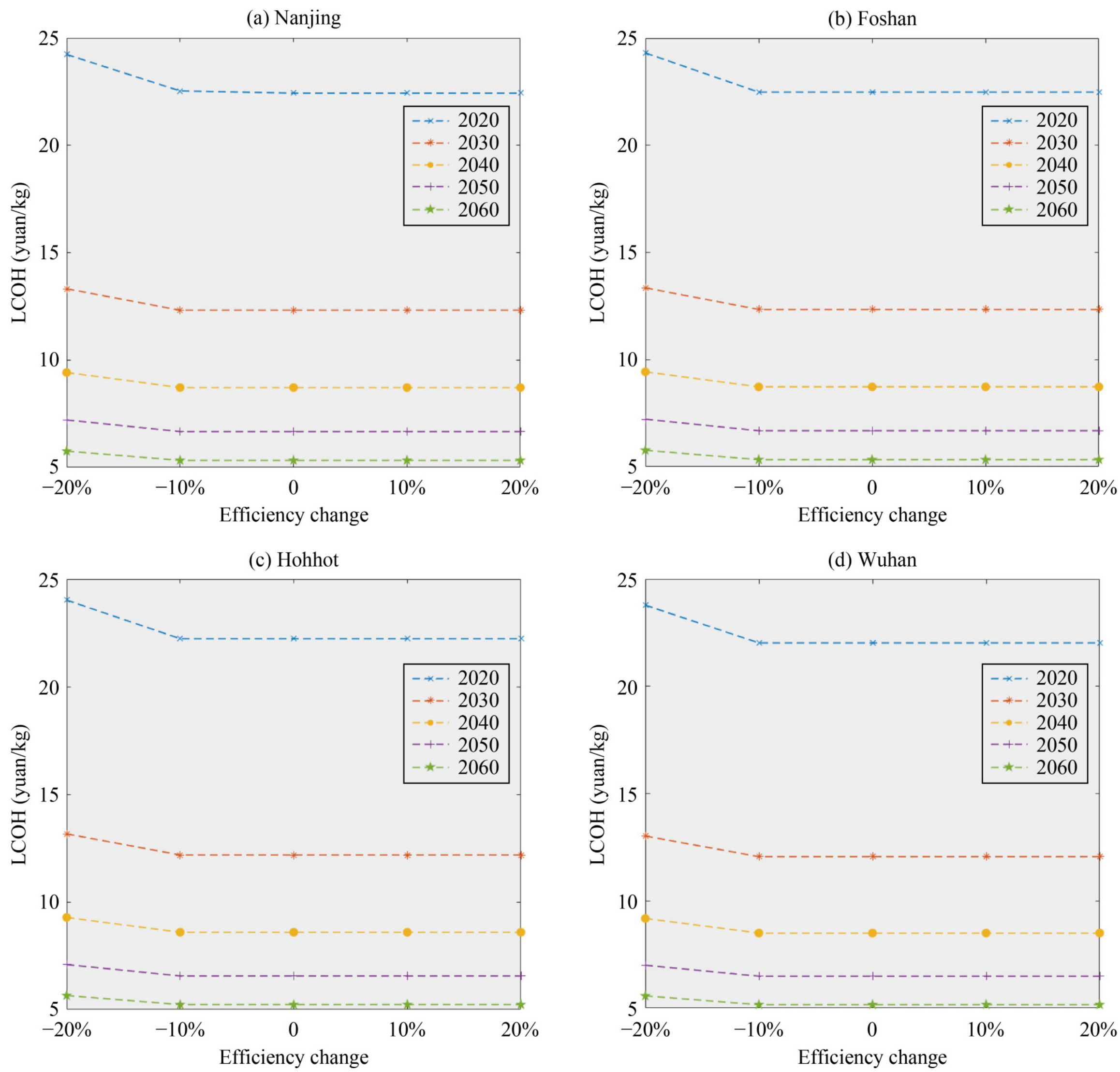


Fig. 9 Influence of electrolyzer efficiency change on LCOH: (a) Nanjing, Jiangsu in East China; (b) Foshan, Guangdong in South China; (c) Hohhot, Inner Mongolia in North China; (d) Wuhan, Hubei in Central China; (e) Xichang, Sichuan in Southwest China; (f) Haixi, Qinghai in Northwest China; (g) Harbin, Heilongjiang in Northeast China.



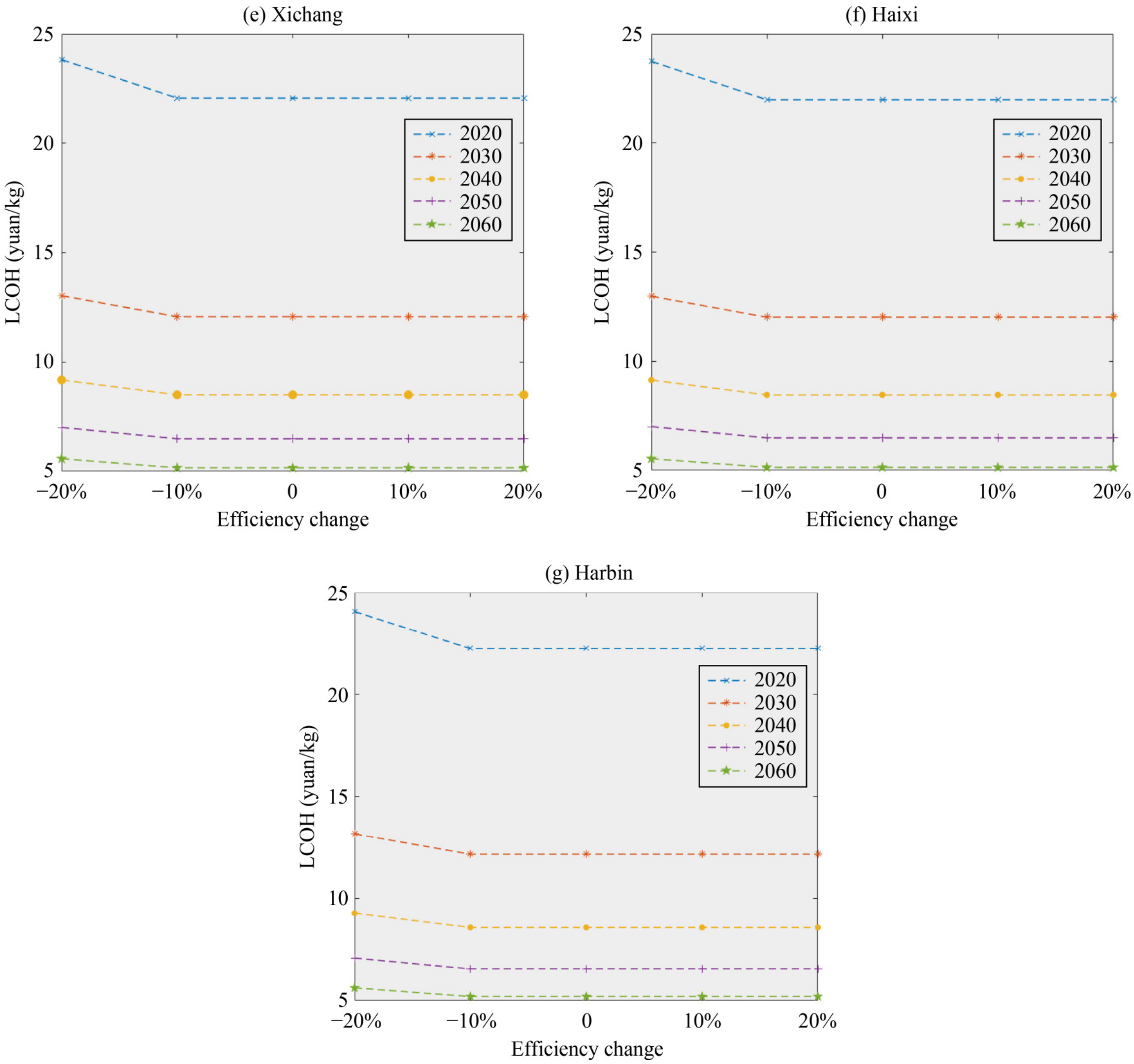


Fig. 10 Influence of Li-ion battery efficiency change on LCOH: (a) Nanjing, Jiangsu in East China; (b) Foshan, Guangdong in South China; (c) Hohhot, Inner Mongolia in North China; (d) Wuhan, Hubei in Central China; (e) Xichang, Sichuan in Southwest China; (f) Haixi, Qinghai in Northwest China; (g) Harbin, Heilongjiang in Northeast China.

6 Conclusions, policy suggestions, and future work

6.1 Conclusions

The PV/hydrogen/Li-ion energy storage system is a safe solution to the problem of discarding sunlight. However, technical and economic analyses of PVEH based on Li-ion energy storage systems are underappreciated in incumbent studies. To this end, a PV/hydrogen/Li-ion energy storage system is analyzed in this study. In the first stage, the amount of electricity that could be used to produce hydrogen annually is calculated, and the amount of hydrogen production in a year is obtained on this basis. Then, the LCOH of PV power generation with and without energy storage is reckoned in pessimistic, neutral, and optimistic scenarios. Finally, the effects of changes in the electrolyzer and Li-ion battery efficiency on LCOH are investigated. The following results are obtained.

(1) Irrespective of whether an energy storage system exists, the unit investment cost of a power plant has a formidable effect on the economy of the PVEH system, whereas the unit investment costs of the electrolysis and energy storage plants have modest effect on the economy of the system.

(2) As for LCOH, by 2030, under the pessimistic, neutral, and optimistic scenarios, the LCOH with energy storage will be less than that without energy storage. In the pessimistic scenario, LCOH with and without energy storage in 2060 can compete with NG, NG CCUS, coal, and coal CCUS simultaneously. In the neutral and optimistic scenarios, this time is advanced to 2050 and 2040, respectively. After considering the carbon trading market, under the pessimistic, neutrality, and optimistic scenarios, the time when the PVEH system with and without energy

storage can compete with NG, NG CCUS, coal, and coal CCUS will be advanced to 2050, 2040, and 2035, respectively.

(3) The effect of the changes in electrolyzer efficiency on the LCOH is more salient than that of the Li-ion battery. Furthermore, when they change simultaneously, the effect on LCOH is more prominent than that of individual changes on LCOH.

6.2 Policy suggestions

(1) Economically, the aforementioned tests show that the unit investment cost of a power plant has a formidable effect on the LCOH. To this end, increasing research and development (R&D) expenditure on power plant components, such as PV panels, and promoting the development of more economical components are necessary to reduce the unit investment cost of the power plant and obtain a smaller LCOH.

(2) Technically, the efficiency of the electrolyzer and Li-ion battery significantly affects hydrogen production. Therefore, on the one hand, improving the efficiency of the electrolyzer and energy storage battery is of great significance to reduce LCOH. Consequently, the state should vigorously promote the development of relevant electrolyzer and Li-ion battery technologies to improve the operational efficiency of the system as much as possible. On the other hand, according to the PV output, the capacity of the electrolyzer and the energy storage battery should be configured reasonably to avoid serious waste of sunlight caused by excessive PV output and unnecessary expenditure caused by small PV output and large-capacity configuration of the electrolyzer and the energy storage battery.

(3) In terms of management, the PVEH system should be designed more flexibly. When the output power exceeds the rated power of the electrolyzer and energy storage battery, the number of PV panels in operation should be adjusted rapidly to reduce the occurrence of power abandonment and unnecessary economic losses as much as possible. However, when the PV output power is less than the rated power of the electrolyzer, some electrolyzers can stop working automatically to reduce the energy loss of the system.

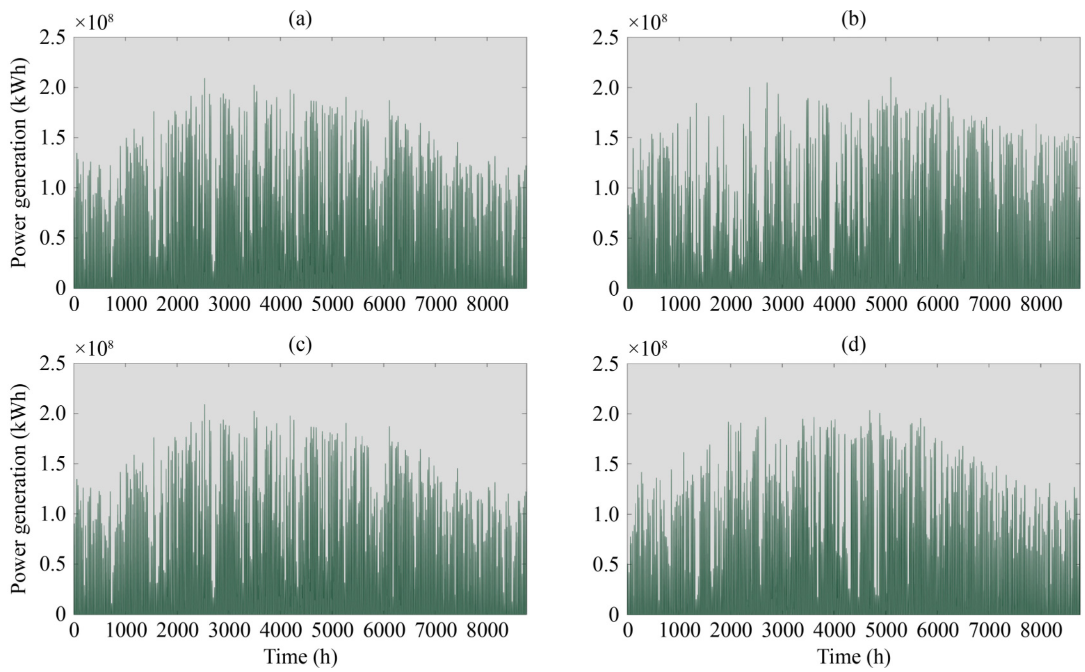
(4) In a pessimistic situation, a subsidy of 0.6–2 yuan/kg needs to be given by the state in 2020 to support the development of hydrogen energy. However, in a neutral and optimistic situation, the government is not required to provide subsidies.

6.3 Future work

In our future work, investigating the optimal capacity configuration of the electrolyzer and energy storage battery will be meaningful to minimize the unit hydrogen production cost pertinent to the advent of energy storage systems. Furthermore, when equipped with energy storage, the comparative analysis of LCOH for PV hydrogen production in each area throughout the country is of equal importance.

Competing Interests The authors declare that they have no competing interests.

Appendix A



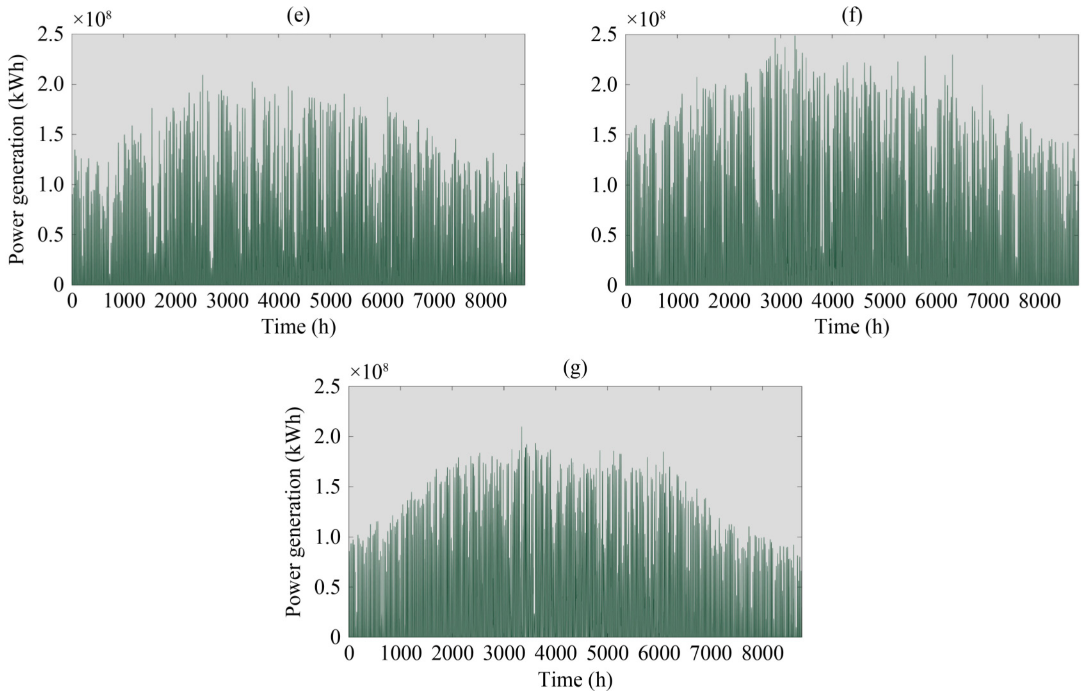


Fig. A1 Hourly output of PV panels in seven areas in 2020: (a) Nanjing, Jiangsu in East China; (b) Foshan, Guangdong in South China; (c) Hohhot, Inner Mongolia in North China; (d) Wuhan, Hubei in Central China; (e) Xichang, Sichuan in Southwest China; (f) Haixi, Qinghai in Northwest China; (g) Harbin, Heilongjiang in Northeast China.

Appendix B

Relevant parameters of power plant, electrolysis plant and energy storage plant.

Table B1 Parameters of power plant

Parameter	Value
Power plant related parameters	
Unit investment cost (yuan/kW)	{6037, 6024, 6018, 6033, 6014, 6010, 6030}*
Installed capacity (kW)	300000
Residual value rate (%)	5
Depreciation period (year)	15
Power plant learning rate β_1	0.02/0.035/0.05
Operation and maintenance parameters	
Repair rate (%)	0 in 1–5 years, 1.2 in 6–10 years, 1.5 in 11–20 years
Number of workers	36
Annual salary per capita (yuan)	{43390, 41029, 31497, 27881, 26522, 24037, 24902}*
Withdrawal rate of employee welfare (%)	14
Overall rate of labor insurance (%)	31
Withdrawal rate of housing provident fund (%)	12
Material cost (yuan/kW)	20
Other expenses (yuan/kW)	30
Premium rate (%)	0.25
Financial parameters	
Capital ratio (%)	20
Annual interest rate of loan (%)	5
Loan term (year)	15
Enterprise benchmark rate of return (%)	8
Unit life (year)	20
Discount rate (%)	8

Note: *The numbers in the set represent Nanjing, Foshan, Hohhot, Wuhan, Xichang, Haixi, and Harbin in order.

Table B2 Parameters of electrolysis plant

Parameter	Value
Electrolysis plant related parameters	
Unit investment cost (yuan/kW)	5500
Installed capacity (kW)	100000
Residual value rate (%)	5
Depreciation period (year)	15
Electrolysis plant learning rate β_2	0.15
Operation and maintenance parameters	
Repair rate (%)	0 in 1–5 years, 1.2 in 6–10 years, 1.5 in 11–20 years
Number of workers	12
Annual salary per capita (yuan)	60000
Withdrawal rate of employee welfare (%)	14
Overall rate of labor insurance (%)	31
Withdrawal rate of housing provident fund (%)	12
Material cost (yuan/kW)	20
Other expenses (yuan/kW)	30
Premium rate (%)	0.25
Financial parameters	
Capital ratio (%)	20
Annual interest rate of loan (%)	5
Loan term (year)	15
Enterprise benchmark rate of return (%)	8
Unit life (year)	15
Discount rate (%)	8
Tax parameters	
Income tax (%)	25 (three exempts and three halves)
Value added tax (%)	7 (50% immediate withdrawal)
Urban construction tax (%)	5
Education surcharges (%)	5

Table B3 Parameters of energy storage plant

Parameter	Value
Energy storage plant related parameters	
Unit investment cost (yuan/kW)	1200
Installed capacity (kW)	150000
Residual value rate (%)	5
Depreciation period (year)	4
Energy storage plant learning rate β_3	0.3
Operation and maintenance parameters	
Repair rate (%)	0 in 1–3 years, 1.2 in 4–5 years
Number of workers	8
Annual salary per capita (yuan)	60000
Withdrawal rate of employee welfare (%)	14
Overall rate of labor insurance (%)	31
Withdrawal rate of housing provident fund (%)	12
Material cost (yuan/kW)	20
Other expenses (yuan/kW)	30
Premium rate (%)	0.25
Financial parameters	
Capital ratio (%)	20
Annual interest rate of loan (%)	5
Loan term (year)	15
Enterprise benchmark rate of return (%)	8
Battery life (year)	5
Discount rate (%)	8

References

Abdin Z, Mérida W (2019). Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis. Energy Conversion and Management, 196: 1068–1079

Al-Qahtani A, Parkinson B, Hellgardt K, Shah N, Guillen-Gosalbez G (2021). Uncovering the true cost of hydrogen production routes using life cycle monetisation. Applied Energy, 281: 115958

Bae J H, Cho G L (2010). A dynamic general equilibrium analysis on fostering a hydrogen economy in Korea. Energy Economics, 32: S57–S66

Bernal-Agustín J L, Dufo-López R (2010). Techno-economical optimization of the production of hydrogen from PV-Wind systems connected to the electrical grid. Renewable Energy, 35(4): 747–758

Bhandari R, Shah R R (2021). Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. Renewable Energy, 177: 915–931

Chen C, Lu Y, Xing L (2021). Levelling renewable power output using hydrogen-based storage systems: A techno-economic analysis. Journal of Energy Storage, 37: 102413

Chi J, Yu H (2018). Water electrolysis based on renewable energy for hydrogen production. Chinese Journal of Catalysis, 39(3): 390–394

Fan J L, Wei S, Yang L, Wang H, Zhong P, Zhang X (2019). Comparison of the LCOE between coal-fired power plants with CCS and main low-carbon generation technologies: Evidence from China. Energy, 176: 143–155

Feng Z, Niu W, Cheng C, Zhou J, Yang T (2022). China's hydropower energy system toward carbon neutrality. Frontiers of Engineering Management, 9(4): 677–682

Giddey S, Kulkarni A, Badwal S (2015). Low emission hydrogen generation through carbon assisted electrolysis. International Journal of Hydrogen Energy, 40(1): 70–74

Hart A, Leeke G, Greaves M, Wood J (2014). Down-hole heavy crude oil upgrading by CAPRI: Effect of hydrogen and methane gases upon upgrading and coke formation. Fuel, 119: 226–235

Holl M, Rausch L, Pelz P F (2017). New methods for new systems: How to find the techno-economically optimal hydrogen conversion system. International Journal of Hydrogen Energy, 42(36): 22641–22654

Khouya A (2020). Levelized costs of energy and hydrogen of wind farms and concentrated photovoltaic thermal systems: A case study in Morocco. International Journal of Hydrogen Energy, 45(56): 31632–31650

Kong L, Li L, Cai G, Liu C, Ma P, Bian Y, Ma T (2021). Techno-economic analysis of hydrogen energy for renewable energy power smoothing. International Journal of Hydrogen Energy, 46(3): 2847–2861

Lockley A, von Hippel T (2021). The carbon dioxide removal potential of Liquid Air Energy Storage: A high-level technical and economic appraisal. Frontiers of Engineering Management, 8(3): 456–464

Longden T, Beck F J, Jotzo F, Andrews R, Prasad M (2022). "Clean" hydrogen? Comparing the emissions and costs of fossil fuel versus renewable electricity based hydrogen. Applied Energy, 306: 118145

Menanteau P, Quéméré M M, Le Duigou A, Le Bastard S (2011). An economic analysis of the production of hydrogen from wind-generated electricity for use in transport applications. Energy Policy, 39(5): 2957–2965

National Energy Administration (2016). What are the disadvantages of geothermal energy? (in Chinese)

National Energy Administration (2021). Summary of energy storage related policies (in Chinese)

National Development and Reform Commission, National Energy Administration (2021). Guidance on Accelerating the Development of New Energy Storage (in Chinese)

Nematollahi O, Alamdari P, Jahangiri M, Sedaghat A, Alemrajabi A A (2019). A techno-economical assessment of solar/wind resources and hydrogen production: A case study with GIS maps. Energy, 175: 914–930

Olateju B, Kumar A (2016). A techno-economic assessment of hydrogen production from hydropower in Western Canada for the upgrading of bitumen from oil sands. Energy, 115: 604–614

Pan G, Gu W, Qiu H, Lu Y, Zhou S, Wu Z (2020). Bi-level mixed-integer planning for electricity-hydrogen integrated energy system considering levelized cost of hydrogen. Applied Energy, 270: 115176

Rahmouni S, Negrou B, Settou N, Dominguez J, Gouareh A (2017). Prospects of hydrogen production potential from renewable resources in Algeria. International Journal of Hydrogen Energy, 42(2): 1383–1395

Rezaei M, Khalilpour K R, Mohamed M A (2021). Co-production of electricity and hydrogen from wind: A comprehensive scenario-based techno-economic analysis. International Journal of Hydrogen Energy, 46(35): 18242–18256

Rezaei M, Mostafaeipour A, Qolipour M, Momeni M (2019). Energy supply for water electrolysis systems using wind and solar energy to produce hydrogen: A case study of Iran. Frontiers in Energy, 13(3): 539–550

Saba S M, Müller M, Robinius M, Stolten D (2018). The investment costs of electrolysis: A comparison of cost studies from the past 30 years. International Journal of Hydrogen Energy, 43(3): 1209–1223

Sanchez V M, Chavez-Ramirez A, Duron-Torres S M, Hernandez J, Arriaga L, Ramirez J M (2014). Techno-economical optimization based on swarm intelligence algorithm for a stand-alone wind-photovoltaic-hydrogen power system at south-east region of Mexico. International Journal of Hydrogen Energy, 39(29): 16646–16655

Shah S A A (2020). Feasibility study of renewable energy sources for developing the hydrogen economy in Pakistan. International Journal of Hydrogen Energy, 45(32): 15841–15854

Squadrito G, Nicita A, Maggio G (2021). A size-dependent financial evaluation of green hydrogen-oxygen co-production. Renewable Energy, 163: 2165–2177

State-owned Assets Supervision and Administration Commission of the State Council (2021). Guidance on Promoting the High-Quality Development of Central Enterprises and Doing a Good Job in Carbon Peak and Carbon Neutralization (in Chinese)

Timilsina G R (2021). Are renewable energy technologies cost competitive for electricity generation? Renewable Energy, 180: 658–672

Xu C, Ke Y, Li Y, Chu H, Wu Y (2020). Data-driven configuration optimization of an off-grid wind/PV/hydrogen system based on modified NSGA-II and CRITIC-TOPSIS. Energy Conversion and Management, 215: 112892

Yang Y, Wang H, Löschel A, Zhou P (2022). Energy transition toward carbon-neutrality in China: Pathways, implications and uncertainties. Frontiers of Engineering Management, 9(3): 358–372

Yates J, Daiyan R, Patterson R, Egan R, Amal R, Ho-Baille A, Chang N L (2020). Techno-economic analysis of hydrogen electrolysis from off-grid stand-alone photovoltaics incorporating uncertainty analysis. Cell Reports Physical Science, 1(10): 100209

Yukesh Kannah R, Kavitha S, Preethi, Parthiba Karthikeyan O, Kumar G, Dai-Viet N V, Rajesh Banu J (2021). Techno-economic assessment of various hydrogen production methods: A review. Bioresource Technology, 319: 124175

Zhang Y, Wei W (2020). Decentralized coordination control of PV generators, storage battery, hydrogen production unit and fuel cell in islanded DC microgrid. International Journal of Hydrogen Energy, 45(15): 8243–8256

Zhao H, Yang R, Wang C, Pabasara W, Wijeratne U, Liu C, Xue X, Abdeen N (2019). Effects of design parameters on rooftop photovoltaic economics in the urban environment: A case study in Melbourne, Australia. Frontiers of Engineering Management, 6(3): 351–367

Zhou D, Ding H, Wang Q, Su B (2021). Literature review on renewable energy development and China's roadmap. Frontiers of Engineering Management, 8(2): 212–222

Zhou K, Zhang Z, Liu L, Yang S (2022). Energy storage resources management: Planning, operation, and business model. Frontiers of Engineering Management, 9(3): 373–391

Ziegler M S, Mueller J M, Pereira G D, Song J, Ferrara M, Chiang Y M, Trancik J E (2019). Storage requirements and costs of shaping renewable energy toward grid decarbonization. Joule, 3(9): 2134–2153