

Integrated energy systems with CCHP and hydrogen production: 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 stability of the power system is challenged by 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. In this paper, we propose a new energy system that integrates the proton exchange membrane (PEM) electrolysis system for hydrogen production to the Combined Cold, Heat, and Power (CCHP) system with significant curtailed wind power to solve these two challenges simultaneously. We find that the new energy system can not only ensure stable energy supply for residential buildings with full use of wind power but also generate a large amount of clean hydrogen for fuel cell vehicles. To evaluate this new system, we compared it with two traditional energy systems: a centralized energy system and a conventional CCHP system. By comparing the annualized total system cost and carbon dioxide emission of the three systems, we find that the proposed new system can achieve lower cost and lower carbon dioxide emissions than both the centralized energy system and the traditional CCHP system.

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

1 Introduction

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. With the increasing pressure of energy saving and emission reduction, distributed energy generation system has attracted more and more attention. As a highly efficient and clean energy generation system, the distributed energy generation 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 generation system [2]. The CCHP system uses the recovered heat for heating or cooling to improve energy efficiency. In the energy production and supply industry, CCHP technology has the advantages of high reliability, high energy efficiency and environmental friendliness [3].

Hydrogen has the potential to decarbonize the transportation sector, which is a significant challenge. Hydrogen, together with the battery, are considered the two technologies with the most potential to decarbonise the transport sector[4]. The International Energy Agency [5]projected that a self-sustaining market for fuel cell electric vehicles (FCEVs) could be achieved 15–20 years after the introduction of the first 10,000 FCEVs due to technological progress, economies of scale and benefit from the learning curve. However, hydrogen is not competitive to fossil fuels due to its high costs than petroleum products.

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. This curtailed electricity can reduce the cost of hydrogen production. In a distributed power system, such hydrogen production can be placed in demand centers and thus cost of transportation, which is equivalent to about a half time of production, can be avoided and thus further increases the competitiveness of hydrogen against fossil fuels. Combined of distributed power generation systems with hydrogen production could not only stabilise the electricity system but also produce more economic hydrogen. The feasibility and benefits of such a hybrid system, however, has not been investigated in the literature.

To fill the gaps, this paper innovatively proposes a new system of coupling wind power generation, proton exchange membrane (PEM) electrolysis for hydrogen production and cold, heat and electricity co-supply system. While making full use of wind power to ensure stable energy supply for residential buildings, the system also generates a large amount of clean energy to supply fuel demand for hydrogen fuel cell vehicles. A new energy system, which is integrated with the traditional CCHP system and hydrogen production (CCHP-H system), is introduced in this study. To evaluate the

CCHP-H system, we present a centralized energy system and a traditional CCHP system. Using a case study in Dalian City, Liaoning Province, we calculate the total annual cost of the three systems through the annuity method, the annual carbon dioxide emissions, and the annual primary energy consumption. By comparison, the CCHP-H system has significant advantages in the total yearly cost-saving and carbon dioxide emission reduction compared with the two reference systems.

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 hydrogen has not been included. 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 gasification and CO₂ capture, which could effectively utilize the cold and residual heat of LNG gas through polygeneration.

As an important part of energy supply, renewable energy can effectively optimize the energy mix, balance the contradiction between emission reduction and energy demand, and protect the environment. In recent years, the development of renewable energy has received extensive attention [15]. The use of renewable energy provides a way to change the current energy mix and effectively solve these environmental problems. Among them, wind energy is one of the most promising renewable energy sources due to its low cost and relatively advanced technology [16]. However, wind power connected to the grid poses challenges to the safe and stable operation of the

power system due to its volatility and intermittency [17]. The effective utilization of surplus electricity has become a big challenge for wind power utilization. To solve this problem, it is necessary to convert and utilize the curtailed power. Siddiqui et al. [18] developed a new integrated renewable energy system to store excess solar and wind power in the form of ammonia. Pu et al. [19] proposed a new method of electric heating at night by utilizing the surplus wind resources in the Beijing area. Safari et al. [20] considered an integrated wind power system consisting of a wind turbine, a proton exchange membrane (PEM) electrolyzer, and a methanation unit for thermal analysis.

Hydrogen as an alternative energy carrier is a favorable choice for sustainable development in many industrial and household applications. Due to increasingly strict emission regulations, the global demand for hydrogen is increasing [21]. In the future, hydrogen energy will play an important role in new energy consumption and carbon emission reduction in the field of transportation [22]. PEM electrolysis provides a sustainable solution for the clean production of high purity hydrogen in the future [23]. Ayodele et al. [24] studied the feasibility of producing hydrogen from South African wind resources. Menia et al. [25] used PV electrolysis system to evaluate the renewable hydrogen production capacity of aqueous methanol electrolysis. Tebibel et al. [26] studied PV electrolytic systems for hydrogen production. They conducted case studies to show the impact of each type of electrolysis on the size of system components and to assess the potential for hydrogen production.

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. D. Apostolou et al. [27] predict an exponential increase in the number of hydrogenation stations in the future. The hydrogen station model proposed by Sean m. Riedl [28] reduced the design cost and accelerated the development of hydrogen facilities. D. Apostolou et al. [29] investigated the potential for on-site production of small autonomous hydrogenation stations using alkaline electrolysis powered by small wind turbines. Fabian Gruger et al. [30] proposed and applied an optimization method to optimize the scale of hydrogenation stations. Mihaela Iordache et al. [31] 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.

Using hydrogen as energy storage for renewable energy generation could ease the current energy crisis and has been under investigation. Lara Welder and others [32], 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.[33] 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.[34] argues that wind and photovoltaic power can be converted by electrolysis into hydrogen and reconverted by a thermal converter to be stored in a liquid organic hydrogen carrier (LOHC). Peng Hou et al.[35] 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.[36] 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.

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 on 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 CCHP-H system is composed of a distributed energy system, wind power generation system and electrolysis hydrogen production system. The distributed energy system includes prime mover, supplementary combustion boiler, waste heat recovery system, absorption refrigerating machine, compression refrigerating machine and heat exchanger. The electrolysis hydrogen production system includes a proton exchange membrane(PEM) electrolytic cell and hydrogen refueling station. The wind power generation system includes wind turbines.

For a more comprehensive evaluation of our proposed CCHP-H energy system, two reference systems are introduced. The reference system 1 is the traditional CCHP system, and the reference system 2 is the centralized energy system. Both systems buy the same amount of hydrogen in the CCHP-H system to meet the hydrogen demand. Carbon dioxide emissions and primary energy emissions of purchased hydrogen are calculated according to the method of producing hydrogen from grid power. Calculate its cost according to the market price.

3.1 Distributed energy system

In the distributed energy system, natural gas is used as the primary energy supply prime mover and secondary combustion boiler. The prime mover can generate electricity to meet the needs of residential power, and the generated waste heat after recycling can be transferred to the heat exchanger or absorption refrigerator. When the

waste heat cannot meet the cold and heat demand, the supplementary combustion boiler is used to supplement the shortage of heat energy of the heat exchanger and absorption refrigerator. When the prime mover produces more electricity than it needs, the excess is allocated by the system, transferred to the grid or produced by electrolysis of water.

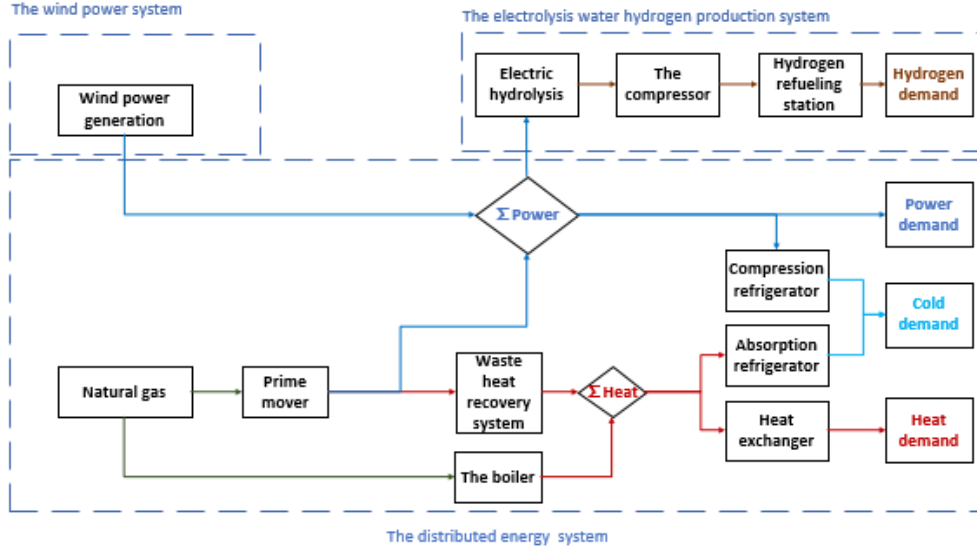


Fig.1. The CCHP-H system energy flow diagram.

The main technical parameters of each equipment in the system are shown in Table 1 [1].

Table 1

Main parameter coefficients of equipment.

Parameter	Symbol	Value
Electricity generation efficiency of Prime mover	η_e	0.36
Efficiency of heat recovery system	η_r	0.8
Coefficient of performance of electric chiller	COP_{ec}	4
Coefficient of performance of absorption chiller	COP_{ac}	0.7
Efficiency of heating exchanger	η_{he}	0.8
Efficiency of boiler	η_b	0.85
Electricity generation efficiency of the reference energy system	η_{re}	0.35
Transmission efficiency of the power grid	η_{grid}	0.92

3.1.1 Prime mover

The prime movers include gas turbines, gas internal combustion engines, micro

gas turbines, external gas turbines, and fuel cells[37]. Due to the high equipment cost, external gas turbine and fuel cell 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[38]. The main features of the prime movers of the three models are shown in Table 2.

Table 2

The main features of various prime movers.

Power generation equipment	Gas turbine	Gas internal combustion engine	Microgas turbine
Power generation efficiency	0.27-0.39	0.30-0.45	0.20-0.28
The comprehensive efficiency	0.50-0.80	0.70-0.90	0.50-0.70
Heat removal/power generation capacity ($\times 10^6$ J/kWh)	7.5-8.2	5.8-6.3	8.4
Single machine capacity (kW)	1000-500000	20-18000	30-350
The startup time (s)	360-3600	10-30	60

According to the selected building type and the main characteristics of the reference equipment, the power generation efficiency, individual capacity and start-up time of the gas internal combustion engine are in line with the residential buildings[39], so the prime mover chooses the gas internal combustion engine. The electric energy provided by the gas internal combustion engine is calculated as follows:

$$E_{pgu} = F_{pgu} \cdot \eta_e \quad (1)$$

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°C[40]. 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[41]. This heat is usually used to heat water so that it turns into steam. The steam supply heat exchanger or absorption refrigerator is used to meet the heat or cold load. The heat recovered by the heat recovery system is calculated as follows:

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

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

3.1.2 The boiler

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

$$Q_b = F_b \cdot \eta_b \quad (3)$$

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

3.1.3 Heat exchanger

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

$$Q_h = Q_{he0} \cdot \eta_{he} \quad (4)$$

Where Q_h is the heat load of residential buildings, and Q_{he0} is the heat generated by heat exchangers from boilers or heat recovery systems.

3.1.4 Refrigerator

The distributed energy system can be cooled by either absorption refrigerating machine with low energy efficiency or compression refrigerating machine with high energy efficiency. Under this combination, the compression refrigerator can adjust the output thermoelectric ratio of the distributed energy system in a certain range[42]. The cooling capacity provided by the two types of cooling equipment is:

$$Q_{ac} = Q_{ac0} \cdot COP_{ac} \quad (5)$$

$$Q_{ec} = E_{ec} \cdot COP_{ec} \quad (6)$$

$$Q_{ac} + Q_{ec} \geq Q_c \quad (7)$$

Where Q_{ac0} is the heat from the boiler or the heat recovery system obtained by the absorption refrigerating machine, Q_{ac} refers to the cold produced by the absorption refrigerating machine, Q_{ec} refers to the cold produced by the compression refrigerating machine.

3.1.5 The power balance

Wind power and gas internal combustion engine jointly meet the electric load of residential buildings and the power required by the compression refrigerating machine, and the surplus electricity is used to produce hydrogen.

$$E_w + E_{pgu} = E + E_{ec} + E_{pH_2} \quad (8)$$

Where E_w is the electricity generated by wind power generation, E is the electric load of residential buildings, and E_{pH_2} is the residual electricity generated by the system,

which will be used to produce hydrogen.

3.1.6 Thermodynamic equilibrium constraint

The heat demand of the building and the cold demand of the absorption refrigerator is supplied by the waste heat generated by the power generation of the gas internal combustion engine. The thermodynamic equilibrium constraint is as follows:

$$Q_b + Q_{hr} \geq Q_{ac0} + Q_{he0} \quad (9)$$

3.1.7 System fossil energy consumption

The sum of gas consumption of the internal combustion engine and gas boiler is the gas consumption of the distributed energy system.

$$F = F_b + F_{pgu} \quad (10)$$

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

3.2 Water electrolysis hydrogen production system

The electrolytic cell is the core equipment of hydrogen production by water electrolysis. Currently, there are approximately three types of electrolytic cells: alkaline electrolytic cells, proton exchange membrane (PEM) electrolytic cells, and solid oxide electrolytic cells (SOE). Among them, the PEM electrolyzer has many advantages, such as small size and lightweight, no lye corrosion[43]. In particular, it can be converted at 0-160% of rated power. Therefore, we use the PEM electrolyzer in the CCHP-H systems to absorb large fluctuations of electricity.

The electrolytic cell is composed of parallel plates connected in series. The control and regulation system is designed so that the electrolytic cell and the whole hydrogen production unit can operate normally in the change of power supply. The hydrogen production rate varies with the power, the consumption of hydrogen per standard cubic meter is reduced from 6kWh to 4kWh, and the efficiency is increased from 60% to 90%. The hydrogen production is calculated as follows:

$$H_p = \left\{ \begin{array}{l} \frac{E_{pH_2}}{6}, \forall E_{pH_2} \leq 20\%Cap_{pH_2} \\ \frac{E_{pH_2}}{5.5}, \forall 20\%Cap_{pH_2} < E_{pH_2} \leq 40\%Cap_{pH_2} \\ \frac{E_{pH_2}}{5}, \forall 40\%Cap_{pH_2} < E_{pH_2} \leq 60\%Cap_{pH_2} \\ \frac{E_{pH_2}}{4.5}, \forall 60\%Cap_{pH_2} < E_{pH_2} \leq 80\%Cap_{pH_2} \\ \frac{E_{pH_2}}{4}, \forall 80\%Cap_{pH_2} < E_{pH_2} \end{array} \right\} \quad (11)$$

Where H_p is the amount of hydrogen produced by the system, and Cap_{pH_2} is the power of the electrolytic cell.

Hydrogenation station is a special place for filling hydrogen for hydrogen fuel cell vehicles, hydrogen internal combustion engine vehicles and other hydrogen storage tanks. The three core pieces of equipment of the hydrogenation station system include hydrogen compressor, high-pressure hydrogen storage container, and hydrogenation station. 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 garbage, and finally refueling for hydrogen vehicles through the hydrogenation machine. According to the construction scale, we set the hydrogen station with 400kg capacity. The price of hydrogen purchased by the reference system is calculated according to the market price, and the hydrogen purchased is calculated according to the primary energy consumption and carbon dioxide emission of hydrolyzed coal.

3.3 Wind power system

The wind generator set is the land fan, rated power is 5000kW, and the installation height of the land fan is 60m. The obtained data is the wind speed detection of the land elevation of 10m. Based on the longitude and latitude of the wind farm, the conversion wind speed formula is finally determined as follows:

$$W_{60} = W_{10} \times \frac{\ln(60/z_0)}{\ln(10/z_0)} \quad (12)$$

Where W_{60} is the land wind speed at the height of 60 meters, W_{10} is the land wind speed at the height 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:

$$E_w = \begin{cases} P_r \frac{w^3 - w_i^3}{w_r^3 - w_i^3}, w_i < w < w_r \\ P_r, w_r < w < w_f \\ 0, \textit{Otherwise} \end{cases} \quad (13)$$

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

3.4.1 The optimization goal

The CCHP-H system optimization model takes the economic optimum of the system, that is, the lowest annual total cost as the optimization target. The annual total cost includes the annual equipment equivalent cost and the annual energy consumption cost. The equipment cost is calculated by the annuity method, and the equipment maintenance cost is converted to 5% of the equipment cost. The equipment includes prime mover, waste heat recovery system, boiler, compression refrigerator, absorption refrigerator, heat exchanger, proton exchange membrane electrolyzer and hydrogenation station.

$$C_c = \sum Cap_i \cdot C_i \cdot A_i \cdot 1.05 + C_{grid} + C_{ng} + C_{H_2} \quad (14)$$

$$A = \frac{r \cdot (1+r)^{y_i}}{(1+r)^{y_i} - 1} \quad (14)$$

$$A = \frac{r \cdot (1+r)^{y_i}}{(1+r)^{y_i} - 1} \quad (15)$$

$$C_{ng} = F \cdot CC_{ng} \quad (16)$$

Where C_c is the total annual cost of the CCHP-H system, Cap_i is the capacity of each equipment, C_i is the unit capacity cost of each equipment, A_i is the capital recovery coefficient of equipment investment, C_{ng} is the annual natural gas purchase cost of the system, r is the bank loan interest rate, y_i is the service life of the i th equipment, and CC_{ng} is the market price of natural gas per unit.

3.4.2 Evaluation standard

To evaluate the economic, energy-saving and emission reduction performance of the distributed energy, two reference systems were selected to calculate the total annual cost saving rate (ACTR), primary energy saving rate (PES) and carbon dioxide emission reduction rate (CDER) of distributed energy.

$$ACTR = \frac{C_{ref} - C_c}{C_{ref}} \quad (17)$$

$$PES = \frac{F_{ref} - F_c}{F_{ref}} \quad (18)$$

$$CDER = \frac{CDE_{ref} - CDE_c}{CDE_{ref}} \quad (19)$$

Where ACTR is the CCHP-H system of annual total cost savings rate, PES is the CCHP-H system of primary energy saving rates, CDER is the CCHP-H system of carbon emission reduction rate, which is the annual total cost of the reference system, the C_c is

the annual total cost of the CCHP-H system, F_{ref} is reference system in primary energy utilization of F_c is the CCHP-H system of annual energy use, CDE_{ref} is reference system in carbon dioxide emissions, CDE_c is the CCHP-H system in carbon dioxide emissions.

$$C_{ref} = \sum Cap_i^{ref} \cdot C_i^{ref} \cdot A_i^{ref} \cdot 1.05 + C_{ng}^{ref} + C_{H_2}^{ref} + C_{grid}^{ref} \quad (20)$$

$$C_{H_2}^{ref} = \sum H_p \cdot CC_{H_2} \quad (21)$$

$$C_{grid}^{ref} = \sum E \cdot CC_{grid} \quad (22)$$

Where C_{H_2} is the total cost of hydrogen purchased in the year of the reference system, C_{grid} is the total cost of electricity purchased in the year of the reference system, CC_{H_2} is the unit market price of hydrogen, and CC_{H_2} is the unit market price of hydrogen.

$$F_c = \sum (F + E_w) \quad (23)$$

$$F_{ref} = \sum \left(F^{ref} + \frac{E_{grid}^{ref}}{\eta_{ref} \eta_{grid}} \right) \quad (24)$$

$$E_{grid}^{ref} = \sum \left(E^{ref} + \frac{H_p^{ref}}{\eta_{pH_2}} \right) \quad (25)$$

Where η_{ref} is thermal power generation efficiency, η_{grid} is thermal power generation efficiency, η_{pH_2} is the efficiency of hydrogen production from coal.

$$CDE_{ng} = AD_{ng} \times EF_{ng,CO_2} \quad (26)$$

$$AD_{ng} = \sum F \times HV_{ng} \times 10^{-6} \quad (27)$$

$$EF_{ng,CO_2} = EF_{ng,C} \times \frac{44}{12} \quad (28)$$

$$CDE_{grid} = \sum E_{grid} \times EF_{grid,CO_2} \quad (29)$$

$$CDE_c = CDE_{ng} \quad (30)$$

$$CDE_{ref} = CDE_{ng}^{ref} + CDE_{grid}^{ref} \quad (31)$$

Where CDE_{ng} is the carbon dioxide emission in the process of natural gas combustion, AD_{ng} is the activity level of natural gas, EF_{ng,CO_2} is the emission factor of carbon dioxide, HV_{ng} is the average low calorific value of natural gas, $EF_{ng,C}$ is the emission factor of carbon, CDE_{grid} is the carbon dioxide emission of power grid, and CDE_c is the annual carbon dioxide emission of the new system.

Through Gurobi programming, the new system model is written into the program to optimize the total annual cost, and the appropriate equipment model, energy consumption, system output and three evaluation indicators can be obtained.

4 Case study

4.1 Parameter setting

The CCHP-H system takes 500,000m² residential buildings in Dalian, Liaoning province as the simulation object, and uses DeST software to simulate and analyze the cold load and heat load of the buildings [44-45].

Dalian is at the southern tip of the Liaodong peninsula. The basic landform is high in the center, with a staircase descending to the east and west sides. It is located in the warm temperate zone of the northern hemisphere, the eastern coast of the Eurasian continent. Dalian is a warm temperate sub-humid continental monsoon climate.

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 (Figure 2).

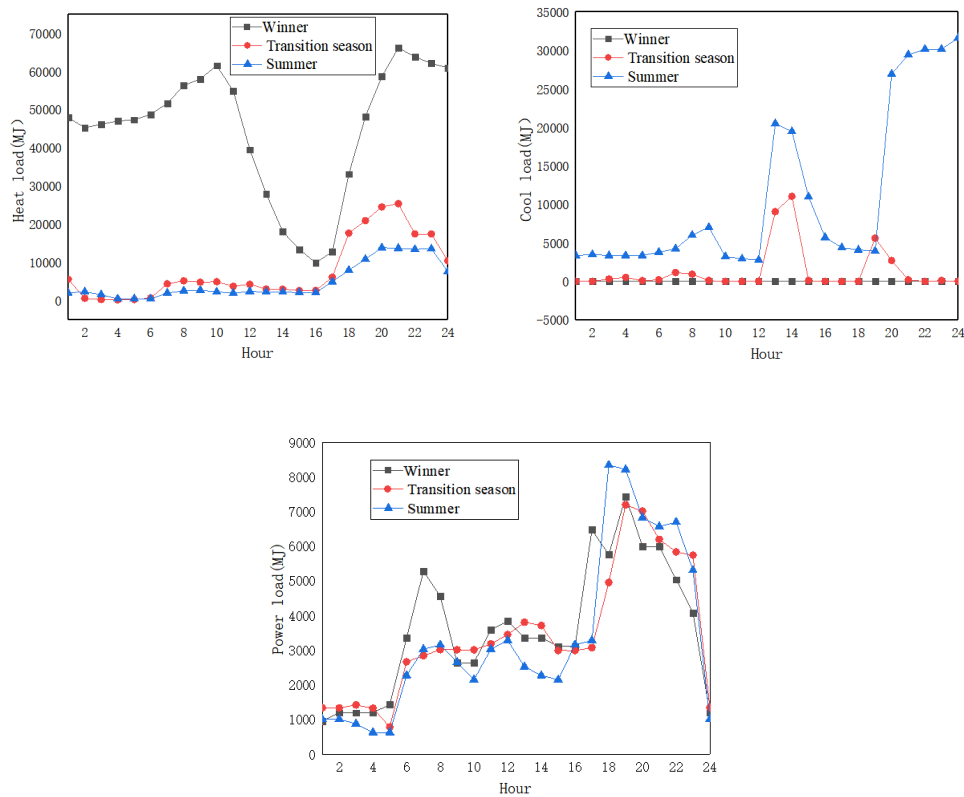


Figure.2. Typical daily heat, cold and power load [1].

In the CCHP-H system, the distributed energy supply system operates according

to the electricity priority mode, that is, "electricity determines heat". In order to ensure that the system can meet the residents' demand for electricity stably and effectively, the gas internal combustion engine operates at a load of 1.1 times the residents' demand for electricity.

According to data provided by the national bureau of statistics, thermal power accounted for about 71.8 percent of the power grid in 2017 [46]. Therefore, it is assumed that 71.8% of the power grid involved in this paper is coal power generation. The rest of the electricity is wind power, hydropower, nuclear power, etc., and there the carbon emissions are assumed to be zero.

The wind turbine with a rated power of 1500kW is selected, and its rated wind speed, the wind speed of the fan cut in and the wind speed of the fan cut out are 12m/s, 3.5m/s and 25m/s respectively. The annual variation of wind speed at the monitored altitude of 10 meters above sea level in Dalian city, Liaoning province, can be obtained by using DeST software [44-45].

Through comparison, the typical daily wind speed of three seasons in Dalian, namely winter, transition season and summer, can be obtained, as shown in Figure.3.

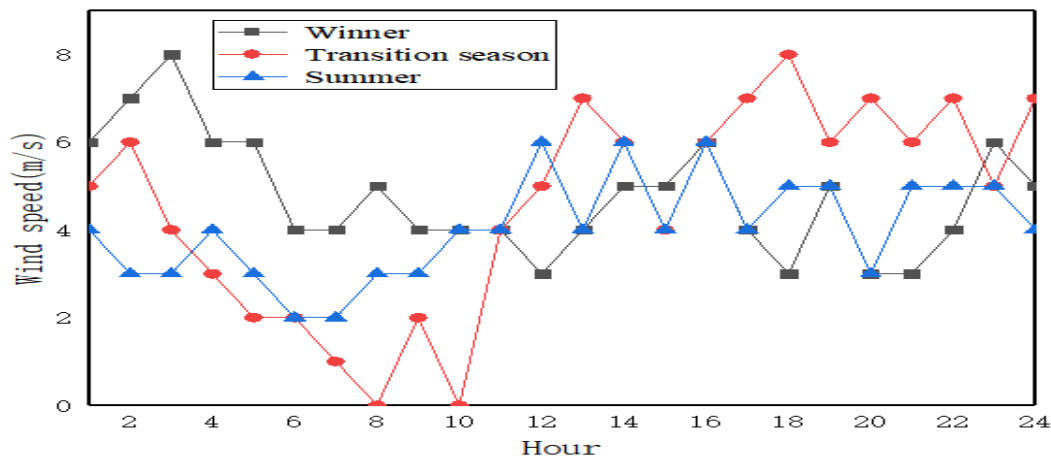


Figure.3. Typical daily wind speed in Dalian.

According to the formula in 2.3, the typical daily wind power can be calculated, as shown in Figure.4.

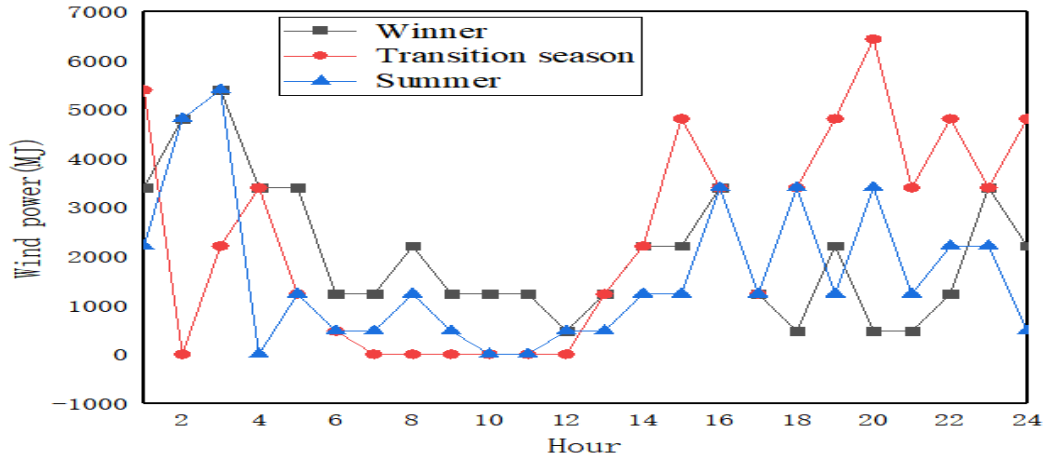


Figure.4. Typical daily wind power of Dalian.

4.2 Results

Through the CCHP-H system programming optimization operation, we can get the running data. Table 3 shows the annual power balance of the CCHP-H system. It can be seen that the prime mover delivers the most power in winter and the least during the transition season. Compression chillers require the most power in summer and no power in winter. The PEM electrolyzer absorbs the remaining uncertain electricity and converts it into hydrogen energy.

Table 3

The CCHP-H system's power balance sheet for the whole year(GJ).

Season	Prime mover	Wind power	Residents	Compression refrigerator	PEM
Winter	15051	7804	13553	0	9302
Transition season	11652	6622	9797	728	7749
Summer	12814	3467	7214	4908	4159
Total	39517	17893	30564	5636	21209

In the annual power supply, the prime mover generates 39.5 million MJ of electricity. Wind power provides about 17.9 million MJ of electricity, or 31 percent of the total. In addition, PEM electrolyzers consume about 37 percent of the electricity to produce hydrogen energy.

Typical hourly hydrogen production in the CCHP-H system in a day is shown in Figure.5. The system can provide 121 tons of hydrogen energy per year, including 338 kg, 386 kg and 256 kg per day in winter, transition and summer, respectively. At present, the capacity of a typical hydrogenation station in China is about 200kg per day.

Therefore, the hydrogen produced by our new system is enough to meet the demand of ordinary hydrogenation stations in China.

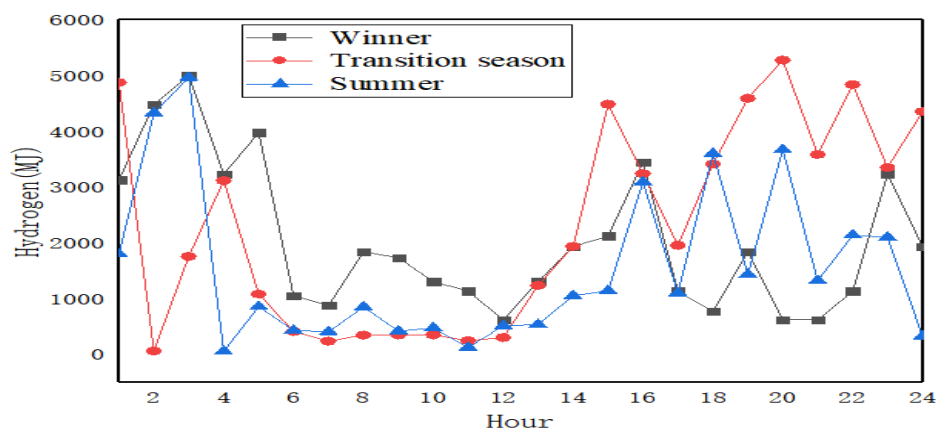


Figure.5. Typical hourly hydrogen production capacity per day (MJ)

Table 4 shows the equipment cost of the CCHP-H system and two reference systems, and Table 5 shows the annual energy consumption cost of the CCHP-H system and two reference systems. The prime movers, compression chillers and boilers account for a large proportion of the cost of CCHP-H system equipment. Natural gas accounts for a large proportion of annual energy consumption costs in all three systems.

Table 4

System equipment cost ($\times 10^5$ USD)

Equipment	CCHP-H system	Traditional CCHP system	Centralized energy system
Prime mover ^a	32.35	32.35	0
Heat recovery ^a	6.13	6.13	0
Absorption refrigerator ^a	1.86	1.86	0
Compression refrigerator ^a	10.68	10.68	12.18
Boiler ^a	18.09	18.09	22.39
Heat exchanger ^a	5.25	5.25	5.25
Electric hydrolysis ^b	8.57	0	0
Hydrogen refueling Station ^b	3.43	3.43	3.43
Total	86.37	77.80	43.26

Note Our estimation of cost saving is conservative as there is no production component in the reference systems.

Sources: a: The unit price of the equipment is derived from Ref[1] ; b: The data were sourced from an industrial hydrogen expert through an interview in September 2019.

Compared with the traditional CCHP system and centralized energy system, the annual total cost saving of the CCHP-H system is 26% and 15%, respectively (Table 5), which are significant cost advantages.

Table 5

System total energy consumption cost ($\times 10^5$ USD).

Equipment	CCHP-H system	Traditional CCHP system	Centralized energy system
Natural gas ^c	46.58	47.13	43.82
Hydrogen ^d	0	13.93	13.93
Electricity ^c	0	0	0.74
Total	46.58	61.05	58.49

Notes c: The price of natural gas and electricity is calculated according to the market price in Liaoning province on October 20, 2019.

d: The price of hydrogen purchased by the reference systems is calculated according to the market price at a refueling station in Guangdong province on October 20, 2019.

According to the annual primary energy consumption of the system (Table 6), the annual energy saving of the CCHP-H system can be calculated. Compared with the traditional CCHP system and centralized energy system, the annual primary energy-saving rate of the CCHP-H system is 4% and 1%, respectively. In terms of energy use, the CCHP-H system is slightly more economical than the two reference systems.

Table 6

Total primary energy consumption(GJ) .

System	Natural gas	Wind power	Coal power	Purchase volume of hydrogen	Total primary energy consumption
The CCHP-H system	345216	17893	0	0	363109
Traditional CCHP system	349298	0	0	28535	377833
Centralized energy system	324753	0	11639	28535	364926

Compared with the traditional CCHP system and centralized energy system, the annual CO₂ emission reduction rate of the CCHP-H system is 10.2% and 8.2%,

respectively (Table 7). The CCHP-H system has considerable advantages in reducing carbon dioxide emissions.

Table 7

Total carbon dioxide emissions (t).

System	Natural gas	Coal power	Purchase volume of hydrogen	Total carbon dioxide emissions
The CCHP-H system	19285	0	0	19285
Traditional CCHP system	19285	0	2188	21473
Centralized energy system	17930	897	2188	21015

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 decarbonisation 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.

The paper innovatively proposes a new system that combines a distributed power system with wind power with traditional combined cold, heat and electricity generation, and reuses the excess electricity to produce hydrogen. It not only recovers a lot of curtailed wind power, but also produces a considerable amount of green hydrogen. The economic, energy and emission performance of the new system was compared with two reference systems: a centralized energy system and a traditional CCHP system.

Using data from Dalian, Liaoning Province of China as a background, the paper demonstrates that the total annual cost saving and emission reduction of the new system are relatively high despite that the advantages of the new system in primary energy saving are not distinct. These cost and emission mitigation advantages indicate that the new system not only has a low price, but also 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 emission and cost. ,

The study could draw the following policy implications: first, energy transition should be promoted in systematic and innovative ways. 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, integration of decentral hydrogen production in a distributed energy systems could advance the development of hydrogen and achieve triple benefits of lowering 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. The proposed model shows that for the decentralized power generation systems with high volatility, the proton exchange membrane electrolyzer can be used to absorb fluctuating power while generating hydrogen for FCEVs.

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