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Integrated energy systems with CCHP and hydrogen supply: A new outlet for curtailed wind power

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Abstract: The present energy system faces at least two challenges. For one thing, the power system's stability is challenged by the increasing penetration of variable renewable energies, especially wind power, due to its fluctuation and intermittency. For the other, the transport sector is facing enormous difficulty to decarbonize. This paper proposes a new energy system that integrates the hydrogen production and distribution system to the combined cooling, heating and power (CCHP) system with significant wind power to solve these two challenges simultaneously. The new energy system can meet the energy needs of the building. At the same time, the wind power utilization rate reaches 92.6%, and the typical daily hydrogen production capacity in winter, transition season and summer is 500kg, 500kg and 266kg, respectively. The system's energy efficiency is 72%, and the energy of the system is utilized efficiently. By comparison, the new system can reduce costs and carbon dioxide emissions, save primary energy, and effectively improve energy efficiency.

Keywords: Hydrogen production; CCHP system; Wind power utilization; Integrated energy systems

1. Introduction

Under China's commitment to peaking carbon emission by 2030 and neutralizing emission by 2060, two challenges in the energy systems are outstanding. The first challenge is on the electricity supply system. With the increasing penetration of variable renewable energies (VREs), the power system stability has frequently become a challenge and such a challenge is especially significant in a distributed energy system. In recent years, the installed capacity of wind power generating units in some provinces in China has increased rapidly, but the rate of wind power curtailment has also increased. To reduce curtailment rates, the local government has restricted the integration of some wind turbines into the national grid, which would waste all the power they generate. With the increasing pressure of energy saving and emission reduction, distributed energy system has attracted more and more attention. As a highly efficient and clean energy generation system, the distributed energy system can minimize environmental pollution and reduce greenhouse gas emissions to achieve energy structure adjustment [1]. Combined cooling, heating and power (CCHP) system is the main form of distributed energy system [2]. The CCHP system uses the recovered heat for heating or cooling to improve energy efficiency. In the energy production and supply industry, the CCHP technology has the advantages of high reliability, high energy efficiency and environmental friendliness [3]. However, distributed energy systems often have limited resources to mitigate their intermittence shocks.

The other challenge is the decarbonization of the transportation sector. Hydrogen and battery are the two technologies considered with the most potential to decarbonize the transport sector[4]. The International Energy Agency[5] projected that a self-sustaining market for fuel cell electric vehicles (FCEVs) could be achieved in 15–20 years after introducing the first 10,000 FCEVs due to technological progress, economies of scale and benefit from the learning curve. However, hydrogen is not competitive with fossil fuels due to its high costs than petroleum products. In the 14th Five-Year Development Plan of China and its provinces, it is mentioned to support the development of the hydrogen industry. Hydrogen refuelling stations have been established in many cities, and hydrogen-fueled buses and special operating vehicles have been gradually applied. Hydrogen industry in Yunfu, Dalian, Foshan and other places has been initially developed, among which Dalian has built the first on-site hydrogen station in China.

Through power-to-gas (P2G) technology, hydrogen could store power generated from VREs that would otherwise be curtailed[6]. Still, the application of curtailed electricity to supply hydrogen to the transport section has not been well studied. This curtailed electricity can reduce the cost of hydrogen production. In a distributed energy system, such hydrogen production can be placed in demand centers. Thus, the cost of transportation, which is equivalent to about half of the production cost, can be avoided and thus further increases the competitiveness of hydrogen against fossil fuels. Combined distributed energy systems with hydrogen supply could stabilize the electricity system and produce more economical hydrogen. However, the feasibility and benefits of such a hybrid system have not been investigated in the literature.

To fill these gaps, this paper innovatively proposes a new system of coupling wind power system, hydrogen production and distribution system, and CCHP system. The effective coupling of the three systems will solve the defect of unreasonable thermoelectric structure in the traditional CCHP system. While making full use of wind power to ensure a stable energy supply for residential buildings, the system also generates a large amount of green hydrogen for hydrogen fuel cell vehicles. To evaluate the wind-hydrogen-CCHP (W-H-CCHP) system, we introduce three other reference systems. Using a case study in Dalian City, Liaoning Province, we calculate the total annual cost, emissions and energy consumption of all four systems. By comparison among the four systems, the W-H-CCHP system has significant advantages in all three aspects.

The rest of the paper is processed as follows. The next section briefly presents a review of relevant studies. Section 3 describes the proposed energy system. Section 4 compares the advantages of this system with a case study. The last section concludes the paper.

2. Literature review

There are many studies in the literature on CCHP system optimization, including solar energy, biomass energy, environmental impact, energy management, storage technology, operation strategy, and other renewable technologies [7], but no of them considers hydrogen. Wu et al. [8] proposed a new CCHP st-orc system operation strategy, which was applied in residential buildings. Zhang et al. [9] proposed a new combined cold, heat, and electricity production system with biomass and geothermal energy as auxiliary materials, which is mainly composed of biomass gasification, compressed air energy storage (CAES) and biogas. Mohammadkhani et al. [10] proposed a multi-objective optimization algorithm to minimize the energy consumption and emissions of residential communities in consideration of beth and TES. Jing et al. [11] developed a SOFC based CCHP system design and operation optimization model using the mixed-integer nonlinear programming (MINLP) method. Li et al. [12] proposed an optimal scheduling strategy for industrial systems with cogeneration of heat and power and wind power. Zhu et al. [13] developed a mixed-integer nonlinear programming (MINLP) model based on a renewable energy CCHP system (namely RCCHP system), which was applied to five different buildings to evaluate the economic and environmental performance under two optimization modes. Liu et al. [14] proposed a CCHP system based on liquefied natural gas (LNG) gasification and CO_2 capture, which could effectively utilize LNG's cold and residual heat through polygeneration.

The effective utilization of curtailed electricity has become a big challenge for wind power utilization and stimulates many studies. Wind energy is a promising renewable energy source due to its low cost and relatively advanced technology [15], but it poses challenges to the safe and stable operation of the power system due to its volatility and intermittency [16]. To solve this problem, it is necessary to convert and utilize the curtailed power. Siddiqui et al. [17] developed a new integrated renewable energy system to store excess solar and wind power in the form of ammonia. Pu et al. [18] proposed a new method of electric heating at night by utilizing the surplus wind resources in the Beijing area. Safari et al. [19] considered an integrated wind power system consisting of a wind turbine, a proton exchange membrane (PEM) electrolyzer, and a methanation unit for thermal analysis.

Producing hydrogen from excess VREs has increasingly been studied. Hydrogen as an alternative energy carrier is a favourable choice for sustainable development in many industrial and household applications. In particular, hydrogen energy will play an important role in new energy consumption and carbon emission reduction in the field of transportation [20]. PEM electrolyzer provides a sustainable solution for the clean production of high purity hydrogen in the future [21]. Ayodele et al. [22] studied the feasibility of producing hydrogen from South African wind resources. Menia et al. [23] used a PV electrolyzer system to evaluate the renewable hydrogen production capacity of an aqueous methanol electrolyzer. Tebibel et al. [24] studied PV electrolytic systems for hydrogen production and conducted case studies to show the impact of each type of electrolyzer on the size of system components and to assess the potential for hydrogen production.

Using hydrogen as energy storage for renewable energy generation could ease the current energy crisis and has been under investigation. Lara Welder and others[25], who studied Germany ’ s hydrogen conversion potential by 2050, see the hydrogen infrastructure as a complement to the grid infrastructure that could promote a safe supply of renewable energy. Mehdi Jahangiri et al.[26] modeled and evaluated the generation potential and used hydrogen energy as an energy storage system. They analyzed several hybrid options for energy production and storage and discussed options for electricity and hydrogen energy economy. Martin Eypasch et al.[27] argues that wind and photovoltaic power can be converted by electrolyzer into hydrogen and reconverted by a thermal converter to be stored in a liquid organic hydrogen carrier (LOHC). Peng Hou et al.[28] discussed the investment potential of coupled offshore wind farms through the optimization strategy of hydrogen energy to improve wind farm investment. Dan Gao et al.[29] proposed an integrated energy storage system (ESS) based on the hydrogen storage and hydrogen-oxygen combined cycle, and believed that the integrated ESS could be used to alleviate the bottleneck of renewable energy development.

With the increasing development of FCEVs, the economies of hydrogen as transportation fuels are frequently studied. As an important direction of technological innovation, hydrogen fuel cell vehicle is gradually becoming an important field of large-scale commercial application of hydrogen energy. Apostolou et al. [30] predict an exponential increase in the number of hydrogenation stations in the future. The hydrogen station model proposed by Riedl [31] reduced the design cost and accelerated the development of hydrogen facilities. Apostolou et al.[32] investigated the potential for on-site production of small autonomous hydrogenation stations using alkaline electrolyzer powered by small wind turbines. Fabian Gruger et al. [33] proposed and applied an optimization method to optimize the scale of hydrogenation stations. Mihaela Iordache et al. [34] contributed to a preliminary indicative assessment of the commercial viability and profitability of the hydrogen station network. Since FCEVs are still not cost-competitive at the current technologies, innovations in the reduction of hydrogen supply costs would be desirable in advancing the deployment of hydrogen.

Overall, while both CCHP and hydrogen generation has been well-studied, and the curtailed wind power has been considered for generating hydrogen, there is no study combining CCHP and hydrogen production in a distributed energy system with wind power. Such a system is realistic and important as increasing VREs will drive for further decentralization of power systems, while hydrogen will face increasing demand.

3. Methods

The proposed W-H-CCHP system is composed of a CCHP system, wind power system, and hydrogen production and distribution system. The energy flow diagram of this system is shown in Fig. 1.

The CCHP system includes a power generation unit (PGU), gas boiler, heat recovery unit, absorption chiller, and heat exchanger. The hydrogen production and distribution system includes the rectifier, a proton exchange membrane (PEM) electrolyzer and a hydrogen refuelling station (HRS). The main equipment of the wind power generation system is a wind turbine set. The W-H-CCHP system will operate under the following hybrid electric-thermal load (FHL) operation strategy. The system is powered by natural gas and wind power. When green hydrogen is in short supply, hydrogen produced by steam methane reforming (SMR) is purchased to replenish and transported by pipeline trailers.

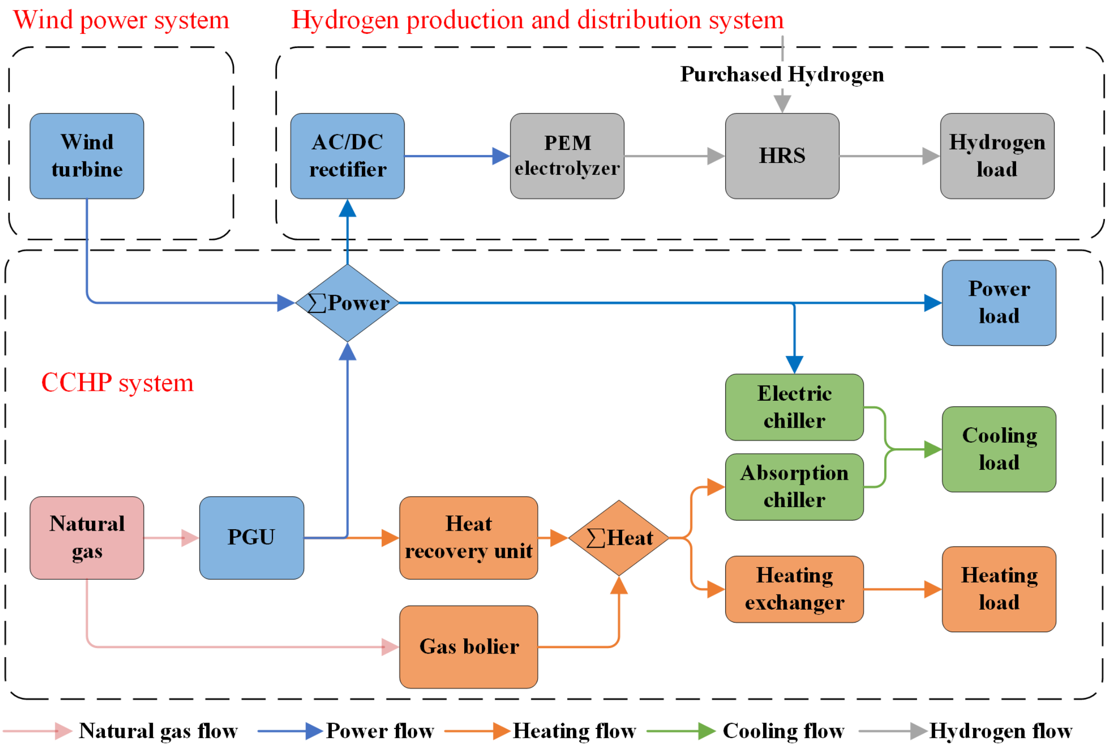


Fig. 1. The structure and energy flow of the W-H-CCHP system.

3.1. CCHP system

In the CCHP system, natural gas fuels the PGU and gas boiler. The electricity generated by the PGU, together with the wind power, supplies the electrolytic cell, the electric chiller, and the power demand of residential buildings. The heat recovery unit recovers waste heat from the PGU, and provides heat for the absorption chiller and heat exchanger together with the gas boiler to meet the cold and heat demand of the building.

- *The power generation units (PGU)*

The power generation units include gas turbines, gas internal combustion engines, micro gas turbines, external gas turbines, and fuel cells[39]. Due to the high equipment cost, gas external gas turbines and fuel cells have not been widely used. Therefore, the most commonly used generator forms in the distributed energy system are gas turbines, gas internal combustion engines, and micro gas turbines[40].

According to the selected building type and the main characteristics of the equipment, the power generation efficiency, individual capacity, and start-up time of the gas internal combustion engine just apply to residential buildings[41], and the gas internal combustion engine is used as the PGU of this system. In order to avoid the loss caused by low power operation, the gas internal combustion engine starts up when the power required reaches more than 25% of the rated power. The power provided by the gas internal combustion engine is calculated as follows:

$$E_{pgu} = F_{pgu} \cdot \eta_e \tag{1}$$

Where E_{pgu} refers to the electricity generated by the gas internal combustion engine, and F_{pgu} refers to the natural gas energy consumed by the gas internal combustion engine.

The exhaust gas from the gas internal combustion engine after work is still at a relatively high temperature, generally around 540℃[42]. The thermal energy of this part of gas can be used to improve the thermal efficiency of the whole device. Heat recovery technology is to recycle a large amount of waste heat discharged to the outside world in the running process of the chiller in a certain way[43]. This heat is usually used to heat water so that it turns into steam. The steam supply heat exchanger or absorption chiller is used to meet the heat or cold load. The heat recovered by the heat recovery unit is calculated as follows:

$$Q_{hr} = F_{pgu} \cdot (1-\eta_e) \cdot \eta_r \tag{2}$$

Where Q_{hr} is the heat recovered from the exhaust gas of the heat recovery unit after the work is done by the gas internal combustion engine.

- *The boiler*

When the heat generated by the PGU is not enough to meet the heat demand, the boiler is a heating device used to provide heat load. The heat supply is calculated as follows:

$$Q_b = F_b \cdot \eta_b \tag{3}$$

Where Q_b refers to the heat generated by the gas boiler, and F_b refers to the natural gas energy consumed by the boiler.

- *The heat exchanger*

The heat exchanger diverts heat from the heat recovery unit and boiler to residential buildings to meet the residential heat load. The heat is calculated as follows:

$$Q_h = Q_{he0} \cdot \eta_{he} \tag{4}$$

Where Q_h is the heat load of residential buildings, and Q_{he0} is the heat generated from the boiler or transferred from the heat recovery unit.

- *The chiller*

The distributed energy system can be cooled by either an absorption chiller with low energy efficiency or an electric chiller with high energy efficiency. Under this combination, chillers can adjust the output thermoelectric ratio of the distributed energy system in a certain range[44]. The cooling capacity provided by the two types of cooling equipment is:

$$Q_{ac} = Q_{ac0} \cdot COP_{ac} \tag{5}$$

$$Q_{ec} = E_{ec} \cdot COP_{ec} \tag{6}$$

$$Q_{ac} + Q_{ec} \geq Q_{c} \tag{7}$$

Where Q_{ac0} is the heat from the boilers or the heat recovery unit and obtained by the absorption chiller, Q_{ac} refers to the cold produced by the absorption chiller, Q_{ec} refers to the cold produced by the electric chiller.

- *The power constraint*

Wind power and PGU jointly meet the electric load of residential buildings, the power required by the electric chiller, and the electricity used to produce hydrogen.

$$E_{w} + E_{PGU} \geq E + E_{ec} + E_{p} + E_{c} \tag{8}$$

Where E_w is the electricity generated by the wind turbine set, E is the electric load of residential buildings, E_c is the electricity that compresses the hydrogen, E_p is the electricity used to produce hydrogen.

- *The thermodynamic constraint*

The heat demand of the building and the cold demand of the absorption chiller is supplied by the boiler and the heat recovery unit. The thermodynamic constraint is as follows:

$$Q_{b} + Q_{hr} \geq Q_{ac0} + Q_{he0} \tag{9}$$

- *System fossil energy consumption*

The sum of gas consumption of the PGU and the gas boiler is the gas consumption of the distributed energy system.

$$F = F_{b} + F_{pgu} \tag{10}$$

Where F is the total amount of natural gas consumed by the system.

3.2. H_2 production and distribution system

H_2 production and distribution system consists of AC/DC rectifier, electrolyzer, and an HRS that collects, stores and distributes hydrogen. AC/DC rectifier converts the electricity generated by wind power or gas internal combustion engine from AC to DC, and then water is electrolyzed by electrolyzer to produce hydrogen. The hydrogen is pressurized and stored in the hydrogen storage tank of the HRS through the compressor. When the electrolyzer produces less than the daily demand of the HRS, the hydrogen will be purchased as a supplement and transported to the HRS by pipeline trailers.

The electrolyzer is the core equipment of hydrogen production by water electrolysis. There are approximately three types of electrolyzers: alkaline electrolyzer, PEM electrolyzer, and solid oxide electrolyzer (SOE). The PEM electrolyzer has many advantages, such as small size and lightweight, no lye corrosion[45]. In particular, it can operate at 0-160% of its rated power, so it can adapt to fluctuating electrical conditions. Therefore, we use a PEM electrolyzer in the W-H-CCHP systems to absorb large fluctuations of electricity.

The electrolyzer is composed of parallel plates connected in series. The control and regulation system is designed so that the electrolyzer and the whole hydrogen production unit can operate normally in the change of power supply. The electrolyzer uses direct current electricity to produce hydrogen, while wind power and electricity from PGU are alternating currents. So the system sets up a rectifier to convert the current before producing hydrogen. The hydrogen production is calculated as follows:

$$H_p = E_p \cdot \eta_p \tag{11}$$

$$E_c = H_p \cdot \eta_c \tag{12}$$

Where H_p is the amount of hydrogen produced by the system.

The HRS is a special place to replenish hydrogen for hydrogen fuel cell vehicles. The three core pieces of equipment of the HRS include a hydrogen compressor, high-pressure hydrogen storage container, and dispenser. After obtaining hydrogen that meets the quality requirements through external hydrogen supply or internal hydrogen production in the high-pressure gas hydrogenation station, it is pressurized into the high-pressure hydrogen storage container through hydrogen compression plant, and finally refuelling for hydrogen vehicles through the dispenser. The price of purchased hydrogen is calculated according to the market price, and the primary energy consumption and carbon dioxide emissions of purchased hydrogen are calculated according to the production of hydrogen from methane.

3.3. Wind power system

Set up 1500 kW wind turbine, and the installation height of the land fan is 60 m. The obtained data is the wind speed detection of the land elevation of 10 m. Based on the longitude and latitude of the wind farm, the conversion wind speed formula is finally determined as follows：

$$W_{60} = W_{10} \times \frac{\ln(60/z_0)}{\ln(10/z_0)} \tag{13}$$

Where W_{60} is the land wind speed at the height of 60 meters, W_{10} is the land wind speed at an altitude of 10 meters, and z_0 is the rough length, 0.03m.

The power output of the wind farm is closely related to the wind speed, and its power generation is:

$$E_w = \begin{cases} P_r \frac{w^2 - w_i^2}{w_r^2 - w_i^2} & w_i < w < w_r \\ P_r & w_r < w < w_f \\ 0 & Otherwise \end{cases} \tag{14}$$

Where P_r is the rated power of the wind turbine, w_i is the wind speed of the fan cut in, w_r is the rated wind speed of the fan, and w_f is the wind speed of the fan cut out.

3.4. Mathematical model

- *The optimization goal*

The optimization model takes the economic optimum of the system, that is, the lowest annual total cost as the optimization target. The total yearly cost includes the annual equipment equivalent cost, operation and maintenance costs, and the annual energy consumption cost. The annual equipment equivalent cost is calculated by the annuity method, and the operation and maintenance costs are converted to 5% of the equipment cost.

$$C_{S1} = \sum Cap_i \cdot C_i \cdot A \cdot 1.05 + C_{ng} + C_H \tag{15}$$

$$A = \frac{r \cdot (1+r)^y}{(1+r)^y - 1} \tag{16}$$

$$C_{ng} = \sum F \cdot CC_{ng} \tag{17}$$

$$C_H = \sum (N - H_P) \cdot CC_H \tag{18}$$

Where C_{S1} is the total annual cost of the W-H-CCHP system, Cap_i is the capacity of each piece of equipment, C_i is the unit capacity cost of each piece of equipment, A is the capital recovery factor of equipment investment, C_{ng} is the annual natural gas purchase cost of the system, C_H is the annual hydrogen purchase cost of the system, r is the bank loan interest rate, which is taken as 5% in this paper[46], y is the service life of all the equipment, which is taken as 20[47], N is the daily hydrogen demand of the HRS, CC_{ng} is the market price of natural gas per unit, CC_H is the market price of hydrogen per unit.

- *The evaluation standard*

To evaluate the economic, energy and emission performance of each seystem, the annual total cost, the primary energy consumption and the carbon dioxide emission (CDE) for all four systems were calculated.

$$C_{Si} = \sum Cap_i \cdot C_i \cdot A \cdot 1.05 + C_{ng} + C_H + C_{grid} \tag{19}$$

$$C_{grid} = \sum E \cdot CC_{grid} \tag{20}$$

Where C_{grid} is the annual electricity purchase cost of each reference system, CC_{grid} is the market price of electricity per unit, C_{Si} is the annual total cost of each reference system. $CDEs_i$ is the total annual carbon dioxide emissions from each system.

$$F_{S1} = \sum \left(F + E_w + \frac{H_P^{S1}}{\eta_{SMR}} \right) \tag{21}$$

$$F_{Si} = \sum \left(F_{gas}^{Si} + F_{coal}^{Si} + \frac{E_{grid}^{Si}}{\eta_{Si}\eta_{grid}} + \frac{H_P^{Si}}{\eta_{SMR}} \right) \tag{22}$$

Where Fs_1 is the total annual primary energy consumption of the W-H-CCHP system, Fs_i is the total annual primary energy consumption of each reference system, η_{Si} is thermal power generation efficiency, η_{grid} is grid transmission efficiency, η_{SMR} is the efficiency of hydrogen production from SMR, F_{gas}^{Si} and F_{coal}^{Si} are the gas and coal consumption in the reference system, respectively.

$$CDE_{ng} = \sum F_{ng} \times EF_{ng,C} \tag{23}$$

$$CDE_{coal} = \sum F_{coal} \times EF_{coal,C} \tag{24}$$

$$CDE_{H} = \sum H_{P} \times EF_{H,C} \tag{25}$$

$$CDE_{grid} = \sum E_{grid} \times EF_{grid,C} \tag{26}$$

$$CDE_{S1} = CDE_{ng} + CDE_{H} \tag{27}$$

$$CDE_{Si} = CDE_{ng}^{Si} + CDE_{coal}^{Si} + CDE_{grid}^{Si} + CDE_{H}^{Si} \tag{28}$$

Where *CDE* is the carbon dioxide emission from the system or energy consumption, $EF_{i,\,C}$ is the emission factor of carbon dioxide.

Through Gurobipy programming, the W-H-CCHP system model is written into the program to optimize the total annual cost, and the appropriate equipment model, energy consumption, system output can be obtained.

3.5. Reference systems

For a more comprehensive evaluation of the proposed system, we added three reference systems, which are the FTL-CCHP system, GB-C system and CB-C system. CB-C system is a widely used energy system in China at present, but it has a great impact on the environment and is gradually replaced by GB-C system, which is strongly supported by the Chinese government. The FTL-CCHP system is one of the traditional CCHP systems, and it has high energy efficiency. By comparing the W-H-CCHP system with the three reference systems, the differences of the four systems in terms of economy, emission reduction and energy saving could be explored, and the advantages, disadvantages and feasibility of the W-H-CCHP system could be identified.

These reference systems supply the cooling, heating and electricity demands for the same building in the W-H-CCHP system and operate at the same scale as a HRS. Hydrogen produced by SMR is purchased to replenish and transported by pipeline trailers in the reference system. The building energy supply methods of the three systems are shown below:

FTL-CCHP system: The system is a CCHP system equipped with an off-site HRS under the following thermal load (FTL) operation strategy. The system is powered by natural gas and grid electricity.

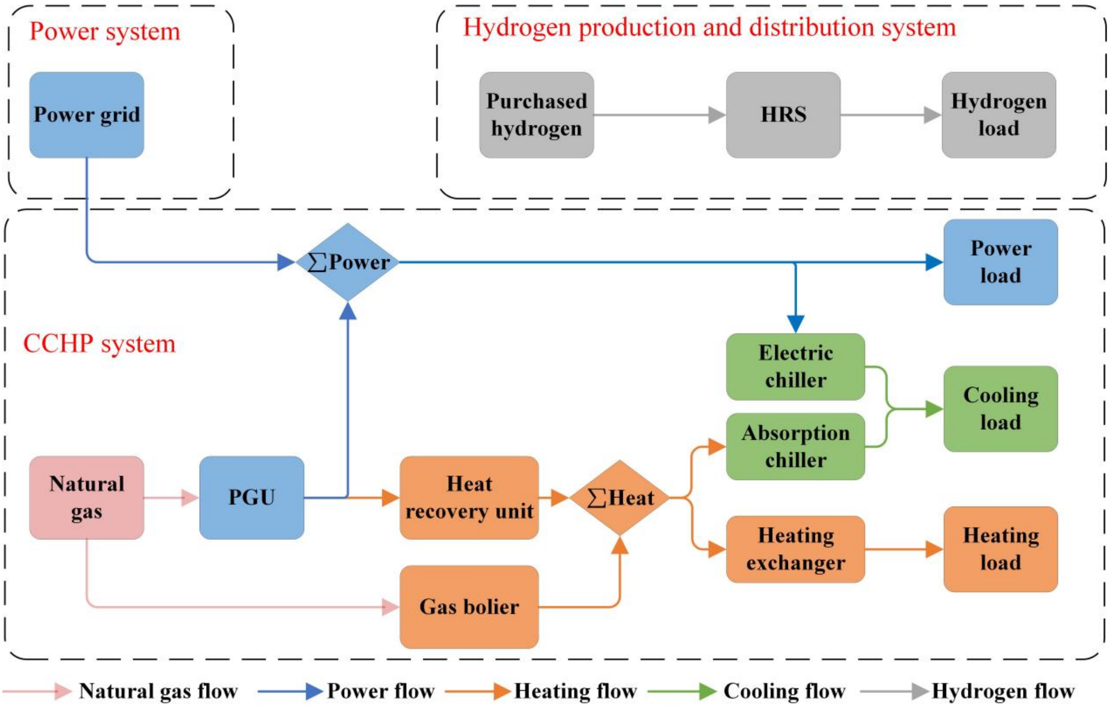


Fig. 2. The structure and energy flow of the FTL-CCHP system.

GB-C system: The system is a concentrated energy system equipped with an off-site HRS. The electricity, heating, and cooling demands in the system are met by the power grid, the gas boiler, and the electric chiller, respectively.

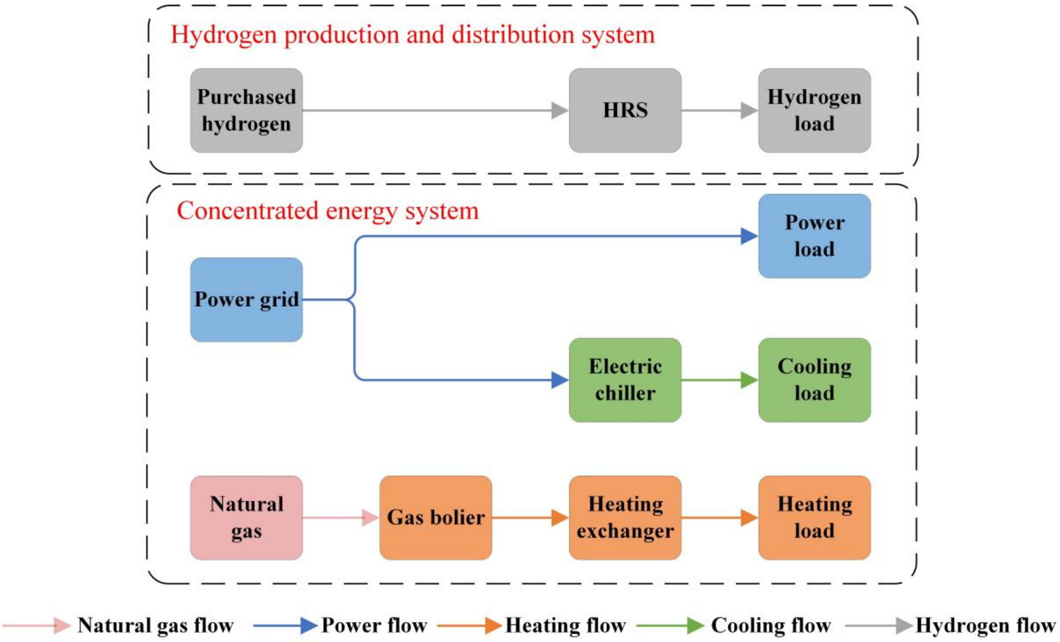


Fig. 3. The structure and energy flow of the GB-C system.

CB-C system: The system is a concentrated energy system equipped with an off-site HRS. The electricity, heating, and cooling demands in the system are met by the power grid, coal-fired boiler, and electric chiller, respectively.

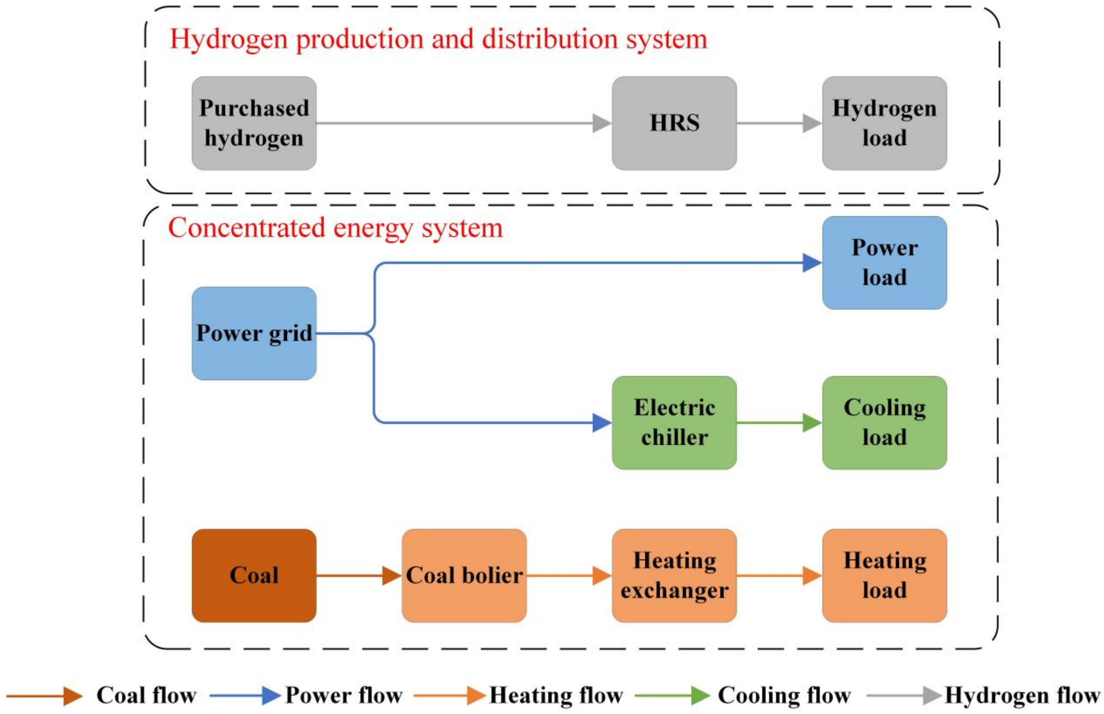


Fig. 4. The structure and energy flow of the CB-C system.

The similarities and differences of the four systems are shown in Table 1.

Table 1
Comparison of the four systems.

System	Type	Operation strategy	Hydrogen source	Heating form
W-H-CCHP system	Distributed energy system	FHL	Self-produced\ Purchased	PGU\ Gas boiler
FTL-CCHP system	Distributed energy system	FTL	Purchased	PGU\ Gas boiler
GB-C system	Concentrated energy system	/	Purchased	Gas boiler
CB-C system	Concentrated energy system	/	Purchased	Coal-fired boiler

4. Case study

4.1. Parameter setting

According to the model of the W-H-CCHP system, the system is more suitable for the regions that support the hydrogen energy industry and are rich in wind resources. Dalian municipal government attaches great importance to the development of the hydrogen energy industry and has issued many policies to encourage the development of the hydrogen energy industry in recent years. Dalian is rich in wind power, but policy constraints have hampered the integration of wind turbines into the national grid. These factors make the system just suitable for the Dalian area, so Dalian is chosen as the research object.

The four system takes 5×10^5 m^2 residential buildings in Dalian, Liaoning province as the simulation object. Dalian city is located in northeast China, the southwest corner of the Liaodong Peninsula. It has a warm temperate semi-humid monsoon climate. DeST software was used to simulate the cold demand, heat demand and power demand of the buildings and to obtain wind speed data. Typical days are selected as the representative of this season, including 156 days in winter, 119 days in a transition season (including spring and autumn), and 90 days in summer.

The wind power system is equipped with four fans with a rated power of 1500 kW, and its rated wind speed, the wind speed of the fan cut in, and the wind speed of the fan cut out are 12 m/s, 3.5 m/s and 25 m/s respectively. The wind speed data in this paper are from the DeST software climate database.

According to the construction scale, we set the HRS as a medium one with a daily hydrogenation capacity of 500 kg.

The economic parameters and technical parameters of the main types of equipment for the systems are described in Table 2 and Table 3, respectively.

Table 2

Technical parameters of equipment for the systems

Main equipment	Parameter	Value	Unit	Reference
PGU	Efficiency	36	%	[1]
Heat recovery unit	Efficiency	80	%	[1]
Electric chiller	COP	4	/	[1]
Absorption chiller	COP	0.70	/	[1]
Heat exchanger	Efficiency	80	%	[1]
Boiler	Efficiency	85	%	[1]
PEM electrolyzer	Efficiency	54.6	kWh/kg H_2	[35]
Compressor	Efficiency	3.3	kWh/kg H_2	[35]
AC/DC rectifier	Efficiency	98	%	[21]

Table 3

Economic parameters of equipment for the systems.

Main equipment	Value	Unit	Reference
Prime mover	6000	CNY/kW	[1]
Heat recovery unit	800	CNY/kW	[1]
Electric chiller	970	CNY/kW	[1]
Absorption chiller	1200	CNY/kW	[1]
Gas boiler	620	CNY/kW	[1]
Heat exchanger	200	CNY/kW	[1]
AC/DC rectifier	130	USD/kW	[36]
PEM electrolyzer	1	MEUR/MW[a]	[37]
H_2 refueling station	4.15	MUSD[b]	[38]

[a] 1CNY = 0.150USD.

[b] 1CNY = 0.128EUR.

Energy prices, energy conversion rates and carbon dioxide emission factors are shown in Table 4.

Table 4
Energy prices, energy conversion rates and carbon dioxide emission factors.

Parameter	Value	Unit	Reference
The unit price of electricity in a residential building	0.5	CNY/kWh	[47]
The unit price of natural gas	3.5	CNY/Nm^3	[48]
The unit price of coal	800	CNY/t	[49]
The unit price of purchased hydrogen	39	CNY/kg	[50]
Primary energy ratio in purchased hydrogen production	15.45	%	[51]
Thermal power generation efficiency	35	%	[47]
Transmission efficiency of the power grid	92	%	[47]
Grid power carbon dioxide emission factor	1.2	kg/ kWh	[47]
Natural gas carbon dioxide emission factor	2.2	kg/ Nm^3	[47]
Coal carbon dioxide emission factor	2.6	kg/t	[52]
Emission factor in purchased hydrogen production	257.32	g/GJ	[51]

4.2. Results and discussions

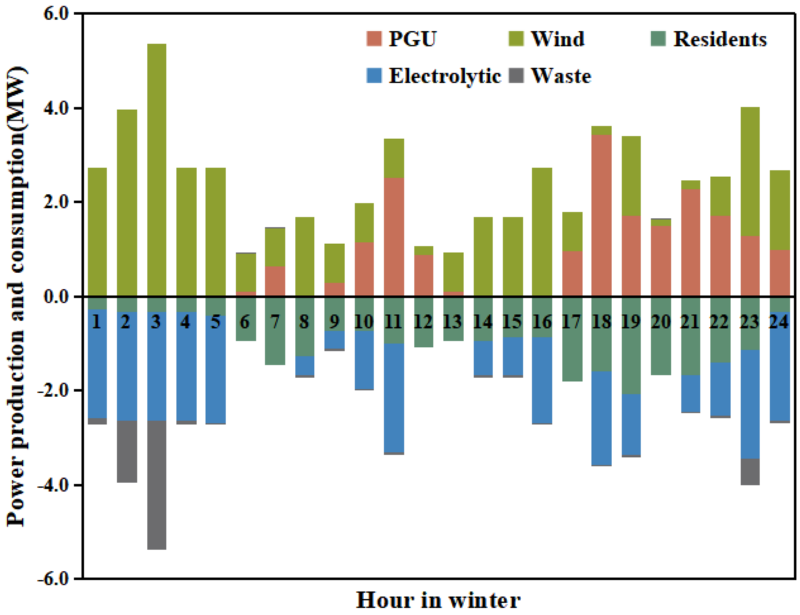
The optimization results show that the W-H-CCHP system can meet the energy needs of the building and the wind power utilization rate reaches 92.6%. And the typical daily hydrogen production capacity in winter, transition season and summer is 500kg, 500kg and 266kg respectively. The rated power of the main equipment of the W-H-CCHP system is shown in Table 5.

Table 5
Rated power of the main equipment of the W-H-CCHP system.

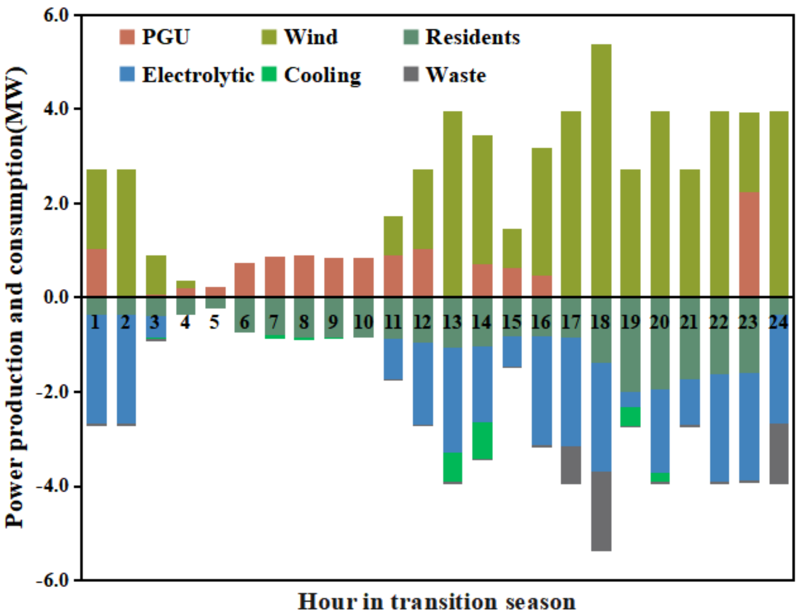
Parameter	Value	Unit
Prime mover	3436	kW
Electric chiller	2096	kW
Absorption chiller	633	kW
Gas boiler	19748	kW
Heat exchanger	18387	kW
AC/DC rectifier	2401	kW
PEM electrolyzer	1470	kW

The power production and consumption of the W-H-CCHP system in three typical days are shown in Fig. 5, and the heating production and consumption are shown in Fig. 6. In Fig. 5, the upper half of the X-axis represents the electricity generated by the system, including wind power generation and PGU power generation. The lower half of the X-axis represents the power consumption of the system, including residential power consumption, hydrogen generation power consumption, electric chiller power consumption and partial redundant power consumption. In Fig. 6, the upper half of the X-axis represents the heating generation of the system, including the heating generation from PGU and the boiler. The lower half of the X-axis represents the heating consumption of the system, including household heat, absorption cooling heat, partial redundant heat and heating loss.

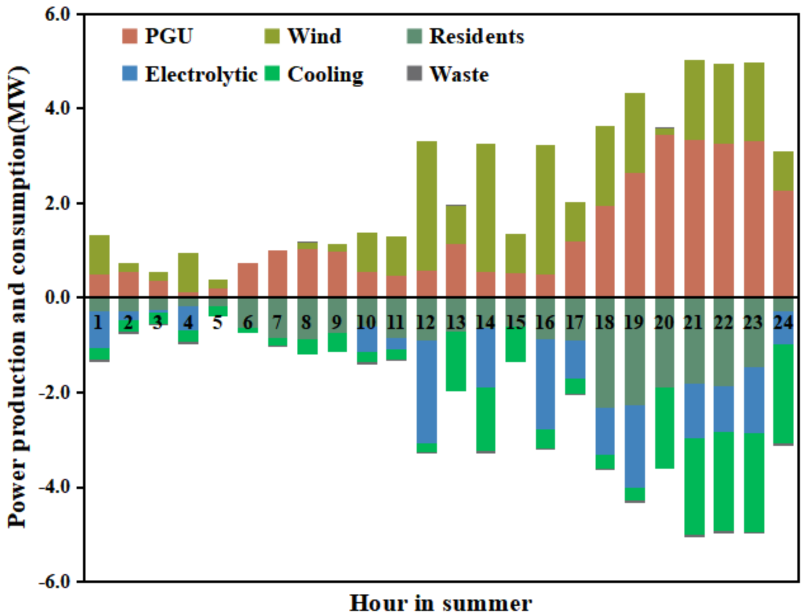
The wind speed in winter and transition season is high enough, so the wind power generation in some moments can meet the needs of residents' power consumption and electrolytic power consumption, and even the phenomenon of power abandonment exists in some moments. Hydrogen production is mostly done at night due to strong winds and low electricity demand from residents. Typical days in winter and transition seasons can generate up to 500kg of power without the need to buy additional hydrogen.



(a)



（b）

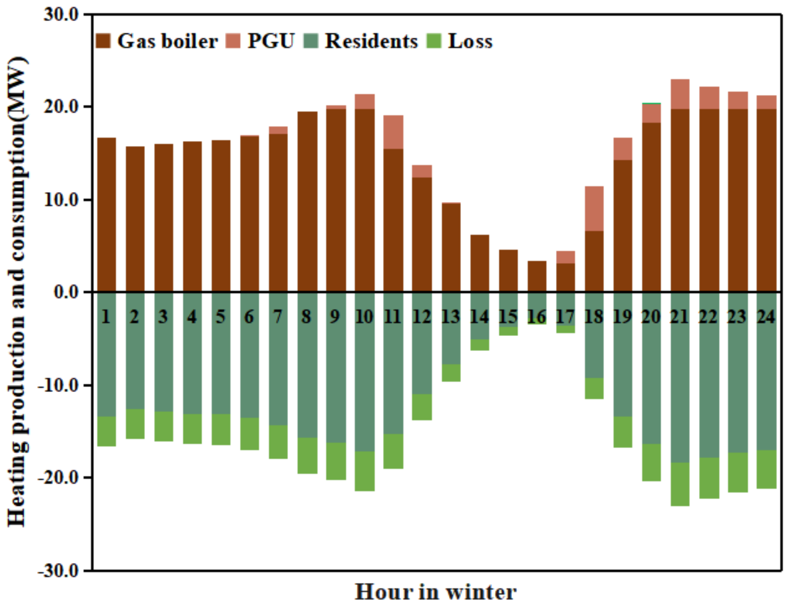


（c）

Fig. 5. Power production and consumption for the typical day in three different seasons

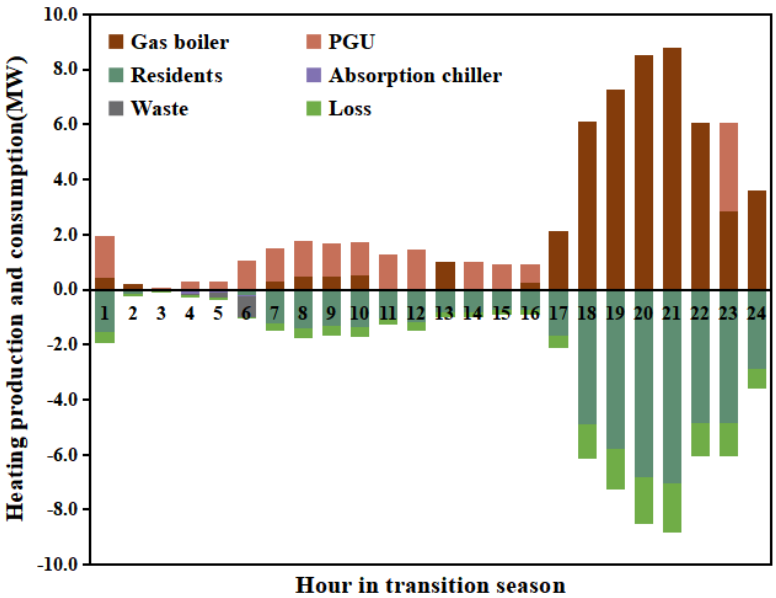
In winter, there is a high demand for heat, which requires gas boilers to operate at a higher load. An unusual phenomenon occurred at 23 o 'clock on a typical winter day when the PGU is still operating while there is power redundancy. This is because the gas boiler is not enough to supply the required heat despite full load operation, so the PGU operation is needed to provide the residual heat.

Wind power generation is low in summer, so the PGU needs to operate all day to provide power and heat. The PGU runs for the most time at full capacity in summer. In summer, the cooling capacity of the electric chiller is larger than that of the absorption chiller, because the efficiency of the electric chiller is higher and the cost of wind power generation is lower, which leads to the lower cost of electric chiller when the same amount of cooling is generated. In the absence of sufficient waste heat, the electric chiller will be given priority for refrigeration during optimal operation because the electric chiller has high refrigeration efficiency. Therefore, the gas boiler was only opened at 20 o 'clock when the heat demand is the highest in summer, and the waste heat of PGU is sufficient to supply residents with heat for daily use at other times. The hydrogen production capacity in summer is about 266kg, and an additional 234kg of hydrogen needs to be purchased to supplement it.



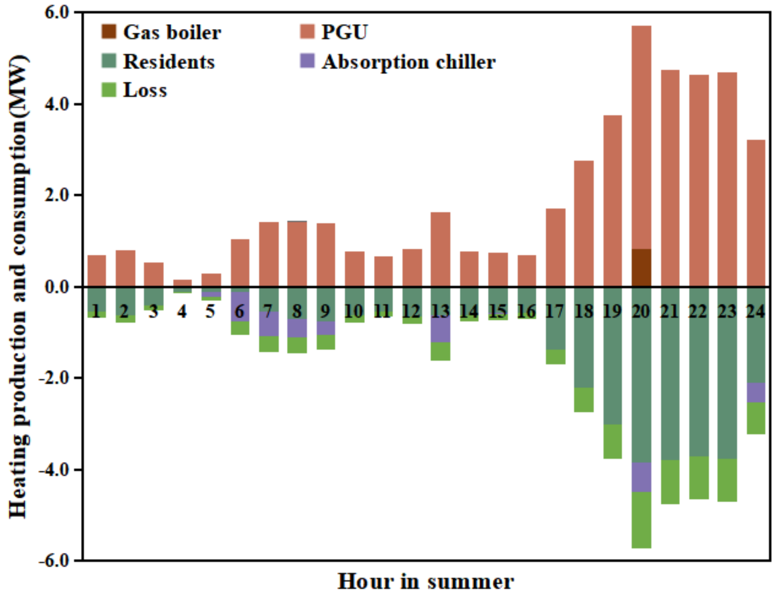
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
Gas boiler
PGU
Residents
Loss
Heating production and consumption(MW)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour in winter

（a）



10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
Gas boiler
PGU
Residents
Absorption chiller
Waste
Loss
Heating production and consumption(MW)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour in transition season

（b）



（c）

Fig. 6. Heating production and consumption for three typical days

In winter, residents have a great demand for heat. Boilers operate at full load most of the time to provide heat, and all the waste heat recovered by PGU is also supplied to residents. The heat for residential use is special in the transition season, which only operates at high load in a small part of the time, and operates at low load in other periods. In summer, PGU needs to be operated all day, and the running time and total output are higher than those in winter and transition season.

In the W-H-CCHP system, the annual utilization rate of wind power generation is 92.6%, which indicates that wind power generation has been fully applied in the W-H-CCHP system. The annual equivalent full-load generating hours of the fan are about 2300 hours, which is consistent with the annual average data of Liaoning Province.

4.2.1 Cost comparison

Fig. 7 shows the annual cost for each of the four systems. Among the systems, the fuel cost accounts for a large proportion of the total cost, among which the fuel cost of the W-H-CCHP system is the highest, reaching 32.1 million CNY.

The annual total cost of the W-H-CCHP system is lower than that of the FTL-CCHP system and the GB-C system, but higher than that of the CB-C system. This is mainly due to the lower cost of coal used in the CB-C system. Since 500kg of hydrogen is required to be purchased every day of the year for the reference system, hydrogen is purchased at the same cost for all three reference systems. The W-H-CCHP system uses wind power generation and PGU to generate power, which saves the cost of the system without the additional purchase of grid power.

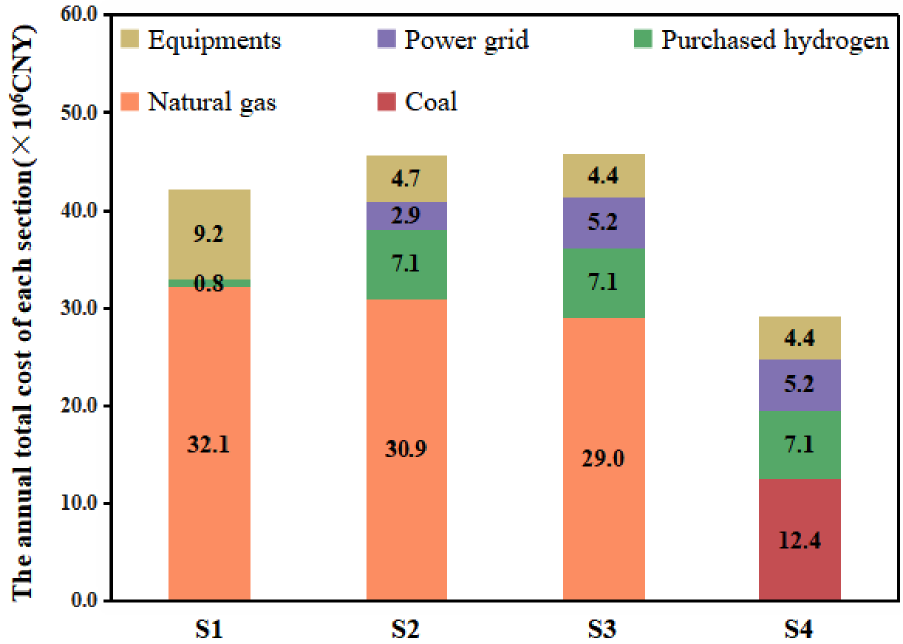


Fig. 7. The annual total cost of each section of the systems

The equipment investment in the W-H-CCHP system is higher than that in all three reference systems. Fig. 8 shows the cost ratio of each piece of equipment in the W-H-CCHP system. It can be seen from the figure that HRS, wind turbines, electrolyzer and PGU account for the main part of the system cost, while hydrogen production and distribution system cost accounts for a large part. The existence of wind turbines, electrolyzer and PGU makes the equipment cost of the W-H-CCHP system higher than that of the three reference systems, but the full use of energy by these equipment saves the total annual cost of the system.

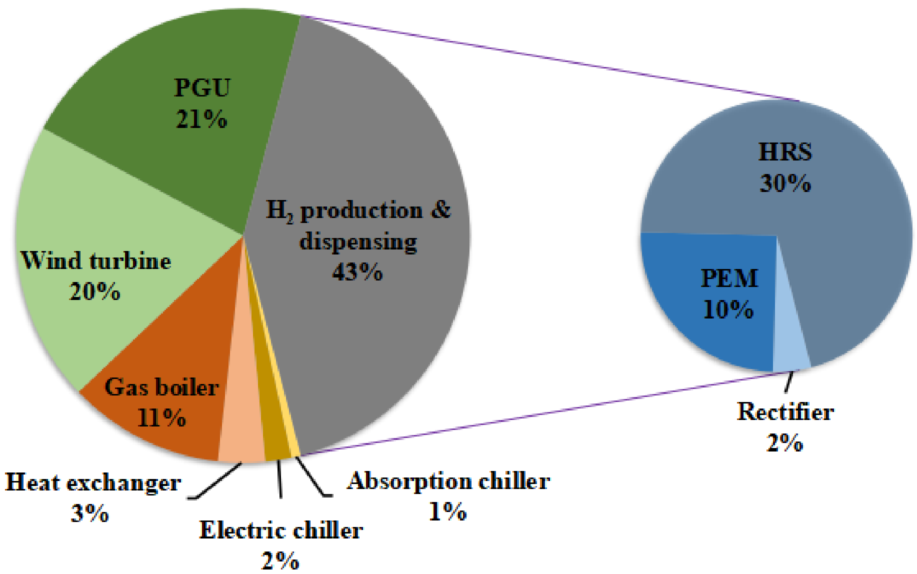


Fig. 8. The cost ratio of each piece of equipment in the W-H-CCHP system

4.2.2 Comparison of primary energy consumption

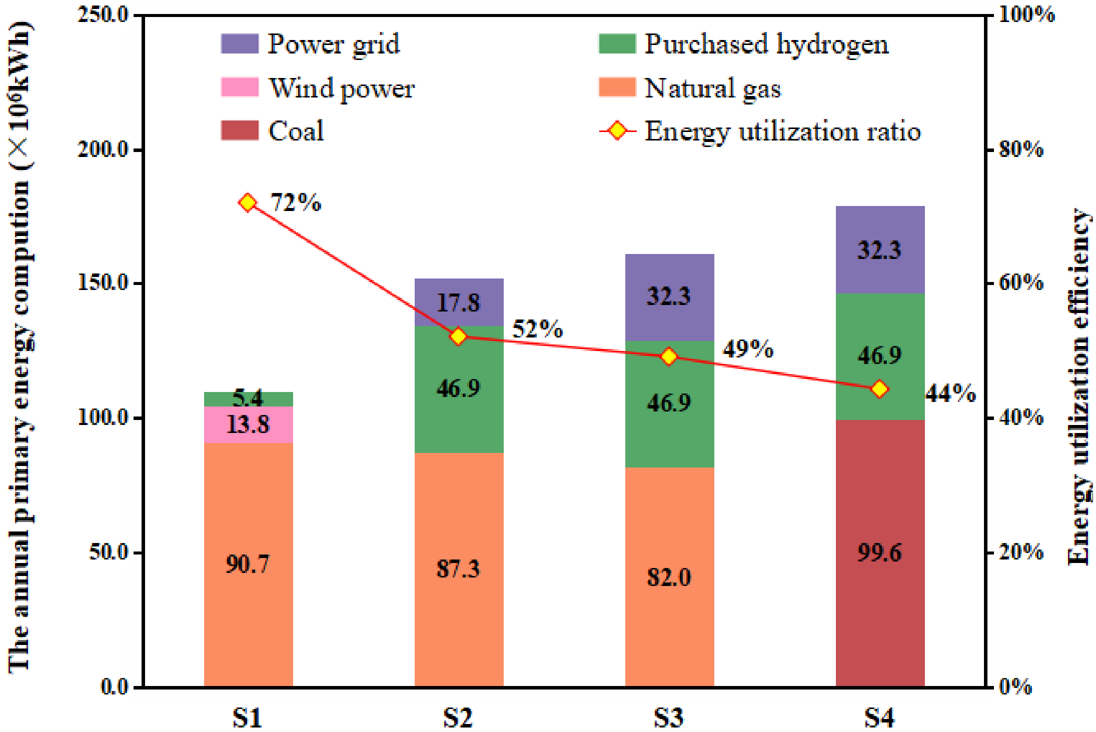


Fig. 9. The annual primary energy consumption of the systems

Fig. 9 shows the annual primary energy consumption of the four systems. It can be seen from the figure that the total energy consumption of the four systems gradually increases. As the energy demand of each system is the same, the energy utilization rate of the four systems gradually decreases. The energy utilization efficiency of the W-H-CCHP system is as high as 72%. The total amount of primary energy of grid power and natural gas in the FTL-CCHP system is lower than that in the GB-C system, which indicates that the distributed system has a higher energy utilization efficiency than the centralized energy system, and the energy cascade utilization of distributed energy system has significant advantages in energy conservation. In the W-H-CCHP system, the coupling of the wind power generation system, CCHP system, and hydrogen production and distribution system makes the primary energy fully utilized. The annual primary energy consumption is significantly reduced.

4.2.3 Carbon dioxide emission comparison

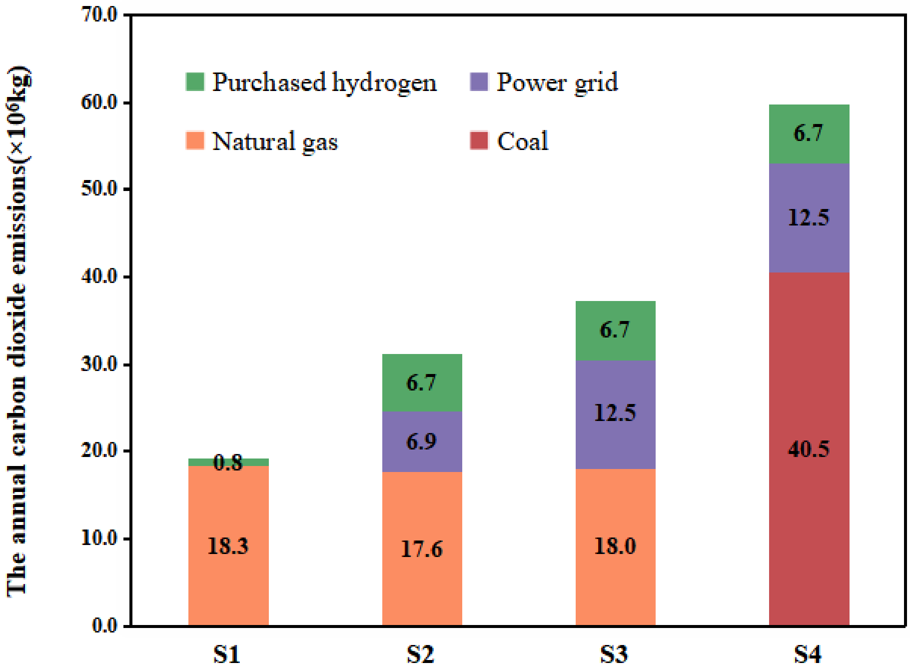


Fig. 10. The annual primary energy consumption of the systems

Fig. 10 shows the annual carbon dioxide emissions of the four systems. As can be seen from the figure, the carbon dioxide emission of the W-H-CCHP system is significantly lower than that of other systems. The W-H-CCHP system only has CO_2 emissions from the combustion of natural gas and the source of hydrogen purchased. The application of wind power reduces the CO_2 emissions of the system by a large amount. The GB-C system and the CB-C system are only different in the type of heating fuel, but the carbon dioxide emission of the CB-C system is much higher than that of the GB-C system, so it can be seen that the carbon dioxide emission of coal is much higher than that of natural gas.

4.2.4 Summary of comparisons

The proposed system (W-H-CCHP system) adopts wind power generation coupling to make cascade utilization of energy and coordinate with hydrogen electrolysis, which not only greatly improves the energy utilization rate of the system, but also produces a large amount of hydrogen energy that is beneficial to road emission reduction. In terms of primary energy consumption and carbon dioxide emission, the W-H-CCHP system has great advantages over the three reference systems. In terms of cost, the annual total cost of the W-H-CCHP system is lower than that of the FTL-CCHP system and the GB-C system and higher than that of the CB-C system. However, the CB-C system is not practical in China because of the government's "coal-to-gas" policy in recent years to reduce the number of small-scale coal-fired boilers.

5. Conclusions

With the increasing penetration of variable renewable energies (VREs), the power system stability has frequently become a challenge and such a challenge is especially significant in a distributed power generation system. Meanwhile, the decarbonization of the transportation sector remains a major challenge and hydrogen has the potential to decarbonize the transportation sector. Through power-to-gas (P2G) technology, hydrogen could store power generated from VREs that would otherwise be curtailed[6], but its benefit to hydrogen production has not been well studied. There is no study on how green hydrogen could be further used to decarbonized the transportation sector.

The paper innovatively proposes a new system that combines a traditional CCHP system with wind power and hydrogen supply. This system can recover a lot of curtailed wind power and produce a considerable amount of green hydrogen.

Using data from Dalian, Liaoning Province of China as a case study, the paper compares the economic, energy and emission performance of the new system with three reference (traditional) systems.

The case study demonstrates that the W-H-CCHP system can achieve primary energy saving, carbon dioxide emission reduction and annual total cost reduction than the reference systems. In addition, the system produces a large amount of hydrogen energy to supply the daily demand of hydrogen refuelling stations in winter and transition seasons. These cost and emission mitigation advantages indicate that the new system has a low price and dramatically reduces carbon dioxide emissions and plays a role in energy conservation and emission reduction. This study demonstrates that a properly designed energy system can reduce both emissions and costs.

The study could draw the following policy implications: first, energy transition should be promoted systematically and innovatively. As this paper demonstrated, by combining different technologies, low carbon energy can be produced with much lower costs, which then can facilitate the energy transition. Second, the integration of decentral hydrogen production in a distributed energy system could advance hydrogen development and achieve triple benefits of lowing cost, reducing emissions and recovering curtailed power. Last, hydrogen can be used simultaneously as transportation fuel and energy storage in a distributed system with VREs.

In the system, there is power redundancy part of the time, which needs to be further studied and solved.

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