



## OPEN Economic and environmental assessment of different energy storage methods for hybrid energy systems

Ying Liu & Yaru Zhang

Due to the environmental impact of fossil fuels, renewable energy, such as wind and solar energy, is rapidly developed. In energy systems, energy storage units are important, which can regulate the safe and stable operation of the power system. However, different energy storage methods have different environmental and economic impacts in renewable energy systems. This paper proposed three different energy storage methods for hybrid energy systems containing different renewable energy including wind, solar, bioenergy and hydropower, meanwhile. Based on Homer Pro software, this paper compared and analyzed the economic and environmental results of different methods in the energy system through the case of a residential community in Baotou City. The result showed that (1) the use of batteries as energy storage in communities posed the lowest energy costs whose NPC was \$197,396 and LCOE was \$0.159, consisting of 20 batteries, 19.3 kW PV, 6 wind turbines, a 12.6 kW converter. (2) Lower fuel cell prices mean lower NPC and the increase in the Electric Load Scaled Average implied a decrease in LCOE and the increase of the NPC. (3) The use of fuel cells also had impacts on the environment, such as resulting CO<sub>2</sub> and SO<sub>2</sub>.

**Keywords** Energy storage, Battery, Fuel cell, Economic analysis, Renewable energy

China officially announced the plan that “Achieve carbon peak by 2030 and carbon neutrality by 2060” at the 75th session of the United Nations General Assembly in 2020<sup>1</sup>. In order to achieve the dual-carbon goal and reduce the proportion of fossil fuel energy in the energy system, China has begun to accelerate the transition from fossil energy to renewable energy. In 2023, China’s total installed capacity of renewable energy power generation was 1.45 billion kWh, accounting for more than 50% of the country’s total installed power generation capacity<sup>2</sup>. However, the electricity generated by renewable energy sources, such as wind and solar, is unstable<sup>3,4</sup>. While energy storage can regulate the fluctuation of electricity and provide stability to the power grid<sup>5–7</sup>. Therefore, energy storage plays an important role in ensuring national energy security<sup>8</sup>.

Many scholars have conducted research. For details, please refer to 2. Literature Review. It can be seen that the integration of various energy storage technologies in the hybrid energy system has been applied and studied. However, few people made a comparative analysis of the economic and environmental aspects of different energy storage methods in renewable energy systems. Therefore, the scientific aim of the work is to propose three different energy storage methods for hybrid energy systems containing different renewable energy such as wind, solar, bioenergy and hydropower, and the subject of the research was to obtain comparison and analysis of the technical and economic results of different methods in the energy system. This study is an extension of the economic and environmental impacts of different energy storage methods in existing research. Three energy storage methods are as following. Method 1: battery as the only energy storage technology. Method 2: hydrogen fuel cell as the only energy storage technology. Method 3: battery and hydrogen fuel cell mixed use as energy storage technology. Then, taking Baotou City as an example, and the simulation analysis will be carried out. The innovation point of this paper lies in that through multi-scenario comparative analysis, for the first time, the economic and environmental benefits of battery, fuel cell and hybrid energy storage technologies are comprehensively evaluated in the community-level hybrid renewable energy system, providing an empirical framework for energy storage selection in areas rich in wind and solar resources. Section 2 presented literature review. Section 3 proposed the design frameworks of three energy storage methods. Section 4 presented the data of the model and used a Baotou residential community case study. Section 5 compared three storage schemes

School of Economics and Management, Shanghai Institute of Technology, Haiquan Road 100, Shanghai 201418, China. ✉email: yaruzhang@sit.edu.cn; zhyremail@163.com

economically and environmentally, analyzes cost sensitivity. Section 6 proposed the conclusion and research limitations and future directions.

The full text is abbreviated as follows in Table 1.

Literature review  
Energy storage technologies

There are many scholars studied renewable energy systems with energy storage technologies. The abbreviation table is shown in Table 1. Das et al. Das, et al.<sup>9</sup> used a hybrid photovoltaic and wind energy system with different energy storage technologies to meet the load needs of remote communities and found that proper energy storage technology can significantly affect system performance. Xin et al. Xin, et al.<sup>10</sup> pointed out that rechargeable batteries, currently occupied the largest share of the energy storage market and were vital to the sustainable energy transition and industrial decarbonization in response to global climate change. Sharma et al.<sup>11</sup> studied the optimal BESS size and the results show that the current input costs of batteries in South Australia were economically beneficial. Li et al.<sup>12</sup> examined the energy management, operation control methods and application methods of large BESS and emphasized that BESS was economical and important, and the normal operation of battery and extending its life was vital. Jahangir et al.<sup>13</sup> introduced an off-grid hybrid renewable energy system composed of photovoltaic panels, wind turbines and biogas generators with battery storage. Fuel cells with hydrogen are generally emerging as a new era of technological development<sup>14</sup>. As a result, many countries have incorporated hydrogen development into their national strategies and taken steps to promote the fuel cell industry<sup>15</sup>. Rekioua et al.<sup>16</sup> investigated a hybrid photovoltaic and fuel cell system for standalone applications to achieve the goal of minimizing system LCC. Abomazid et al.<sup>17</sup> investigated how to optimize the energy management of hydrogen facilities by integrating battery storage systems and solar photovoltaic systems. Hu<sup>18</sup> analyzed the current situation of hydrogen energy and fuel cell development in China, pointing out that the Chinese government attached great importance to hydrogen energy and fuel cell technology. Das et al.<sup>19</sup> focused on independent hybrid renewable energy systems in remote areas of Australia to explore the impact of energy storage technologies, including battery energy storage, hydrogen energy storage, and photovoltaic technology tracking technology on system performance. Hoang and Yue et al.<sup>20,21</sup> studied the importance of combining battery energy storage system with solar photovoltaic system in hydrogen energy production and this integration can improve the economy and efficiency of the system, enabling efficient conversion from solar to hydrogen energy. González et al.<sup>22</sup> evaluated the energy efficiency and economy of solar and hydrogen storage facilities in different application methods, and points out that the cost of hydrogen energy storage was significantly lower than that of traditional power storage technologies. Kalinci et al.<sup>23</sup> built a conceptual model for a hybrid renewable energy system of hydrogen energy and battery storage on Bozcaada Island in Turkey, including photovoltaic, wind and fuel cells.

Economic and environmental analysis

Many scholars have also studied the economic and environmental analysis of energy storage. Alqahtani and Balta-Ozkan<sup>24</sup> evaluated PVsystems with battery storage in Neom. The techno-economic analysis showed that the current tariff structure was not economically viable and suggested that tariff of \$0.08/kWh would be feasible. Seedahmed and Mustafa et al.<sup>25</sup> optimized energy systems with PV panels, converters, and batteries for commercial applications in Mecca, achieved a minimum COE of \$0.11/kWh and reduced NPC by eight times. Chung et al.<sup>26</sup> studied the economic evaluation of renewable energy including wind and solar energy and used a fuel cell and diesel engine generator as the base power supply in off-grid and grid-connected situations in South Korea and found greenhouse gas emissions would fall. Jahangir et al.<sup>13</sup> proposed a solar-wind-biomass hybrid renewable energy system with battery storage and found that the COE range of the optimal system was 0.128 to 0.223 \$/kWh. Increasing the price of biomass from \$20 / ton to \$60 / ton can reduce the power generation of biogas generators by at least 86% and also found that carbon dioxide was reduced by 67.49% compared to the base case. Odetoye<sup>27</sup> et al. proposed a power generation mix consisting of PV, CSP and small hydropower (SH) with NPC of \$55.7 million for a renewable microgrid with battery storage and \$408 million for a diesel microgrid with LCOE of \$0.26 and \$1.01 per kWh, respectively and found that the system could reduce carbon dioxide (CO<sub>2</sub>) emissions by up to 7,540 metric tons per year. Khan<sup>28</sup> et al. proposed various feasible configurations for the integration of energy storage systems such as batteries and hydrogen in remote communities in Pakistan, resulting in COE of \$0.127 /kWh and NPC of \$0.127 /kWh. Abdulrhman<sup>29</sup> et al. simulated grid-connected

Full name	Abbreviation
Net Present Cost	NPC
Levelized Cost of Energy	LCOE
Wind turbine	WT
Photovoltaic panel	PV
Energy Cost	COE
Life Cycle Cost	LCC
Battery Energy Storage System	BESS
Concentrated Solar Thermal	CSP

Table 1. Nomenclature.

PV and PV with cells configurations and found that grid-connected PV systems are more viable at industrial electricity prices, with a levelized energy cost of \$0.016/kWh, a net present value of \$4233,274, a return on investment of 426.5%, and a payback period of 4.7 years.

### The model of the energy system

Energy system modeling tools are widely used in academic research, with scholars selecting different platforms based on specific research objectives. Yang and Li<sup>30</sup> used HOMER Pro to design an off-grid solar-wind-battery system for a remote community, optimizing cost and reliability, while Song et al.<sup>31</sup> employed it to assess the impact of battery degradation on long-term system economics. Coban et al.<sup>32,33</sup> conducted a technical and economic study on the hybrid renewable energy system in the energy-deficient cities of Cadaado and Beledweyne in Somalia, and analyzed the feasibility of centralized and decentralized configurations based on HOMER Pro software modeling.

In contrast, EnergyPLAN is favored for national or regional energy transition studies, where long-term policy and sector coupling are key concerns. Davide et al.<sup>34</sup> applied EnergyPLAN to analyze 100% renewable scenarios in Europe, integrating wind, solar, and hydrogen storage, whereas Ieva et al.<sup>35</sup> used it to evaluate the role of biomass in decarbonizing district heating systems. Meanwhile, RETScreen is commonly used for preliminary feasibility and carbon reduction assessments due to its simplicity. Owolabi et al.<sup>36</sup> applied RETScreen to compare the financial viability of solar PV projects across different climates, and used it to estimate emissions reductions from rural electrification projects in developing countries. DER-CAM has been utilized for distributed energy resource optimization and policy analysis, particularly in urban microgrid studies. Michael et al.<sup>37</sup> employed DER-CAM to assess the economic benefits of demand response in commercial buildings, while Eskander, Monica and Silva<sup>38</sup> modeled the impact of carbon pricing on DER adoption in microgrids. Jalaei et al.<sup>39</sup> successfully applied the COA-ANN hybrid method to global carbon emission prediction, and Jalaei et al.<sup>40</sup> used the WOA-ANFIS framework in coal consumption prediction under high-noise data. Furthermore, the evaluation of AI-driven hydrogen storage technologies provides key technical support for the system design of renewable energy-coupled hydrogen storage<sup>41,42</sup>. At the prediction level, Mao et al.<sup>43–45</sup> proposed the wind and solar power range prediction method based on meteorological reconstruction and deep learning to enhance the ability of uncertainty management. In system optimization, physical models and data-driven strategies are integrated to achieve motor efficiency improvement, collaborative planning of hydrogen energy chains, and multi-objective regulation of microbial fuel cells<sup>46–48</sup>. Building load management refines itemized prediction through generative adversarial networks to support dynamic response<sup>49,50</sup>.

HOMER Pro has been extensively applied in microgrid and hybrid renewable energy system optimization due to its minute-level simulation capability, which takes the minimum NPC as the objective function, and the constraint is the battery charge and discharge, power balance and other technical limitations. It generates the optimized system configuration according to the LCOE and NPC ordering, and the results show the economic benefits and gas emission of each scheme<sup>51–54</sup>. Homer Pro supports hourly high temporal resolution energy supply and demand matching analysis, accurately simulating the seasonal and intraday fluctuation characteristics of wind/solar resources, providing a scientific basis for energy storage configuration and system redundancy design. Homer Pro allows users to customize component parameters such as photovoltaic panel efficiency and is compatible with traditional energy equipment like diesel generators, providing a seamless technical path for the future construction of renewable hybrid systems. Meanwhile, Homer has been widely adopted by the global academic and industrial communities and has become a benchmark tool in the field of optimizing renewable energy systems.

### Methodology

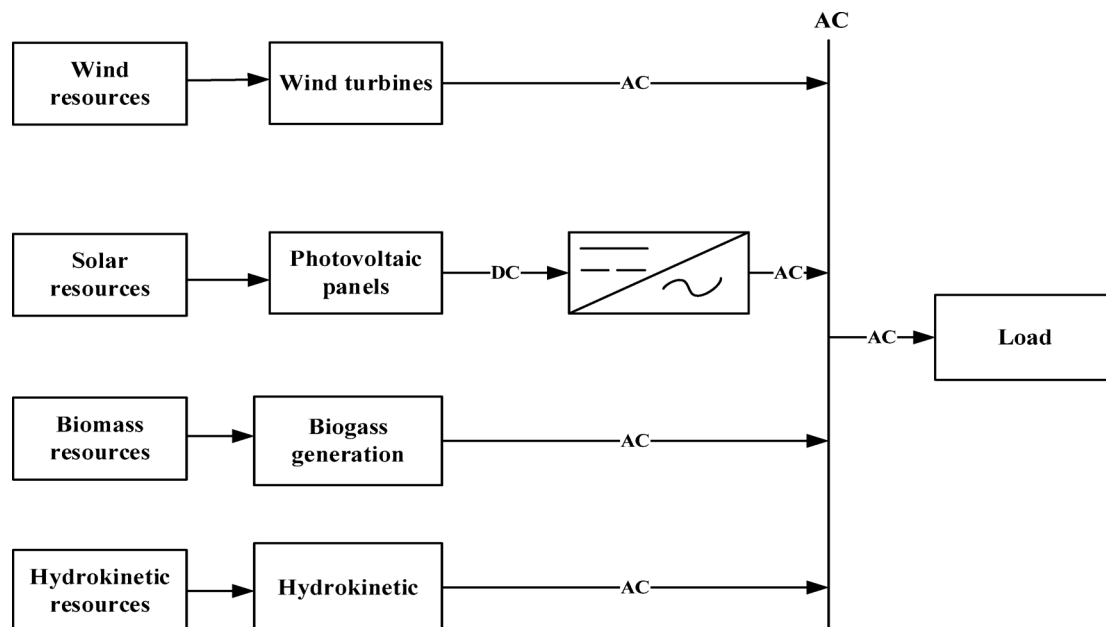
In order to simulate and compare the economic utility of different methods, four scenarios were constructed. They are Scenario 1: Hybrid renewable energy systems without storage energy, Scenario 2: Hybrid energy systems with battery storage energy, Scenario 3: Hybrid energy systems with fuel cell storage energy, Scenario 4: Hybrid energy systems with battery and fuel cell storage.

#### Hybrid renewable energy systems without storage energy

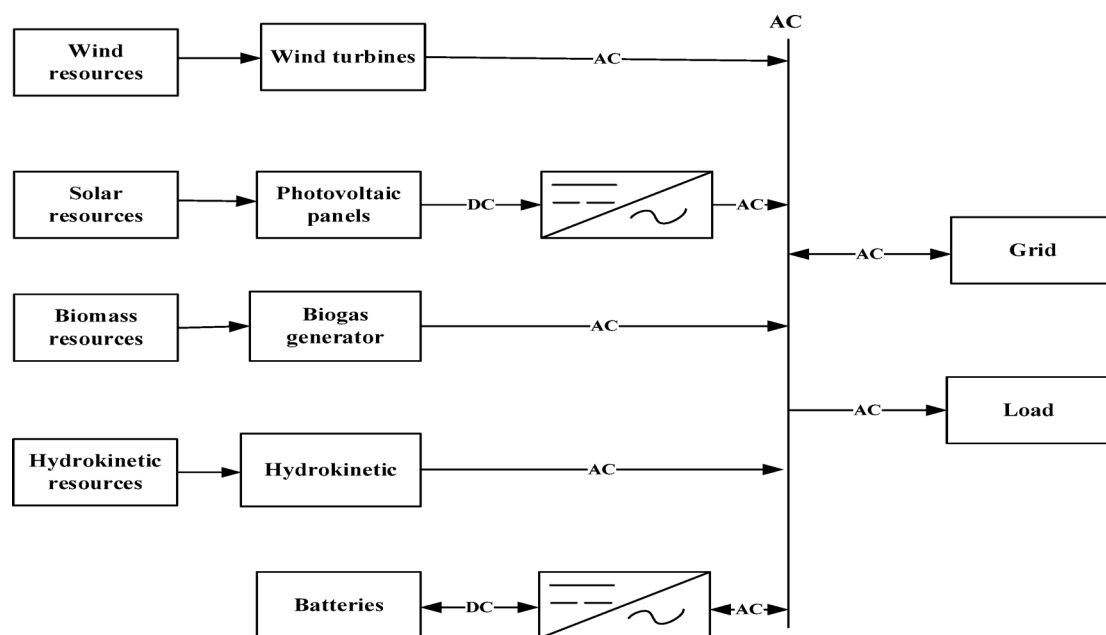
In this scenario, there is no energy storage which serves as a foundation, which provides a basic comparison for the subsequent research on the necessity of energy storage systems. The basic energy architecture is shown in Fig. 1, including wind resources, solar resources, biomass, grid, where AC refers to alternating current, and DC refers to direct current. The system consists of photovoltaics, wind turbines, hydrokinetic, biogas generator, batteries and converters. The photovoltaic (PV) subsystem which converts solar radiation into electricity and the wind turbine (WT) subsystem which converts wind energy into electricity and then provides it to the alternating current (AC) are the main source of energy. The biogas power generation system converts organic waste such as crop straw into biogas through anaerobic fermentation technology, which drives the generator to produce electricity. The hydropower system utilizes the water resources. It converts the kinetic energy of water into mechanical energy through micro hydro turbine units and then converts it into electrical energy through generators. Among them, Converters are used to maintain the energy flow between DC and AC, and are capable of converting AC power to DC power (rectification), or DC power to AC power (inverter). Conversion in the form of current is essential for the electrical load of household appliances and is also important in renewable energy hybrid system.

#### Hybrid energy systems with battery storage energy

Figure 2 shows the architecture of the first method to store energy is hybrid energy systems with battery storage. The battery can help the hybrid system eliminate the lack of power generation and absorb the surplus electricity



**Fig. 1.** Architecture diagram of hybrid renewable energy systems without storage energy.



**Fig. 2.** Architecture diagram of hybrid renewable energy systems with battery storage energy.

generated by renewable energy to achieve the purpose of improving the energy conversion efficiency. Since the output of renewable energy such as solar and wind energy is intermittent and uncertain, the battery can store excess electrical energy and release it during peak demand, the existence of batteries may balance supply and demand and improve the stability and reliability of the system. Through the storage function of batteries, renewable energy may be better utilized<sup>19</sup>.

### Hybrid energy systems with fuel cell storage energy

Fuel cell converts chemical energy directly into electricity, which is generated by a series of chemical reactions that occur inside the cell and has high energy conversion efficiency and low environmental pollution and they work by using hydrogen and oxygen in a biochemical reaction under the action of a catalyst to produce water and electricity<sup>55</sup>. The classification of fuel cells is based on several electrolyte materials selected in fuel cell design, and hydrogen fuel cells are one of the most widely used fuel cell types because they use hydrogen as a fuel and

oxygen as an oxidizer and hydrogen fuel cell has high electrical efficiency, up to 70%<sup>56–59</sup>. Therefore, hydrogen fuel cell is selected in this paper.

The system architecture of method 2 is shown in Fig. 3 in which fuel cell, electrolyzer and hydrogen storage tank were added. The system consists of photovoltaic panel, wind turbine, biogas generator, electrolyzer, hydrogen storage tank, fuel cell and converter. The third sub-system electrolyzer started to work when there was a surplus of solar and wind energy, using the excess electrical energy for water electrolysis to produce hydrogen and oxygen, and the hydrogen can be fed into the hydrogen storage tank. The hydrogen generated is used by a fourth sub-system fuel cell stack, which generates electricity to DC.

### Hybrid energy systems with battery and fuel cell storage energy

The overall architecture is shown in Fig. 4. The system consists of photovoltaic panel, wind turbine, biogas generator, electrolyzer, hydrogen storage tank, fuel cell, battery and converter. The hybrid energy system of fuel cell and battery can combine the high efficiency of fuel cell and the high power density of battery. As a device that converts chemical energy directly into electric energy, the fuel cell has the advantages of high efficiency and low emission. However, fuel cells are slow to respond to cold starts and cannot provide enough power quickly when the load changes<sup>60,61</sup>. To reduce the impact of these questions, batteries are introduced into the system, whose fast response characteristics may quickly replenish or absorb power when the fuel cell starts or the load changes to guarantee the stability and reliability of the system.

### Data

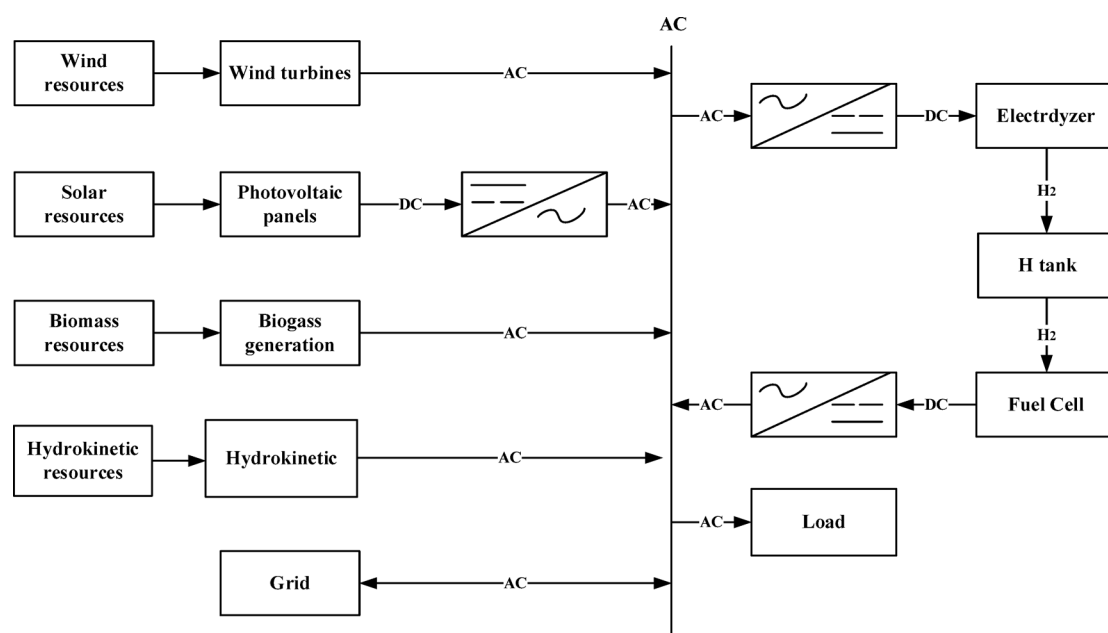
#### Site description

The case data is selected from Baotou whose geographical location is 40°39.2'N and 109°50.3'E with the population of 600 people, which is consist of 300 households. The reason why Baotou can be energy development base is its richness in renewable resources, and its huge space for the development of renewable energy technology. The landform of Baotou is mainly composed of plateaus, grassland, forest and cultivated land<sup>62</sup>. Therefore, biomass energy from agriculture and livestock is abundant. Second, Baotou has sufficient sunshine and massive solar energy resources, with an average annual sunshine time of more than 2,700 h in most areas, and the amount of wind energy reached 69.611 million kW, an increase of 52.38% in 2023<sup>63</sup>. Besides, Baotou has strong winds throughout the year, and the windier phase of the year lasts for 3 or 4 months from February to June, with an average wind speed of more than 15.3 km per hour, of which April is the highest average hourly wind speed in January, reaching 18.1 km per hour. At the same time, Baotou accounts for 14.49% of the mountainous land, 75.51% of the hilly grassland, and 10% of the plains, with developed agriculture and abundant biomass natural resources. Besides, Baotou has broad prospects for the development of hydrogen energy industry market<sup>64</sup>.

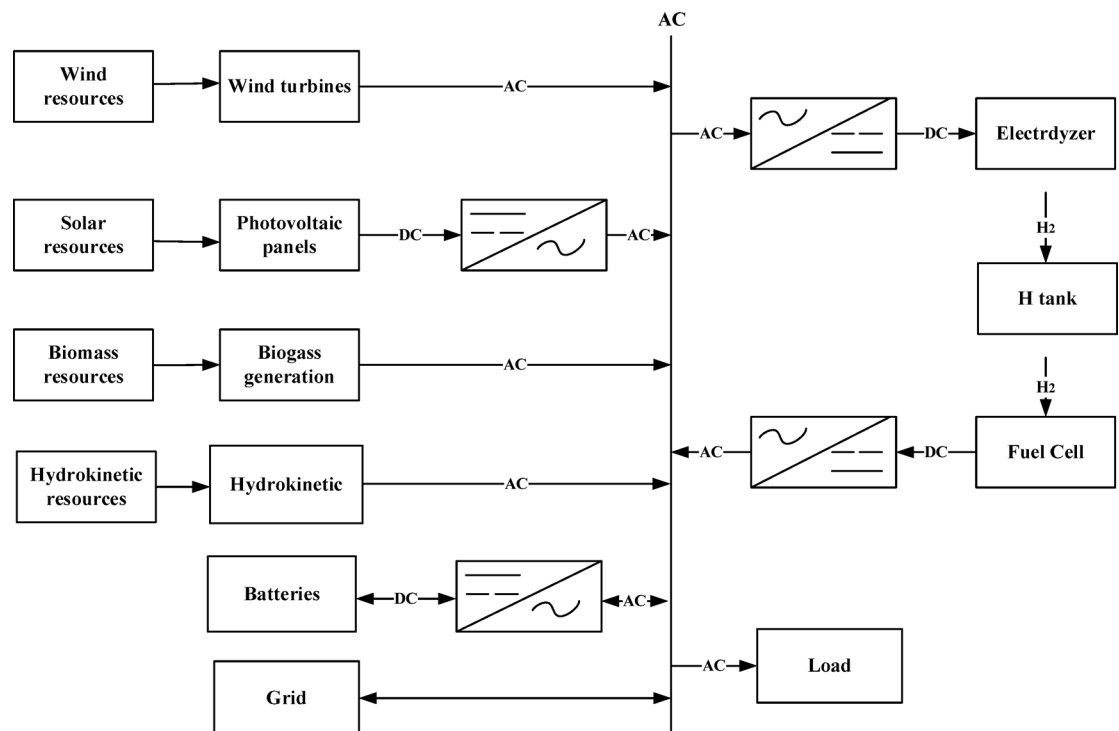
### Natural resources

#### Solar resources

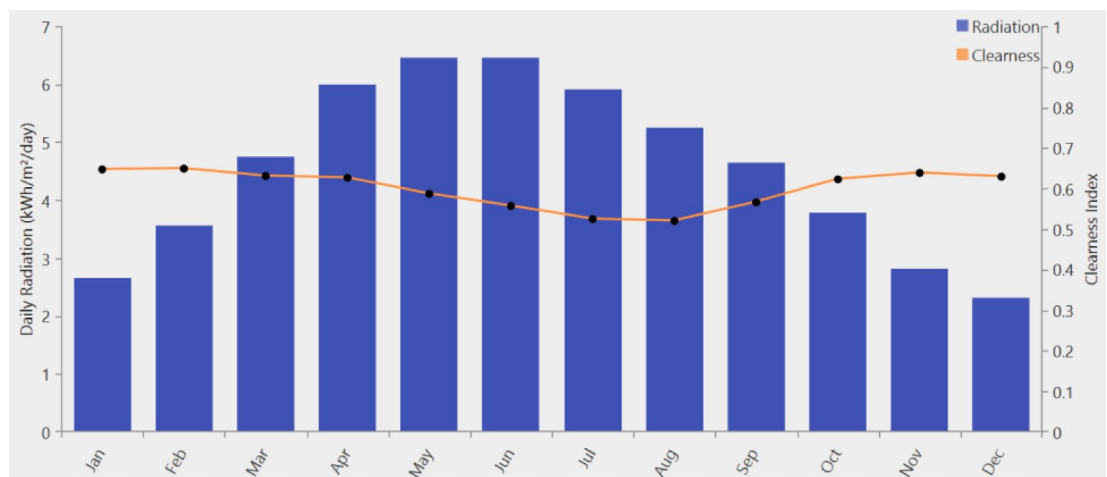
The greater the value of annual radiation intensity and annual sunshine duration, the more abundant solar energy resources, the more favorable for the development of the photovoltaic industry. The monthly average daily solar Global Horizontal Irradiance (GHI) and Clarity Index (CI) data for Baotou City during a 22-year period (July 1983–June 2005) were selected for the photovoltaic panel POWER calculation, and the data were



**Fig. 3.** Architecture diagram of hybrid renewable energy systems with fuel cell storage.



**Fig. 4.** Architecture diagram of hybrid renewable energy systems with battery and fuel cell hybrid storage energy.



**Fig. 5.** Monthly average solar global horizontal irradiance GHI and clarity index CI in Baotou.

obtained from the NASA Global Energy Forecast (POWER) database. The monthly average daily GHI and CI data are shown in Fig. 5, and the highest average monthly GHI in Baotou is estimated to be 6.39 kWh/m<sup>2</sup>.

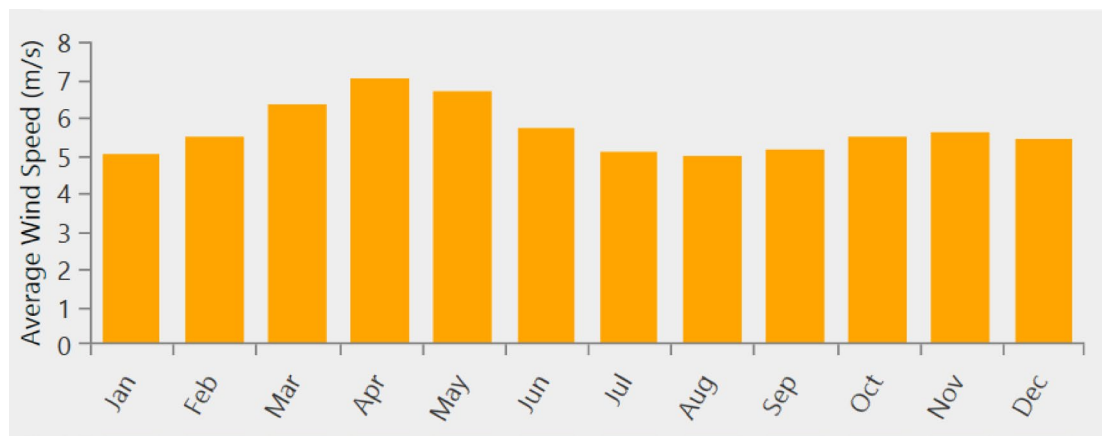
#### Wind resources

Wind speed of the case location during the 22 years (July 1983–June 2005) was selected, and the data is from NASA's Global Energy Forecast (POWER) database, and the monthly average wind speed is shown in Fig. 6. With an average wind speed of 5.67 m/s, the region has a suitable wind potential, with the highest average wind speed in April being 7.05 m/s.

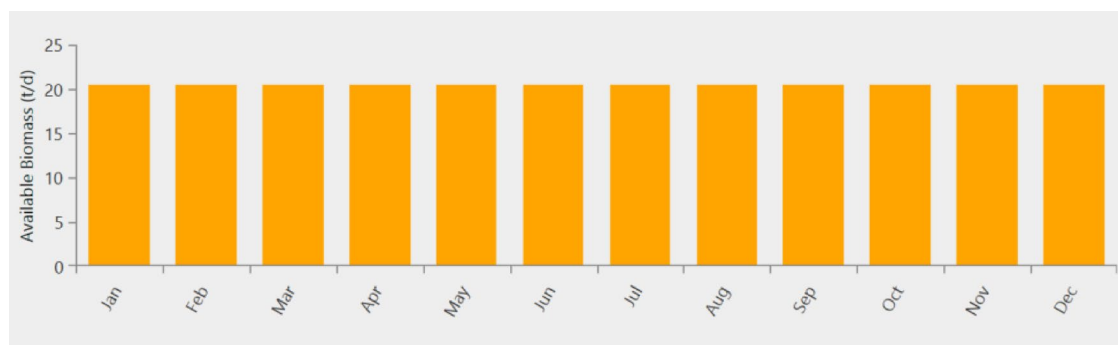
#### Biomass resources

Baotou plants a large number of crops every year. Crop straw and agricultural product processing residues, urban and rural organic waste and other biomass resources are rich, the development of biomass power generation industry has good resources. Baotou's agricultural sector plays an important role in biomass production.





**Fig. 6.** Average monthly wind speed in Baotou.



**Fig. 7.** Available biomass per month in Baotou.

According to the data, corn, sunflower and bean straw account for more than 90% of the resources that can be collected from the main crop waste straw in Baotou. The annual collection and utilization of agricultural waste straw in Baotou are 1,588,500 tons<sup>65</sup>. In this study, Fig. 7 shows the biomass technology potential of Baotou City, assuming a gasification rate of 0.59 kg/kg for agricultural waste (the amount of biogas produced per unit mass of biomass), considering a lower calorific value of biogas LHV (energy contained in 1 kg of biogas that can be used by a biogas generator set) of 5.5 MJ/kg, a carbon content of 7%, and a biomass cost of 0 \$/t<sup>51,66</sup>.

### Generation unit

#### Wind turbine

The output power of a power generator depends on air density, wind speed and rotor area. The output power of the wavelet transform is calculated by Eq. (1)<sup>67</sup>:

$$P_{Wind} = \frac{1}{2} \times \rho \times A_w \times V^3 \times PowerCoefficient \quad (1)$$

Where  $\rho$  is the air density,  $A_w$  is the area swept by the air,  $V$  is the wind speed, *Power Coefficient* is the power coefficient, indicating how much energy is converted into electricity, usually provided by the fan manufacturer, the air density  $\rho$  is calculated according to formula (2)<sup>67</sup>:

$$\rho = \frac{Pressure}{R \times Temperature} \quad (2)$$

Where *Pressure* is the atmospheric pressure,  $R$  is the gas constant, *Temperature* is the temperature, this data is from HOMER Pro. The value of  $V$  is derived from NASA meteorological data, which is an academic literature or standard. We present it in the Wind resources section, while  $A_w$ , which is the swept area of the rotor, is the value provided by the manufacturer in the software after the wind turbine model is selected. The air density  $\rho$  of 1.225 kg/m<sup>3</sup> is the standard atmospheric condition, which is the built-in data of HOMER Pro. *PowerCoefficient* is the default value of HOMER. In this study, the model of wind turbine selected is AWS HC 4.2 kW, and the specifications of this model of wind turbine are shown in Table 2<sup>52</sup>.

Component characteristics	Value
Nominal power (W)	4200
Capital cost (\$/unit)	9660
Replacement cost (\$/unit)	7560
Operation and maintenance cost (\$/year)	100
Life cycle (year)	20
Efficiency (%)	40

**Table 2.** Description of technical and economic parameters of wind turbines.

Component characteristics	Value
Nominal power (W)	250
Capital cost (\$/kW)	1300
Replacement cost (\$/kW)	1300
Operation and maintenance cost (\$/year)	20
Life cycle (year)	20
Efficiency (%)	15.2
Derating factor (%)	80

**Table 3.** Description of technical and economic parameters of solar photovoltaic panels.

#### Photovoltaic panel

The available output power of photovoltaic power generation is calculated using formula (3) according to input parameters such as the size of photovoltaic array, ambient temperature and solar radiation intensity, and continuously optimizes the final optimal power of photovoltaic power<sup>68,69</sup>:

$$P_{PV} = Y_{PV} \times f_{PV} \times \frac{Tt}{1000} \times [1 + \alpha (T_C - T_S)] \quad (3)$$

Among them,  $P_{PV}$  refers to the power generation of solar panels,  $Y_{PV}$  represents the output power of photovoltaic arrays under standard tests,  $f_{PV}$  represents the derating factor (considering the loss caused by pollution on solar panels and the impact of environmental temperature effects),  $Tt$  is the total solar radiation incident on PV panels,  $\alpha$  is the temperature coefficient,  $T_C$  is the battery temperature, and the temperature of the solar panels.  $T_S$  is the battery temperature. The battery temperature is calculated by Eq. (4)<sup>70</sup>:

$$T_C(t) = T_a(t) + \left( \frac{NOCT - 20}{0.8} \right) \times \frac{I_T}{I_S} \quad (4)$$

In formula (4),  $T_a$  is the ambient temperature (°C) and  $NOCT$  is the nominal operating temperature of the battery (°C). The solar photovoltaic panel used in this study is Sharp ND-250QCS, and the efficiency of the selected solar photovoltaic panel is 15.2%. The economic and technical data of the specific photovoltaic panel modules are shown in Table 3<sup>71</sup>.

#### Biogas generator

Biomass is organic matter that can be converted into energy, and the recovery of energy from biomass can produce heat or electricity. Most internal combustion engines can use biogas as fuel, and the reported electrical efficiency is usually 30 to 40%. The selected biogas generator (BioGen) set has a service life of 20,000 h, assuming that the investment, replacement and maintenance costs of the biogas generator set are 1500 dollars/kW, 1500 dollars/kW and 60 dollars/year, and the specifications of the biogas generator set are shown in Table 4<sup>61,72</sup>.

#### Grid

In hybrid renewable energy systems, grid connectivity helps to ensure the stability of the energy supply side, while also facilitating the access and utilization of clean energy sources such as hydrogen. And depending on the grid recovery price, additional economic benefits can be gained by selling excess power and participating in demand response. The residential electricity ladder price in Baotou is divided into three grades, with the first grade (annual electricity consumption of 2040 kWh and below) : 0.07\$/ kWh; The peak electricity price: 0.10\$/ kWh; Valley Electricity price: 0.035\$/ kWh. The grid recycling price is 0.04 \$/kWh.

#### Energy storage unit

##### Battery

The nominal capacity and voltage are factors that affect the efficiency of the battery. The battery efficiency and voltage can be calculated by Eqs. (5), (6), and the storage capacity of the battery is calculated by Eq. (7)<sup>73</sup>.



Component characteristics	Value
Capacity (W)	15
Capital cost (\$/kW)	1500
Replacement cost (\$/kW)	1500
Operation and maintenance cost (\$/year)	60
Life cycle (hour)	20,000
Fuel price (\$/kg)	0.053
Sulfur content (%)	0
Carbon content (%)	7
Density (kg/m <sup>3</sup> )	0.720
Low heating value (MJ/kg)	5.5
Minimum load ratio (%)	30

**Table 4.** Description of technical and economic parameters of biogas generator.

Component characteristics	Value
Voltage (V)	6
Life cycle (year)	12
Minimum charging ratio (%)	20
Capital cost (\$/kW)	1100
Replacement cost (\$/kW)	1100
Operation and maintenance cost (\$/year)	10
Efficiency (%)	80

**Table 5.** Description of technical and economic parameters of batteries.

$$\eta_{batt} = 1 - \left( \frac{I_{nom} \times R_{int} \times I_{batt}}{V_{nom} \times I_{nom}} \right) \quad (5)$$

$$V_{batt} = E_0 - (R_{int} \times I_{batt}) \quad (6)$$

$$P_{max.b} = \frac{N_{batt} \times V_{batt} \times I_{max}}{1000} \quad (7)$$

In Formula (5), (6) and (7),  $\eta_{batt}$  represents the battery efficiency,  $I_{nom}$  represents the nominal current,  $R_{int}$  represents the internal resistance,  $i_{batt}$  represents the battery current,  $V_{nom}$  represents the nominal voltage,  $E_0$  represents the no-load voltage,  $N_{batt}$  represents the number of batteries, and  $I_{max}$  represents the maximum current of the battery.  $R_{int}$ ,  $V_{nom}$ ,  $E_0$  are cited from the Battery Modeling Review. This study systematically compared the typical parameter ranges of lead-acid/lithium-ion batteries, and the specific values were calibrated from the technical manual of the Surrette 6CS25P battery. The system configuration parameters,  $N_{batt}$ ,  $I_{max}$  are optimized and generated based on the built-in algorithm of HOMER Pro software Version 3.14. The calculation method of battery capacity (kW) is shown in Eq. (8)<sup>73</sup>:

$$C_B = \frac{E_L \times AD}{DOD \times \eta_{in} \times \eta_{batt}} \quad (8)$$

$E_L$  is the total energy demand,  $AD$  is the days of autonomy, and  $DOD$  is the depth of discharge,  $\eta_{in}$  and  $\eta_{batt}$  are inverter efficiency and battery efficiency respectively. The calculation formulas for efficiency and capacity in Formula 10 adopts the energy storage capacity calculation standard released by the Renewable Energy Laboratory (NREL) of the United States. Surrette 6 CS 25P battery was used in this study. The technical and economic parameters of the selected battery were shown in Table 5. Assuming a life of 12 years, the investment, replacement and maintenance costs of the battery were 1100 \$/kW, 1100 \$/kW and 10 \$/year respectively<sup>74</sup>.

#### Fuel cell

The output voltage from the fuel cell stack is calculated from Eq. (9)<sup>75</sup>:

$$V_{FC} = N_{cell} \cdot E_{cell} = E - V_{act} - V_{ohm} - V_{con} \quad (9)$$

$V_{FC}$ ,  $N_{cell}$ ,  $E_{cell}$ ,  $E$ ,  $V_{act}$ ,  $V_{ohm}$ ,  $V_{con}$  represent fuel cell output voltage, open circuit voltage, activation, ohm, and concentration fuel cell overvoltage, respectively. Table 6 shows the technical and economic parameters of fuel cells<sup>76</sup>.

Component characteristics	Value
Capital cost (\$/kW)	2000
Replacement cost (\$/kW)	1800
Operation and maintenance cost (\$/year)	200
Life cycle (year)	12
Efficiency (%)	85

**Table 6.** Description of technical and economic parameters of fuel cells.

Component characteristics	Value
Capital cost (\$/kW)	2000
Replacement cost (\$/kW)	1800
Operation and maintenance cost (\$/year)	200
Life cycle (year)	15

**Table 7.** Description of technical and economic parameters of hydrogen storage tank.

Component characteristics	Value
Capital cost (\$/kW)	2000
Replacement cost (\$/kW)	1800
Operation and maintenance cost (\$/year)	200
Life cycle (year)	12
Efficiency (%)	85

**Table 8.** Description of technical and economic parameters of electrolyzer.

Component characteristics	Value
Capital cost (\$/kW)	550
Replacement cost (\$/kW)	550
Operation and maintenance cost (\$/year)	10
Life cycle (year)	15
Efficiency (%)	95
Relative capacity (%)	80

**Table 9.** Description of technical and economic parameters of the converters.

#### Hydrogen storage tank

Technical and economic parameters of hydrogen storage tank are shown in Table 7<sup>77</sup>.

#### Electrolyzer

At the end of the reaction, hydrogen is produced at the cathode as Eq. (10) and oxygen at the anode as Eq. (11), using a combination of electrolyzers, fuel cells, and hydrogen tanks, the storage requirements of the battery can be reduced. The economic and technical parameters of the electrolyzer selected in this study are shown in Table 8<sup>78</sup>.



#### Converter

The output power of the inverter is based on the input power and fixed efficiency, which can be obtained from Eq. (12)<sup>79</sup>:

$$P_{out} = P_{in} \times \eta_{inv} \quad (12)$$

Where  $P_{out}$  refers to the output power of the inverter,  $P_{in}$  is the input power, and  $\eta_{inv}$  is the fixed efficiency. In this study, the technical and economic parameters of the selected converter are shown in Table 9<sup>80</sup>.

Application description	Average daily usage time (h)	Utilization number (n)	Power (W)	Total load (kWh)
Lighting	8	6	30	1.44
Refrigerator	24	1	240	5.76
Phone charging	7.5	3	5	0.45
Television	7	1	36	0.252
Air conditioner	4	1	2870	11.48
Laptop	6	1	100	0.6
Random load	5	1	15	7.5
Water heater	1	1	1500	1.5
Total	–	–	–	32.03

Table 10. Electrical load required for each household.

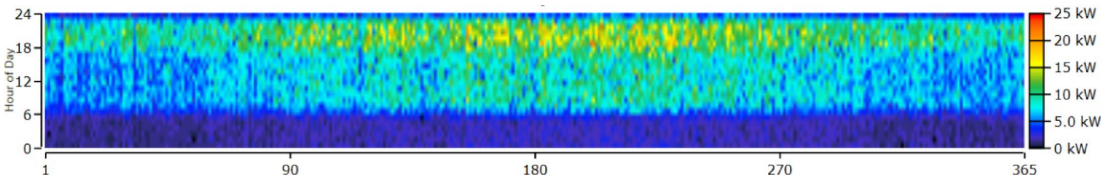


Fig. 8. Annual load heat map of the community.

Parameter	Fuel cell	Load
Sensitivity parameter	Initial Capital	Scaled annual average electric load
Values	50,000;100,000;200,000; 300,000; 500,000;	100; 200; 250; 300; 350; 400

Table 11. Various sensitive variables with different values.

Electrical load demand

When designing a hybrid energy system, it is first necessary to determine the load demand. This stage is very important to ensure that the energy generated by the system is at an optimal level and whether to build a large system. Load demand can be determined by calculating the electricity consumption of each household in a small system. Load demand is determined by estimating the daily usage of electrical equipment in the house. In larger systems, statistics on energy use in the region are used. In determining the demand, you can directly use the total energy consumption data in the area, or you can use the per capita daily electricity consumption data to calculate the load demand. Through data statistics, Table 10 shows that the average power load required per household in this community is 32.03 kWh.

Figure 8 shows the thermal map of the load at the site, with an average load demand of approximately 165.59 kWh/day and a peak load demand of 23.31 kW. Due to the dry climate of the region, most of the electricity consumption is in July, as the load continues to grow with the arrival of summer. This data is entered into HOMER Pro as the main load requirement.

Sensitivity analysis

Sensitivity analysis helps illustrate how system variables affect the overall performance of a system. In this study, the influence of several sensitive variables on the cost parameters of hybrid energy system was discussed through comprehensive sensitivity analysis. Table 11 describes the different sensitive parameters evaluated in the analysis and their corresponding values. Sensitivity analysis is carried out on Method 3 of using hybrid storage, mainly on the fuel cell price at the power supply end and the Scaled annual average electric load at the power end.

Results and discussions

In this paper, three PV-WT-BioGen- Hydrokinetic hybrid renewable energy systems with different storage methods are optimized to meet the electricity needs of a community in Baotou. The economic analysis of the impact of energy storage on the system is mainly based on the NPC and LCOE of the optimization results obtained by different simulation methods, and the environmental impact of the carbon content, carbon dioxide content and sulfur dioxide content of the optimization results on the three energy storage methods is analyzed. The sensitivity analysis of fuel cell price and power demand parameters is used to study the impact of different price parameters and demand parameters on the economic environment of hybrid energy storage system.

Results	1	2	3	4	5
NPC (\$)	197,396	226,315	255,051	309,036	379,803
LCOE (\$)	0.159	0.201	0.208	0.236	0.29
Battery (n)	20	15	43	35	45
PV (kW)	19.3	–	52.7	37.1	–
WT (n)	6	13	8	8	14
BioGen (kW)	–	–	–	15	15
Converter (kW)	12.6	12.7	17.8	22.8	23.6
Dispatch	CC	CC	CC	LF	LF

**Table 12.** Different optimization options for renewable energy systems with battery storage energy.

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Salvage (\$)	Total (\$)
Battery	22,000.00	38,127.58	4,338.07	1,639.61	62,826.03
WT	57,960.00	36,276.30	13,014.20	25,728.93	81,521.57
PV	25,072.39	20,051.45	8,366.59	14,221.47	39,268.96
Converter	6,931.50	5,861.92	2,733.57	1,747.40	13,779.58
System	111,963.89	100,317.24	28,452.43	43,337.42	197,396.15

**Table 13.** Component cost of renewable energy system optimization solution with battery storage energy.

Generating capacity	kWh/yr	proportion (%)
Photovoltaic panel	31,287	34.9
Wind turbine	58,407	65.1
Total	89,693	10

**Table 14.** Average annual output of photovoltaic panels and wind turbines.

### Hybrid renewable energy systems with battery storage energy

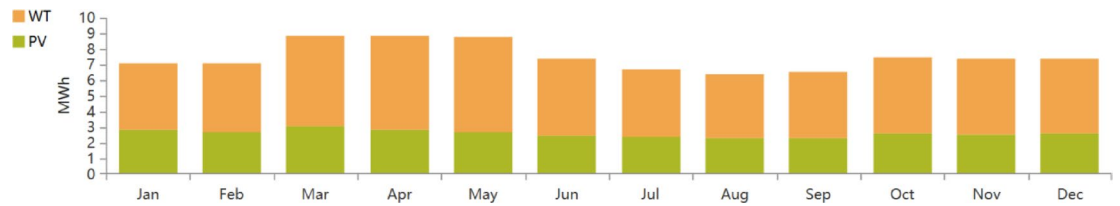
The simulation results of the method with battery energy storage are shown in Table 12. First of all, the optimal result based on the NPC minimum is displayed on the second column, with the system configuration consisting of 20 batteries, 19.3 kW PV, 6 wind turbines, a 12.6 kW converter. As for the economics of the optimization results, we can see NPC is 197,396\$. And LCOE is \$0.159, and the selected scheduling strategy is a cyclic charging strategy. We can see batteries being used in every optimization solution, and the reduction of battery consumption in result 2 leads to an increase in NPC from \$197,396 to \$246,314, an increase of 25%, and in LCOE from \$0.159 to \$0.201, an increase of 26%. Compared with result 1, result 3, 4, 5, the optimal configuration scheme did not use the biogas generator set with low initial cost compared to the wind turbine, but chose the wind turbine, which can show that the power output of Baotou wind resources is stable whose power generation may be higher.

In the 25-year project cycle model, the total net present value cost of the system's optimal Method is \$197,396. Table 13 shows the NPC of each component in the optimization method over the project lifecycle. Among them, the highest capital cost is the investment of wind turbines, the capital cost of 6 AWS HC 4.2Kw wind turbines in the initial stage of the project is \$57,960, because the life cycle of wind turbines is 20 years, the project life cycle are 25 years, at the 20th year, the wind turbines are scrapped and 6 new wind turbines are replaced. The total investment for the wind turbine at the end of the project was \$81,512.57. The capital cost of photovoltaic panels and battery energy storage ranked second and third in the project, respectively \$25,072.39 and \$22,000. Therefore, this more reflects the advantages of Baotou's wind resources and the reasons for choosing wind turbines in the optimal scheme of this model.

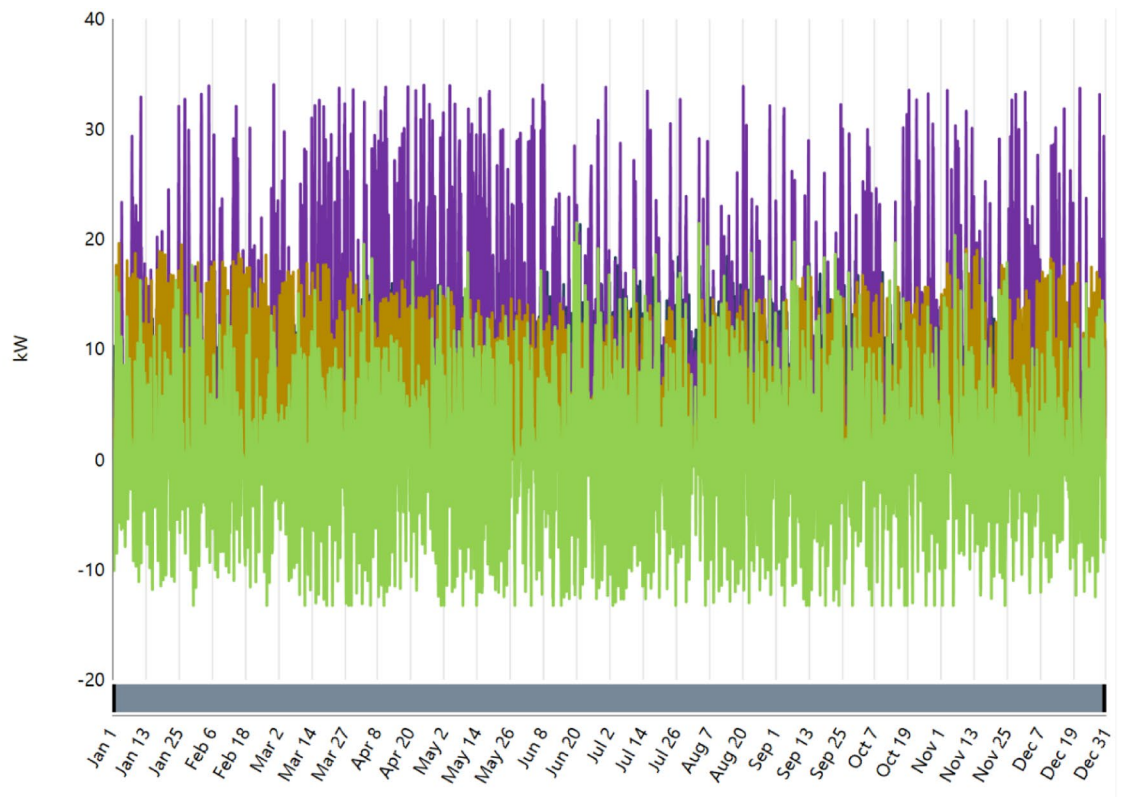
The average annual output of photovoltaic panels and wind turbines is shown in Table 14. Photovoltaic panels are the stable output of the model, accounting for 34.9% of the system's power generation, generating 31,287kWh in the year, while wind power accounts for 65.1% of the annual power generation, with the largest output in March, April and May, due to the strongest wind speed and abundant wind resources in Baotou during these three months.

Figure 9 shows the monthly power generation of photovoltaic panels and wind turbines in the system throughout the year in the optimal Method.

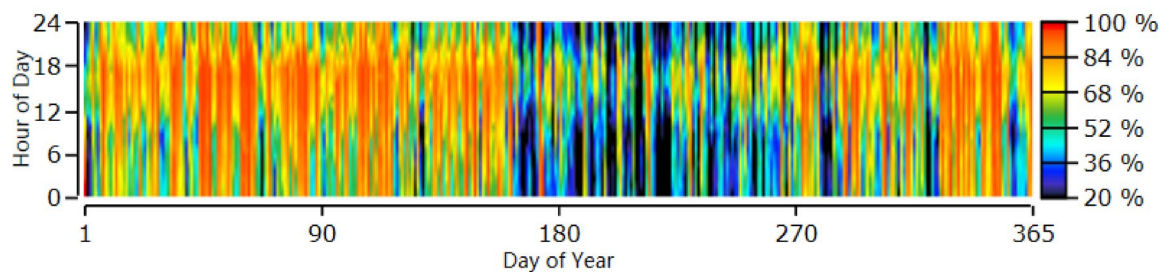
Figure 10(a) shows the annual hourly energy generation of each component in the optimal solution of renewable energy system with battery energy storage, and (b) shows the charging state of the battery in a year. In figure (a), the purple part is the hourly power output of wind turbines, the brown part is the hourly power generation of photovoltaic panels, the green part is the charging and discharging of batteries, and the dark blue part is the total power load.



**Fig. 9.** Energy yield of components in the optimal scheme of renewable energy system with battery storage.

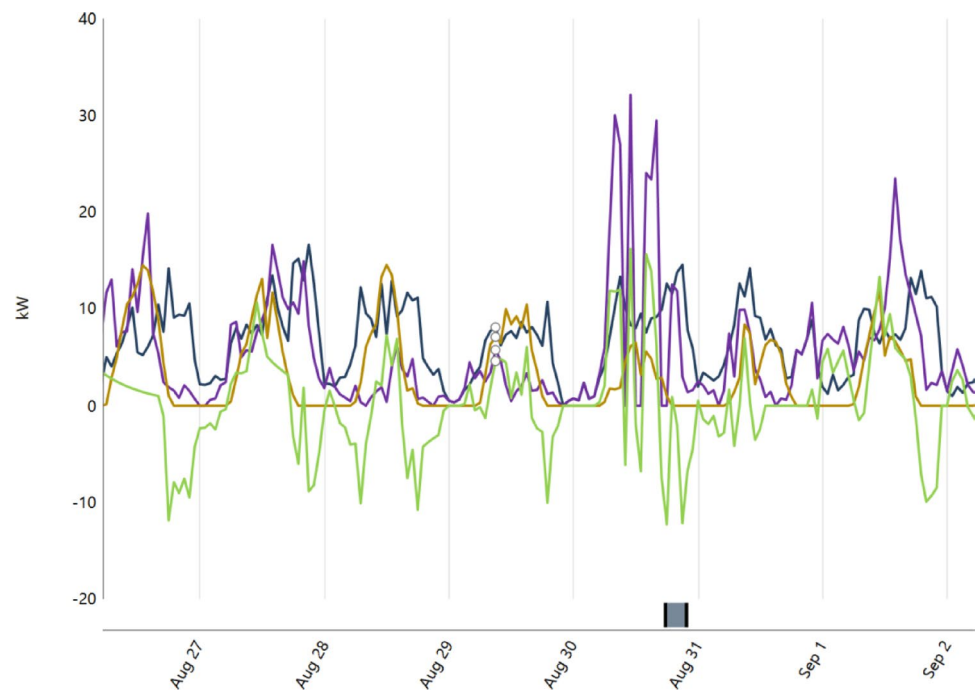


(a) Annual hourly output of each component



(b) State of charging

**Fig. 10.** Annual hourly energy generation of each component of the optimal renewable energy system with battery storage.



**Fig. 11.** Select the hourly power generation of the system from August 27 to September 2 as shown in Fig. 11.

Results	1	2	3	4
NPC (\$)	4.80 M	5.96 M	6.24 M	6.53 M
LCOE (\$)	3.85	4.82	4.75	4.98
FC (kW)	250	250	–	250
PV (kW)	101	214	145	148
WT(n)	31	–	66	76
BioGen(kW)	–	–	15	15
Electrolyzer(kW)	50	50	50	50
Refomer(kW)	100	100	100	100
HTank(kg)	100	100	50	50
Converter(kW)	5.38	10.6	50.3	50.5
Dispatch	CC	CC	CC	CC

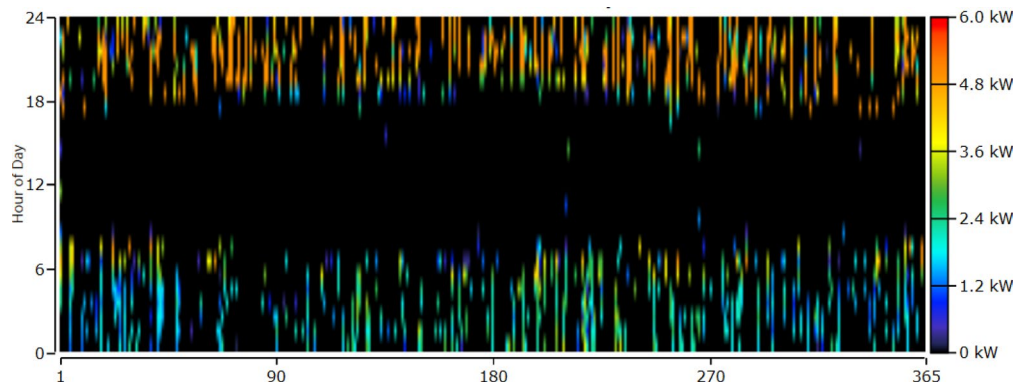
**Table 15.** Different optimization options for renewable energy systems with fuel cell storage.

Since the hourly power generation of each component fluctuates most significantly from August to September, the system power generation from August 27 to September 2 in Fig. 10 is selected, as shown in Fig. 11. We can see that in each day photovoltaic panels (brown curve) and wind turbines (purple curve) generate electricity to provide the energy required for the daytime power load (dark blue curve), while batteries (green curve) charge during the day and discharge at night to meet the nighttime power demand. The disadvantage of the system is low flexibility, because the extra power generation after the system is operated is 27,444kWh, accounting for 30.6% of the system’s power generation, which means that the power generation is wasted. And, in the event that any of the wind or photovoltaic components need to be repaired, there is no other backup power supply available.

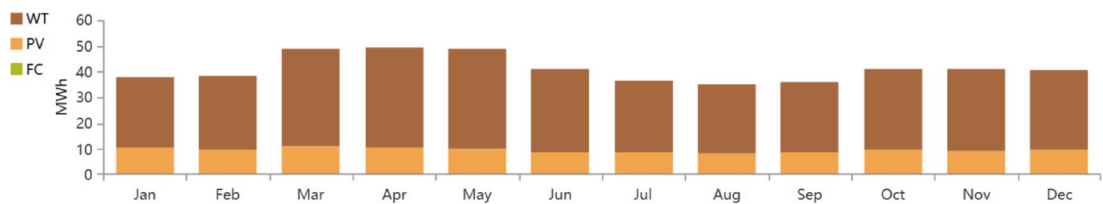
**Hybrid renewable energy systems with fuel cell storage energy**

Table 15 shows the optimal configuration of the hybrid system with fuel cell for the community meeting the power demand of households. The optimization result of the candidate winning system is the first solution output by HOMER. The optimization result shows that the solution includes photovoltaic power generation and wind turbine, and the scheduling strategy is cyclic charging. The cost of the fuel cell is much higher than the cost pricing of the battery, thus it can be seen that the NPC and LCOE of the optimization result in Table 12 are higher, whose NPC was \$48,000,000 and LCOE was \$3.85. As shown in Table 14 result 4: fuel cell 250 kW, PV 148 kW, 76 wind turbines, electrolyzer 250 kW, converter 50.5 kW, and the NPC reached \$6530,000. Result 2 did not use wind turbines, all chose to use photovoltaic panels, NPC rose from \$4.4Mz to \$5.95 M, also increased by





**Fig. 12.** Overview of fuel cell power generation per hour in renewable energy system optimization with fuel cell storage.



**Fig. 13.** Overview of the power generation of each component in the optimization scheme of a renewable energy system with fuel cell storage.

Quantity	kWh/yr	%
Excess power	437,017	88.4
Unmet electrical load	3190	5.28
Capacity shortage	6092	10.1

**Table 16.** Electricity services in an optimal method for renewable energy systems with fuel cell storage.

24%, LCOE increased by 26%. Result 3 did not use fuel cells, and the NPC increase was significantly lower, only 4.7%. On the contrary, the LCOE had decreased, becoming \$4.75. The NPC of result 4 went up to \$6.53 M and the LCOE went up to \$4.98.

Figure 12 is an overview of the hourly power generation of the fuel cell in the optimal scheme. From the figure, it can be seen that the fuel cell does not generate power during the day, but basically provides power at night, because the photovoltaic panel absorbs solar energy during the day to provide power energy and the wind turbine provides power output during the day.

Figure 13 shows an overview of the power generation of each component in the optimization scheme of a renewable energy system with fuel cell storage. As can be seen from the figure, as in result 1, wind power is still the main output source of power generation equipment, photovoltaic panels stable output in a year, and fuel cell discharge accounts for only a small part.

As can be seen from Table 16, due to the high cost of fuel cells and the shortage of energy storage equipment, the optimal scheme in the system leads to 437,017kwh of excess power per year, accounting for 88.4%. The energy waste in Method 1 occurs when renewable generation exceeds load demand and battery storage capacity, often due to insufficient battery capacity, leading to unutilized excess energy. This reduces system efficiency, sustainability, and increases LCOE. Similarly, Method 2 exhibits a high excess energy rate (88.4%), primarily from peak renewable generation outpacing demand and limited fuel cell storage.

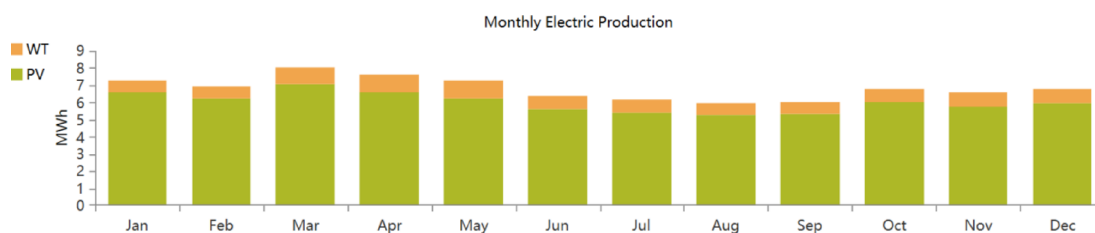
**Hybrid renewable energy systems with battery and fuel cell hybrid storage energy**

Table 17 shows the architecture of the system and associated scheduling policies, the various costs and the amount of power generated by each component of the architecture. Overall, in the optimal configuration, the system has an NPC of \$3,110,000 and an average power cost of \$2.37. The solutions shown in the optimization results include biogas power generation, photovoltaic power generation, wind power generation, using a scheduling strategy of load following, 39 batteries, 37 kW PV, 8 wind turbines, and 15 kW BioGen. The optimal solution for model optimization with hybrid energy storage in Homer Pro did not use fuel cell power storage. It

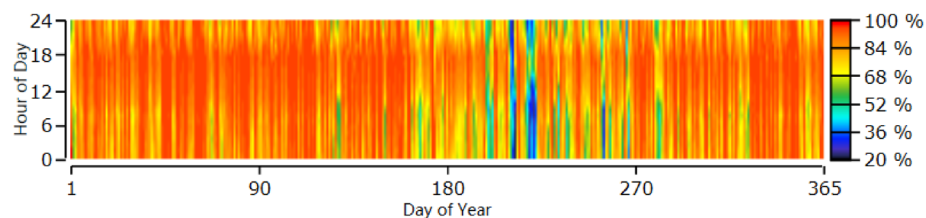


Results	1	2	3	4
NPC (\$)	3.11 M	3.16 M	3.39 M	3.44 M
LCOE (\$)	2.37	2.40	2.58	2.51
FC (kW)	–	–	250	250
Battery (n)	39	37	45	44
PV (kW)	37	–	24.7	28.5
WT (n)	8	14	8	8
BioGen (kW)	15	15	15	15
Electrolyzer (kW)	–	50	50	–
Refome r(kW)	–	–	50	50
HTank (kg)	–	50	–	50
Converter (kW)	23.2	25.9	25.9	26.0
Dispatch	LF	LF	CC	CC

**Table 17.** Local optimization options for renewable energy systems with battery storage and fuel cell hybrid storage.



(a) Annual hourly output of each component



(b) State of Charging

**Fig. 14.** Power generation of each component in an optimal result for a renewable energy system with battery and fuel cell storage.

can be seen that in the optimal result of Method 3, the NPC of the system rise from \$3,110,000 to \$3,160,000, an increase of \$50,000, reaching 6%, and LCOE also rise from \$2.37 to \$2.40.

In the optimal scheme of renewable energy system with battery and fuel cell energy storage, the power generation of each component is shown in Fig. 14(a), while the energy storage device only invokes the battery pack, and the annual charging state of the battery is shown in Fig. 14(b).

Optimization Method 3 includes two kinds of energy storage, battery and fuel cell. The power generation of each component in the system is shown in Fig. 15. The proportion of fuel cells is also very low.

### Comparison of results of three methods

The optimization schemes of the three Methods are shown in Table 18. Method 1 using only batteries as energy storage has a net present value cost of \$197,396 and a unit power cost of \$0.159. Method 2 using only hydrogen fuel cells has a net present value of \$4.8 million and a unit power cost of \$3.85. The NPC of Method 2 significantly higher than that of Method 1, with an increase of 24 times. In Method 3, when both batteries and hydrogen fuel cells can be used, the optimal simulation scheme does not choose to use hydrogen fuel cells. Accordingly, the NPC is 3.11 million dollars, and the unit power cost is \$2.37. Compared with Method 1, both economic parameters are significantly increased. According to the comparison of the optimized configuration capacity and net present value cost of each component in the above three Method optimal schemes, it can be seen that under the same power demand and resource allocation, due to the high cost of fuel cells, the optimization result

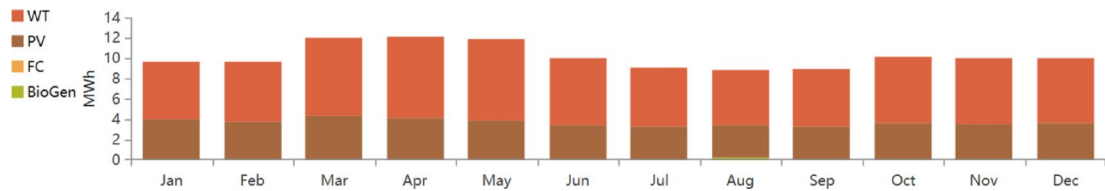


Fig. 15. Power output of each component of Method 3.

Method	battery storage	fuel cell storage	battery and fuel cell hybrid storage
NPC (\$)	197,396	4.80 M	3.11 M
LCOE (\$)	0.159	3.85	2.37
Battery (n)	20	250	39
FC (kW)	–	50	–
PV (kW)	19.3	101	37
WT (n)	6	31	8
BioGen (kW)	–	–	15
Electrolyzer (kW)	–	100	–
HTank (kg)	–	100	–
Converter (kW)	12.6	5.38	23.2
Dispatch	CC	CC	LF

Table 18. Economic and technical results of three method optimization schemes.

Method	battery storage	fuel cell storage	battery and fuel cell hybrid storage
Carbon Dioxide (kg/yr)	0	19,102	19,103
Carbon Monoxide (kg/yr)	0	0.32340	0.22260
Sulfur Dioxide (kg/yr)	0	45.0	47.4
Nitrogen Oxides (kg/yr)	0	0	0.0232
Particulate Matter (kg/yr)	0	0	0.000196

Table 19. Environmental results of three method optimization methods.

of the system when hybrid energy storage is proposed in Method 3 tends to use batteries instead of fuel cell. The research by Das et al.<sup>9</sup> and Sharma et al.<sup>11</sup> also indicates that battery energy storage has more economic advantages, but fuel cells have potential in terms of high energy density and long-term storage. The conclusion of this paper is consistent with these studies, but it further quantifies the cost differences among different energy storage technologies.

The actual use of fuel cells will lead to the total cost of the system is high, therefore, when using HOMER Pro for simulation, the optimal configuration of the system and the final cost will be affected. HOMER Pro simulates different electrical and thermal production and storage technology modules and uses optimization algorithms to find the best system configurations, where batteries are often prioritized because of their lower cost, while fuel cells may be marginalized because of their high cost. Although fuel cells can provide efficient energy conversion in some cases, their high initial investment and operating costs make them less economical than batteries.

Table 19 shows that the Carbon Dioxide (CO<sub>2</sub>) emission of the hybrid renewable energy system using batteries is 0, and Method 2 used fuel cells resulting in the highest CO<sub>2</sub> emission, and the CO<sub>2</sub> emission of the hybrid energy system using battery and fuel cell combined energy storage is increased. The results show that the hybrid energy storage of battery and fuel cell may increase the environmental pollution. At the same time, the CO emissions of hybrid renewable energy systems using batteries are 0, while the fuel cell used in method 2 has the highest CO emissions. The hybrid energy system using a combination of batteries and fuel cells for energy storage also leads to an increase in CO emissions. Moreover, SO<sub>2</sub> emissions of hybrid renewable energy systems using batteries are zero, while the use of fuel cells in method 2 leads to an increase in SO<sub>2</sub> emissions. The hybrid energy system using a combination of batteries and fuel cells for energy storage has the highest SO<sub>2</sub> emissions. Another issue is that NO<sub>2</sub> emissions of hybrid renewable energy systems using batteries are zero. The NO<sub>2</sub> emissions caused by the use of fuel cells in method 2 are also zero. The hybrid energy system using a combination of batteries and fuel cells for energy storage in method 3 will result in NO<sub>2</sub> emissions. Finally, the Particulate Matter (PM) emissions of the hybrid renewable energy system using batteries are zero, and the PM emissions caused by the fuel cell used in method 2 are also zero. The hybrid energy system using a combination of batteries and fuel cells for energy storage in method 3 will result in PM emissions. The results indicate that

Sensitivity/ Electric Load Scaled Average (kWh/d)	Cost/ NPC (\$)	Cost/ LCOE (\$)	Cost/ Operating cost (\$/yr)	Cost/ Initial capital (\$)	Emission/ Carbon Dioxide(kg/yr)
100	2,989,927	3.77	116,538.3	462,172.7	0
165	3,107,959	2.36	119,081.4	525,042.5	0
200	3,170,703	2.0	120,551.6	555,898.9	0
250	3,260,246	1.64	122,247.4	608,659.4	0
300	3,350,830	1.41	124,340.1	653,850.9	0
350	3,437,776	1.24	125,596.9	713,537.2	0
400	3,526,107	1.11	127,357	763,691.1	0

**Table 20.** Sensitivity analysis in method 3 on the electric load scaled Average.

Sensitivity/ Initial Capital of Fuel Cell (\$)	Cost/ NPC (\$)	Cost/ LCOE (\$)	Cost/ Operating cost (\$/yr)	Cost/ Initial capital (\$)	Emission/ Carbon Dioxide(kg/yr)
2500	2.65 M	2.19	96,643	531,127	19,103
5000	2.75 M	2.01	97,543	533,627	19,103
50,000	3.11 M	2.37	118,809	532,586	19,103
100,000	3.11 M	2.37	118,809	532,586	19,103
200,000	3.11 M	2.37	118,809	532,586	19,103
300,000	3.11 M	2.37	118,809	532,586	19,103
750,000	3.11 M	2.37	118,809	532,586	19,103

**Table 21.** Sensitivity analysis in method 3 on the initial capital of fuel cell.

the mixed energy consumption of batteries and fuel cells may increase environmental pollution. The studies of Jahangir et al.<sup>15</sup> and Odetoye et al.<sup>27</sup> also pointed out the environmental advantages of battery energy storage, while the emission problem of fuel cells needs to be solved through technological improvements. The emission data in this article is consistent with these studies, but provides more specific case data.

This paper combines research hotspots and uses the currently more advanced energy storage technologies, including batteries and fuel cells, as well as the rapidly developing renewable energy power generation technologies, including wind power generation and solar power generation and so on. However, due to the differences in various resources in the actual region and the possible differences in technical and economic parameters and scales of components, the economic and environmental results obtained may be different.

### Sensitivity results

CO<sub>2</sub> values vary the most in the emission data, so CO<sub>2</sub> is selected for sensitivity analysis. The results of the first sensitivity analysis in Method 3 on the Electric Load Scaled Average are shown in Table 20. The results of the first sensitivity analysis on the Electric Load Scaled Average are shown in Table 21. As can be seen from the table, as the Electric Load Scaled Average increases, the NPC, operating cost of the system and initial capital also increases. On the contrary, the larger the Electric Load Scaled Average, the smaller the LCOE. Carbon dioxide emissions are zero and the value remains the same.

The results of sensitivity analysis for fuel cell prices in Method 3 are shown in Tables 20 and 21. As can be seen from the table, when the cost price of fuel cell drops to \$5,000, the economic cost of the hybrid energy system changes and decreases. That is because when the price of fuel cell is expensive, HOMER Pro's optimization result does not use fuel cell. When the cost of fuel cells drops to a certain level, such as \$5000, the system will start to use fuel cells as energy storage devices, and the NPC, system operation cost and initial capital of the optimization result of the hybrid energy system will also decrease. Similarly, the lower the capital cost of fuel cells is, the smaller the LCOE will be.

## Conclusions and policy implications

### Conclusions

Three energy storage methods were purposed, which produced electricity by photovoltaic modules, wind turbine modules, biogas generators in Baotou City. Three energy storage systems including battery (Method 1), fuel cell (Method 2) and battery mixed fuel cell (Method 3) are considered. The study found that:

1. The use of batteries as energy storage in communities posed the lowest energy costs, that NPC was \$197,396 and LCOE was \$0.159\$, consisting of 20 batteries, 19.3 kW PV, 6 wind turbines, a 12.6 kW converter;
2. An increase in the Electric Load Scaled Average implied a decrease in LCOE and the increase of the NPC. For example, Electric Load Scaled Average increased from 100 kWh/d to 400 kWh/d, then LCOE decreased from \$3.77 to \$1.11 and NPC increased from \$2,989 to \$3,526;

3. Lower fuel cell prices mean lower NPC and LCOE. Among them, when the initial capital cost of fuel cells dropped from \$7,500,000 to \$5,000, the NPC began to change, decreasing from 3.11 M to 2.75 M, and the LCOE dropped from \$2.37 to \$2.01;
4. Method 2 and 3 have relatively high total CO<sub>2</sub> and SO<sub>2</sub> emissions compared to Method 1. Respectively, CO<sub>2</sub> and SO<sub>2</sub> increased from 0 to 19,102 kg/yr and 19,103 kg/yr.

### Policy implications

In view of the high energy costs and electricity prices that hinder the viability of hydrogen fuel cells in renewable energy systems, the following policy implications are proposed:

1. In order to facilitate the “electricity-hydrogen” coupling, the government should promote the research to accelerate development of the water, wind, solar, hydrogen storage integrated system;
2. By national appeal, researchers should enhance fuel cell research and development, and reduce fuel cell prices and environmental pollution to attract investment in renewable energy;
3. The government should implement financial support policies for science and technology, and provide long-term and stable financing support. Meanwhile, piloting application of key technologies for renewable energy substitution to gradually increase the proportion of renewable electricity consumption;
4. The government should choose to support renewable energy power generation projects to carry out direct transactions with various types of users and enter into multi-year power purchase and sales agreements with users to stabilize the electricity cost of hydrogen fuel cell projects.
5. The development of storage batteries should be continued. Fuel cells and hybrid energy storage are suitable for high-energy-density, large-scale and long-cycle storage scenarios. Renewable energy systems can collaboratively improve air quality through CO<sub>2</sub> reduction and regional environmental compliance through SO<sub>2</sub> control.
6. The development of new energy vehicles relies on battery and fuel cell technologies. However, at present, fuel cells are relatively expensive and face technical challenges. Meanwhile, the safety issue of storage batteries has also drawn much attention. The government needs to strengthen supervision and introduce relevant policies to ensure battery safety, enhance technical reliability, and promote the sustainable development of the industry.

### Limitations and future research

1. The model of this study shows that fuel cells are not cost optimal, but their practical feasibility is affected by a wide range of factors, including policy support, environmental benefits and system reliability. These additional factors could be included in future research to make a more comprehensive assessment of the feasibility of method 3 in practical application.
2. Social acceptance, policy support, public attitude and social and cultural background have an important impact on the adoption of energy storage technology. In order to improve the accuracy and practicability of the calculation results, incorporating these additional factors into the energy storage model of the energy system may be the future research direction.
3. The model is universal and future research can be applied to larger energy systems or industrial systems. Modifications could be made based on the characteristics of different energy systems to obtain the results.
4. Extreme weather conditions and the climate resilience of renewable energy availability in different seasons will have an impact on the implementation of the system. In the future, we will take extreme weather factors into account in the paper.

### Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Received: 31 December 2024; Accepted: 30 June 2025

Published online: 15 July 2025

### References

1. Su, J., Liang, Y., Ding, L., Zhang, G. & Liu, H. Research on China's Energy Development Strategy under Carbon Neutrality. *Bull. Chin. Acad. Sci.* **36**, 1001–1009. <https://doi.org/10.16418/j.issn.1000-3045.20210727001> (2021).
2. *China Statistical Yearbook*, <https://www.stats.gov.cn/sj/ndsj/2023/indexch.htm> (2023).
3. Ozdamar, A., Ozbalta, N., Akin, A. & Yildirim, E. D. An application of a combined wind and solar energy system in Izmir. *Renew. Sustain. Energy Rev.* **9**, 624–637. <https://doi.org/10.1016/j.rser.2004.06.002> (2005).
4. Rohit, A. K., Devi, K. P. & Rangnekar, S. An overview of energy storage and its importance in Indian renewable energy sector. *J. Energy Storage*. **13**, 10–23. <https://doi.org/10.1016/j.est.2017.07.012> (2017).
5. Chen, G., Li, Y., Bick, M. & Chen, J. Smart textiles for electricity generation. *Chem. Rev.* **120**, 3668–3720. <https://doi.org/10.1021/acs.chemrev.9b00821> (2020).
6. Elmoustapha, H., Hoppe, T. & Bressers, H. Consumer renewable energy technology adoption decision-making; comparing models on perceived attributes and attitudinal constructs in the case of solar water heaters in Lebanon. *J. Clean. Prod.* **172**, 347–357. <https://doi.org/10.1016/j.jclepro.2017.10.131> (2018).
7. Tripathi, L., Mishra, A. K., Dubey, A. K., Tripathi, C. B. & Baredar, P. Renewable energy: an overview on its contribution in current energy scenario of India. *Renew. Sustain. Energy Rev.* **60**, 226–233. <https://doi.org/10.1016/j.rser.2016.01.047> (2016).
8. Jin, Z. & Zhang, C. On china's energy transition pathway towards carbon neutrality. *Acta Scie. Nat. Univ. Pekin.* **60**, 767–774. <https://doi.org/10.13209/j.0479-8023.2024.017> (2024).

9. Das, B. K., Hasan, M. & Das, P. Impact of storage technologies, Temporal resolution, and PV tracking on stand-alone hybrid renewable energy for an Australian remote area application. *Renew. Energy*. **173**, 362–380. <https://doi.org/10.1016/j.renene.2021.03.131> (2021).
10. Xin, S. et al. Roadmap for rechargeable batteries: present and beyond. *Sci. China Chem.* **67**, 13–42. <https://doi.org/10.1007/s11426-023-1908-9> (2024).
11. Sharma, V., Haque, M. H. & Aziz, S. M. Energy cost minimization for net zero energy homes through optimal sizing of battery storage system. *Renew. Energy*. **141**, 278–286. <https://doi.org/10.1016/j.renene.2019.03.144> (2019).
12. Li, X. & Wang, S. Energy management and operational control methods for grid battery energy storage systems. *CSEE J. Power Energy Syst.* **7**, 1026–1040. <https://doi.org/10.17775/CSEEJPES.2019.00160> (2019).
13. Jahangir, M. H. & Cheraghi, R. Economic and environmental assessment of solar-wind-biomass hybrid renewable energy system supplying rural settlement load. *Sustain. Energy Technol. Assess.* **42**, 100895. <https://doi.org/10.1016/j.seta.2020.100895> (2020).
14. Wang, Y. et al. Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology. *Energy AI*. **1**, 100014. <https://doi.org/10.1016/j.egyai.2020.100014> (2020).
15. Mehrpooya, M., Rahbari, C. & Moosavian, S. M. A. Introducing a hybrid multi-generation fuel cell system, hydrogen production and cryogenic CO<sub>2</sub> capturing process. *Chem. Eng. Process. - Process Intensif.* **120**, 134–147. <https://doi.org/10.1016/j.cep.2017.07.008> (2017).
16. Rekioua, D., Bensmail, S. & Bettar, N. Development of hybrid photovoltaic-fuel cell system for stand-alone application. *Int. J. Hydrog. Energy*. **39**, 1604–1611. <https://doi.org/10.1016/j.ijhydene.2013.03.040> (2014).
17. Abomazid, A. M., El-Taweel, N. A. & Farag, H. E. Z. Optimal energy management of hydrogen energy facility using integrated battery energy storage and solar photovoltaic systems. *IEEE Trans. Sustain. Energy*. **13**, 1457–1468. <https://doi.org/10.1109/TSTE.2022.3161891> (2022).
18. Hu, M. The current status of hydrogen and fuel cell development in China. *J. Electrochem. Energy Convers. Storage*. **17**, 034001. <https://doi.org/10.1115/1.4045702> (2020).
19. Das, B. K., Al-Abdeli, Y. M. & Woolridge, M. Effects of battery technology and load scalability on stand-alone PV/ICE hybrid micro-grid system performance. *Energy*. **168**, 57–69. <https://doi.org/10.1016/j.energy.2018.11.033> (2019).
20. Hoang, A. T., Pham, V. V. & Nguyen, X. P. Integrating renewable sources into energy system for smart City as a sagacious strategy towards clean and sustainable process. *J. Clean. Prod.* **305**, 127161. <https://doi.org/10.1016/j.jclepro.2021.127161> (2021).
21. Yue, M. et al. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renew. Sustain. Energy Rev.* **146**, 111180. <https://doi.org/10.1016/j.rser.2021.111180> (2021).
22. González, E. L., Llerena, F. I., Pérez, M. S., Iglesias, F. R. & Macho, J. G. Energy evaluation of a solar hydrogen storage facility: comparison with other electrical energy storage technologies. *Int. J. Hydrog. Energy*. **40**, 5518–5525. <https://doi.org/10.1016/j.ijhydene.2015.01.181> (2015).
23. Kalinci, Y., Hepbasli, A. & Dincer, I. Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options. *Int. J. Hydrog. Energy*. **40**, 7652–7664. <https://doi.org/10.1016/j.ijhydene.2014.10.147> (2015).
24. Alqahtani, N. & Balta-Ozkan, N. Assessment of rooftop solar power generation to Meet residential loads in the City of neom, Saudi Arabia. *Energies*. **14**, 3805. <https://www.mdpi.com/1996-1073/14/13/3805#> (2021).
25. Seedahmed, M. M. A. et al. Optimal sizing of grid-connected photovoltaic system for a large commercial load in Saudi Arabia. *Alexandria Eng. J.* **61**, 6523–6540. <https://doi.org/10.1016/j.aej.2021.12.013> (2022).
26. Chung, M. et al. Economic evaluation of renewable energy systems for the optimal planning and design in Korea—a case study. *J. Sustainable Dev. Energy Water Environ. Syst.* **6**, 725–741. <https://doi.org/10.13044/j.sdewes.d6.0216> (2018).
27. Odetoye, O. A., Olulope, P. K., Olanrewaju, O. M., Alimi, A. O. & Igbinsola, O. G. Multi-year techno-economic assessment of proposed zero-emission hybrid community microgrid in Nigeria using HOMER. *Heliyon* <https://doi.org/10.1016/j.heliyon.2023.e19189> (2023).
28. Khan, T., Ullah, Z., Agyekum, E. B., Hasanien, H. M. & Yu, M. Multi-objective optimization of combined heat and power system integrated with multi-energy storage systems for rural communities. *J. Energy Storage*. **99**, 113433. <https://doi.org/10.1016/j.est.2024.113433> (2024).
29. Al-Hanoot, A. K. et al. Economic feasibility assessment of optimum grid-connected pv/battery systems to Meet electricity demand for industrial buildings in Saudi Arabia. *Energy Build.* **328**, 115126 (2024).
30. Yong, Y. & Rong, L. Techno-economic optimization of an off-grid solar/wind/battery hybrid system with a novel multi-objective differential evolution algorithm. *Energies* **13**, 1585 (2020).
31. Song, Z. et al. Economy analysis of second-life battery in wind power systems considering battery degradation in dynamic processes: real case scenarios. *Appl. Energy*. **251**, 113411 (2019).
32. Coban, H., Rehman, A. & Mohamed, A. Technical and economical investigation of a centralized and decentralized hybrid renewable energy system in cadaado, somalia. *Processes*. **10**, 667 (2022).
33. Coban, H. H. Assessment of hybrid renewable energy system in Beledweyne City somalia, technical and economical analysis. *J. Eng. Res.* **11**, 2307–1877 (2023).
34. Astiaso Garcia, D., Barbanera, F., Cumo, F., Di Matteo, U. & Nastasi, B. Expert opinion analysis on renewable hydrogen storage systems potential in Europe. *Energies*. **9**, 963 (2016).
35. Pakere, I., Feofilovs, M., Lepiksaar, K., Vitolinš, V. & Blumberga, D. Multi-source district heating system full decarbonization strategies: technical, economic, and environmental assessment. *Energy*. **285**, 129296 (2023).
36. Owolabi, A. B., Nsafon, B. E. K., Roh, J. W., Suh, D. & Huh, J. S. S. E. T. Validating the techno-economic and environmental sustainability of solar PV technology in Nigeria using retscon experts to assess its viability. *Sustain. Energy Technol. Assess.* **36**, 100542 (2019).
37. Stadler, M., Groissböck, M., Cardoso, G. & Marnay, C. Optimizing distributed energy resources and Building retrofits with the strategic DER-CAModel. *Appl. Energy*. **132**, 557–567 (2014).
38. Eskander, M. M. & Silva, C. A. Techno-economic and environmental comparative analysis for DC microgrids in households: Portuguese and French household case study. *Appl. Energy*. **349**, 121495 (2023).
39. Jalaei, S. A. et al. A novel hybrid method based on cuckoo optimization algorithm and artificial neural network to forecast world's carbon dioxide emission. *MethodsX* **8**, 101310 (2021).
40. Jalaei, M., GhasemiNejad, A., Jalaei, S. A., Amani Zarin, N. & Derakhshani, R. A novel hybrid artificial intelligence approach to the future of global coal consumption using Whale optimization algorithm and adaptive neuro-fuzzy inference system. *Energies*. **15**, 2578 (2022).
41. Derakhshani, R., Lankof, L., GhasemiNejad, A. & Zaresefat, M. Artificial intelligence-driven assessment of salt caverns for underground hydrogen storage in Poland. *Sci. Rep.* **14**, 14246 (2024).
42. Derakhshani, R. et al. A Novel Sustainable Approach for Site Selection of Underground Hydrogen Storage in Poland Using Deep Learning. *Energies* **17**, 3677 (2024).
43. Yang, M., Jiang, Y., Zhang, W., Li, Y. & Su, X. Short-term interval prediction strategy of photovoltaic power based on meteorological reconstruction with Spatiotemporal correlation and multi-factor interval constraints. *Renew. Energy*. **237**, 121834 (2024).
44. Li, N., Dong, J., Liu, L., Li, H. & Yan, J. A novel EMD and causal convolutional network integrated with transformer for ultra short-term wind power forecasting. *Int. J. Electr. Power Energy Syst.* **154**, 109470 (2023).
45. Wang, H., Sun, W., Jiang, D. & Qu, R. A MTPA and flux-weakening curve identification method based on physics-informed network without calibration. *IEEE Trans. Power Electron.* **38**, 12370–12375 (2023).



46. Ma, Z. et al. A review of energy supply for biomachine hybrid robots. *Cyborg Bionic Syst.* **4**, 0053 (2023).
47. Yi, X., Lu, T., Li, Y., Ai, Q. & Hao, R. Collaborative planning of multi-energy systems integrating complete hydrogen energy chain. *Renew. Sustain. Energy Rev.* **210**, 115147 (2025).
48. Zhu, L. et al. Optimization of power generation and sewage treatment in stacked pulsating gas-liquid-solid Circulating fluidized bed microbial fuel cell using response surface methodology. *Int. J. Hydrog. Energy.* **101**, 161–172 (2025).
49. Fu, L., Wang, J., Fu, X. & Zhao, G. Finite-time Pade-based adaptive FNN controller implementation for microbial fuel cell with delay and multi-disturbance. *Int. J. Hydrog. Energy.* **98**, 1034–1043 (2025).
50. Zhang, Y., Deng, X. & Zhang, Y. Generation of sub-item load profiles for public buildings based on the conditional generative adversarial network and moving average method. *Energy Build.* **268**, 112185 (2022).
51. Noorollahi, Y., Kheirrouz, M., Asl, H. F., Yousefi, H. & Hajinezhad, A. Biogas production potential from livestock manure in Iran. *Renew. Sustain. Energy Rev.* **50**, 748–754. <https://doi.org/10.1016/j.rser.2015.04.190> (2015).
52. Shahzad, M. K. et al. Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software. *Renew. Energy.* **106**, 264–273. <https://doi.org/10.1016/j.renene.2017.01.033> (2017).
53. Antonio Barrozo Budes, F., Valencia Ochoa, G., Obregon, L. G. & Arango-Manrique, A. Ricardo Núñez Álvarez, J. Energy, economic, and environmental evaluation of a proposed solar-wind power on-grid system using HOMER Pro<sup>®</sup>: A case study in Colombia. *Energies* **13**, 1662. <https://doi.org/10.3390/en13071662> (2020).
54. Al-Hanoot, A. K. et al. Economic feasibility assessment of optimum grid-connected pv/battery systems to Meet electricity demand for industrial buildings in Saudi Arabia. *Energy Build.* <https://doi.org/10.1016/j.enbuild.2024.115126> (2024).
55. Lu, Y. et al. Solid oxide fuel cell technology for sustainable development in china: an over-view. *Int. J. Hydrog. Energy.* **43**, 12870–12891. <https://doi.org/10.1016/j.ijhydene.2018.05.008> (2018).
56. Gang, B. G. & Kwon, S. Design of an energy management technique for high endurance unmanned aerial vehicles powered by fuel and solar cell systems. *Int. J. Hydrog. Energy.* **43**, 9787–9796. <https://doi.org/10.1016/j.ijhydene.2018.04.049> (2018).
57. Rahimi, S., Meratizaman, M., Monadizadeh, S. & Amidpour, M. Techno-economic analysis of wind turbine-PEM (polymer electrolyte membrane) fuel cell hybrid system in standalone area. *Energy* **67**, 381–396. <https://doi.org/10.1016/j.energy.2014.01.072> (2014).
58. Chong, L. W., Wong, Y. W., Rajkumar, R. K., Rajkumar, R. K. & Isa, D. Hybrid energy storage systems and control strategies for stand-alone renewable energy power systems. *Renew. Sustain. Energy Rev.* **66**, 174–189. <https://doi.org/10.1016/j.rser.2016.07.059> (2016).
59. Singh, A., Baredar, P. & Gupta, B. Techno-economic feasibility analysis of hydrogen fuel cell and solar photovoltaic hybrid renewable energy system for academic research Building. *Energy. Conv. Manag.* **145**, 398–414. <https://doi.org/10.1016/j.enconman.2017.05.014> (2017).
60. Li, Y., Zhou, L. W. & Wang, R. Z. Urban biomass and methods of estimating municipal biomass resources. *Renew. Sustain. Energy Rev.* **80**, 1017–1030. <https://doi.org/10.1016/j.rser.2017.05.214> (2017).
61. Sarker, S. Feasibility analysis of a renewable hybrid energy system with producer gas generator fulfilling remote household electricity demand in Southern Norway. *Renew. Energy.* **87**, 772–781. <https://doi.org/10.1016/j.renene.2015.11.013> (2016).
62. Zhang, Y. & Qin, J. Analysis of the coupling degree between agricultural economic growth and tourism development in inner Mongolia. *Chin. J. Agric. Resour. Reg. Plann.* **45**, 108–116. <https://doi.org/10.7621/cjarrp.1005-9121.20240311> (2024).
63. Yang, L., Jiang, L. & Zhao, H. Evaluation on the coupling of suitability of grazing-photovoltaics development and the regional energy demand potential in inner Mongolia. *J. Arid Land. Resour. Environ.* **37**, 122–129. <https://doi.org/10.13448/j.cnki.jalre.2023.120> (2023).
64. Region, O. o. t. P. s. G. o. I. M. A. Inner Mongolia Autonomous Region's 14th Five-Year Plan for Climate Change, [http://fgw.nmg.gov.cn/ywgz/jndt/202111/t20211117\\_1953435.html](http://fgw.nmg.gov.cn/ywgz/jndt/202111/t20211117_1953435.html) (2021).
65. Hong, X. Straw yield and potential utilization for forage in inner Mongolia. *Pratacultural Sci.* **40**, 2927–2936. <https://doi.org/10.11829/j.issn.1001-0629.2022-0846> (2023).
66. Ahmad, J. et al. Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of Kallar Kahar. *Energy* **148**, 208–234. <https://doi.org/10.1016/j.energy.2018.01.133> (2018).
67. Khalil, L. et al. Optimization and designing of hybrid power system using HOMER pro. *Mater. Today: Proc.* **47** (S110–S115). <https://doi.org/10.1016/j.matpr.2020.06.054> (2021).
68. Luta, D. N. & Raji, A. K. Optimal sizing of hybrid fuel cell-supercapacitor storage system for off-grid renewable applications. *Energy* **166**, 530–540. <https://doi.org/10.1016/j.energy.2018.10.070> (2019).
69. Singh, S., Chauhan, P. & Singh, N. Capacity optimization of grid connected solar/fuel cell energy system using hybrid ABC-PSO algorithm. *Int. J. Hydrog. Energy.* **45**, 10070–10088. <https://doi.org/10.1016/j.ijhydene.2020.02.018> (2020).
70. Kaabeche, A. & Bakelli, Y. Renewable hybrid system size optimization considering various electrochemical energy storage technologies. *Energy. Conv. Manag.* **193**, 162–175. <https://doi.org/10.1016/j.enconman.2019.04.064> (2019).
71. Mandal, S., Das, B. K. & Hoque, N. Optimum sizing of a stand-alone hybrid energy system for rural electrification in Bangladesh. *J. Clean. Prod.* **200**, 12–27. <https://doi.org/10.1016/j.jclepro.2018.07.257> (2018).
72. Gas Generator price, <https://pulitaenergy.en.made-in-china.com/product/KSPxOIVvhQAY/China-High-Discount-Ce-ISO-Gas-Generator-15-Kw-Self-Use.html> (2024).
73. Campagna, N. et al. Battery models for battery powered applications: A comparative study. *Energies.* **13**, 4085. <https://doi.org/10.3390/en13164085> (2020).
74. Li, C., Zhou, D. & Zheng, Y. Techno-economic comparative study of grid-connected PV power systems in five climate zones. *China Energy.* **165**, 1352–1369. <https://doi.org/10.1016/j.energy.2018.10.062> (2018).
75. Ghenai, C. & Bettayeb, M. Modelling and performance analysis of a stand-alone hybrid solar pv/fuel cell/diesel generator power system for university Building. *Energy* **171**, 180–189. <https://doi.org/10.1016/j.energy.2019.01.019> (2019).
76. Harrabi, N., Souissi, M., Aitouche, A. & Chaabane, M. Modeling and control of photovoltaic and fuel cell based alternative power systems. *Int. J. Hydrog. Energy.* **43**, 11442–11451. <https://doi.org/10.1016/j.ijhydene.2018.03.012> (2018).
77. Luta, D. N., Raji, A. & K. J. E. Optimal sizing of hybrid fuel cell-supercapacitor storage system for off-grid renewable applications. *Energy* **166**, 530–540 (2019).
78. Rezk, H. et al. Fuel cell as an effective energy storage in reverse osmosis desalination plant powered by photovoltaic system. *Energy* **175**, 423–433. <https://doi.org/10.1016/j.energy.2019.02.167> (2019).
79. Brka, A., Al-Abdeli, Y. M. & Kothapalli, G. Predictive power management strategies for stand-alone hydrogen systems: operational impact. *Int. J. Hydrog. Energy.* **41**, 6685–6698. <https://doi.org/10.1016/j.ijhydene.2016.03.085> (2016).
80. Lau, K. Y., Tan, C. W. & Yatim, A. J. E. Photovoltaic systems for Malaysian islands: effects of interest rates, diesel prices and load sizes. *Energy* **83**, 204–216 (2015).

## Acknowledgements

This research was sponsored by the National Natural Science Foundation of China [NO.72304186].

## Author contributions

Ying Liu: Conceptualization. Methodology. Software. Data curation. Writing—Original draft preparation. Yaru

Zhang: Conceptualization. Methodology. Project administration. Supervision. Resources. Writing—Review & Editing.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-09732-2>.

**Correspondence** and requests for materials should be addressed to Y.Z.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025