

Article

Study on the Application of a Multi-Energy Complementary Distributed Energy System Integrating Waste Heat and Surplus Electricity for Hydrogen Production

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Abstract: To improve the recovery of waste heat and avoid the problem of abandoning wind and solar energy, a multi-energy complementary distributed energy system (MECDES) is proposed, integrating waste heat and surplus electricity for hydrogen storage. The system comprises a combined cooling, heating, and power (CCHP) system with a gas engine (GE), solar and wind power generation, and miniaturized natural gas hydrogen production equipment (MNGHPE). In this novel system, the GE's waste heat is recycled as water vapor for hydrogen production in the waste heat boiler, while surplus electricity from renewable sources powers the MNGHPE. A mathematical model was developed to simulate hydrogen production in three building types: offices, hotels, and hospitals. Simulation results demonstrate the system's ability to store waste heat and surplus electricity as hydrogen, thereby providing economic benefit, energy savings, and carbon reduction. Compared with traditional energy supply methods, the integrated system achieves maximum energy savings and carbon emission reduction in office buildings, with an annual primary energy reduction rate of 49.42–85.10% and an annual carbon emission reduction rate of 34.88–47.00%. The hydrogen production's profit rate is approximately 70%. If the produced hydrogen is supplied to building through a hydrogen fuel cell, the primary energy reduction rate is further decreased by 2.86–3.04%, and the carbon emission reduction rate is further decreased by 12.67–14.26%. This research solves the problem of waste heat and surplus energy in MECDESs by the method of hydrogen storage and system integration. The economic benefits, energy savings, and carbon reduction effects of different building types and different energy allocation scenarios were compared, as well as the profitability of hydrogen production and the factors affecting it. This has a positive technical guidance role for the practical application of MECDESs.

Keywords: multiple energy complementation; distributed energy systems; waste heat and surplus electricity; hydrogen production; energy storage



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1. Introduction

China has proposed achieving a carbon peak target by the year 2030 and carbon neutrality by 2060. To realize these goals, multi-energy complementary distributed energy systems, comprising combined cooling, heating, and power (CCHP), solar power generation, and wind power generation, are increasingly being applied in China. Additionally, hydrogen, as a green energy source, can aid in meeting the aforementioned goals. The main hydrogen production methods in China encompass production from coal, natural gas, methanol, etc. Currently, hydrogen production from natural gas is widely used around the world [1,2]. “Blue hydrogen” from natural gas exhibits lower carbon emissions than

“gray hydrogen” from coal, and it is more cost-effective than “green hydrogen” produced from water through photovoltaic electrolysis.

In 2020, buildings’ energy consumption accounted for 45.5% of total energy consumption in China, and the total carbon emissions from the production of building materials to building operation represented 50.9% of the country’s overall carbon emissions [3]. Energy saving and reducing carbon emissions are becoming increasingly crucial. The application of distributed energy systems, such as solar power generation, wind power generation, and CCHP, plays a significant role in energy saving and carbon reduction. Therefore, the analysis of multi-energy complementary distributed energy systems (MECDESs) including wind, solar electricity generation, and CCHP in buildings is essential.

As an effective supplement to the centralized commercial power supply system, a MECDES can independently output multiple energy products, including cold, heat, and electricity, to buildings by integrating systems scientifically. It can recover waste heat through co-generation technologies such as absorption refrigeration. However, during intermediate seasons or at night, the cooling or heating load of buildings may decrease, or even sometimes there is no load at all. During such periods, the waste heat generated by the gas engine (GE) cannot be utilized for cooling or heating through the lithium bromide absorption refrigerating and heating machine (LBARHM). It may have to be discharged into the atmosphere, resulting in energy waste and environmental thermal pollution. Due to the direct impact of climate change, the electricity generation of solar and wind, which are important parts of a MECDES, may not align well with the hourly electricity demand of buildings. This mismatch leads to surplus electricity from solar and wind power. The reverse input of surplus electricity into the grid affects the stable operation of the power grid. Storing and utilizing the waste heat and surplus electricity of the MECDES becomes a crucial challenge in its application. Investigation reveals that a lot of waste heat and surplus electricity can be utilized in the hydrogen production process by using miniaturized natural gas hydrogen production equipment (MNGHPE) at a hydrogen station [4–6]. Hence, finding a scientific method to store the waste heat and surplus electricity of the MECDES as hydrogen and making the integrated system’s produced energy meet the building’s energy demand is meaningful.

Regarding past MECDES research, C. Weber et al. [7] in 2011 studied distributed energy planning and optimized the layout of a district heating and cooling pipe network. In 2013, Akomeno Omu et al. [8] proposed a configuration model for optimizing distributed energy networks. In 2014, Hongbo Ren et al. [9] used multi-scale modeling methods to analyze distributed energy systems in China at different scales. In 2016, German Tobias Falke et al. [10] proposed a multi-objective optimization model for investment planning and operation management of a distributed thermal power supply system and applied it to the area of a medium-sized town in Germany to analyze the cost and CO₂ emission reduction effect. In 2017, M. Di Somma et al. [11] conducted a multi-objective design optimization of distributed energy systems through cost and exergy assessment. In 2018, Georgios Mavromatidis et al. [12] from Switzerland proposed a model to optimize the design of distributed energy systems under uncertainty, expressing it as a two-stage random mixed integer linear program. In 2019, Yurou Zheng [13] conducted an in-depth discussion on common optimization methods for developing distributed energy systems, summarized the application status of optimization algorithms in optimization problems, and put forth suggestions for the integrated application of algorithms according to different actual situations. In 2020, Hui Liu et al. [14] proposed a new MECDES comprising a gas boiler, back pressure unit, wind power generation equipment, solar power generation equipment, and battery energy storage. They conducted modeling, simulation, and case analysis of the proposed system. In 2021, Zichi Wang et al. [15] analyzed the microgrid formed by MECDES and an integrated energy management system and realized an optimization model to minimize economic cost and energy consumption.

Regarding past research on hydrogen production, in 2012, Juyuan Jiang et al. [16] presented the design, fabrication, and testing of an electrochemical reactor for wastewater

treatment, hydrogen production, and waste heat recovery. Po-Jui Li et al. [17] analyzed high-temperature gas-cooled reactors for optimal waste heat recovery and hydrogen production. In 2016, Ethem Toklu et al. [18] created an efficient, effective, and multi-disciplinary solution package to produce hydrogen by evaluating waste heat. In 2017, Jinfang Chen et al. [19] described the process flow of hydrogen production from natural gas, analyzing the total investment and cost of hydrogen production with a capacity of 2000 m³/h. Siyi Luo et al. [20] produced glassy slag and reused the heat for the production of hydrogen-rich gas via biomass catalytic pyrolysis. In 2018, H. Ishaq et al. [21] analyzed an integrated trigeneration system for electricity, hydrogen, and fresh water production using waste heat from a glass melting furnace. In 2020, Bin Zheng et al. [22] analyzed the influence of changes in fin structure on the hydrogen production capacity of a methane–steam reforming system. Their results showed that when the fin type changed from a straight fin to a triangular fin, the average temperature of the solid particle decreased by 30.5 K, the heat recovery efficiency increased by 7.9%, and the system's hydrogen production increased. In 2021, Zhimei Zheng et al. [23] generated concentrated solar heat (473.15–573.15 K) through medium- and low-temperature solar thermochemistry to drive the methanol decomposition reaction and produce hydrogen. Subsequently, the hydrogen produced electricity and heat through the chemical reaction of solid oxide fuel cells. The waste heat was utilized in the micro gas turbine for power generation. Fu Wang et al. [24] attempted to integrate the engine with the solid oxide electrolyzer, using the engine's waste heat to enhance the electric energy conversion efficiency of electrolytic hydrogen production. Dmitry Pashchenko [25] conducted a thermodynamic analysis of various hydrocarbon reforming reactions to determine the effectiveness of thermochemical waste heat recuperation systems, to assess the feasibility of hydrogen production. Abdullan E. Alali et al. [26] utilized waste heat to enhance the thermal performance of the gas turbine modular helium reactor by waste heat utilization in power generation and hydrogen production. In 2022, Zisong Wang et al. [27] reviewed the research progress of miniaturized natural gas hydrogen production technology by domestic and foreign research teams. They explained the basic principle of natural gas hydrogen production. Yan Cao et al. [28] tried to recover heat from biomass for hydrogen production. Yan Cao et al. [29] researched a novel hybrid energy system consisting of a molten carbonate fuel cell (MCFC) and explored different options for generating hydrogen from the waste heat of the MCFC. Somayeh Parsa et al. [30] utilized the exhaust gas from a homogeneous charge compression ignition engine containing waste heat for hydrogen production. Yan Cao et al. [31] proposed a new energy system based on a fuel cell, RR-ORC, and PEME for green generation of hydrogen and power from the recovery of waste heat from an efficient solid oxide fuel cell. Merve Ozturk et al. [32] utilized waste heat from a cement plant to generate hydrogen and blend it with natural gas. In 2023, Mohamed M. Ismail et al. [33] developed a renewable energy-based multigenerational waste-to-energy system using the pyrolysis of polyethylene plastic waste to produce hydrogen. Kubilay Bayramoglu [34] utilized waste exhaust gas from marine diesel engines for hydrogen production. He increased the temperature and employed catalysts throughout the system to enhance hydrogen production. Mohamed Nasser et al. [35] utilized waste heat from a hybrid system of the Rankine cycle with a proton exchange membrane and a solid oxide electrolyzer for hydrogen production. Shayan Sharafilaleh et al. [36] proposed a novel combined cycle based on gas turbines for a fixed power output of 10 MW using biomass as a co-fuel with natural gas, integrated with hydrogen production via a proton-exchange membrane electrolyzer. Amira H. Ali et al. [37] used novel lead-free inorganic CuO/Cs₂SnCl₆-KI perovskites as efficient photocatalysts for generating H₂ from wastewater. Yi Ge et al. [38] proposed a natural-gas-based combined cooling, heating, and power (CCHP) system with waste heat to hydrogen for energy storage. In the novel system, steam reforming of methanol (SRM) was applied between the internal combustion engine (ICE) and absorption chiller, integrated with a hydrogen tank, and a proton-exchange membrane fuel cell (PEMFC) for energy storage. Maria Camila Garcia Vallejo et al. [39] analyzed hydrogen production in stand-alone processes and energy-driven biorefineries.

The thermochemical processes presented higher economic profitability than the electrolytic processes. This can also prove that natural gas hydrogen production by thermal chemical methods is more economical than electrolytic hydrogen production by renewable energy. In China, Guishi Cheng et al. [40] analyzed and predicted the potential of green hydrogen production by photovoltaic-powered water electrolysis using machine learning methods. G.Kubilay Karayel et al. [41] developed a unique approach to examine the possibility of hydrogen generation through the utilization of renewable energy sources, specifically onshore and offshore wind power in Canada. The study explored the potential of these sources for the production of green hydrogen, and helped establish hydrogen hubs and the growth of hydrogen networks across the country based on the potentials identified. Muhammed Arslan et al. [42] developed models for assessing Turkey's geothermal resources' green hydrogen production potential, employing thermodynamic and thermoeconomic analyses. They revealed the optimal conditions and configurations for efficient hydrogen production from Turkey's geothermal resources, through exploring the thermophysical properties of geothermal fluids. Tuo Zhang et al. [43] proposed a solar-to-hydrogen electricity and thermal storage system, in which low-grade waste heat was converted into electrical energy by the flexible thermoelectric generator within the system. They used photothermal catalytic water splitting to produce renewable hydrogen.

Regarding past research on waste heat utilization, in 2013, Hao Fang et al. [44] from Tsinghua University proposed a holistic method for the comprehensive and efficient utilization of low-grade industrial waste heat. They attempted to recycle industrial waste heat for district heating in northern China. In 2017, Pawel Ziolkowski et al. [45] analyzed a waste heat recovery system based on a binary steam cycle. They aimed to replace steam with a low-boiling fluid to effectively utilize a large amount of low-grade waste heat. In 2018, M. Kofinger et al. [46] simulated the integration of renewable heat sources and industrial waste heat for seasonal storage and cross-season utilization. Yan Li et al. [47] proposed a new multi-heat source cascade heating system based on the utilization of power plant waste heat. Hacer Akhan et al. [48] studied a novel waste heat utilization system, consisting of transpired solar collector panels and a capillary tube heat exchanger. In 2020, Yang Liu et al. [49] proposed a CCHP system based on LNG cold energy utilization and flue gas waste heat recovery with CO₂ capture. Chao Chu et al. [50] constructed a MECDES with cross-season heat storage for an office building in Beijing. The MECDES consisted of CCHP, a solar collector, and a cross-season heat storage system. Most of the above studies focused on using waste heat for district heating or absorption heat pumps to provide cooling and heating water for buildings. There have been few studies on using waste heat from natural gas to produce hydrogen. Yihan Wang et al. [51] developed and evaluated a novel carbon dioxide capture system that combines cooling, heating, and power (CCHP) based on a cement plant with waste heat utilization. Yongyi Li et al. [52] studied a novel combined cooling and power (CCP) system utilizing liquefied natural gas (LNG), cryogenic energy, and low-temperature waste heat. Yongjia Wang et al. [53] analyzed and evaluated the performance of a heat pipe flue gas waste heat utilization system. Yuan Wang et al. [54] proposed a water-heating and dish-drying system based on a heat recovery unit to recover heat from the exhaust air of a commercial kitchen. In 2023, Weiming Song et al. [55] proposed a new method for obtaining gaseous fuels by pyrolyzing waste biomass and using waste heat in the converter vaporization cooling flue (CVCF) to ensure the proper utilization of waste biomass and high-temperature waste heat. Andrei Wallin et al. [56] investigated the techno-economic feasibility of utilizing two commonly available waste heat sources (waste air and wastewater) in an urban environment. The results show a significant reduction in the required borehole length with waste heat utilization, particularly in shallow borefields, with maximum reductions of 53.9% (apartment building) and 25.8% (office building). Lili Wang et al. [57] proposed a novel CO₂ hybrid geothermal system that incorporates a GSHP heating system. The hybrid geothermal system used CO₂ as the underground working fluid, and electricity and waste heat were employed to assist the ground source heat pump for heating, ventilation, and air conditioning. Fu Wang et al. [58] used a solid

oxide electrolyzer cell integrated with a marine diesel engine to utilize both electricity and waste heat for hydrogen production. Yuncheng Lan et al. [59] proposed a method using a thermoelectric generator to recover waste heat from proton-exchange membrane fuel cell exhaust gas to produce hydrogen and established economic and life-cycle climate performance models to evaluate the economic and environmental performance of the system. Matjaz Valant et al. [60] proposed an inventive thermochemical cycle that utilizes a reaction between iron and HCl acid for hydrogen production. The reaction occurs spontaneously at room temperature, yielding hydrogen and a FeCl solution as a by-product. This study explored the thermal decomposition of low-temperature industrial waste heat (250 °C) and reported that chlorine gas formation can be circumvented. Lianbo Mu et al. [61] studied the performance of a heat exchanger added at the rail of a gas-fired boiler (FGCHE) under different hydrogen blending ratios. Their results show that the mass heating value of the hydrogen-enriched natural gas and the water vapor content increase as the hydrogen blending ratio increases, and the flue gas waste heat recovery utilization ratio and energy-saving efficiency of the FGCHS can be promoted. Xinyue Zhao et al. [62] proposed a new method of waste heat utilization that combines waste heat from clean biogas power generation with flue gas from industrial silicon production to power supercritical carbon dioxide cycles.

Most of the previous studies on hydrogen production and waste heat utilization have discussed integrated systems of hydrogen production and waste heat utilization. However, the integration of a hydrogen production energy storage system and building energy modules has not been studied. According to previous studies, high-temperature water vapor is required for hydrogen production. On the other hand, a large amount of high-temperature residual smoke (368–469 °C) is generated by natural power generation. So, it is possible to try to produce high-temperature water vapor for hydrogen production through a waste heat recovery boiler to reduce the energy consumption of hydrogen production from natural gas. The solar radiation, wind speed, and some other factors may be the main factors affecting this system. We investigated the energy-saving rate, carbon reduction rate, and economic effect of the integrated hydrogen production system in various types of public buildings such as office buildings, hotels, and hospitals. This innovative research puts forward a new energy system integrating waste heat and surplus electricity for hydrogen production, and clarifies the mathematical model of waste heat and surplus electricity for hydrogen production and energy storage through the MECDES. The parameters that affect hydrogen production in the integrated system were extracted, and sensitivity analysis of each parameter factor was carried out. In addition, the integrated system was applied in different types of public buildings, and the economic benefits, energy savings, and carbon reduction effects of the integrated system were analyzed.

2. Research Methodology

2.1. Technical Approach

Figure 1 illustrates the technical approach of this study. An integrated system utilizing waste heat and surplus electricity to produce hydrogen for energy storage was created through a combination of the MECDES and MNGHPE. The multi-energy complementary distributed energy system consists of CCHP with a gas engine, solar, and wind power. The gas engine produces waste heat during periods of no heating or cooling load in the building, while solar and wind energy generate surplus electricity when the building's demand is lower than the supply. The waste heat and surplus electricity are transmitted to the MNGHPE for hydrogen production.

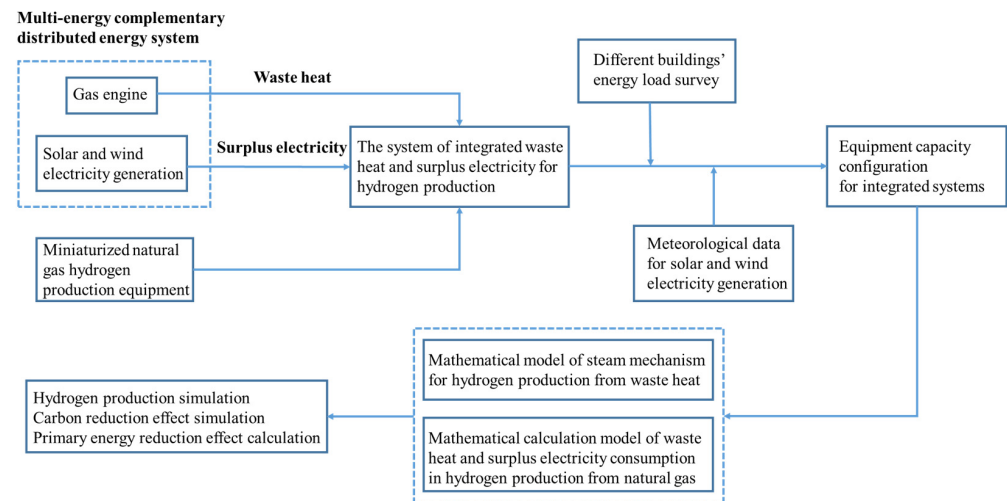


Figure 1. Technical path of hydrogen production by integrating waste heat and surplus electricity in a multi-energy complementary distributed energy system.

The comparison of energy efficiency between the traditional energy supply mode and the mode of waste heat and surplus electricity for hydrogen production is shown in Figure 2a,b. The traditional energy supply method involves supplying commercial electricity for the building's power load and cooling load, and natural gas for the heating load and hot water load through a gas-fired hot water boiler. The thermal electricity generation efficiency in China is about 38.6%. If we consider electricity transmission loss of 4.6%, the terminal electricity generation efficiency is about 34%. In other words, if 100% of the energy is put into electricity generation, then only 34% of the energy will be the final amount of electricity used in buildings. The thermal efficiency of the gas boiler is about 95%; that is, if 100% of the energy is put into the boiler, about 95 % of the energy is finally used in the building. As shown in Figure 2b, the electricity generation efficiency of natural gas through a gas engine can generally reach 44%. Due to the negligible transmission loss from the gas engine in the building, its terminal electricity generation efficiency remains at 44%. The gas engine's residual smoke can be utilized in the LBARHM to produce cold or hot water. In periods of no cooling and heating load, the gas engine's waste heat can be recovered by a waste heat boiler. The recovered waste heat can be converted into high-temperature water vapor for the hydrogenation reaction in the MNGHPE. While the hydrogen production efficiency of the MNGHPE is approximately 70% [63], the generated hydrogen can serve as fuel for electricity generation through hydrogen fuel cells with electricity generation efficiency of 56%. Consequently, the terminal electricity generation efficiency will be 39% [64], which is still higher than the 34% electricity generation efficiency of the grid. Therefore, this combination method of a multi-energy complementary distributed energy system and a hydrogen production system has better energy efficiency than the traditional energy supply method.

As shown in Figure 3, the components of the MECDES discussed in this study include a gas engine (GE), a lithium bromide absorption refrigerating and heating machine (LBARHM) using waste heat from the GE, several solar panels, several small wind turbines, the battery, and an inverter. The GE uses natural gas as raw material to generate electricity and generates high-temperature smoke at the same time. The high-temperature smoke enters the LBARHM to produce hot or cold water, which is used for cooling or heating the building. The electricity generated by solar and wind energy is used to power the building through the battery and inverter, and the rest will be returned to the grid if there is no integrated system for hydrogen production.

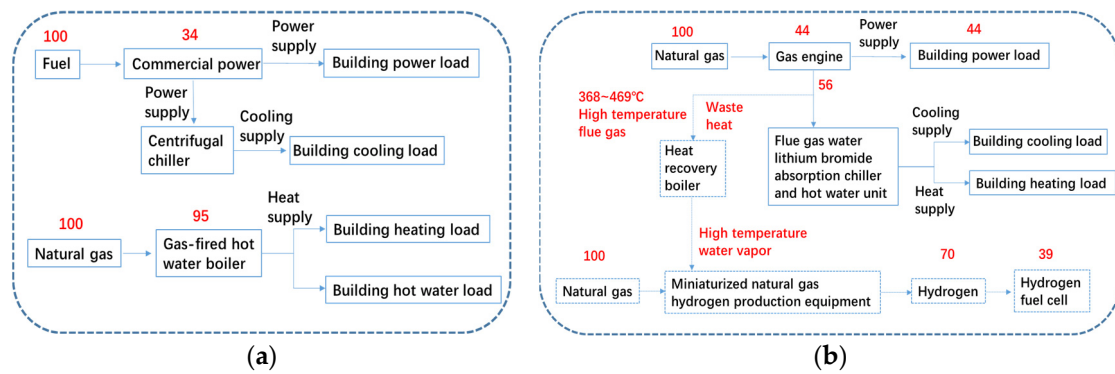


Figure 2. Comparison of energy efficiency between the traditional mode and waste energy for hydrogen production. (a) Model A; (b) Model B. (Note: the red numbers in the figure represent energy efficiency of the equipment).

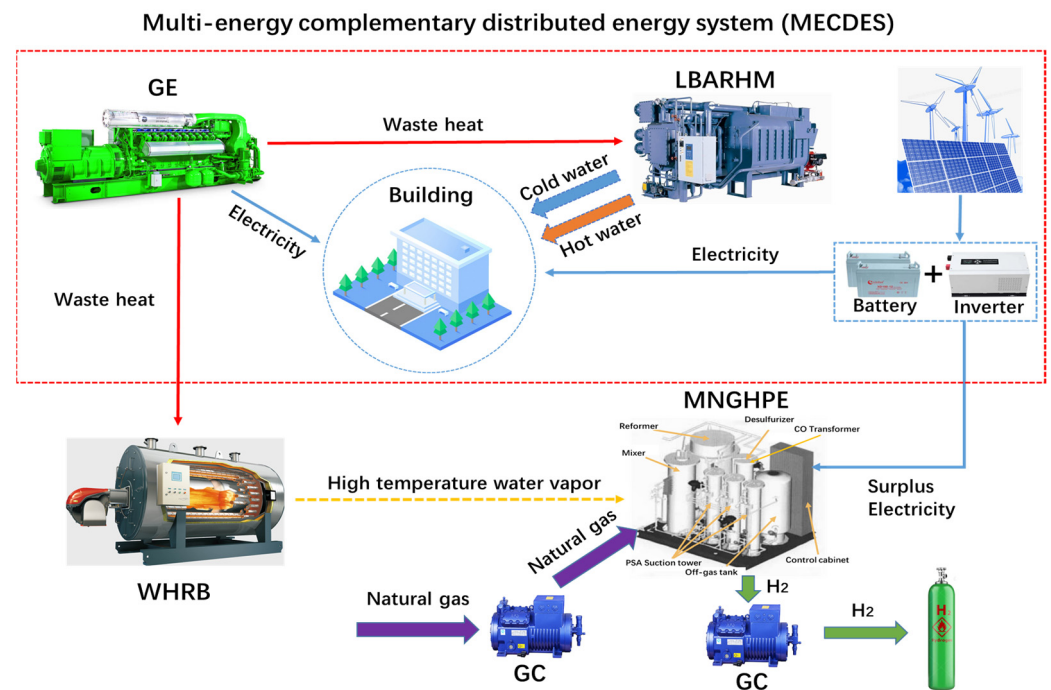


Figure 3. Multi-energy complementary system (MECDES) and integrated system for hydrogen production. (Note: “GE” stands for gas engine; “LBARHM” stands for lithium bromide absorption refrigerating and heating machine; “WHRB” stands for waste heat recovery boiler; “GC” stands for gas compressor; “MNGHPE” stands for miniaturized natural gas hydrogen production equipment. The charging and discharging efficiency of the battery is 95%, respectively).

The integrated system for hydrogen production is based on the MECDES plus a waste heat recovery boiler (WHRB) that can recover waste heat, miniaturized natural gas hydrogen production equipment (MNGHPE), and the gas compressor (GC). When the building has a cooling or heating load demand, the smoke generated by the GE is passed into the LBARHM to produce cold or hot water for cooling or heating. The remaining smoke is passed into the WHRB to produce high-temperature water vapor for hydrogen production. The electricity generated by solar panels and small wind turbines is preferentially supplied to the building, and the remaining power (surplus electricity) is supplied to the miniaturized natural gas hydrogen production equipment (MNGHPE). The WHRB is a waste heat recovery boiler that can use waste smoke to produce high-temperature water vapor for hydrogen production. The water vapor is then transferred to the MNGHPE for hydrogenation. The MNGHPE is an integrated device for easy installation and movement on site. It

includes the reactor required for hydrogenation reaction, a medium converter, the system control panel, desulfurizer, waste gas tank, etc. In addition, the integrated system includes the gas compressor (GC) for compressing the natural gas before entering the MNGHPE or compressing the produced hydrogen before entering the hydrogen tank. In the MECDES, the electricity generated by solar and wind energy is first stored through batteries, and then converted into AC power through the inverter for supply to the building preferentially. When there is surplus electricity after supply to the building, then the surplus electricity is supplied to the MNGHPE to provide the operating power for the equipment and the power load for hydrogen purification. The charging and discharging efficiency of the battery is 95%, respectively.

2.2. Model of the System

2.2.1. Gas Engine

The gas engine can generate electricity and heat at the same time by using natural gas. The equations for electricity generation and thermal power production are as follows [65]:

$$P_{GE} = V_{gas} \times Q_{gas} \times \eta_{GE} / 3.6 \quad (1)$$

$$Q_{GE} = \frac{P_{GE}}{\eta_{GE}} (1 - \eta_{GE} - \eta_L) \quad (2)$$

where P_{GE} (kW) is the generation electricity of the gas engine, V_{gas} (m³/h) is the natural gas consumption of the gas engine, Q_{gas} (MJ/m³) is the calorific value of natural gas, η_{GE} is the electricity generation efficiency of the GE, Q_{GE} (kW) is the waste heat recovery of the gas engine, η_L is the rate of the heat loss of the GE.

Table 1 displays the technical parameters of a gas engine of a type which is widely used in China. Electricity generation efficiency increases as the load rate increases. It reaches a peak of 43.6% at 100% load rate, with gas consumption of 974 Nm³/h, smoke volume output of 23,502 kg/h, and power output of 4000 kW. At 75% and 50% load rates, efficiency is 42.3% and 39.9%, with natural gas consumption of 750 Nm³/h and 527 Nm³/h, and smoke volume outputs of 18,097 kg/h and 12,716 kg/h, respectively. For equipment safety, the gas engine typically operates at a load rate exceeding 50%.

Table 1. Technical parameters of the gas engine. (Note: Gas engines generally operate at a load rate of more than 50%, “smoke volume” indicates the residual smoke generated by the gas engine’s power generation).

Technical Parameters of the Gas Engine			
Power load rate	100%	75%	50%
Electricity generating efficiency	43.6%	42.3%	39.9%
Gas consumption (Nm ³ /h)	974	750	527
Smoke volume (kg/h)	23,502	18,097	12,716
Input energy (kW)	9249	7129	5010
Rated electricity generation (kW)	4000	3000	2000

The electricity generation of the GE P_{GE} (kwh/h) is decided using the following formula:

$$P_{GE} = \begin{cases} E_{TGE} \times 50\% & E_L - E_P - E_W \leq E_{TGE} \times 50\% \\ E_L - E_P - E_W & E_{TGE} \times 50\% < E_L - E_P - E_W \leq E_{TGE} \\ E_{TGE} & E_L - E_P - E_W > E_{TGE} \end{cases} \quad (3)$$

where P_{GE} (kW) is electricity generation of the GE, E_{TGE} (kW) is the total generating capacity of the GE, E_L (kW) is the building’s electricity load, E_P (kW) is the solar electricity generation capacity, E_W (kW) is the wind electricity generation capacity. For the safe

operation of the GE, its operating load is generally set at more than 50%. In the absence of hydrogen fuel cells' power, the building's electricity load is provided by the GE, solar, and wind electricity generation. When the electricity generation of the GE is known, the amount of natural gas consumed by the GE can be calculated using the aforementioned Formula (1).

According to the performance data analysis of this GE, the smoke volume M_T (kg/h), the P_{GE} (kW), and the E_{TGE} (kW) of the GE follow the relationship outlined in Formula (4). According to actual investigation, the load rate of the GE is maintained at more than 50%.

$$M_T = 21572 \times \frac{P_{GE}}{E_{TGE}} + 1926 \quad (4)$$

The power generated by the gas engine is all used in the buildings and will not be returned to the grid. To ensure that all the electricity generated by the gas engine is used in the building, the total floor area of the simulated building park should be set to at least 3,000,000 m². Therefore, the simulated application object of this integrated system is a building with a total floor area of 3,000,000 m². A building with a total floor area of 3,000,000 m² was selected as the case study. In addition, the waste heat generated by the gas engine is preferentially supplied to the building for heating and cooling. Only when the cooling and heating load of the building is satisfied and there is still waste heat remaining will the remaining waste heat be used to produce water vapor through the waste heat boiler. The performance data of the miniaturized natural gas hydrogen production equipment and hydrogen fuel cell are derived from the world's leading products, which are manufactured by Japanese manufacturers.

2.2.2. Absorption Chiller/Heater

The absorption chiller/heater (AC/H) of the LBARHM absorbs the heat of the exhaust smoke from the GE to produce cold or hot water. The output of the AC/H is as follows [65]:

$$P_{AC/H} = COP_{AC/H} \times Q_{GE} \quad (5)$$

where $P_{AC/H}$ (kW) is the output of the AC/H, $COP_{AC/H}$ is the coefficient of performance (COP) of the AC/H, Q_{GE} (kW) is the waste heat recovery of the GE that can be used for the absorption chiller/heater.

2.2.3. Waste Heat Recovery Boiler

The high-temperature flue smoke is transported to the inlet of the waste heat boiler through the flue. It flows through the superheater, evaporator, and economizer before finally draining into the atmosphere. Based on the equipment performance survey, the exhaust smoke temperature will not be less than 150 °C, as tail heating surface corrosion will be produced otherwise. The reason is that high temperature may increase heat loss. The formula for calculating heat recovery of flue smoke by using the waste heat boiler is as follows [66]:

$$\Delta Q = C \times M_b \times (t_1 - t_0) \times \alpha \quad (6)$$

where ΔQ signifies that the waste heat boiler can recover the residual heat of the flue gas (kJ/h), C is the mass specific heat capacity of flue gas (kJ/(kg·°C)); 1.15 kJ/(kg·°C) was taken in this study, M_b is the mass flow rate of flue smoke gas in the waste heat boiler (kg/h), t_1 is the average temperature of flue smoke gas in the inlet of the waste heat boiler (°C), t_0 is the average flue smoke gas temperature at the outlet of the waste heat boiler (°C); 150 °C was taken in this study, α is the coefficient of flue gas heat loss; generally, 0.9 was taken.

2.2.4. Photovoltaic Panels

The formula for calculating solar electricity generation is as follows [67]:

$$E_P = H_A \times S \times K_1 \times K_2 \quad (7)$$

where E_P is solar electricity generation (kW), H_A is solar radiation per unit area (kW/m²), S is solar panel area (m²), K_1 is component conversion efficiency (generally 16–18%; 17% was taken in this study), K_2 is overall system efficiency (generally 75–85%; 80% was taken in this study).

The H_A (kW/m²) data were derived from the climate data obtained by the survey [60].

2.2.5. Wind Driven Generator

To use wind power effectively, a small type of wind turbine suitable for civic buildings was chosen. With a cut-in wind speed of 1.5 m/s, the wind turbine can consistently generate electricity even in cities with lower wind speed. Figure 4 displays the turbine's image and performance curve. It begins producing electricity when the wind speed exceeds 1.5 m/s. The maximum output power of 640 W is reached at a wind speed of 13 m/s.

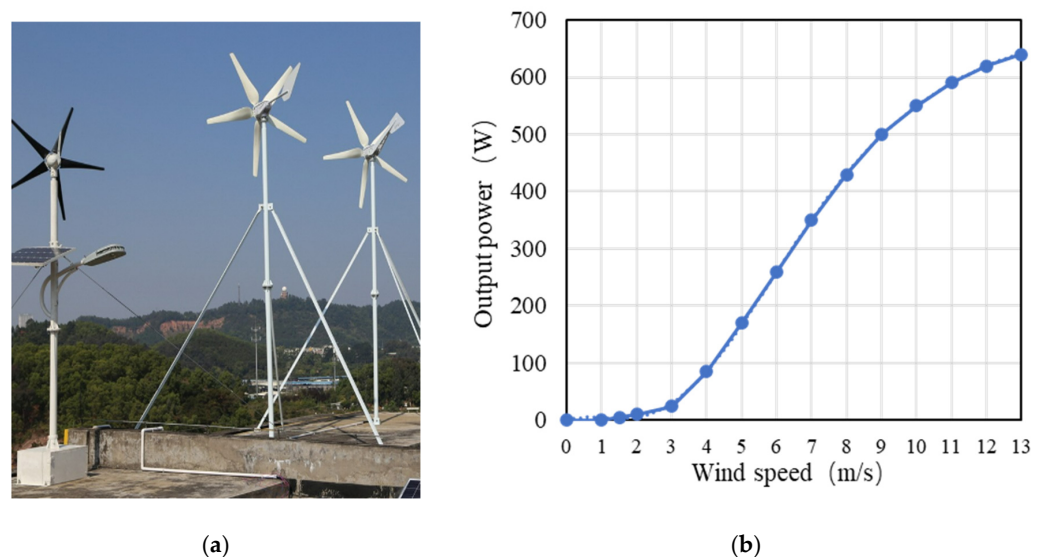


Figure 4. Wind turbine. (a) Wind turbine picture; (b) performance curve.

The relationship between output power and wind speed for a single wind turbine can be expressed by Formula (8):

$$E_W = \begin{cases} 0 & V < 1.5 \\ -0.0025 \times V^6 + 0.1118 \times V^5 - 1.8683 \times V^4 + 13.358 \times V^3 - 30.538 \times V^2 + 23.64 \times V - 0.5789 & 1.5 \leq V \leq 17 \\ 0 & V > 17 \end{cases} \quad (8)$$

where E_W (W) is the output power of the wind turbine, V (m/s) is wind speed. The cut-in wind speed of the wind turbine is 1.5 m/s. When the wind speed is less than the cut-in wind speed, the output power is 0 W. The cut-out wind speed of the wind turbine is 17 m/s. When the wind speed is more than the cut-out wind speed, the wind turbine stops running and the output power becomes 0 W.

2.2.6. Miniaturized Natural Gas Hydrogen Production Equipment

Figure 5 depicts the appearance and internal structure of the MNGHPE. The MNGHPE is skid-mounted, consisting of a mixer, natural gas reformer, desulfurizer, CO transformer, pressure swing adsorption (PSA) hydrogen purification equipment, off gas tank, and so on. The MNGHPE must be compact and integrated for convenient placement around the building.

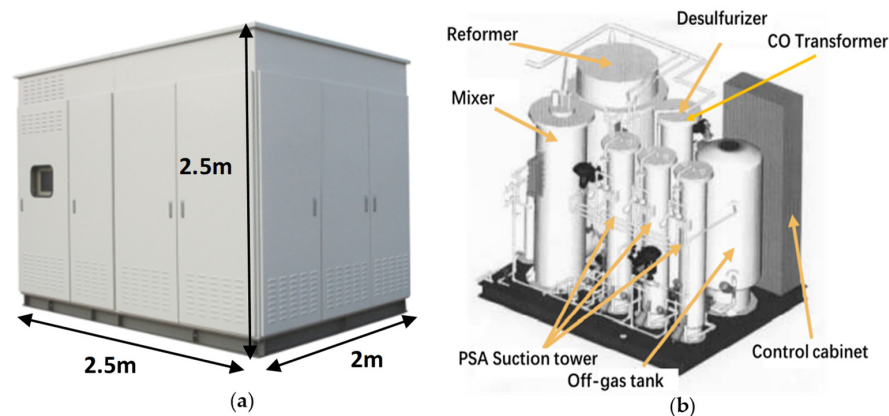


Figure 5. Miniaturized natural gas hydrogen production equipment [6,63]. (a) Appearance; (b) internal structure. (Note: the selected equipment is currently at the world's leading level in hydrogen production performance and integration).

Table 2 shows the relevant performance parameters of the MNGHPE. The MNGHPE uses natural gas as fuel to produce hydrogen, and the purity of the produced hydrogen is more than 99.999 vol%. Within this system, 40 Nm³ of natural gas can produce about 100 Nm³ of hydrogen and consume 4.5 kWh/h of electricity in the MNGHPE. The operating mode of the device is one-button start–stop. The operating load rate is 40–100%, and the set area is about 5 m².

Table 2. The parameters of miniaturized natural gas hydrogen production equipment [6,63]. (Note: the input pressure of natural gas is 0.5 Mpa, which is the pressure of the urban medium-pressure natural gas pipeline. The operating load rate of the equipment is 40–100%, the devices do not run if the load is less than 40%).

Set of Data	Specification
Fuel	Natural gas
Natural gas inlet pressure	0.5 Mpa
Hydrogen purity	More than 99.999 vol%
Hydrogen production capacity	40 Nm ³ Natural gas/100 Nm ³ H ₂
H ₂ production pressure	0.75 Mpa
Electricity consumption	4.5 kWh/h
Hydrogenation reaction temperature	753.4 °C
Equipment configuration	Modularization (boiler, reformer, desulfurizer, PSA suction tower, etc.)
Operation	Button start, automatic load tracking, load rate range (40–100%)
Set area	5.0 m ² (2 m × 2.5 m × 2.5 mH)

Table 3 displays the proportion of each constituent gas in natural gas. The primary component of natural gas is methane (CH₄), accounting for 85% by volume, followed by ethane (C₂H₆) at 9%, propane (C₃H₈) at 3%, and butane (C₄H₁₀) at 1%. Additionally, it contains 2% nitrogen (N₂) and trace amounts of hydrogen sulfide (H₂S).

The calculation formula of carbon atoms in natural gas is given in Equation (9):

$$\sum V_C = \omega_{CH_4} + \omega_{C_2H_6} \times 2 + \omega_{C_3H_8} \times 3 + \omega_{C_4H_{10}} \times 4 \quad (9)$$

where $\sum V_C$ is the total carbon atom content of natural gas, ω_{CH_4} is percentage of methane (CH_4) by volume in natural gas, $\omega_{C_2H_6}$ is percentage of ethane (C_2H_6), $\omega_{C_3H_8}$ is percentage of propane (C_3H_8), $\omega_{C_4H_{10}}$ is percentage of butane (C_4H_{10}) by volume. The total carbon atoms in natural gas were calculated as 1.16 according to Equation (9). The content of carbon atoms in natural gas is directly related to the amount of water vapor required for the hydrogenation reaction. The waste heat determines the amount of water vapor produced.

Table 3. The composition of natural gas. (Note: the percentage is the volume ratio of each component gas in natural gas).

Gas Composition of Natural Gas		Percentage by Volume
ω_{CH_4}	Methane (CH_4)	85%
$\omega_{C_2H_6}$	Ethane (C_2H_6)	9%
$\omega_{C_3H_8}$	Propane (C_3H_8)	3%
-	Nitrogen (N_2)	2%
$\omega_{C_4H_{10}}$	Butane (C_4H_{10})	1%

The hydrogen production efficiency of the MNGHPE is shown in Figure 6, and the hydrogen production efficiency of the equipment is about 70%. The formula to calculate hydrogen production efficiency is shown in Equation (10) [6,63], where η is hydrogen production efficiency, V_H (Nm^3/h) is hydrogen production, Q_H (kJ/Nm^3) is the combustion calorific value of hydrogen per unit volume, V_N (Nm^3/h) is natural gas consumption, Q_N (kJ/Nm^3) is the combustion calorific value of natural gas per unit volume, and E (kWh/h) is the electric energy consumption for hydrogen production. Electricity E requires a unit conversion in the calculation:

$$\eta = \frac{V_H \times Q_H}{V_N \times Q_N + E} \quad (10)$$

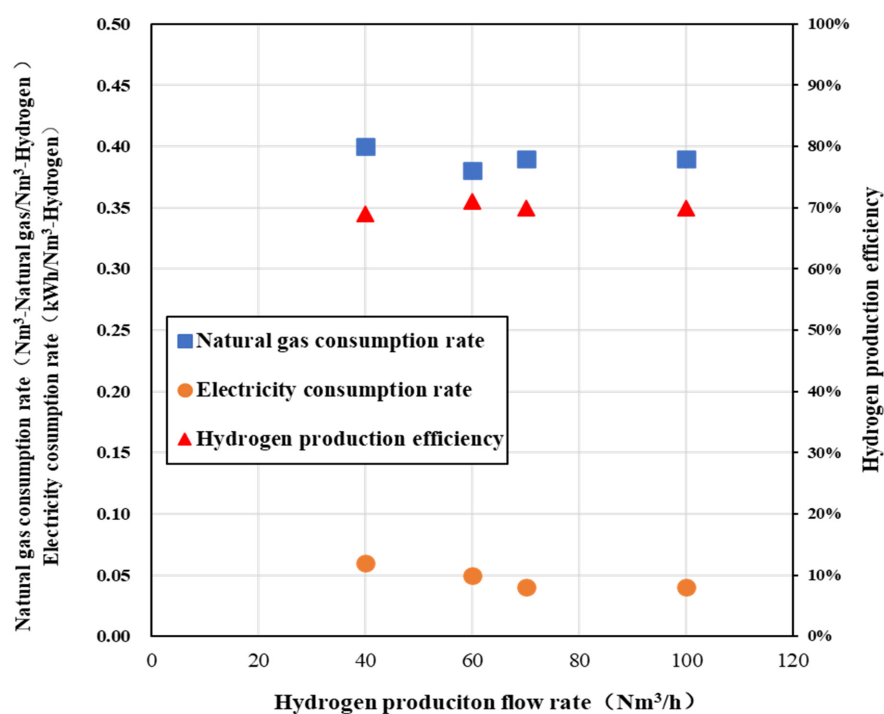


Figure 6. Hydrogen production efficiency of miniaturized natural gas hydrogen production equipment [6,63]. (Note: Hydrogen production efficiency refers to the ratio of the calorific value of hydrogen produced to the sum of the calorific value of natural gas and electricity consumed for hydrogen production).

2.2.7. Water–Carbon Ratio in Hydrogenation of Natural Gas

When calculating the amount of water vapor required for hydrogen production in the hydrogenation reaction, it is necessary to determine the total carbon atom content in natural gas to calculate the water–carbon ratio. Controlling the water–carbon ratio of water vapor and natural gas is crucial for natural gas hydrogenation under normal production conditions. The water–carbon ratio for hydrogen production typically ranges from 3 to 5, with the normal ratio set at 3.5 [4]. Deviating from this ratio may result in either wasting water vapor if too large or causing carbon deposition on the catalyst and deactivating it if too small. Based on previous research [4], the water–carbon ratio in this study was set as 3.5. Equation (11) presents the formula for calculating the water–carbon ratio, and the carbon flow rate is determined by the superposition of each carbon-containing gas in natural gas:

$$\varepsilon = \frac{V_W}{V_{gas} \times \sum V_C} \quad (11)$$

where ε is the ratio of water–carbon; the value in this study is 3.5, V_{gas} is the volume flow of natural gas (Nm^3/h), V_w is the volume flow of water vapor (Nm^3/h), $\sum V_C$ is the total volume flow of carbon in the natural gas (Nm^3/h); 1.16 is the total carbon atoms of natural gas by calculation.

Based on the above Formula (11), the total carbon atoms of natural gas are 1.16. If $40 \text{ Nm}^3/\text{h}$ natural gas is used to produce hydrogen, then the carbon flow rate of the natural gas is the product of the volume flow rate and the total carbon atoms, resulting in $46.4 \text{ Nm}^3/\text{h}$. Since the water–carbon ratio is generally selected as 3.5, the water vapor flow required for the hydrogenation reaction of $40 \text{ Nm}^3/\text{h}$ natural gas is $162.4 \text{ Nm}^3/\text{h}$.

2.2.8. Hydrogen Fuel Cell

A hydrogen fuel cell is an electricity generation device that can convert the chemical energy of hydrogen and oxygen directly into electrical energy. It can generate electricity while also producing waste heat at the same time. This waste heat can be recycled in the hydrogen fuel cell. Therefore, the hydrogen fuel cell can supply heat and electricity for the building. If combined with the LBARHM, the hydrogen fuel cell can generate cold or hot water for air conditioning through the LBARHM.

Japan and the United States currently lead the world in hydrogen fuel cell manufacturing. Figure 7 shows a hydrogen fuel cell made in Japan, and Table 4 displays the parameters of the hydrogen fuel cell. This type of hydrogen fuel cell utilizes pure hydrogen (more than 99.97 vol%) as fuel. The total electricity generation capacity is 5000 W, the rated electricity generation efficiency is 47.3%, the heat recovery efficiency is 32.9%, and the reaction temperature is about 753.4°C . In this study, the hydrogen produced by waste heat and surplus electricity can be directly used as fuel in this type of hydrogen fuel cell for generating electricity and hot and cold water and then supplied to the building.

Table 4. Parameters of the hydrogen fuel cell [68].

Parameters of the Hydrogen Fuel Cell	
Types of fuel cell	Solid polymer fuel cell (PEFC)
Type of fuel	Pure hydrogen (more than 99.97 vol%)
Generating electricity capacity	5000 W
Hydrogen consumption	$2.976 \text{ Nm}^3/\text{h}$
Heat dissipation under rated Conditions	3480 W
Generating efficiency	47.3%
Heat recovery efficiency	32.9%
Reforming temperature	753.4°C



Figure 7. Hydrogen fuel cell [68].

The equations for electricity generation and waste heat recovery of the hydrogen fuel cell are as shown below [68]:

$$P_{HFC} = V_H \times Q_H \times \eta_{EFC} / 3.6 \quad (12)$$

$$Q_{HFC} = V_H \times Q_H \times \eta_{WFC} / 3.6 \quad (13)$$

where P_{HFC} (kW) is the generation electricity of the hydrogen fuel cell, V_H (m^3/h) is hydrogen consumption of the hydrogen fuel cell, Q_H (MJ/m^3) is the calorific value of hydrogen, η_{EFC} is the electricity generation efficiency of the hydrogen fuel cell, Q_{HFC} (kW) is the waste heat recovery of the hydrogen fuel cell, η_{WFC} is the heat recovery efficiency of the hydrogen fuel cell.

2.2.9. Multi-Energy Complementary Distributed Energy System Integrating Waste Heat and Surplus Electricity for Hydrogen Production

In this study, the waste smoke from the GE was utilized to produce high-temperature water vapor for the hydrogenation reaction through a waste heat boiler. Surplus electricity from solar and wind energy was employed to meet the electricity demand of the hydrogen production equipment. Figure 8 illustrates a multi-energy complementary distributed energy system integrating waste heat and surplus electricity for hydrogen production. The system comprises CCHP with a gas engine, solar, and wind electricity generation.

The GE ① generates high-temperature waste heat and smoke at 368–469 °C during power generation. When the building requires heating or cooling, the residual smoke can be utilized for cold or hot water using a lithium bromide absorption refrigerating and heating machine (LBARHM) ② for cooling and heating the building. When there is no demand for heating or cooling load in the building during the intermediate season or late at night, the system can produce high-temperature water vapor required for the hydrogenation of natural gas by providing high-temperature waste heat and smoke to the waste heat recovery boiler (WHRB) ③. The natural gas from the desulfurization reaction and the high-temperature water vapor (561) are mixed in the water vapor and natural gas mixer (WVNGM) ④, and then the mixed gas is sent to the high-temperature hydrogenation reactor, the natural gas reformer (NGR) ⑤. Before the reaction, the mixed gas can be heated by the heat exchanger (HE) ⑥, which is set in the gas (GB) ⑦ to reduce the amount of fuel used for heating the hydrogenation reaction at high temperature (753 °C) in the burner. The hydrogenation reaction is shown in Formula (19). The fuel for the hydrogenation reaction needs to be compressed and pressurized by the gas compressor (GC) ⑧. Because the sulfur may carbonize the catalyst of the hydrogenation reaction, the pressurized natural

gas should enter the natural gas desulfurizer (NGD) ⑨ for desulfurization reaction and removal of the sulfur element from natural gas. The chemical formula of the desulfurization reaction is shown in Equation (20). Since the desulfurization reaction is an endothermic process (with a reaction temperature ranging between 290–350 °C), to conserve energy, the compressed natural gas (CNG) can first exchange heat with the high-temperature gas from the hydrogenation reactor (NGR) ⑤ in the heat exchanger (HE) ⑩. After the natural gas is heated, it is then directed into the desulfurizer ⑨. The mixed gas is subsequently cooled by the heat exchanger (HE) ⑩ before entering the medium converter (MC) ⑪ for an intermediate exothermic reaction, occurring at a temperature range of 200–300 °C; the formula for this reaction is provided in Equation (21). The resulting gas mixture, primarily composed of H_2 , CO_2 , and small amounts of other gases such as CO and H_2O , requires separation of hydrogenation. To achieve this, the mixture is cooled through the heat exchanger (HE) ⑫ using cooling water and then passed into the gas–liquid separator (GLS) ⑬ for efficient gas–liquid separation. Then, the separated gases are passed into the pressure swing adsorption (PSA) ⑭ hydrogen purification equipment for hydrogen purification. The hydrogen should be passed into the GC ⑯, while other combustible gases, such as CO and CH_4 in the gas mixture, are stored in the off gas tank (OGT) ⑮. Surplus electricity from solar and wind power is utilized to supply the electricity load of the MNGHPE. This MNGHPE can use $40 \text{ Nm}^3/\text{h}$ natural gas to produce approximately $100 \text{ Nm}^3/\text{h}$ hydrogen while consuming $4.5 \text{ kWh}/\text{h}$ electricity at the same time.

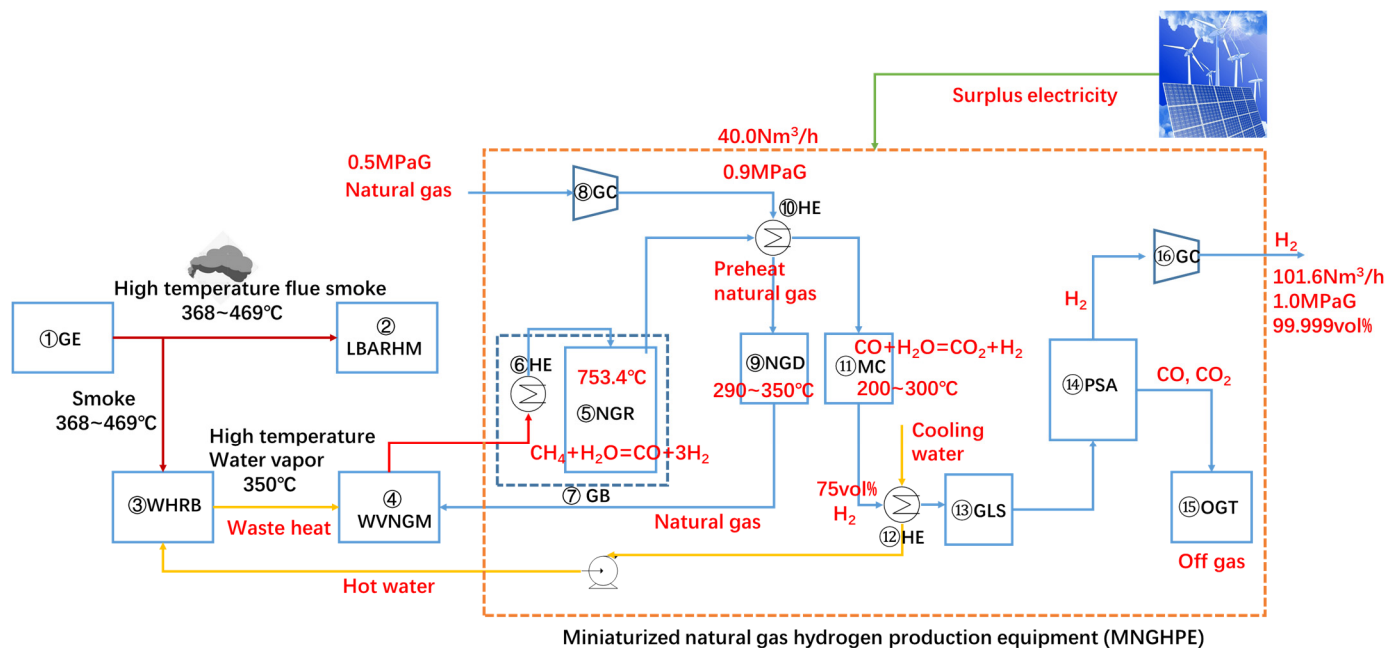
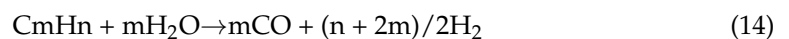


Figure 8. The system of multi-energy complementary distributed energy integrating waste heat and surplus electricity for hydrogen production. (Note: “GE” stands for gas engine, “LBARHM” stands for lithium bromide absorption refrigeration and heating machine, “WHRB” stands for waste heat recovery boiler, “HE” stands for heat exchange, “GC” stands for gas compressor, “NGR” stands for natural gas reformer, “NGD” stands for natural gas desulfurizer, “MC” stands for medium converter, “PSA” stands for pressure swing adsorption, “OGT” stands for off gas tank. The pressure of the urban medium-pressure natural gas pipeline is 0.5 Mpa. The surplus electricity is used to provide the power load for the MNGHPE for hydrogen production).

The following is the primary reaction that occurs in the hydrogen production process [6,63]:





The calculation process of hydrogen output and carbon flow in natural gas is shown in Figure 9. Natural gas mainly includes four kinds of gases, including CH_4 , that can produce hydrogen. In the first stage, the reaction of the four gases follows the following chemical formula: $\text{C}_m\text{H}_n + m\text{H}_2\text{O} \rightarrow m\text{CO} + (n + 2m)/2\text{H}_2$. In the second stage, the reaction follows the following chemical formula: $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$. In summary, the chemical reaction of the two stages of each gas in natural gas is shown in the following chemical formula: $\text{C}_m\text{H}_n + 2m\text{H}_2\text{O} \rightarrow m\text{CO}_2 + (4m + n)/2\text{H}_2$, where “ m ” can take the value of 1, 2, 3, or 4, and “ n ” can take the corresponding value of 4, 6, 8, or 10, representing four different gases in natural gas. In natural gas, from methane (CH_4) to butane (C_4H_{10}), the volume ratio of the four gases is 85%, 9%, 3%, and 1%, respectively. Therefore, the carbon flow rate in natural gas is calculated according to this formula: $\sum V_c = \omega_{\text{CH}_4} + 2 \times \omega_{\text{C}_2\text{H}_6} + 3 \times \omega_{\text{C}_3\text{H}_8} + 4 \times \omega_{\text{C}_4\text{H}_{10}}$. That is, the number of carbon atoms in each gas is multiplied by the corresponding volume ratio, then the result of the carbon flow rate in natural gas is obtained. There is one carbon atom in CH_4 , two carbon atoms in C_2H_6 , three carbon atoms in C_3H_8 , and four carbon atoms in C_4H_{10} , so the carbon flow rate in natural gas was eventually calculated to be 1.16. If there is 1 unit volume of natural gas, then it will include 0.85 unit volume of methane (CH_4). The reaction requires 2×0.85 unit volume of water vapor, which corresponds to 0.85 unit volume of CO_2 and 4×0.85 unit volume of H_2 . The hydrogenation of other gases is also carried out as shown in the Figure 9. A unit volume of natural gas reaction requires $2 \times 0.85 + 4 \times 0.09 + 6 \times 0.03 + 8 \times 0.01 = 2.32$ unit volume of water vapor and produces $4 \times 0.85 + 7 \times 0.09 + 10 \times 0.03 + 13 \times 0.01 = 4.46$ unit volume of hydrogen. Therefore, $40 \text{ m}^3/\text{h}$, 0.9 MpaG of natural gas will be able to output $40 \times 4.46 = 178.4 \text{ m}^3/\text{h}$, 0.9 MpaG of H_2 . When hydrogen is compressed, it becomes $101.6 \text{ m}^3/\text{h}$, 1.0 MpaG of H_2 . The $40 \text{ m}^3/\text{h}$, 0.9 MpaG of natural gas that can output about $100 \text{ m}^3/\text{h}$, 1.0 MpaG hydrogen is mainly determined by the performance of the MNGHPE; the actual output is larger than this value, but some hydrogen that cannot be extracted is stored in the off gas tank.

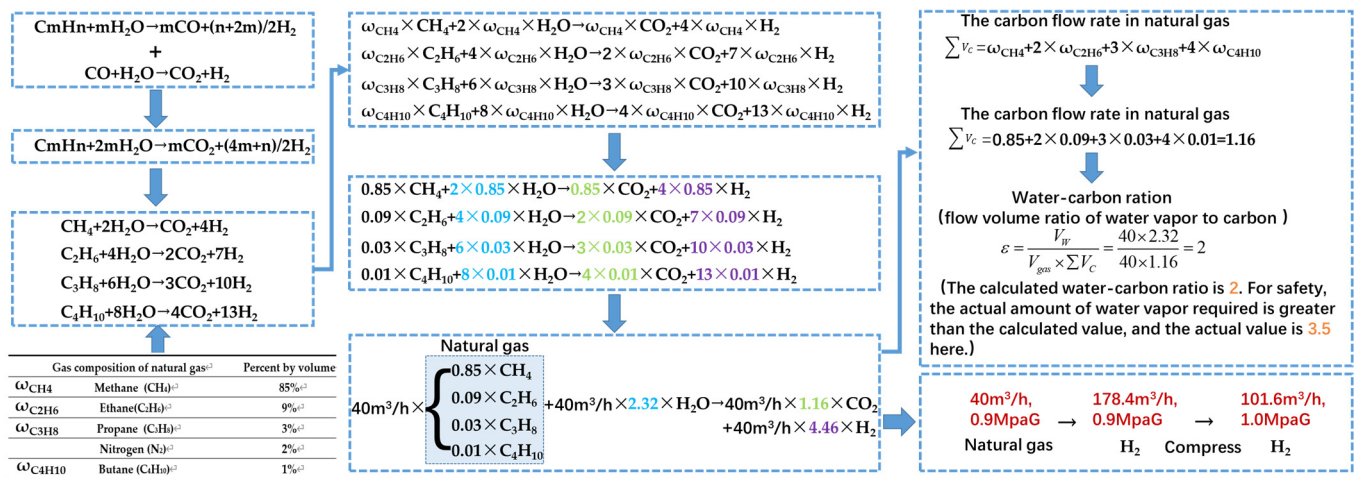


Figure 9. The calculation process of the hydrogen output and the carbon flow rate in natural gas. (Note: ω_{CH_4} represents the percentage of methane (CH_4) by volume in natural gas; here, the value of ω_{CH_4} is 85%. Other gases are similar. The $40 \text{ m}^3/\text{h}$ of natural gas that can output about $100 \text{ m}^3/\text{h}$ hydrogen is mainly determined by the performance of the MNGHPE; the actual output is larger than this value, but some hydrogen that cannot be extracted is stored in the off gas tank).

2.2.10. Calculation Method of Primary Energy Reduction Rate and Carbon Emission Reduction Rate

The formula for calculating the primary energy consumption of the multi-energy complementary distributed energy system is shown in Equation (17). The primary energy

consumption of the system includes natural gas, commercial electricity, and the additional heating and cooling load energy required by the LBARHM when the cooling or hot water is insufficient for the building.

$$Q_1 = A_1 \times 3.6/\eta_1 + A_2 \times 3.6/\eta_2 + (B_1 - B_2) \times (h_1 - h_2) \times C_1 \times 3.6/D_1 \times 3600 \times \eta_2 \quad (17)$$

Q_1 —Primary energy consumption of multi-energy complementary distributed energy system (MJ/h);

A_1 —Electricity generation by gas engine (kWh/h);

η_1 —Electricity generation efficiency of gas engine;

A_2 —Commercial electricity supply (kWh/h);

η_2 —Commercial electricity generation efficiency;

B_1 —The amount of smoke required for cooling or heating load in the building (kg/h);

B_2 —Total smoke output of gas engine (kg/h);

h_1 —Enthalpy of flue gas at the inlet of lithium bromide absorption cooling and heating machine (kJ/kg);

h_2 —Enthalpy of flue gas at the outlet of lithium bromide absorption cooling and heating machine (kJ/kg);

C_1 —Cold or heat coefficient of lithium bromide absorption cooling and heating machine;

D_1 —Annual performance factor of air conditioning; 4.5 was taken in this study.

The calculation formula for primary energy consumption in the traditional energy supply mode is depicted in Equation (18). In this mode, commercial electricity meets the general electricity demand of the building, and it powers the air conditioning system to fulfill the building's cooling and heating load.

$$Q_2 = E_1 \times 3.6/\eta_2 + F_1 \times 3.6/\eta_2 + G_1 \times 3.6/\eta_2 \quad (18)$$

Q_2 —Primary energy consumption by conventional energy supply (MJ/h);

E_1 —General electricity demand of building (kWh/h);

F_1 —Electricity demand for cooling (kWh/h);

G_1 —Electricity demand for heating (kWh/h);

η_2 —Commercial electricity generation efficiency, it was set to 36.8% in this study [54].

The calculation formula for the carbon emission of the MECDES is shown in Equation (19). Carbon emission factors for commercial electricity are derived from the data pertaining to Zhejiang Province, China.

$$Y_1 = K_1 \times V_1 + K_2 \times A_2 + (B_1 - B_2) \times (h_1 - h_2) \times C_1 \times K_2/D_1 \times 3600 \quad (19)$$

Y_1 —Carbon emissions of multi-energy complementary distributed energy systems (t/h);

K_1 —Carbon emission factors of natural gas (t/Nm³);

V_1 —Usage amount of natural gas for electricity generation using gas engine (Nm³/h);

K_2 —Commercial electricity carbon emission factors (t/kWh);

A_2 —Commercial electricity supply (kWh/h);

B_1 —The amount of smoke required for cooling or heating load in the building (kg/h);

B_2 —Total smoke output of gas engine (kg/h);

h_1 —Enthalpy of flue gas at the inlet of lithium bromide absorption cooling and heating machine (kJ/kg);

h_2 —Enthalpy of flue gas at the outlet of lithium bromide absorption cooling and heating machine (kJ/kg);

C_1 —Cold or heat coefficient of lithium bromide absorption cooling and heating machine;

D_1 —Annual performance factor of air conditioning; 4.5 was taken in this study.

The calculation formula for the carbon emission of the traditional energy supply mode is shown in Equation (20):

$$Y_2 = K_2 \times (E_1 + F_1 + G_1) \quad (20)$$

Y_2 —Carbon emissions by conventional energy supply (t/h);

K_2 —Commercial electricity carbon emission factors (t/kWh);

E_1 —General electricity demand (kWh/h);

F_1 —Electricity demand for cooling (kWh/h);

G_1 —Electricity demand for heating (kWh/h).

The calculation formula of primary energy reduction rate is shown in Equation (21):

$$\lambda = \frac{Q_2 - Q_1}{Q_2} \quad (21)$$

λ —Primary energy reduction rate;

Q_1 —Primary energy consumption of multi-energy complementary distributed energy system (MJ/h);

Q_2 —Primary energy consumption by conventional energy supply (MJ/h).

The calculation formula of carbon emission reduction rate is shown in Equation (22):

$$\gamma = \frac{Y_2 - Y_1}{Y_2} \quad (22)$$

γ —Carbon emission reduction rate;

Y_1 —Carbon emission of multi-energy complementary distributed energy system (t/h);

Y_2 —Carbon emission of conventional energy supply (t/h).

2.2.11. Calculation Method of Hydrogen Production in Different Types of Buildings

The formula for calculating hydrogen production is shown in Equation (23):

$$M_H = \frac{100 \times M_W}{130.5} \quad (23)$$

where M_H (Nm³/h) is the actual hydrogen production; M_W (kg/h) is the water vapor produced by the waste heat recovery boiler.

The water vapor production calculation formula for the hydrogen production reaction is calculated using the following formula:

$$M_W = \frac{\Delta Q}{h_1 - h_2} = \frac{C \times M_b \times (t_1 - t_0) \times \alpha}{h_1 - h_2} \quad (24)$$

M_W —Mass flow of water vapor produced by waste heat recovery boiler (kg/h);

ΔQ —Waste heat boiler that can recover the waste heat of flue smoke gas (kJ/h);

h_1 —Enthalpy of water vapor for hydrogen reaction (kJ/kg);

h_2 —Industrial water enthalpy at room temperature (kJ/kg); room temperature is set as 20 °C.

C —Mass specific heat capacity of flue gas (kJ/(kg·°C)); 1.15 kJ/(kg·°C) was taken in this study;

M_b —Mass flow rate of flue smoke gas in waste heat boiler (kg/h);

t_1 —Average temperature of flue smoke gas in inlet of waste heat boiler (°C);

t_0 —Average flue smoke gas temperature at the outlet of waste heat boiler (°C); 150 °C was taken in this study;

α —Coefficient of flue gas heat loss; generally, 0.9 was taken.

The flue smoke intake of waste heat boiler M_b (kg/h) is calculated using the following formula:

$$M_b = \begin{cases} 0 & M_T - M_{AC/H} < 0 \\ M_T - M_{AC/H} & M_T - M_{AC/H} \geq 0 \end{cases} \quad (25)$$

where M_T (kg/h) is the total smoke output of the GE, $M_{AC/H}$ (kg/h) is the amount of waste smoke required for cooling or heating in the LBARHM. The flue smoke is preferentially supplied to the LBARHM to produce hot or cold water, the remaining smoke

re-enters into the waste heat recovery boiler to produce high-temperature water vapor for hydrogen production.

$$M_T = 21572 \times \varphi + 1926 \quad (26)$$

where M_T (kg/h) is the total smoke output of the GE, φ is the load rate of the gas engine.

$$M_{AC/H} = \frac{Q_{AC/H} \times 4.5 \times 3600}{COP_{AC/H} \times (h_{S1} - h_{S2})} \quad (27)$$

where $M_{AC/H}$ (kg/h) is the amount of smoke required for cooling or heating through the LBARHM, h_{S1} (kJ/kg) is the enthalpy of the flue smoke entering the LBARHM, h_{S2} (kJ/kg) is the enthalpy of the flue smoke leaving the LBARHM, $COP_{AC/H}$ is the coefficient of performance (COP) of the LBARHM. In this study, the cooling coefficient COP_{AC} is 1.05, the heating coefficient COP_H is 1.75. $Q_{AC/H}$ (kWh/h) is the hourly cooling or heating load of different types of buildings. The hourly cooling or heating load of different types of buildings can be obtained by investigation. Its value is the product of the daily cooling or heating load value and the hourly load proportion.

$$h_S = 11.157 \times t - 306.2 \quad (28)$$

where h_S (kJ/kg) is the enthalpy of the flue smoke, t (°C) is the temperature of the flue smoke.

The cooling and heating load of the building is provided by the LBARHM when driven by smoke and electric multi-line air conditioning. The corresponding calculation is depicted in Formula (29):

$$Q_E = Q_L - Q_{AC/H} \quad (29)$$

where Q_L (kW) is the heating and cooling load of the building, $Q_{AC/H}$ (kW) is the heat and cold provided by smoke through the LBARHM, Q_E (kW) is the heat and cold provided by electric multi-line air conditioning.

The profit rate of hydrogen production is calculated as follows:

$$\psi = \frac{\kappa_1 - \kappa_2}{\kappa_1} \quad (30)$$

where ψ is the profit rate of hydrogen production, κ_1 (\$) is the total cost of hydrogen production, κ_2 (\$) is the total selling price of hydrogen production.

$$\kappa_1 = \kappa_{m1} + \kappa_{n1} + \kappa_{w1} + \kappa_{e1} + \kappa_{l1} \quad (31)$$

where κ_1 (\$) is the total cost of hydrogen production, κ_{m1} (\$) is the cost of raw gas for hydrogen production, κ_{n1} (\$) is the cost of heating gas for hydrogen production, κ_{w1} (\$) is the water cost for hydrogen production, κ_{e1} (\$) is the cost of commercial electricity for hydrogen production, κ_{l1} (\$) is the labor cost for hydrogen production.

In this study, the economic benefits of hydrogen production are reflected by the profit rate ψ of hydrogen production. When the profit rate ψ of hydrogen production is greater than 0, it means that hydrogen production has economic benefits; otherwise, hydrogen production has no economic benefits. As shown in Formulas (30) and (31), the key factors affecting the profit rate of hydrogen production include the capacity of hydrogen production, the selling price of hydrogen, the cost of hydrogen production, and other factors. The factors that affect the capacity of hydrogen production include the solar panel area of the integrated system, the horizontal radiation, the number of small wind turbines, the local wind speed, and the cooling and heating coefficients $COP_{AC/H}$ of the LBARHM in the integrated system. The selling price of hydrogen is related to local policy and the level of economic development. The cost of hydrogen production κ_1 mainly consists of the cost of raw gas κ_{m1} for hydrogen production, the cost of heating gas κ_{n1} , the cost of water

κ_{w1} , the cost of commercial electricity κ_{e1} , and the cost of labor κ_{l1} . The higher the cost of the corresponding components, the lower the profit rate ψ of hydrogen production.

3. Case Study Information

3.1. Representative Urban Climate Data of Zhejiang Province, China

This study selected buildings in Zhejiang Province, China, as the research object. Figure 10 depicts the geographical location of Zhejiang Province and its cities. Zhejiang Province is situated in the southeast of China, bordering the East China Sea to the east and Shanghai to the north. It spans $27^{\circ}02'$ – $31^{\circ}11'$ north latitude and $118^{\circ}01'$ – $123^{\circ}10'$ east longitude. Four representative cities in Zhejiang Province were selected. Hangzhou, Ningbo, Zhoushan, and Lishui were chosen for this study. Due to variations in solar radiation and wind speed in the four cities, which significantly impact renewable electricity generation, four different cities with distinct levels of renewable electricity generation were selected as research objects.

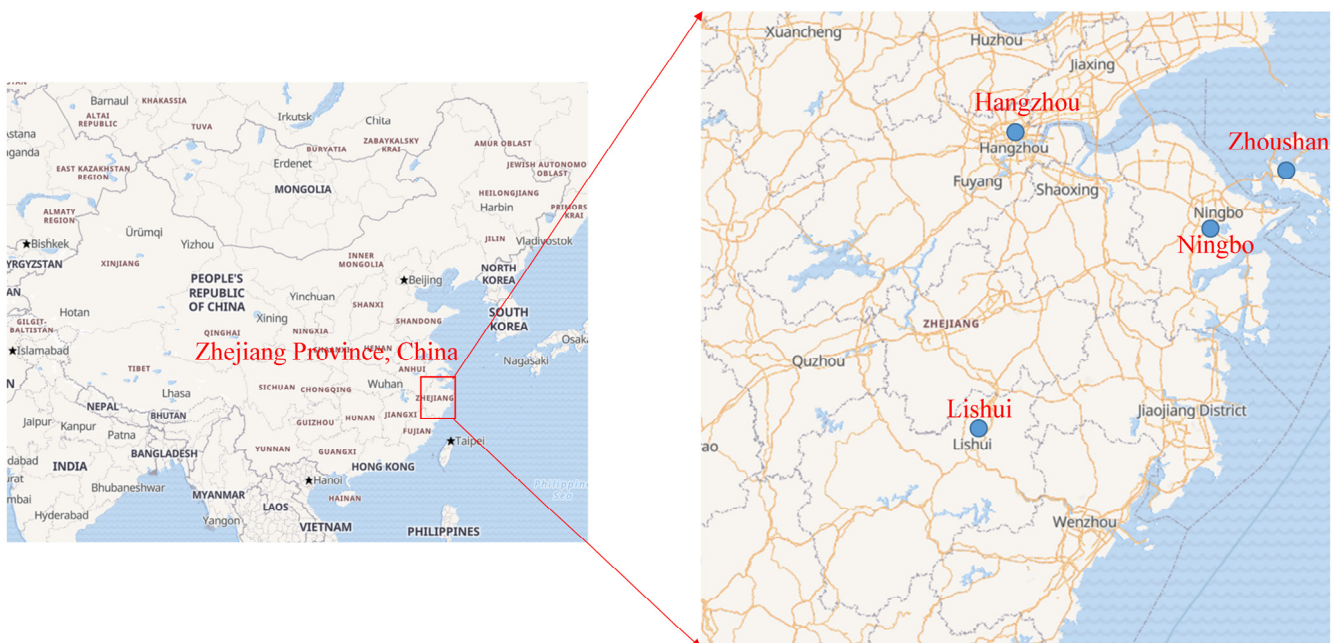


Figure 10. Geographical location of Zhejiang Province and its cities in China.

The average horizontal radiation and wind speeds of four representative cities in Zhejiang Province over the past three years (2020–2022) are illustrated in Figure 11. Zhoushan City has the highest horizontal radiation, followed by Ningbo, Hangzhou, and Lishui. Monthly comparisons between various cities reveal that horizontal radiation peaks in August, when Zhoushan City reached a maximum of 739.5 W/m^2 , while January has the lowest radiation in the four cities. In terms of wind speed, Zhoushan City, as an island in Zhejiang Province, consistently has significantly higher wind speeds than the other three cities, reaching a maximum of 7.5 m/s in December. Ningbo City has the second-highest wind speed, while Lishui City experienced the lowest at 1.27 m/s in June. Consequently, Zhoushan City has the most favorable renewable resources among the four cities.



Figure 11. Urban meteorological data of Zhejiang Province's cities from 2020 to 2022 year [69].

3.2. Investigation of Energy Consumption of Buildings

3.2.1. Energy Consumption of Buildings in Zhejiang Province

To simulate the energy-saving and carbon reduction effects of the integrated system in different types of buildings, energy consumption data of buildings in Zhejiang Province were obtained. Figure 12 depicts the average annual electricity consumption of 43 office buildings, 51 educational buildings, nine shopping buildings, eight hotel buildings, six hospital buildings, four cultural buildings, and one sports building, totaling 122 public buildings in Hangzhou over the past three years (2020–2022). The building data were derived from actual surveys conducted in January 2023. The maximum annual average electricity consumption is $93.0 \text{ kWh}/(\text{m}^2 \times \text{a})$, while the minimum is $3.5 \text{ kWh}/(\text{m}^2 \times \text{a})$. Additionally, the maximum total floor area is $430,000 \text{ m}^2$ and the minimum total floor area is $10,775 \text{ m}^2$.

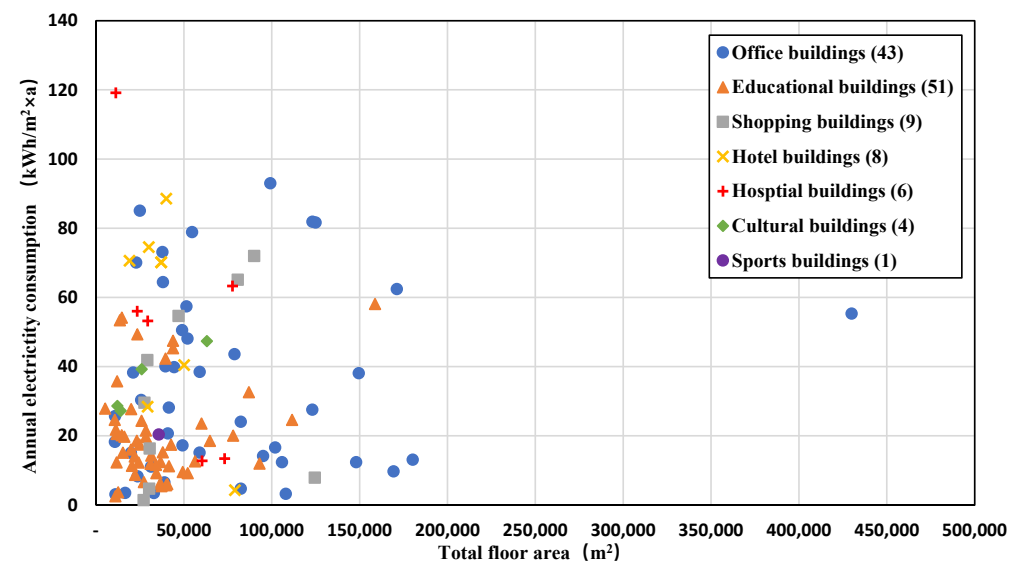


Figure 12. Average annual electricity consumption of buildings in Hangzhou City.

Next, three types of buildings—office buildings, hotel buildings, and hospital buildings—with different electricity consumption characteristics were selected for detailed analysis. The results are shown in the next section.

3.2.2. Monthly Energy Consumption of Different Type Buildings

The average monthly electricity consumption of office buildings, hotel buildings, and hospital buildings over the past three years (2020–2022) was obtained through a survey. The data included general electricity demand, electricity demand for cooling, and electricity demand for heating. Therefore, in this study, the average monthly minimum power load is identified as the general electricity demand. Electricity demand exceeding the minimum load from April to October is identified as demand for cooling, while demand exceeding the minimum from November to March is identified as demand for heating. Based on this method and the survey results, the monthly average electricity consumption of office buildings, hotel buildings, and hospital buildings is shown in Figures 13–15, respectively.

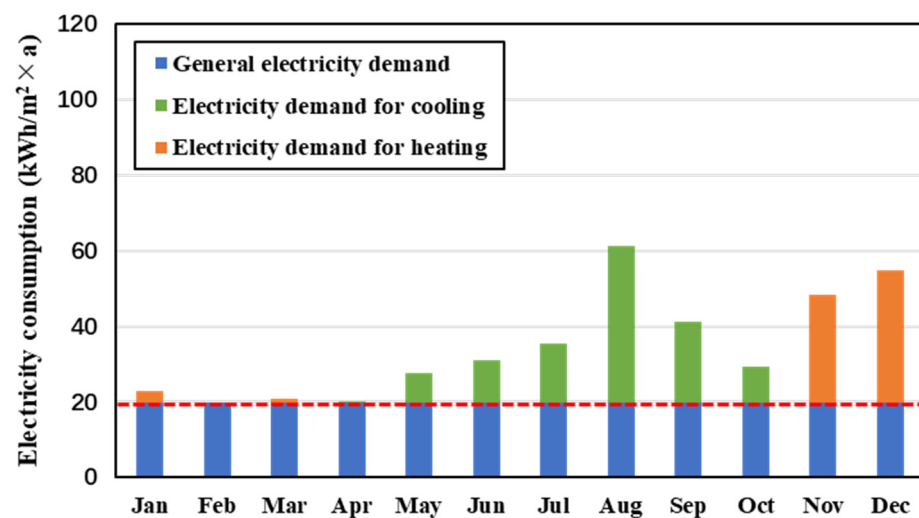


Figure 13. Monthly electricity consumption of office buildings. (Note: since the electricity data obtained from the survey represent the total electricity consumption, the data also include electricity consumption for air conditioning. Therefore, the monthly average minimum power load is here set as the general electricity demand, higher than the base load part, while April to October is set as electricity demand for cooling, and November to April is set as electricity demand for heating).

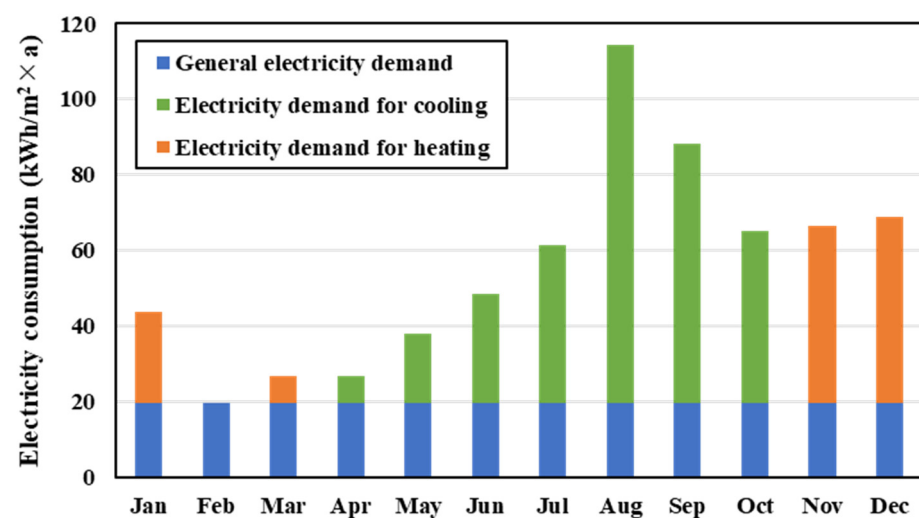


Figure 14. Monthly electricity consumption of hotel buildings.

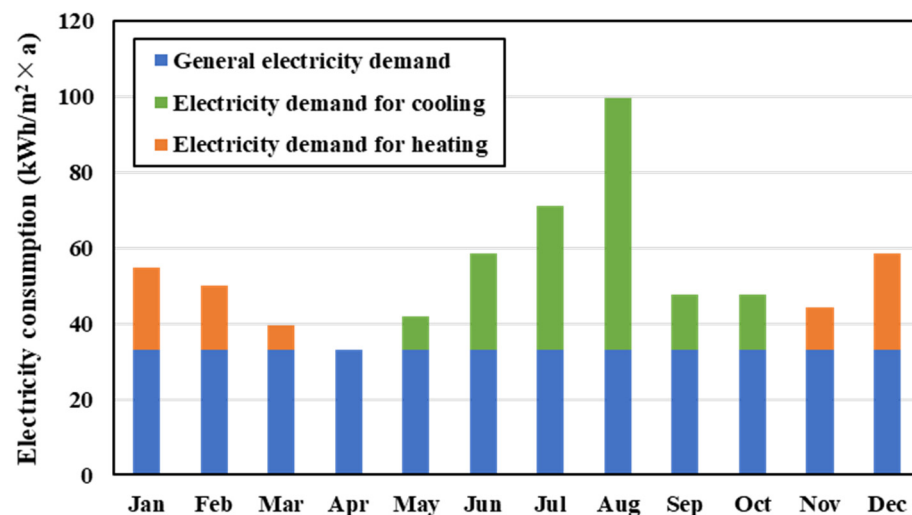


Figure 15. Monthly electricity consumption of hospital buildings.

Figure 13 illustrates the average monthly electricity consumption of 43 office buildings. The blue columns represent the general electricity load, the green columns denote the electricity required for cooling, and the orange columns signify the electricity needed for heating. The general electricity demand is $19.7 \text{ kWh}/(\text{m}^2 \times \text{a})$, with the maximum electricity demand reaching $41.7 \text{ kWh}/(\text{m}^2 \times \text{a})$ in August for cooling and $35.0 \text{ kWh}/(\text{m}^2 \times \text{a})$ in December for heating. The total monthly electricity demand is the sum of the general electricity demand and the electricity demand for cooling or heating. The maximum total electricity demand peaks at $61.4 \text{ kWh}/(\text{m}^2 \times \text{a})$ in August, while the minimum is $19.7 \text{ kWh}/(\text{m}^2 \times \text{a})$ in February. Accordingly, Figures 14 and 15 show the monthly electricity consumption of hotel buildings and hospital buildings, respectively.

3.2.3. The Setting of Electrical Load and Calculation Method

The monthly electricity consumption data for various types of buildings were obtained through an investigation. In this study, since the accurate electricity consumption data for cooling and heating loads cannot be accurately known, the lowest monthly electricity consumption in a year was considered as the general electricity consumption.

Any electricity consumption beyond the general level was identified as cooling or heating load. The specific method for setting electrical load and energy supply composition is illustrated in Figure 16. The hourly load was calculated by multiplying the hourly percentage by daily electricity demand. The hourly percentages for each building type are summarized in Table 5; these data are specific to the survey results and not universal. General electricity demand is met by natural gas electricity, solar power electricity, wind power electricity, and commercial electricity. Electricity demand for air conditioning includes cooling of the lithium bromide absorption unit and cooling of the electric multi-line air conditioning, and the same applies to electricity demand for heating.

Figure 17 presents the flowchart of the integrated system model. In the modeling and calculation process, monthly and hourly loads for each building type were calculated based on survey results and hourly load percentages summarized from the survey. With a total E_{TGE} capacity of 4000 kW, the total floor area for various buildings was set at $3,000,000 \text{ m}^2$ for calculation and comparison to ensure the GE's power output over a 50% load rate. The general electricity demand E_L consists of GE electricity generation P_{GE} , solar power generation E_P , and wind power generation E_W . The GE operates at a load rate exceeding 50%, for stable and safe operation. Solar power generation depends on solar radiation and panel area, while wind power generation is influenced by wind speed and the number of turbines. To analyze the influence of solar panel area and the number of wind turbines on hydrogen production, seven cases were set up for both solar panel area and wind turbine numbers in buildings totaling $3,000,000 \text{ m}^2$ floor area, based on

construction experience. Because the building's general electricity demand is determined, the GE's electricity generation can also be determined when calculating solar and wind power generation. When the GE runs at 100% full load, it has a maximum power output of 4000 kW. If the combined power output of GE, solar, and wind power are insufficient for the building's electricity demand, commercial electricity E_C will be used to supplement it. When the total electricity generated exceeds the building's electricity demand E_L , surplus electricity is used for the hydrogen production equipment. The surplus electricity can be stored in the battery with a charge and discharge efficiency η_B of 0.95. The flue smoke production M_T of the GE is determined by two factors: power generation P_{GE} and the total capacity E_{TGE} of the GE. The smoke produced by the GE is preferentially applied to the cooling and heating load requirements of the building through the LBARHM. If there is excess flue smoke, then the smoke M_b will be used in the waste heat boiler for producing water vapor for the hydrogen production reaction. The flue smoke required by the building's cooling and heating load $M_{AC/H}$ is determined by the cooling and heating load $Q_{AC/H}$, the cooling and heating coefficients $COP_{AC/H}$ of the LBARHM, the inflow H_{in} , and outflow enthalpy H_{out} of the flue smoke. When the cold and hot water generated by the flue smoke is insufficient to meet the building's cooling and heating load demand, it is supplemented by the electric multi-line. The amount of water vapor M_W produced by the waste heat boiler is determined by the amount of smoke M_b entering it, the temperature of the flue smoke inlet and outlet, and the enthalpy value of the water vapor. The amount of hydrogen produced M_H is determined by the amount of water vapor M_W produced. There is a linear relationship between the amount of water vapor in the hydrogenation reaction and the amount of hydrogen production. When the amount of hydrogen produced M_H is known, the amount of natural gas V_{gas} as fuel required for the corresponding amount of hydrogen production can be calculated using the ratio of water to carbon ε for hydrogen production. When the cooling and heating load $Q_{AC/H}$ provided by the flue smoke is insufficient, the cooling and heating load Q_E provided by the electric multi-line air conditioning system equals the total cooling and heating load Q_L of the building minus the cooling and heating load $Q_{AC/H}$ provided by the flue smoke.

Table 5. Percentage of electricity consumption in each time period.

Time	Office Buildings (%)			Hotel Buildings (%)			Hospital Buildings (%)		
	General Electricity Demand	Demand for Cooling	Demand for Heating	General Electricity Demand	Demand for Cooling	Demand for Heating	General Electricity Demand	Demand for Cooling	Demand for Heating
0:00	1.85	0.00	0.00	2.72	2.34	3.05	2.09	1.60	0.20
1:00	1.62	0.00	0.00	2.58	1.80	3.43	2.01	1.60	0.30
2:00	1.62	0.00	0.00	2.35	1.71	3.81	1.95	1.50	0.30
3:00	1.62	0.00	0.00	2.35	1.53	3.43	1.93	1.50	0.30
4:00	1.62	0.00	0.00	2.32	1.44	3.05	1.92	1.50	0.30
5:00	1.62	0.00	0.00	2.44	1.35	3.05	2.08	3.40	5.10
6:00	1.62	0.00	0.00	3.12	1.80	3.24	3.04	2.60	4.70
7:00	1.56	1.28	0.30	3.64	1.98	4.19	4.31	2.80	4.70
8:00	5.50	9.43	16.99	3.97	2.71	5.71	5.48	6.40	10.30
9:00	6.14	9.15	12.29	4.59	3.52	4.95	6.06	6.30	8.30
10:00	6.67	9.00	8.09	5.00	3.61	5.14	6.18	6.60	7.50
11:00	6.90	9.22	10.29	5.30	3.61	4.95	6.17	6.80	6.90

Table 5. Cont.

Time	Office Buildings (%)			Hotel Buildings (%)			Hospital Buildings (%)		
	General Electricity Demand	Demand for Cooling	Demand for Heating	General Electricity Demand	Demand for Cooling	Demand for Heating	General Electricity Demand	Demand for Cooling	Demand for Heating
12:00	6.90	9.00	10.49	5.37	7.13	4.95	5.98	6.90	6.40
13:00	6.90	9.22	10.29	5.39	7.22	5.14	6.01	6.10	5.20
14:00	6.90	9.30	8.39	5.33	8.68	4.95	6.11	6.10	5.00
15:00	6.90	10.23	8.19	5.38	6.49	6.10	6.01	6.30	4.80
16:00	6.90	9.00	9.09	5.48	6.58	7.24	5.80	6.30	4.90
17:00	6.90	9.22	5.59	5.62	6.67	6.86	5.30	6.20	5.00
18:00	6.84	5.37	0.00	5.46	6.94	6.10	4.98	5.80	5.00
19:00	3.37	0.29	0.00	5.25	7.03	5.33	4.70	3.20	3.50
20:00	3.13	0.29	0.00	4.81	6.85	1.52	4.09	3.10	3.50
21:00	2.65	0.00	0.00	4.31	4.51	1.14	3.03	3.00	3.60
22:00	2.26	0.00	0.00	4.23	2.34	0.00	2.50	2.80	4.00
23:00	2.02	0.00	0.00	3.00	2.16	2.67	2.25	1.60	0.20
Total	100	100	100	100	100	100	100	100	100

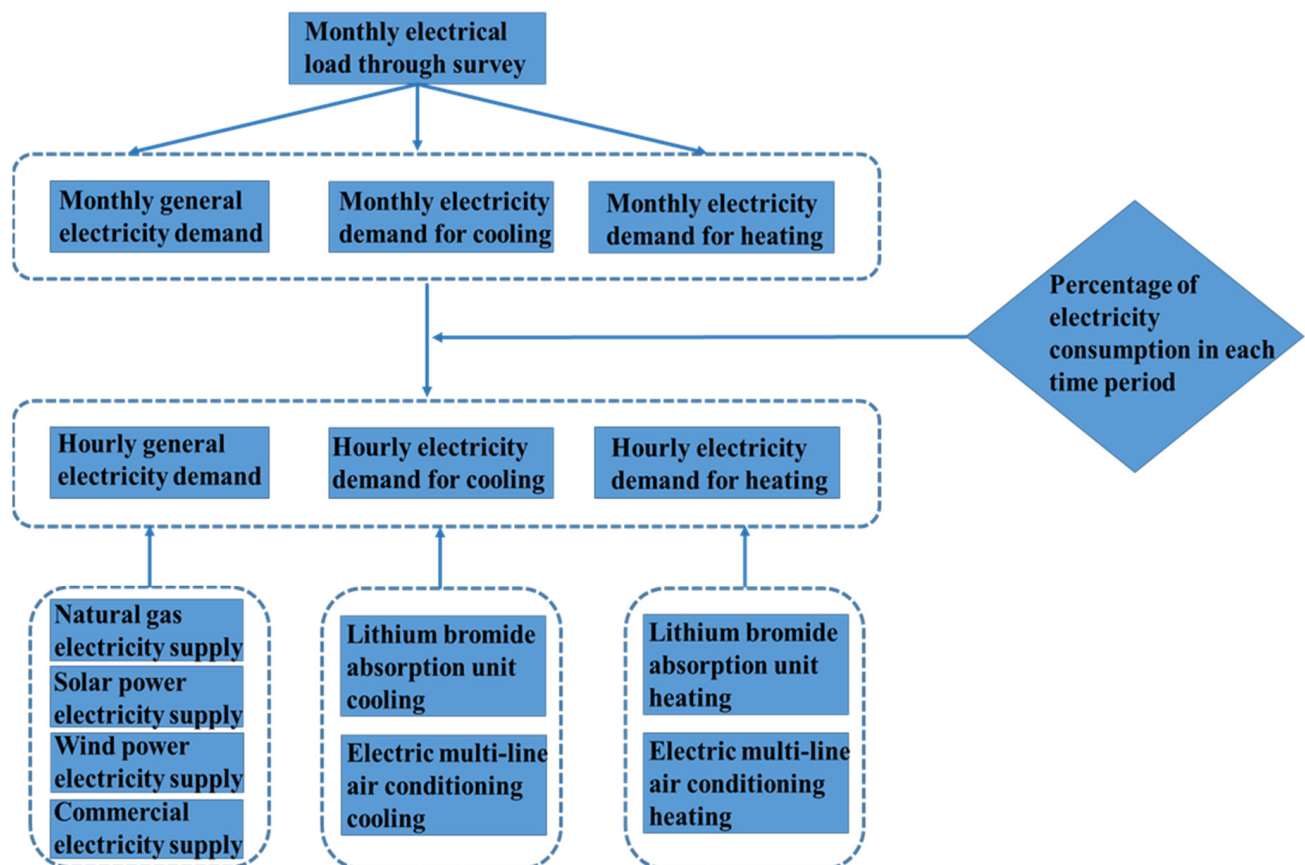


Figure 16. The setting of electrical load and energy supply composition.

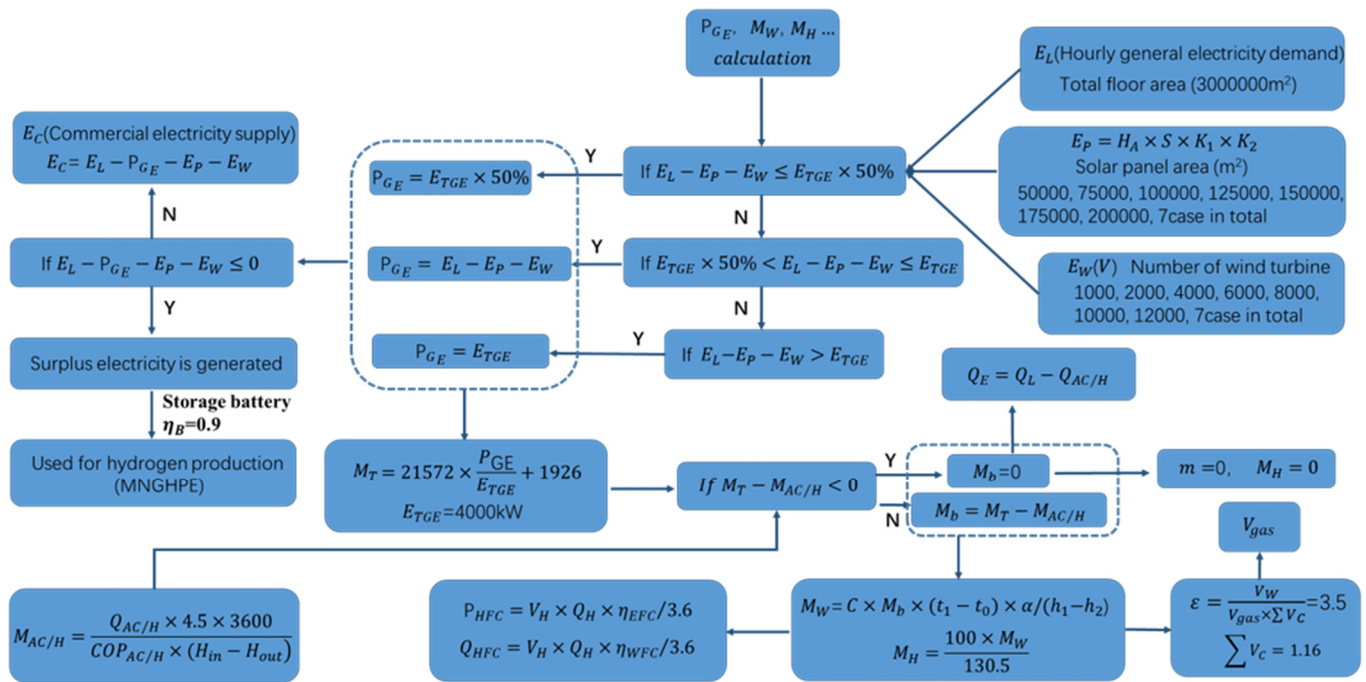


Figure 17. The calculation flow chart of the integrated system. (Note: “ E_L ” stands for hourly general electricity demand of buildings, “ E_P ” stands for solar panel power generation, “ E_W ” stands for wind turbine power generation, “ E_{TGE} ” stands for the total generating capacity of the gas engine, “ P_{GE} ” stands for the power generation of the gas engine, “ M_T ” stands for the total smoke output of the gas engine, “ $M_{AC/H}$ ” stands for the amount of smoke required for cooling and heating in the LBARHM, “ M_W ” stands for the mass flow of water vapor produced by the waste heat boiler, “ M_H ” stands for the hydrogen production capacity, “ ϵ ” stands for the ratio of water–carbon).

3.3. Electricity Supply Composition in Different Types of Buildings

The electrical load of office buildings is supplied by commercial electricity, GE-generated electricity, solar, and wind power. To ensure safe operation, the GE’s hourly load rate is set at 50% or above. The simulation employed a 4000 kW GE widely used in Chinese office parks, ensuring a minimum hourly supply of 2000 kW. To maintain this supply, the office buildings’ total floor area was set as 3,000,000 m². In terms of electricity supply, the GE’s generated electricity is preferential, followed by solar and wind-generated electricity. If the supply is insufficient, commercial electricity will be used as a supplement. Any surplus electricity from solar and wind power is allocated to the MNGHPE’s electricity supply, and any excess is stored in batteries to power the MNGHPE for the next hour. In the 3,000,000 m² office buildings, seven solar panel configurations were set up, including 50,000 m², 75,000 m², 100,000 m², 125,000 m², 150,000 m², 175,000 m², and 200,000 m². Additionally, seven cases of wind electricity generators were set up, including 1000, 2000, 4000, 6000, 8000, 10,000, and 12,000 turbines. This study compares the influence of different urban climates on integrated systems pertaining to the same type of building by using buildings’ energy consumption data from Hangzhou City for the four cities.

Figure 18 depicts a simulation of average daily electricity supply in Zhoushan City in October. In this case, the solar panel area is 100,000 m² with 10,000 wind turbines. The dashed black line illustrates hourly electrical loads for the three building types, while bar charts display various electricity supply forms. Solar electricity generation depends on panel area and hourly radiation; wind electricity generation relies on turbine count and hourly wind speed. As shown in Figure 18a, office buildings experience a high electrical load from 8:00 to 18:00, aligning with solar electricity generation (6:00 to 18:00), while wind electricity is constant (24 h). Therefore, except from 14:00 to 18:00, surplus renewable energy is generated continuously. Due to low office building load and high wind speed in

Zhoushan at night in October, there is a substantial surplus of wind-generated electricity surplus. As illustrated in Figure 18b, the electrical load of the hotel buildings is primarily concentrated from 8:00 to 23:00, and surplus electricity is generated between 0:00 and 15:00. As shown in Figure 18c, the electrical load of hospital buildings is significantly higher than that of office buildings and hotel buildings, and almost no surplus electricity is generated except from 3:00 to 5:00.

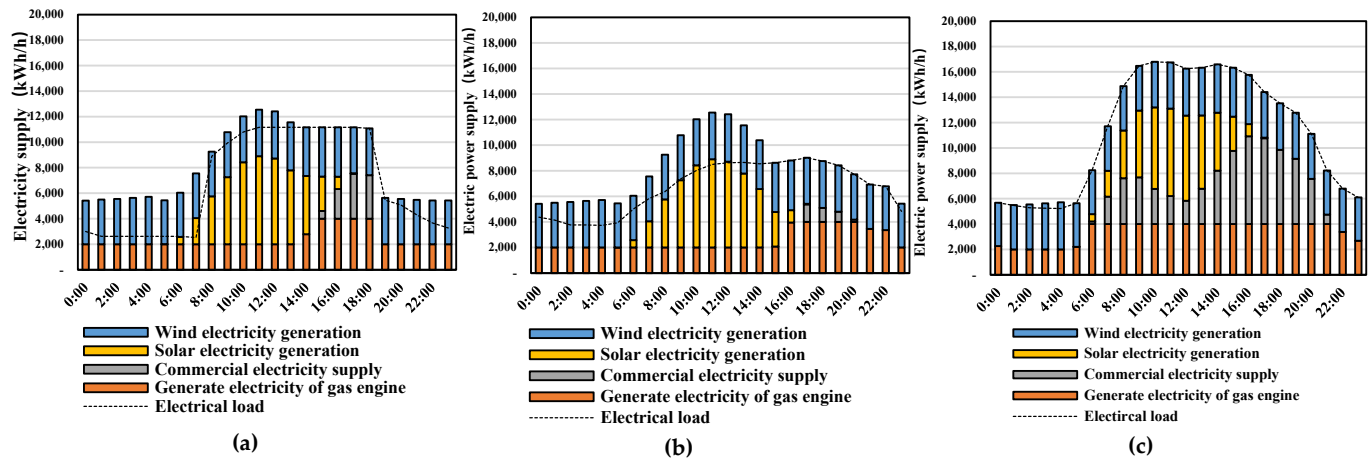


Figure 18. Average daily electricity supply in three types of buildings in October in Zhoushan City. (a) Office buildings; (b) hotel buildings; (c) hospital buildings. (Note: in the simulation, when renewable energy is available, solar power is preferentially used, followed by wind power, and the remaining power is not enough to be supplemented by the grid).

4. Results

4.1. Waste Heat Utilization and Hydrogen Production

4.1.1. Waste Heat Utilization and Hydrogen Production in a Typical Day

When the office building has a demand for heating or cooling load, the smoke generated by the GE is sent into the LBARHM to produce hot or cold water. When the cooling and heating load of the building is small and there is still residual smoke, the remaining high-temperature smoke ($368\sim 469\text{ }^{\circ}\text{C}$) passes into the waste heat boiler to produce high-temperature water vapor for hydrogen production. Figure 19 shows the residual smoke and hydrogen production on a typical day in Zhoushan City in October. As shown in Figure 19a, during the periods of 0:00~6:00 and 20:00~23:00, the office building has no heating or cooling load. Consequently, all the smoke produced by the GE is utilized to generate water vapor. The maximum hourly residual smoke of the GE is $12,712\text{ kg/h}$, and the peak value of hydrogen production reaches $1045.3\text{ Nm}^3/\text{h}$. From 8:00 to 16:00, the cooling load of the office building exceeds the smoke generated by the GE, resulting in no residual smoke for hydrogen production. The hydrogen produced during this time is $0\text{ Nm}^3/\text{h}$. To supplement the insufficient energy to meet the cooling load, electrical air conditioning equipment powered by commercial electricity is utilized. As shown in Figure 19b, since the heating and cooling load of hotel buildings is much higher than office buildings, during the peak period of demand from 8:00 to 23:00, all flue smoke is used to produce cold or hot water for air conditioning. There is no excess flue smoke for water vapor production during this period, resulting in the hotel building's hydrogen production being $0\text{ Nm}^3/\text{h}$. The electric multi-line air conditioning equipment supplies most of the hotel's heating and cooling load. As shown in Figure 19c, hotel buildings have a relatively stable heating and cooling load over 24 h, particularly from 8:00 to 18:00. Compared with office and hospital buildings, less smoke can be utilized for hydrogen production, resulting in the least amount of hydrogen generated among these three building types.

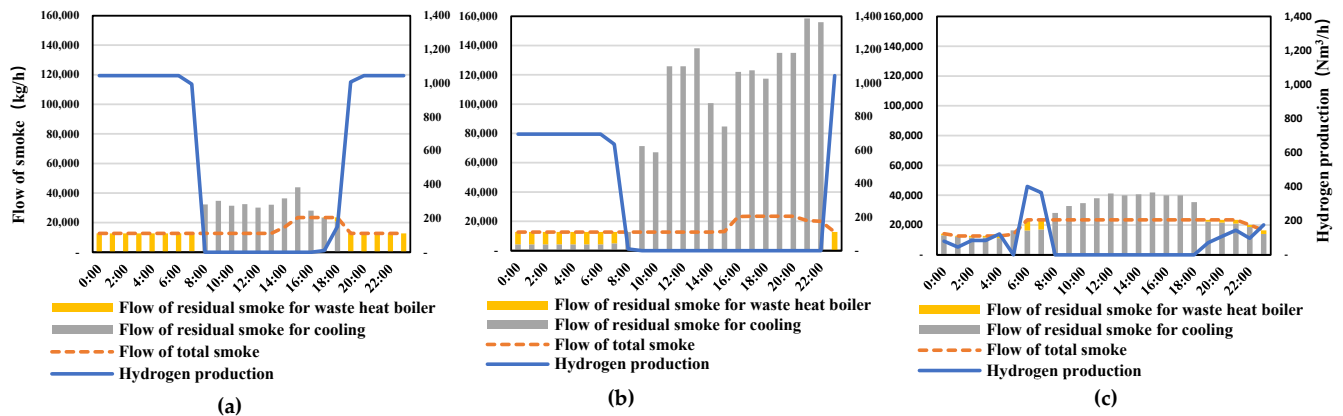


Figure 19. Hydrogen production of three types of buildings on a representative day in Zhoushan City in October. (a) Office buildings; (b) hotel buildings; (c) hospital buildings.

4.1.2. Monthly Hydrogen Production in the City

Figure 20 illustrates the monthly hydrogen production comparison for the same type of building (office) in different cities. The simulation results show that Lishui City has the highest monthly hydrogen production, while Zhoushan City records the lowest. This discrepancy is attributed to Zhoushan City's substantial solar and wind electricity generation. This leads to the largest renewable energy electricity generation for office buildings among the four cities. Consequently, the electricity provided by the GE for supplying the office building decreases, leading to a corresponding reduction in the GE's electricity and smoke generation. In monthly comparisons, the lowest hydrogen production occurs in August due to the highest demand for cooling load. Conversely, March has the highest hydrogen production because the demand for cooling or heating load is minimal, and renewable energy electricity generation is also limited. The peak of hydrogen production is in Lishui City in March, reaching 885,018.3 Nm³, while the lowest is in Zhoushan City in August, amounting to 370,076.8 Nm³. Additionally, it is noteworthy that hydrogen production decreases with the increase of the buildings' heating and cooling loads.

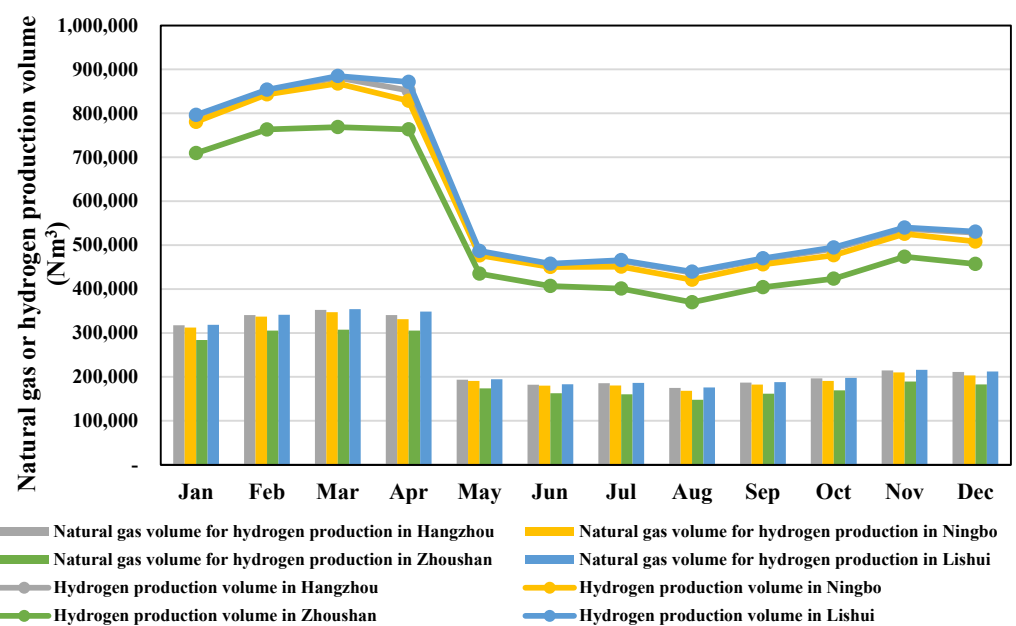


Figure 20. Comparison of monthly hydrogen production of office buildings in different cities, solar panel area 100,000 m², wind turbines 10,000.

4.2. The Ratio of Solar and Wind Surplus Electricity Supply for Hydrogen Production

4.2.1. Surplus Electricity Supply Ratio for Hydrogen Production with Different Solar Panel Areas

For office buildings with a total floor area of 3,000,000 m², seven cases of different solar panel areas were considered based on previous studies [70] and construction experience, ranging from 50,000–200,000 m². There were 10,000 wind turbines. Figure 21 illustrates the ratio of surplus solar and wind electricity for hydrogen production. This ratio is the ratio of the surplus electricity to the electricity required by the MNGHPE. The hydrogen production volume is determined by the water vapor generated by the GE's exhaust smoke. Furthermore, it must be noted that the amount of high-temperature water vapor for producing hydrogen is determined by the electricity generated by the GE. The simulation results indicate that Zhoushan City has the highest ratio of hydrogen production electricity supply, followed by Ningbo City, Hangzhou City, and Lishui City. In Zhoushan City, with high wind speed and solar radiation intensity, the 3,000,000 m² office buildings require only 50,000 m² solar panels and 10,000 wind turbines that can supply all electricity needs for hydrogen production. Ningbo City requires a minimum of 175,000 m² of solar panel, while Hangzhou City and Lishui City need 200,000 m² of solar panels for the electricity supply for hydrogen production.

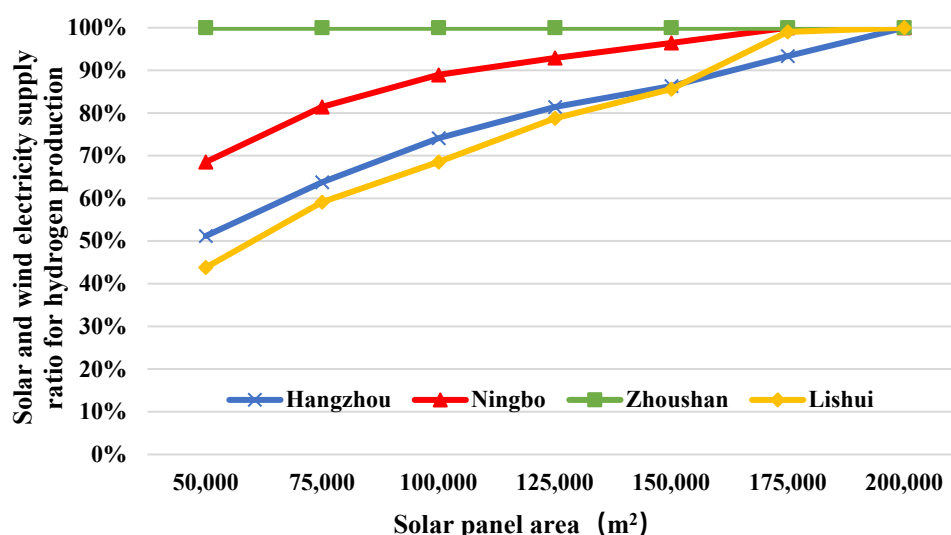


Figure 21. The ratio under different solar panel areas in office buildings with 10,000 wind turbines.

4.2.2. Ratio of Surplus Electricity Supply for Hydrogen Production with Different Numbers of Wind Turbines

If the solar panel area is 100,000 m², the ratio of solar and wind electricity supply for hydrogen production varies with the number of wind turbines, as shown in Figure 22. The increase in the number of wind turbines increased the surplus electricity supply ratio in Zhoushan City and Ningbo City, while Hangzhou City and Lishui City were less affected. This indicates that Zhoushan City and Ningbo City have substantial potential for wind electricity generation. In Zhoushan City, installing 100,000 m² of solar panels and 4000 wind turbines can supply all the electricity needed for hydrogen production. In Ningbo City, setting up 12,000 wind turbines can supply 90% of the required electricity for hydrogen production. However, in Lishui City, the ratio of electricity supply remains nearly unchanged with an increasing number of wind turbines. Even with 12,000 wind turbines, the surplus solar and wind electricity provides less than 70% of the required electricity for hydrogen production.

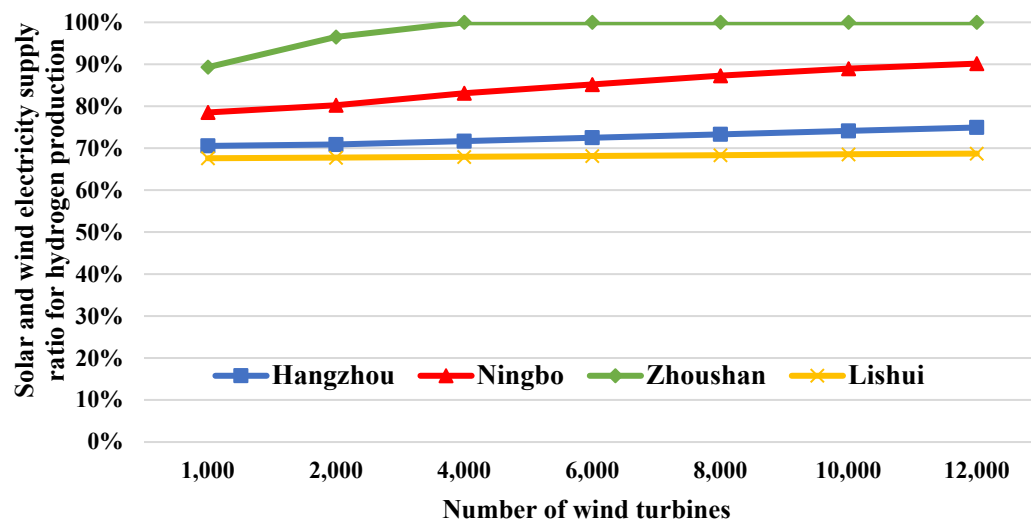


Figure 22. The ratio under different numbers of wind turbines in office buildings with 100,000 m² solar panel area. (Note: the figure shows the proportion of surplus renewable energy electricity used for hydrogen production in a building with a total area of 3,000,000 m² and fixed solar panels of 100,000 m²).

4.3. Single-Parameter Sensitivity Analysis of Hydrogen Production

Single-parameter sensitivity analysis is a commonly used method, known as local sensitivity analysis or single-factor analysis. The main steps involve keeping other parameters unchanged as the reference value, altering only one parameter at a time, and assessing sensitivity by comparing the degree of change in the polarization curve.

In modeling hydrogen production using waste heat and surplus electricity, factors such as solar panel area, wind turbine count, horizontal radiation, wind speed, and refrigeration and heating coefficients of the LBARHM significantly influence the amount of hydrogen produced. The investigation parameters and empirical parameters used for modeling exhibit a certain degree of variability. Therefore, six representative parameters were selected for sensitivity analysis; the initial values of each parameter are shown in Table 6. The six factors are solar panel area, number of wind turbines, annual average wind speed, annual average horizontal radiation, refrigeration coefficient of LBARHM COP_{AC} , heating coefficient of LBARHM COP_H .

Table 6. Parameters and initial values.

Parameters	Initial Value
Solar panel area/(m ²)	100,000
Number of wind turbines	10,000
Annual average wind speed/(m/s)	6.18
Annual average horizontal radiation/(W/m ²)	167.95
Refrigeration coefficient of LBARHM COP_{AC}	1.05
Heating coefficient of LBARHM COP_H	1.75

The values of the influencing factors were increased or decreased by 10% for comparative analysis. Figure 23 illustrates the impact of single-parameter variation on hydrogen production. It is evident that the change of a single parameter, such as wind speed, cooling, or heating coefficient, will significantly affect the hydrogen production amount. The cooling and heating coefficients influence the final hydrogen production in the corresponding months. Formula (8) further indicates that the average hourly wind speed throughout the year directly affects wind power generation. Because the building power supply consists of

GE power generation, solar power generation, and wind power generation, fluctuations in wind power affect GE power and smoke production, subsequently impacting hydrogen production. Low wind speeds make the wind power generation minimal. This brings an increase in GE power generation. The increase in GE power generation raises smoke and waste heat, thereby increasing hydrogen production. Formula (27) reveals that the refrigeration and heating coefficients of the LBARHM influence the GE's flue smoke utilization, which alters the amount of flue smoke that finally enters into the hydrogenation reaction. Higher cooling and heating coefficients reduce the smoke gas available for the building's cooling and heating, and higher production of smoke gas leads to increased production of hydrogen.

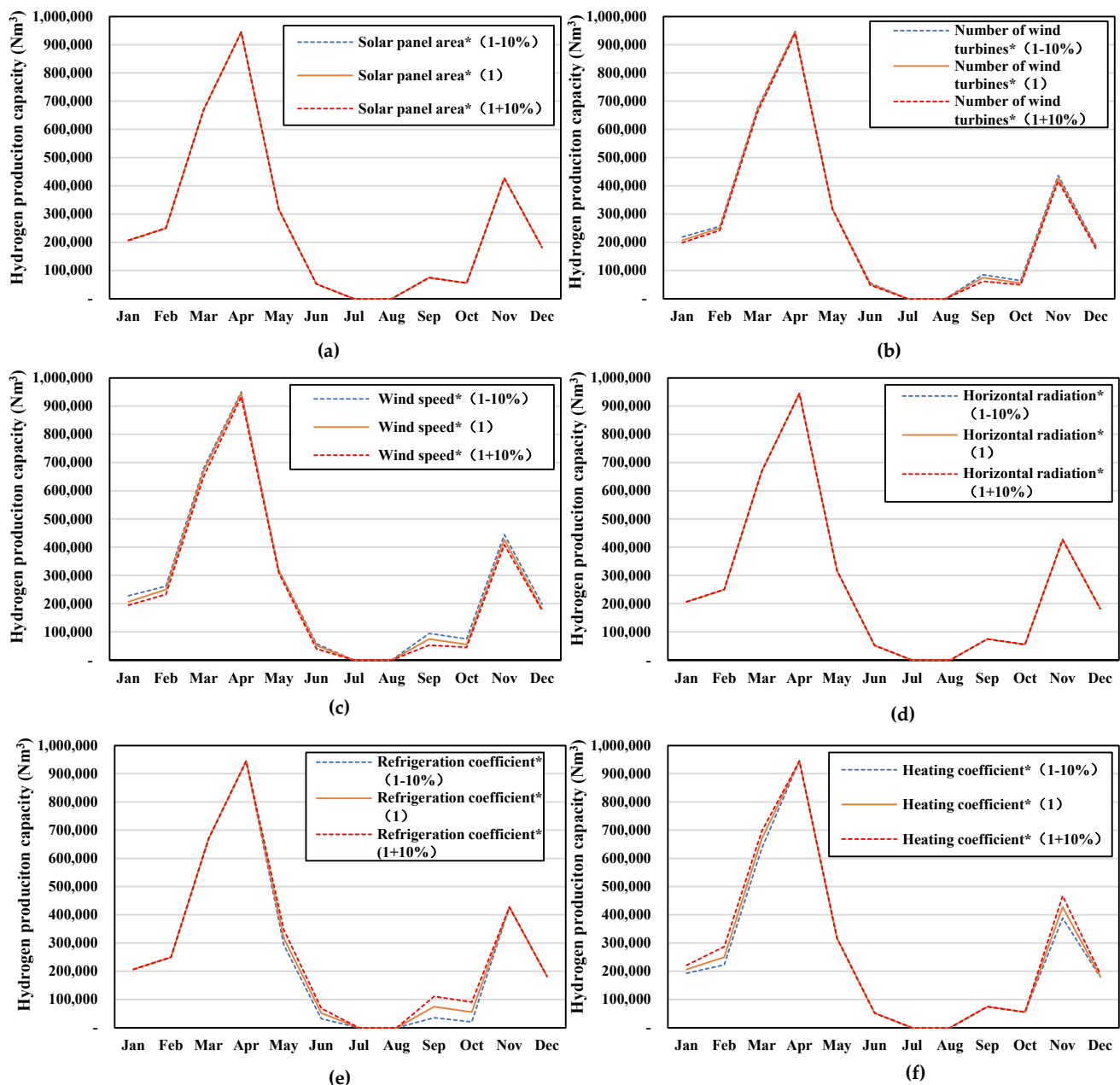


Figure 23. Effects of single parameter variation on hydrogen production. (a) Solar panel area; (b) number of wind turbines; (c) wind speed; (d) horizontal radiation; (e) refrigeration coefficient; (f) heating coefficient. (Note: “+10%” means that the value has increased by 10% from the original value, “−10%” means that the value has reduced by 10% from the original value).

The higher the wind speed, the larger the number of wind turbines, the greater the horizontal radiation, and the larger the solar panel area of the integrated system, the smaller the hydrogen production capacity will be. The reason is that as more renewable energy electricity is generated, more renewable energy electricity is supplied to the building, which leads to a corresponding decrease in the electricity supplied to the building from the gas engine. If the amount of electricity generated by the gas engine decreases, the amount of waste smoke, the amount of water vapor, and the capacity for hydrogen production will also be reduced.

4.4. Primary Energy Reduction Rate and Carbon Emission Reduction Rate of Integrated Systems

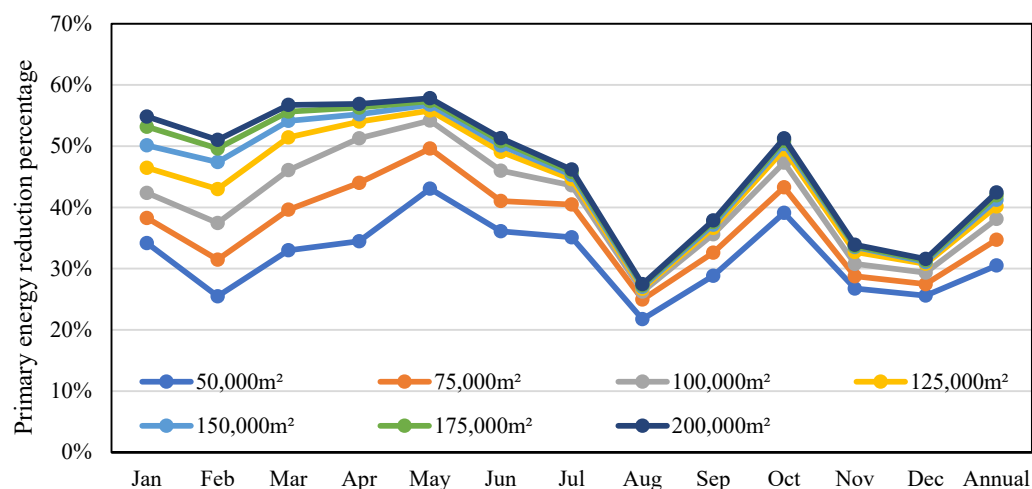
To calculate carbon emissions, it is necessary to investigate the carbon emission factors of the energy sources. Table 7 shows the carbon emission factors of commercial electricity, natural gas, and some other energy sources in Zhejiang Province, China, over the past three years (2020–2022). The carbon emission factor for commercial electricity in Zhejiang Province has gradually reduced from 1.75317 ton/standard coal in 2020 to 1.60615 ton/standard coal in 2022. This reduction is due to the increasing proportion of renewable energy and natural gas electricity generation supply in the province each year. Additionally, the carbon emission factor for natural gas is 0.056 kgCO₂/MJ, with a calorific value of 35.6 MJ/Nm³ or 41.9 MJ/kg. The calorific value of hydrogen is 12.8 MJ/Nm³ or 140.4 MJ/kg. Notably, the combustion calorific value of hydrogen per unit mass is more than three times that of natural gas.

Table 7. Carbon emission factors of Zhejiang Province in China.

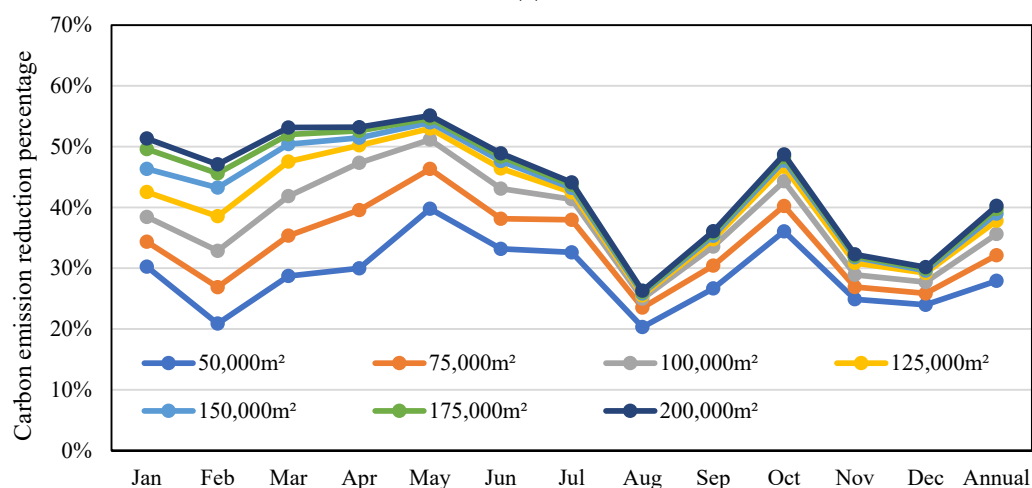
Year	Natural Gas Converted into Standard Coal (10,000 tons Standard Coal/ 100,000,000 m ³ Natural Gas)	Electricity Converted into Standard Coal (10,000 Tons Standard Coal/ 100,000,000 kWh Electricity)	Carbon Emission Factor of Electricity (10,000 Tons CO ₂ / 100,000,000 kWh Electricity)	Carbon Emission Factor of Electricity (ton CO ₂ / Standard Coal)	Carbon Emission Factor of Coal (Ton Carbon Emission/ Standard Coal)	Carbon Emission Factor of Natural Gas (kgCO ₂ /MJ)
2020	12.338535	2.83258	4.966	1.75317	2.66	0.056
2021	12.338535	2.83258	4.821	1.70195	2.66	0.056
2022	12.338535	2.83258	4.550	1.60615	2.66	0.056

Figure 24 illustrates the monthly primary energy reduction rate and carbon emission reduction rate of the MECDES compared with traditional energy supply in Ningbo City. The figure displays the simulation results with 10,000 wind turbines. The terminal generation efficiency of commercial electricity is calculated at 36.8% [25]. As shown in Figure 24a, an increase in solar panel area leads to an increase in the primary energy reduction rate. Larger cooling and heating loads in office buildings, like in August and February, result in smaller primary energy reduction rates for the MECDES. When the office buildings' cooling and heating load becomes smaller, like in April and October, this leads to larger reduction rates. This occurs because the larger cooling and heating loads of office buildings increase the total primary energy consumption. Although the primary energy consumption of the MECDES was reduced, the ratio of the total primary energy reduction was still smaller compared with the overall cooling load of the building in August. Therefore, the primary energy reduction rate is the smallest in August. In contrast, the primary energy reduction rate is larger in April and October during the intermediate season. Additionally, the primary energy reduction rates with various solar panel areas are all more than 20%, and the annual primary energy reduction rates are between 30% and 45%. The maximum value is 57.8% in May with the installation of a 200,000 m² solar panel area, and the minimum value is 21.8% in August with the installation of a 50,000 m² solar panel area. Consequently, the MECDES has a good energy-saving effect. In Figure 24b, the month-to-month trend of

the carbon emission reduction rate is the same as the primary energy reduction rate. The annual carbon emission reduction rate is between 25% and 40%.



(a)

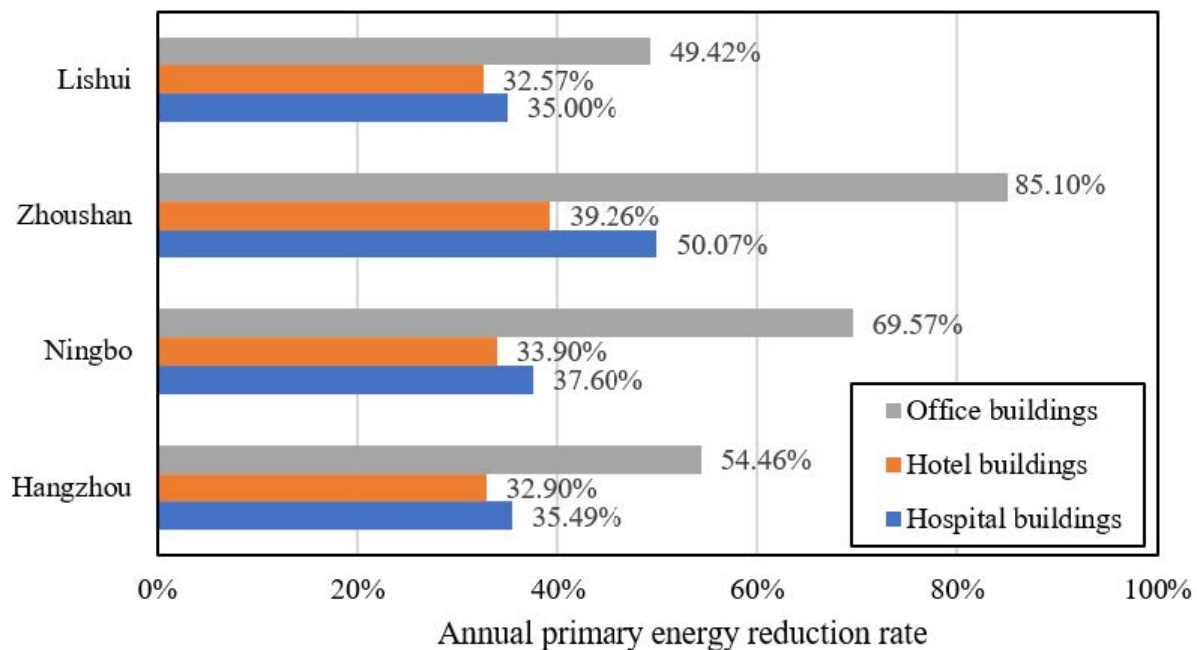


(b)

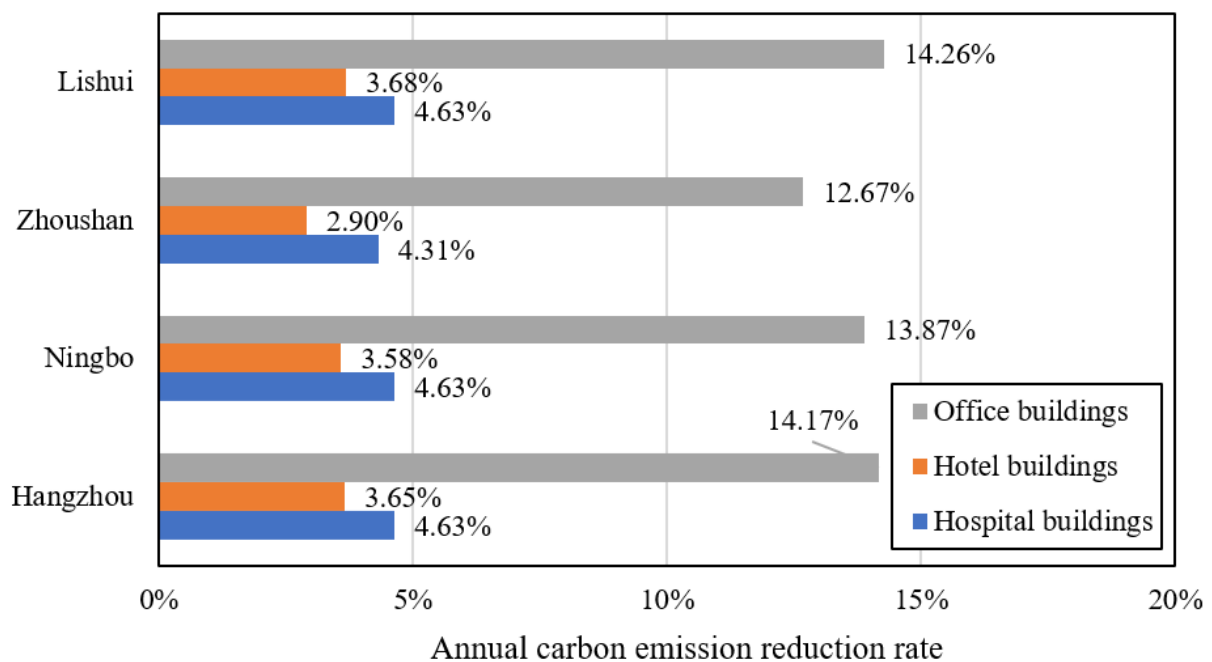
Figure 24. The primary energy reduction rate and carbon emission reduction rate of multi-energy complementary energy systems in office buildings with 100,000 wind turbines. (a) Primary energy reduction rate, comparison between the multi-energy complementary energy supply system and traditional energy supply mode; (b) Carbon emission reduction rate. Comparison between multi-energy complementary energy supply system and traditional energy supply mode. (Note: The different colored lines in the figure represent the different areas of solar panels installed in the buildings of 3,000,000 m² total floor area).

Figure 25a,b show the comparison of the annual primary energy reduction rates and annual carbon emission reduction rates of three types of buildings in four different cities. For all types of buildings, Zhoushan City has the largest primary energy reduction rate and carbon emission reduction rate, followed by Ningbo City, Hangzhou City, and Lishui City. The most significant factor that influences these rates is the consumption of renewable energy electricity in the buildings. Zhoushan City achieves the highest reduction rate due to greater solar and wind electricity generation compared with the other cities. The annual primary energy reduction rate in Zhoushan City can reach 85.10% in office buildings, 39.26% in hotel buildings, and 50.07% in hospital buildings. The annual primary carbon emission reduction rate can reach 47.00% in office buildings, 37.98% in hotel buildings, and

48.28% in hospital buildings. This result does not take into account the use of hydrogen made of waste heat and surplus electricity.



(a)



(b)

Figure 25. Annual primary energy reduction rate and annual carbon emission reduction rate of multi-energy complementary energy systems in different cities. (a) Annual primary energy reduction rate, comparison between multi-energy complementary energy supply system and traditional energy supply mode; (b) annual carbon emission reduction rate; comparison between multi-energy complementary energy supply system and traditional energy supply mode.

If we consider the use of produced hydrogen, the new approach involves utilizing the generated hydrogen for electricity generation through hydrogen fuel cells. The high-temperature waste heat from hydrogen fuel cells can be employed in the LBARHM to produce hot or cold water for buildings. Insufficient electricity will be supplemented by

commercial electricity, and air-conditioning equipment powered by commercial electricity will address the cooling and heating load. The primary energy reduction rate and carbon emission reduction rate of CCHP with hydrogen fuel cells is shown in Figure 26a,b. When calculating the primary energy reduction rate, hydrogen for hydrogen fuel cells is derived from natural gas, waste heat, and surplus electricity. In the traditional model, the waste heat and surplus electricity of the MECDES were discarded if they could not be effectively used. Therefore, only natural gas is considered here when calculating the primary energy of hydrogen. In the simulation, the hydrogen fuel cell had an electricity generation efficiency of 47.3% and a heat recovery efficiency of 32.9% [27]. Throughout the simulation, the high-temperature waste heat generated by the hydrogen fuel cell was utilized to produce hot or cold water in the LBARHM for the three different building types.

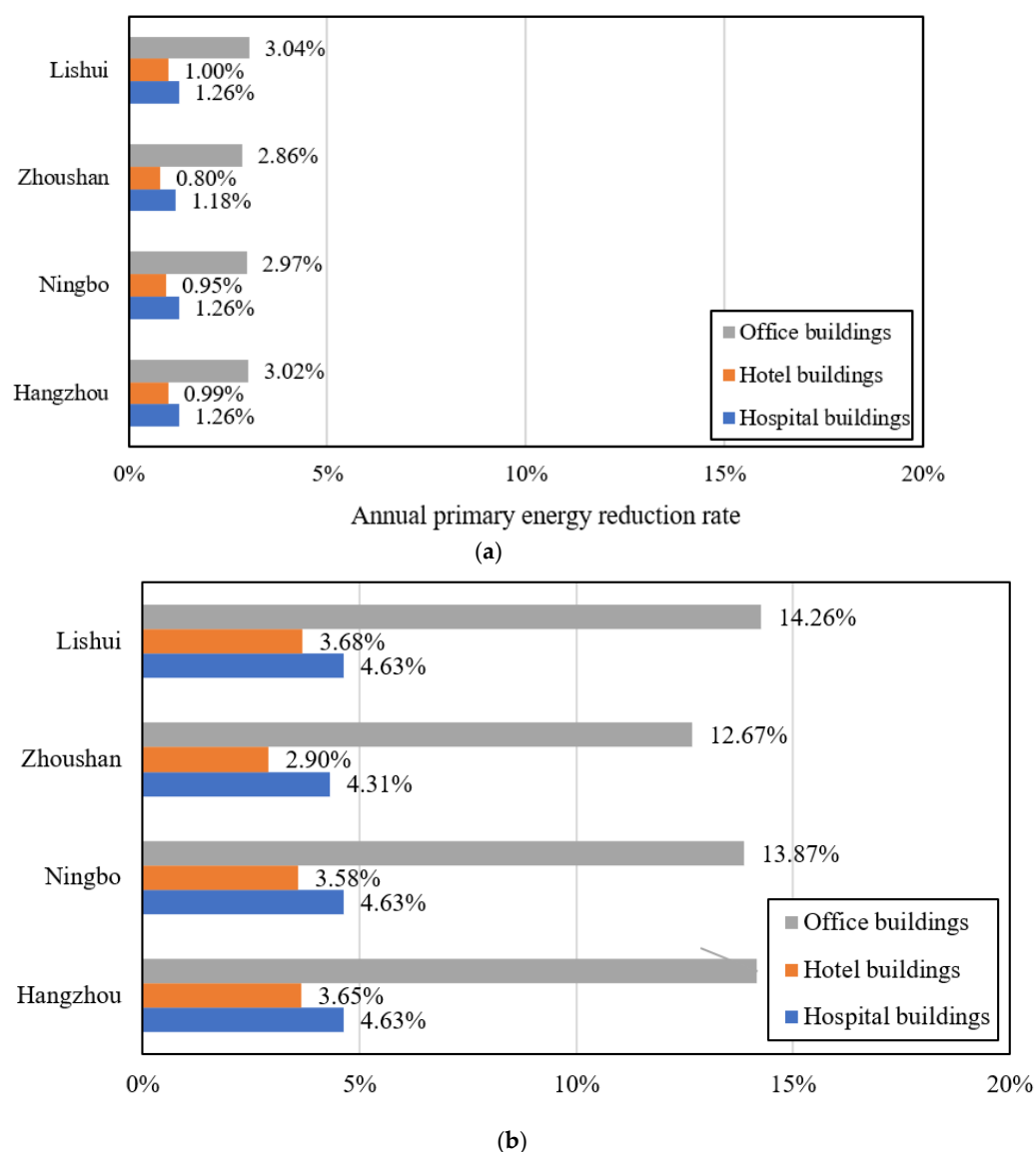


Figure 26. Annual primary energy reduction rate and annual carbon emission reduction rate using hydrogen fuel cells. (a) Annual primary energy reduction rate, comparison of CCHP of hydrogen fuel cell and traditional energy supply mode; (b) annual primary energy reduction rate; comparison of CCHP of hydrogen fuel cell and traditional energy supply mode.

As shown in Figure 26a, in the comparison of the annual primary energy reduction rate in four cities, Lishui City has the largest reduction rate of primary energy, reaching 3.04% in office buildings, 1.00% in hotel buildings, and 1.26% in hospital buildings, due to

having the largest hydrogen production. The hydrogen production in Zhoushan City is the smallest, and the primary energy reduction rate is the lowest, at 2.86% in office buildings, 0.80% in hotel buildings, and 1.08% in hospital buildings. This indicates that integrating waste heat and surplus electricity for hydrogen production is an effective energy-saving technology. As shown in Figure 26b, the rate of carbon emission reduction is better than the primary energy reduction rate. Lishui City has the largest carbon emission reduction rate, at 14.26% in office buildings, 3.68% in hotel buildings, and 4.63% in hospital buildings, while Zhoushan City has the lowest carbon emission reduction rate, at 12.67% in office buildings, 2.90% in hotel buildings, and 4.31% in hospital buildings, all of which are far greater than the primary energy reduction rate.

Although the energy efficiency in the process of hydrogen production is reduced (the efficiency of hydrogen production is reduced by about 30%) compared with the traditional energy supply method (commercial power provides the energy for the building's heating, cooling, and electricity), the produced hydrogen used to supply energy to the building through a hydrogen fuel cell still has a good energy-saving and carbon reduction effect. In Lishui City, the annual primary energy reduction rate of office buildings is 3.04%, but the annual carbon emission reduction rate is 14.26%, which is about 4.7 times the primary energy reduction rate. The reason is that there are no carbon emissions from the hydrogen fuel cells, but the energy efficiency in the process of hydrogen production decreases, so the final reduction rate of primary energy is small. Although there are some carbon emissions from the hydrogenation process, compared with traditional energy sources (mainly commercial power generated by coal or natural gas), hydrogen has almost no carbon emissions in the energy supply process. Therefore, the carbon emission reduction rate of the hydrogen fuel cell increases more than primary energy reduction rate.

In the comparison of building types, the primary energy reduction rate and carbon emission reduction rate of office buildings powered by hydrogen fuel cells are the largest, followed by hospital buildings. The hotel buildings have the worst energy-saving and carbon reduction effects. The primary energy reduction rate and carbon emission reduction rate of the office buildings are significantly higher than those of the hospital buildings and hotel buildings. The reason is that the cooling or heating load of office buildings is highly concentrated in the daytime working time from 8:00 to 18:00, and there is almost no cooling or heating load at night, so that most of the waste smoke generated by the gas engine can be used to produce hydrogen at night. In the comparison of the cities, Lishui City has the largest primary energy reduction rate and carbon emission reduction rate for the same types of buildings, followed by Hangzhou City, Ningbo City, and Zhoushan City. This result is closely related to the amount of hydrogen produced in each city. The greater the amount of hydrogen produced, the greater the reduction rates of primary energy and carbon emissions generated by hydrogen fuel cells. Lishui City has the largest hydrogen production capacity, while Zhoushan City has the smallest hydrogen production capacity. In Zhoushan City, a large amount of renewable electricity is supplied to buildings and the amount of electricity generated by gas engines will be reduced, and so too is the amount of waste smoke and the final produced hydrogen. Therefore, the primary energy reduction rate and carbon emission reduction rate of hydrogen fuel cells are the largest in Lishui City and the smallest in Zhoushan City.

The above results show that, even if the energy efficiency in the process of hydrogen production is reduced, it still has the effect of energy saving and carbon reduction. This is achieved by utilizing waste heat and surplus electricity to produce hydrogen, which is then used to supply energy through hydrogen fuel cells. This demonstrates that the integrated system has practical application value.

4.5. Economic Benefit Analysis

To analyze the economic benefits of the integrated system, the current prices of energy and industrial water related to hydrogen production in Zhejiang Province were investigated. The relevant survey results are shown in Table 8. The price of natural gas or fuel in Zhejiang

Province is RMB 3.919/m³, equivalent to USD 0.548660/m³. The corresponding price of hydrogen in Zhejiang Province is USD 4.71660/kg, and industrial water is USD 0.000742/kg. To alleviate electricity consumption during peak hours and increase consumption during trough periods, the price of commercial electricity in Zhejiang Province is divided into three categories: USD 0.118804/kWh in the rush time period, USD 0.125776/kWh in the peak time period, and USD 0.051688/kWh in the trough period. The labor cost of hydrogen production is RMB 200,000 per person per year, equivalent to USD 27311.21/year.

Table 8. Prices of energy and industrial water related to hydrogen production in Zhejiang Province.

	Natural Gas/Fuel (USD/m ³)	Hydrogen (USD/kg)	Industrial Water (USD/kg)	Commercial Electricity (USD/kWh)		
Price	0.548660	4.71660	0.000742	Rush time period	8:00~11:00	0.118804
					13:00~19:00	
					21:00~22:00	
				Peak time period	19:00~21:00	0.125776
					11:00~13:00	
				Trough period	22:00~8:00	0.051688

Next, consider a solar panel area of 100,000 m² and 10,000 wind turbines for office buildings as a case study to analyze the economic benefits of the integrated system. Based on the energy and labor cost prices for hydrogen production in Zhejiang Province (refer to Table 8), the annual cost ratio for each part of the hydrogen production in the integrated system was determined. Figure 27 illustrates the annual cost percentage of each component in the office buildings of Zhoushan City. When the integrated system makes full use of waste heat and surplus electricity, fuel accounts for the largest proportion of cost in the process of hydrogen production, at 88.91%. The second is the fuel cost required for high-temperature heating in the hydrogenation process. In this study, the heating cost required for the chemical reaction is also considered, and the fuel accounts for 8.29% of the total cost. The water vapor required for the hydrogenation reaction comes from industrial water. This cost accounts for the smallest proportion of the cost, only 0.39%. After surplus renewable energy electricity is used, the insufficient electricity is supplemented by commercial electricity, which accounts for 0.63% of the total cost. Additionally, labor costs account for 1.78%.

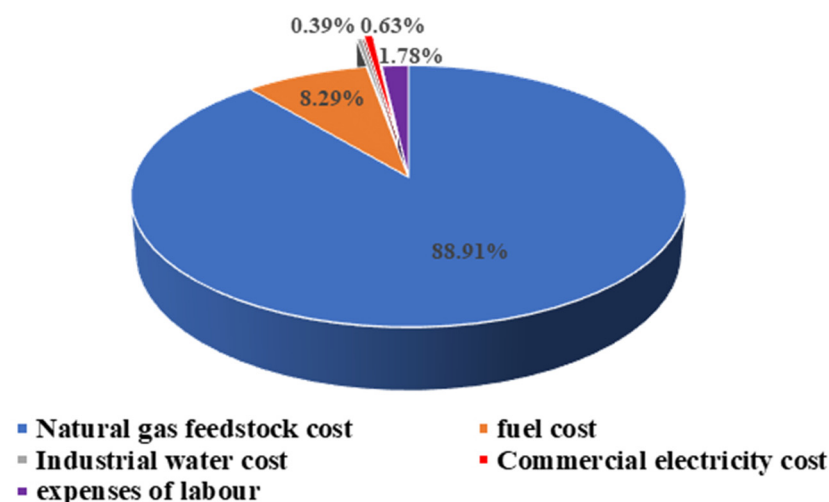


Figure 27. Percentages of the annual cost of hydrogen production in Zhoushan City, Zhejiang Province, in the case of office buildings, solar panel area 100,000 m², wind turbines 10,000.

The results of the monthly economic analysis of the integrated system in Zhoushan City is shown in Figure 28. Compared with the traditional energy supply mode, the energy cost of the MECDES is significantly lower. For office buildings with a total floor area of 3,000,000 m², the maximum energy cost of the traditional energy supply model is USD 1,617,984 in August, or about USD 0.539/m². The maximum energy cost of the MECDES in August is USD 1,235,508, or about USD 0.412/m², which is 23.64% less than the traditional mode. For hydrogen production using waste heat and surplus electricity, the maximum amount of hydrogen production occurs in March, with a production cost of USD 189,166. The total selling price of the hydrogen produced is USD 325,937, and the profit rate is 72.30%. The profit rate of hydrogen production for the whole year remains around 70%. This demonstrates that this integrated system with hydrogen production can be economical.

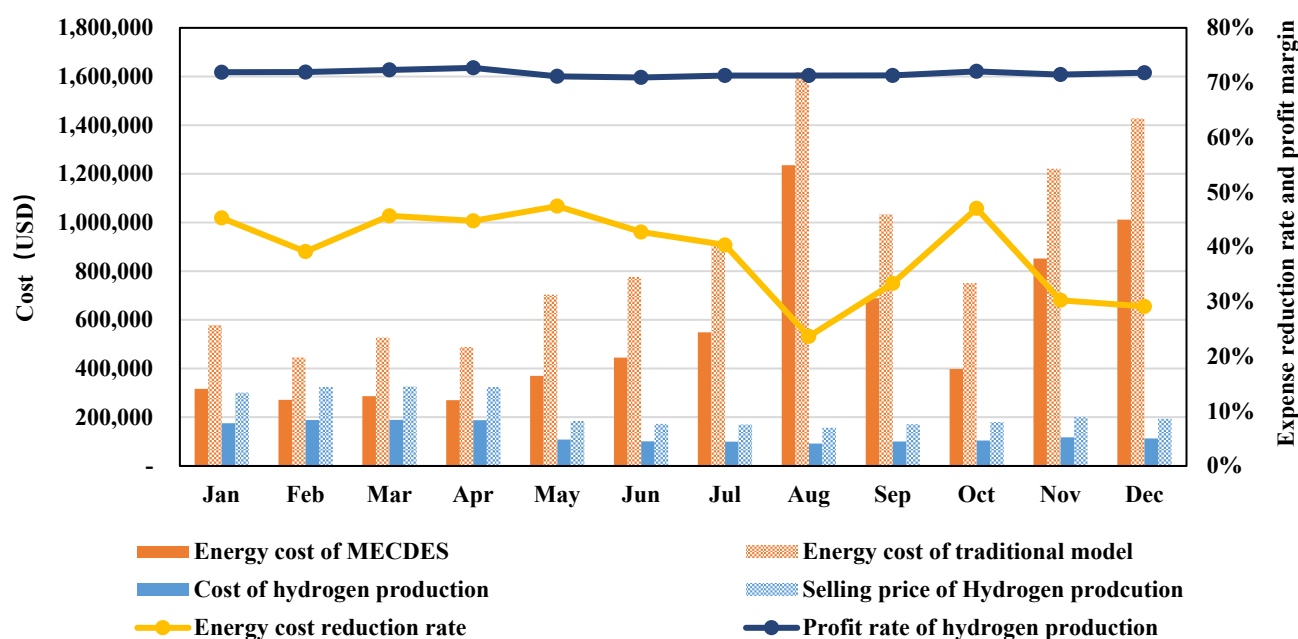


Figure 28. Monthly operating costs of integrated systems and economic benefits of hydrogen production in Zhoushan City office buildings, solar panel area 100,000 m², wind turbine 10,000.

Figure 29 illustrates the results of the annual economic benefit analysis of the integrated hydrogen production system in office buildings. Among the cities, Zhoushan City's MECDES demonstrates the most favorable operating economic benefits, with an annual energy cost of USD 5,457,660. This represents a 38.48% reduction compared with the traditional energy supply mode's annual energy cost. Following Zhoushan, Ningbo shows a reduction rate of 24.73%, with 20.97% in Hangzhou and 20.12% in Lishui. Zhoushan's climate is conducive to solar and wind electricity generation. This contributes to its superior hydrogen production efficiency, boasting an annual profit rate of 72.01%. Lishui follows at 70.92%, Hangzhou at 70.90%, and Ningbo at 70.88%.

Figures 30 and 31 illustrate the results of the annual economic benefit analysis of the integrated hydrogen production system in hotel buildings and hospital buildings. It can be seen from the simulation results that Zhoushan City has the best economic benefit of integrated system operation for these types of buildings, followed by Ningbo City, Hangzhou City, and Lishui City. The main factors affecting the economic benefits of this operation are the solar radiation and wind speed; the greater the solar radiation and wind speed, the better the economic benefits of the operation will be. Comparing different building types, office buildings have the best operating economic benefit, followed by hospital buildings and hotel buildings. Compared with the profitability of hydrogen production, the buildings with the highest profit rate of hydrogen production are the hospital buildings, at about 91%, followed by office buildings, where the profit rate of

hydrogen production is about 71%. The worst profit rate of hydrogen production in hospital buildings is about 68%. This is mainly due to the stable hourly heating and cooling load in hospital buildings, meaning that the integrated system has more residual smoke for hydrogen production. At the same time, more surplus electricity from renewable energy for hydrogen production will reduce the cost of hydrogen production and increase the profit rate of hydrogen production.

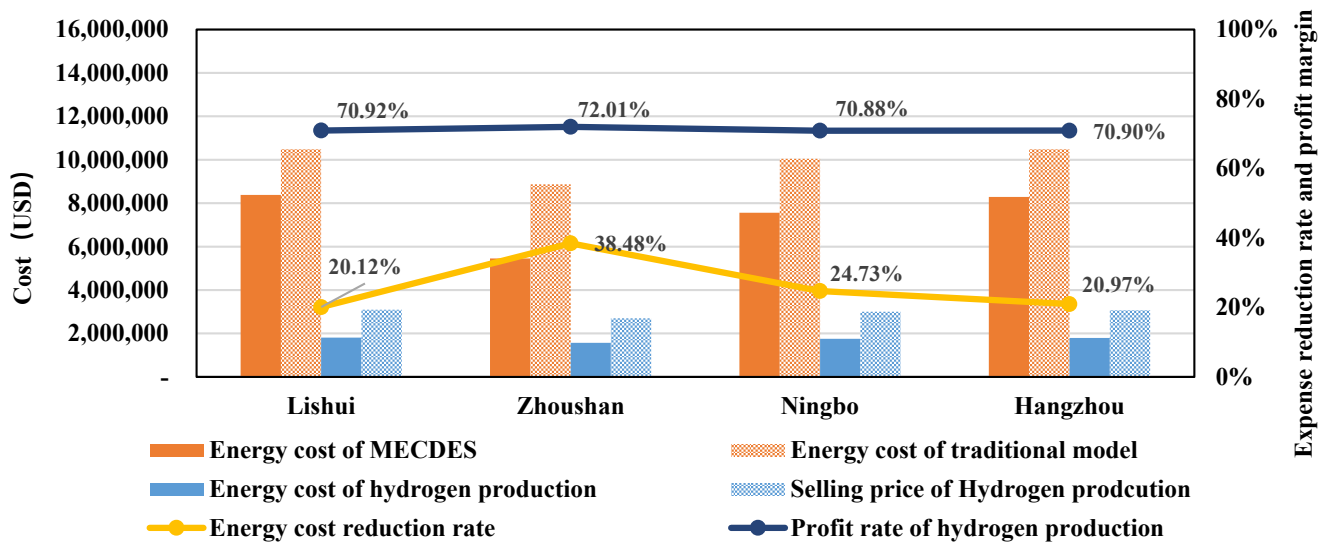


Figure 29. Annual operating costs of integrated systems and economic benefits of hydrogen production in office buildings in different cities, solar panel area 100,000 m², wind turbines 10,000.

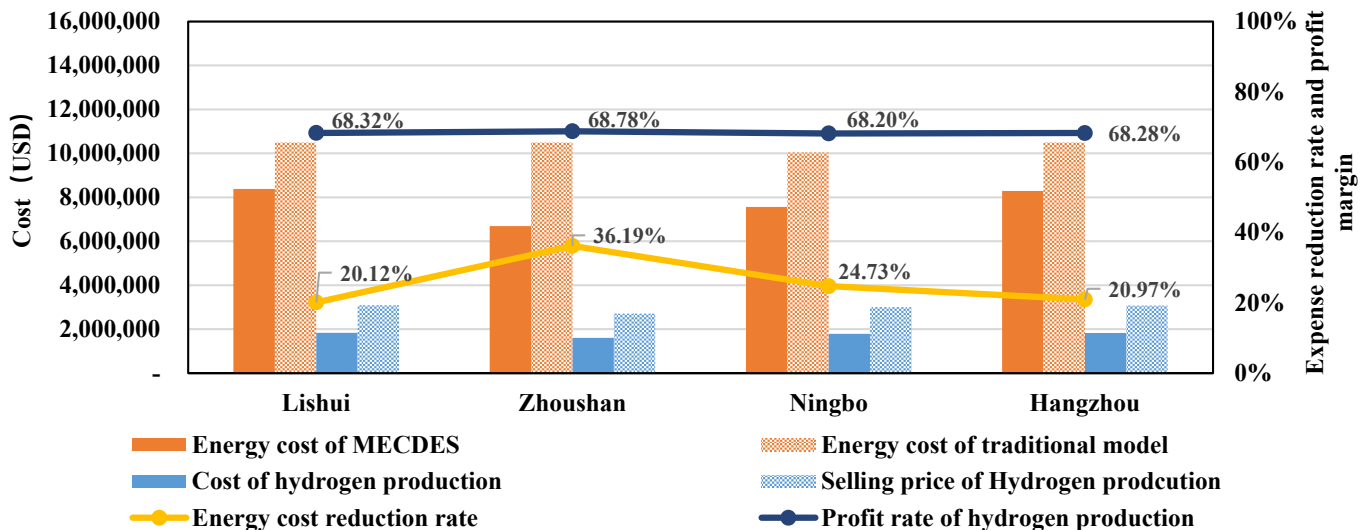


Figure 30. Annual operating costs of integrated systems and economic benefits of hydrogen production in hotels buildings in different cities, solar panel area 100,000 m², wind turbines 10,000.

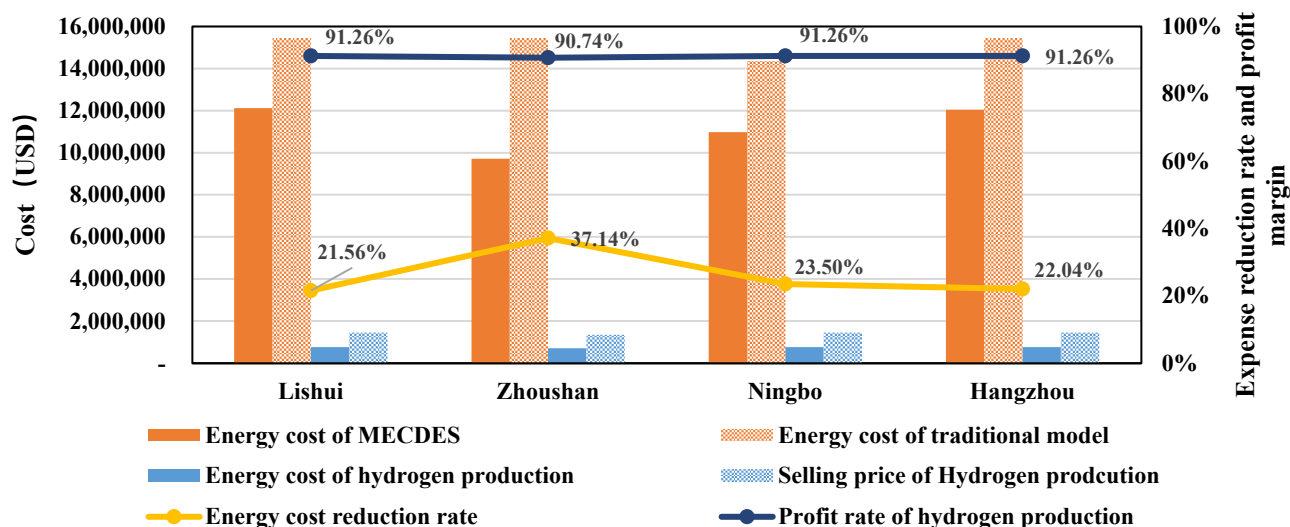


Figure 31. Annual operating costs of integrated systems and economic benefits of hydrogen production in hospital buildings in different cities, solar panel area 100,000 m², wind turbines 10,000.

5. Discussion

5.1. Feasibility of Application of the Integrated System

The waste heat and surplus electricity for the hydrogen production system are suitable for large-scale energy supply projects, and the equipment can be placed in an integrated energy station. The main equipment of the system includes the LBARHM, WHRB, MNGHPE, hydrogen tank, storage battery, and so on. If the application of hydrogen in building energy supply is further considered, hydrogen fuel cells will also need to be added to the integrated energy station. The GE can supply energy in the form of CCHP, and the hydrogen fuel cell can supply energy in the same mode. The electricity generated by solar panels and wind turbines located outside the integrated energy station is connected to the MNGHPE and batteries through cables, and the surplus electricity is used for hydrogen production. Hydrogen can also be fed into natural gas pipelines for cooking or stored in hydrogen cylinders for hydrogen fuel cell vehicles.

Based on the research results, the MECDES has a better energy-saving and carbon reduction effect when it is introduced into office buildings and hospital buildings than hotel buildings. If the MECDES is applied in places with large solar radiation and high wind speed, it will bring greater energy savings and carbon reduction effects. So, this system is more suitable for introduction in cities where renewable energy is abundant, such as Zhoushan City and Ningbo City near the sea. If the MECDES is combined with the hydrogen production system, it is recommended that the produced hydrogen is used in a hydrogen fuel cell alongside the integrated system. This will bring further energy savings and carbon reduction effects to the building. It is suggested that the produced hydrogen should be used on site to reduce the long-distance transportation of hydrogen and avoid unnecessarily high transportation costs. This method can also reduce the capacity of hydrogen storage tanks and reduce the initial investment in equipment. The produced hydrogen can be used in the following two scenarios:

- (1) One is to directly supply energy to office buildings through hydrogen fuel cells, because office buildings can obtain greater energy savings and carbon reduction benefits.
- (2) Another is to build a hydrogen refueling station alongside the MECDES, and directly transport the hydrogen to the hydrogen refueling station for short-distance storage, reducing the high cost of long-distance hydrogen transportation.

5.2. Potential Challenges or Limitations of the Integrated System

The integrated system can store waste heat and surplus electricity in the form of hydrogen energy. If the produced hydrogen is sold through a hydrogen refueling station

nearby, or used to power the building through hydrogen fuel cells on site, it can bring good economic benefits, carbon reduction, and energy-saving effects. However, the following potential challenges and limitations still remain:

- (1) The hydrogen produced by the integrated system needs to be stored on site. Hydrogen is a flammable and explosive gas, and the integrated system is located around the building, so there are certain challenges in the safe storage and safe operation of hydrogen. The integrated system requires safe storage of hydrogen and protective measures for safe use.
- (2) The integrated system requires a lot of high-temperature water vapor for hydrogen production. When the building's cooling or heating load demand is large and the gas engine does not have excess smoke for the production of high-temperature water vapor, it needs to generate additional high-temperature water vapor through the gas boiler for hydrogen production, to consume the surplus electricity from renewable energy. Otherwise, the surplus electricity will have to be stored in batteries or returned to the grid. Therefore, the selected waste heat recovery boiler needs to be a boiler that can generate water vapor by burning natural gas or an additional gas-fired boiler needs to be set up.
- (3) The produced hydrogen needs to be used on site to bring economic benefits. If the produced hydrogen is stored at high pressure and transported for long distance, the profit rate of hydrogen production will decrease or there may even be no economic benefits. Therefore, in order to ensure the economic benefits of hydrogen production, it is necessary to use or sell produced hydrogen on site.

5.3. Limitations of the Study

This study focuses on the performance of a specific type of GE in conducting simulated research on hydrogen production using waste heat and surplus electricity. To maintain the GE load rate above 50%, a total floor area of only 3,000,000 m² was taken for the simulation. Subsequent studies should incorporate additional cases for comparative simulation analysis. The simulation results show that the integrated hydrogen production system can store waste heat and surplus electricity in the form of hydrogen, and it also has a good effect of energy saving and carbon reduction. However, these simulations were based on specific climate areas and equipment performance data. Therefore, the application of this result is currently limited to the Zhejiang Province of China. In addition, the hydrogen production benefit of the integrated hydrogen production system is about 70%, which is based on the premise that the produced hydrogen is used through hydrogen fuel cells on site and does not take into account the cost of long-distance delivery and compressed storage of hydrogen. If the cost of long-distance transportation is added, the profit rate of hydrogen production of the integrated system gradually reduces as the transportation distance increases. In future studies, the effects of energy saving and carbon reduction and the benefits of hydrogen production using the integrated system under different climatic regions and at moderate transportation distances in China will be considered.

6. Conclusions

The purpose of this study is to explore the feasibility of waste heat and surplus electricity for hydrogen production and energy storage using a multi-energy complementary distributed energy system, and to analyze the energy savings, carbon reduction effect, and economic benefits of the integrated system in different types of public buildings. In this study, a multi-energy complementary distributed energy system integrating waste heat and surplus electricity for hydrogen production and energy storage is proposed, and a MECDES is introduced for the use of waste heat and surplus electricity to provide water vapor and electricity for hydrogen production, thereby increasing energy efficiency, reducing carbon emissions, and enabling energy storage. The main conclusions of the article are as follows:

- (1) This study proposes a multi-energy complementary distributed energy system that integrates waste heat and surplus electricity to produce hydrogen. This system can

store the waste heat of the GE and the surplus electricity of solar and wind energy as hydrogen energy. Based on the proposed integrated system, a mathematical model was established to simulate the hydrogen production capacity of the integrated system. Through simulation analysis, the energy saving and carbon reduction effects of the integrated system in different types of buildings were verified, and the economic benefit of the integrated system was also verified.

- (2) Among different types of buildings, offices will experience the most significant impact effect on energy conservation and carbon reduction. The primary energy reduction rate ranges from 49.2 to 85.10%, and the carbon emission reduction rate ranges from 34.88 to 47.00%. When comparing Lishui City, Zhoushan City, Ningbo City, and Hangzhou City, four representative cities with similar building types in Zhejiang Province, Zhoushan City demonstrates the most effective energy-saving and carbon reduction measures. This indicates that cities with optimal solar and wind energy resources can achieve the best results through integrated multi-energy complementary distributed energy systems.
- (3) Comparing building type, the best energy-saving and carbon reduction effects of the integrated system are in office buildings, followed by hotels and hospitals. This indicates that the larger the variation in the hourly power load throughout the day, the greater the energy-saving and carbon reduction effect of the integrated system will be. When comparing cities, Zhoushan City will experience the most significant effect of energy saving and carbon reduction, followed by Ningbo City, Hangzhou City, and Lishui City. This shows that cities with higher renewable energy generation obtain better energy saving and carbon reduction effects by using integrated systems.
- (4) The hydrogen produced by the integrated system can supply energy to the building through the hydrogen fuel cell in CCHP mode, resulting in additional energy savings and carbon reduction compared with traditional energy supply methods. Among the three types of buildings, office buildings will undergo the most significant impact on energy conservation and carbon reduction, with a primary energy reduction rate of 2.86–3.04% and a carbon emission reduction rate of 12.67–14.26%.
- (5) The integrated system has good economic benefits for hydrogen production. The earnings from hydrogen are greater than the cost of hydrogen production, and the annual profit rate of hydrogen production is about 70% in office buildings, 68% in hotel buildings, and 91% in hospital buildings. Because hospital buildings have a stable hourly cooling and heating load, most of the time the hydrogen production is powered by renewable energy, and the cost of hydrogen production is low. Hospital buildings have the highest profit rate of hydrogen production.
- (6) Through the parameter sensitivity analysis, it can be seen that the wind speed and the refrigeration and heating coefficients of the LBARHM greatly affect the hydrogen production of the integrated system. The lower the wind speed, the more hydrogen will be produced. The greater the refrigeration coefficient and heating coefficient, the more hydrogen will be produced.

The results show that the hydrogen production of the integrated system decreases with the increase of the building's heating or cooling load. In addition, relative to the solar panel area, solar radiation, and other influencing factors, the wind speed, the number of wind turbines, and the cold or heat coefficient of the absorption chiller/heater have a greater impact on the hydrogen production of the integrated system. Under the same climate conditions, office buildings have the best energy saving and carbon reduction effect, followed by hospital buildings and hotel buildings. The results of this study prove the practical feasibility for hydrogen production storage by using waste heat and surplus electricity and reveal the mathematical mechanism of hydrogen production by using waste heat and surplus electricity through a MECDES. The key factors that affect the amount of hydrogen produced were analyzed. This study provides a new method for the storage of waste heat and surplus electricity and provides scientific reference and guidance for the practical application of MECDESs with integrated waste energy for hydrogen production.

Author Contributions: All authors contributed to the study’s conception and design. S.Y., Y.Y., S.C., H.X., Y.G., W.F., J.Z. (Jianchao Zhang) and J.Z. (Junhan Zhang) performed material preparation, data collection, and analysis. S.Y. wrote the first draft, and all authors commented on previous versions. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

CCHP	combined cooling heating and power
MECDES	multi-energy complementary distributed energy system
MNGHPE	miniaturized natural gas hydrogen production equipment
GE	gas engine
LBARHM	lithium bromide absorption refrigerating and heating machine
WHRB	waste heat recovery boiler
WVNGM	water vapor and natural gas mixer
HE	heat exchange
GB	gas burner
NGR	natural gas reformer
NGD	natural gas desulfurizer
GC	gas compressor
MC	medium converter
GLS	gas–liquid separator
PSA	pressure swing adsorption
OGT	off gas tank
PSA	pressure swing adsorption

References

1. Omidvar, M.R.; Khanmohammadi, S.; Shababi, Z.; Kumar, R. Performance assessment and exergy analysis of hydrogen production from natural gas in a petrochemical unit (A real case study). *Hydrog. Energy* **2023**, *5*, 320–334. [CrossRef]
2. Kwon, H.; Do, T.N.; Kim, J. Energy-efficient liquid hydrogen production using cold energy in liquefied natural gas: Process intensification and techno-economic analysis. *Clean. Prod.* **2022**, *380*, 135034. [CrossRef]
3. Building Energy Consumption and Carbon Emission Data Platform of China. Available online: www.cbeed.cn (accessed on 10 January 2023).
4. Jianguo, H.; Shan, T.; Zhang, C.; Song, P.; Zheng, H.; Wang, X.; Sui, Y.; Wang, L. Current situation and development trend analysis of small skid mounted natural gas hydrogen production. *Technol. Nat. Gas Chem. Ind.* **2021**, *46*, 1–6.
5. Zhang, C.; Song, P.; Xiao, L.; Zhang, Y.; Wang, X.; Hou, J.; Wang, X.; Lu, L. Research and development of on-site small skid-mounted natural gas to hydrogen generator in China. *Hydrog. Energy* **2023**, *48*, 18601–18611. [CrossRef]
6. Asakura, T.; Mori, T.; Tanaka, T.; Azuma, T. Development of on-site hydrogen production system based on SMR. *Press. Technol.* **2024**, *42*, 115–120.
7. Weber, C.; Shah, N. Optimisation based design of a district energy system for an eco-town in the United Kingdom. *Energy* **2011**, *36*, 1292–1308. [CrossRef]
8. Omu, A.; Choudhary, R.; Boies, A. Distributed energy resource system optimisation using mixed integer linear programming. *Energy Policy* **2013**, *61*, 249–266. [CrossRef]
9. Ren, H.; Gao, W. A MILP model for integrated plan and evaluation of distributed energy systems. *Appl. Energy* **2010**, *87*, 1001–1014. [CrossRef]

10. Falke, T.; Krengel, S.; Meinerzhagen, A.-K.; Schnettler, A. Multi-objective optimization and simulation model for the design of distributed energy systems. *Appl. Energy* **2016**, *184*, 1508–1516. [\[CrossRef\]](#)
11. Di Somma, M.; Yan, B.; Bianco, N.; Graditi, G.; Luh, P.B.; Mongibello, L.; Naso, V. Multi-objective design optimization of distributed energy systems through cost and exergy assessments. *Appl. Energy* **2017**, *204*, 1299–1316. [\[CrossRef\]](#)
12. Mavromatidis, G.; Orehounig, K.; Carmeliet, J. Design of distributed energy systems under uncertainty: A two-stage stochastic programming approach. *Appl. Energy* **2018**, *222*, 932–950. [\[CrossRef\]](#)
13. Yurou, Z. Study on optimization of multi-energy complementary distributed energy systems. *Energy Conserv.* **2018**, *3*, 127–128.
14. Liu, H.; Zhang, L.; Zhang, J.; Wang, S.; Xie, Y. Research on the hybrid distributed energy system based on wind, solar and nature gas. *Energy Conserv. Technol.* **2020**, *38*, 60–65.
15. Wang, Z.; Lei, B.; Xu, L.; Tian, L.; Gao, S. Optimization of multi-energy complementary distributed energy and integrated energy management system. *Microcomput. Appl.* **2021**, *37*, 119–122.
16. Jiang, J.; Hu, J.; Cui, M.; Tian, H. Integration of hydrogen production and waste heat recovery in electrochemical wastewater treatment. *Renew. Energy* **2012**, *43*, 179–182. [\[CrossRef\]](#)
17. Li, P.-J.; Hung, T.-C.; Pei, B.-S.; Lin, J.-R.; Chieng, C.-C.; Yu, G.-P. A thermodynamic analysis of high temperature gas-cooled reactors for optimal waste heat recovery and hydrogen. *Prod. Appl. Energy* **2012**, *99*, 183–191. [\[CrossRef\]](#)
18. Tolku, E.; Avci, A.C.; Kaygusuz, K.; Gur, M. A research on hydrogen production from industrial waste heat by thermal water splitting. *Hydrog. Energy* **2016**, *41*, 10071–10079.
19. Chen, J.; Ge, W.; Wang, Z. Process introduction and cost analysis of hydrogen production from natural gas. *Gas Heat* **2017**, *37*, 8–11.
20. Luo, S.; Fu, J.; Zhou, Y.; Yi, C. The production of hydrogen-rich gas by catalytic pyrolysis of biomass using waste heat from blast-furnace slag. *Renew. Energy* **2017**, *101*, 1030–1036. [\[CrossRef\]](#)
21. Ishaqa, H.; Dincer, I.; Naterer, G.F. New trigeneration system integrated with desalination and industrial waste heat recovery for hydrogen. *Prod. Appl. Therm. Eng.* **2018**, *142*, 767–778. [\[CrossRef\]](#)
22. Zheng, B.; Sun, P.; Meng, J.; Liu, Y.; Wang, G.; Tang, S.; Xu, J.; Zhang, K. Effects of fin structure size on methane-steam reforming for hydrogen production in a reactor heated by waste heat. *Hydrog. Energy* **2020**, *45*, 20465–20471. [\[CrossRef\]](#)
23. Zheng, Z.; Liu, T.; Liu, Q.; Lei, J.; Fang, J. A distributed energy system integrating SOFC-MGT with mid-and-low temperature solar thermochemical hydrogen fuel. *Prod. Hydrog. Energy* **2021**, *46*, 19846–19860. [\[CrossRef\]](#)
24. Wang, F.; Wang, L.; Ou, Y.; Lei, X.; Yuan, J.; Liu, X.; Zhu, Y. Thermodynamic analysis of solid oxide electrolyzer integration with engine waste heat recovery for hydrogen. *Prod. Case Stud. Therm. Eng.* **2021**, *27*, 101240. [\[CrossRef\]](#)
25. Pashchenko, D. Thermochemical waste-heat recuperation as on-board hydrogen production. *Technol. Hydrog. Energy* **2021**, *46*, 28961–28968. [\[CrossRef\]](#)
26. Alali, A.E.; Abulawi, Z.B.; Obeidat, A.Y.M. Assessment of thermal performance improvement of GT-MHR by waste heat utilization in power generation and hydrogen. *Prod. Hydrog. Energy* **2021**, *46*, 22719–22734. [\[CrossRef\]](#)
27. Wang, Z.; Wang, Y.; Zhang, C.; Ye, G. Study progress and exploration of small scale hydrogen production technology by natural gas. *Sol. Energy* **2022**, *5*, 40–47.
28. Cao, Y.; Hani, E.H.B.; Mansir, I.B.; Mehdi, S. Design analysis and tri-objective optimization of a novel integrated energy system based on two methods for hydrogen production: By using power or waste heat. *Hydrog. Energy* **2022**, *47*, 26574–26588. [\[CrossRef\]](#)
29. Cao, Y.; Dhahad, H.A.; Sharma, K.; El-Shafay, A.S.; Ahmed, A.N.; Shamseldin, M.A.; Almojil, S.F.; Almohana, A.I.; Alali, A.F.; Farhang, B. Techno-economic evaluation and parametric study of generating green hydrogen from waste heat recovery of efficient solid oxide fuel cell. *Hydrog. Energy* **2022**, *47*, 26632–26645. [\[CrossRef\]](#)
30. Parsa, S.; Jafarmadar, S.; Neshat, E. Application of waste heat in a novel trigeneration system integrated with an HCCI engine for power, heat and hydrogen. *Prod. Hydrog. Energy* **2022**, *47*, 26303–26315. [\[CrossRef\]](#)
31. Cao, Y.; Hani, E.H.B.; Khanmohammadi, S.; Ahmadi, P. The optimum solution for a biofuel-based fuel cell waste heat recovery from biomass for hydrogen. *Prod. Fuel* **2022**, *317*, 123380. [\[CrossRef\]](#)
32. Ozturk, M.; Dincer, I. Utilization of waste heat from cement plant to generate hydrogen and blend it with natural gas. *Hydrog. Energy* **2022**, *47*, 20695–20704. [\[CrossRef\]](#)
33. Ismail, M.M.; Dincer, I. Development and evaluation of an integrated waste to energy system based on polyethylene plastic wastes pyrolysis for production of hydrogen fuel and other useful commodities. *Fuel* **2023**, *334*, 126409. [\[CrossRef\]](#)
34. Kubilay, B. Determination of hydrogen production performance with waste exhaust gas in marine diesel engines. *Hydrog. Energy* **2023**, *52*, 1319–1333.
35. Nasser, M.; Hassan, H. Assessment of hydrogen production from waste heat using hybrid systems of Rankine cycle with proton exchange membrane/solid oxide electrolyzer. *Hydrog. Energy* **2023**, *47*, 7135–7153. [\[CrossRef\]](#)
36. Sharafilaleh, S.; Zeinali, M.; Mahmoudi, S.M.S.; Soltani, S.; Rosen, M.A. Biomass co-fired combined cycle with hydrogen production via proton exchange membrane electrolysis and waste heat recovery: Thermodynamic assessment. *Hydrog. Energy* **2023**, *48*, 33795–33809. [\[CrossRef\]](#)
37. Ali, A.H.; Ahmed, A.M.; Abdel-Khaliek, A.A.; El Khalik, S.A.; Abass, S.M.; Shaban, M.; Rabia, M. Preparation of inorganic lead-free CuO/Cs₂SnCl₆-KI perovskite for green hydrogen production from wastewater by using solar. *Energy Photochem. Photobiol.* **2023**, *445*, 115102. [\[CrossRef\]](#)

38. Ge, Y.; Han, J.; Zhu, X.; Zhu, W.; Yang, J. A combined cooling, heating and power system with energy storage of waste heat to hydrogen. *Appl. Therm. Eng.* **2023**, *225*, 120224. [\[CrossRef\]](#)
39. Vallejo, M.C.G.; Alzate, C.A.C. Prefeasibility analysis of biomass gasification and electrolysis for hydrogen. *Prod. Environ. Res.* **2023**, 118003.
40. Cheng, G.; Zhao, E.L.Y.; Yang, Y.; Chen, B.; Cai, Y.; Wang, X.; Dong, C. Analysis and prediction of green hydrogen production potential by photovoltaic-powered water electrolysis using machine learning in China. *Energy* **2023**, *284*, 129302. [\[CrossRef\]](#)
41. Karayel, G.K.; Dincer, I. A study on green hydrogen production potential of Canada with onshore and offshore wind. *J. Cleaner Prod.* **2024**, 140660. [\[CrossRef\]](#)
42. Arslan, M.; Yilmaz, C. Development of models for green hydrogen production of Turkey geothermal Resources: A case study demonstration of thermodynamics and thermoeconomics analyses. *Fuel* **2024**, *359*, 130430. [\[CrossRef\]](#)
43. Zhang, T.; Guan, X.; Zhang, Z.; Wang, B.; Qu, J.; Zeng, W.; Guo, X.Y.L. Photothermal catalytic hydrogen production coupled with thermoelectric waste heat utilization and thermal energy storage for continuous power generation. *Nano Energy* **2024**, *121*, 109273. [\[CrossRef\]](#)
44. Fang, H.; Xia, J.; Zhu, K.; Su, Y.; Jiang, Y. Industrial waste heat utilization for low temperature district heating. *Energy Policy* **2013**, *62*, 236–246. [\[CrossRef\]](#)
45. Ziolkowski, P.; Kowalczyk, T.; Kornet, S.; Badur, J. On low-grade waste heat utilization from a supercritical steam power plant using an ORC-bottoming cycle coupled with two sources of heat. *Energy Convers. Manag.* **2017**, *146*, 158–173. [\[CrossRef\]](#)
46. Köfinger, M.; Schmidt, R.R.; Basciotti, D.; Terreros, O.; Baldvinsson, I.; Mayrhofer, J.; Moser, S.; Tichler, R.; Pauli, H. Simulation based evaluation of large scale waste heat utilization in urban district heating networks: Optimized integration and operation of a seasonal storage. *Energy* **2018**, *159*, 1161–1174. [\[CrossRef\]](#)
47. Li, Y.; Wang, W.; Ma, Y.; Li, W. Study of new cascade heating system with multi-heat sources based on exhausted steam waste heat utilization in power plant. *Appl. Therm. Eng.* **2018**, *136*, 475–483. [\[CrossRef\]](#)
48. Akhan, H.; Eryener, D. Building integrated solar air heating with waste heat utilization. *Energy Convers. Manag.* **2018**, *157*, 136–145. [\[CrossRef\]](#)
49. Liu, Y.; Han, J.; You, H. Exergoeconomic analysis and multi-objective optimization of a CCHP system based on LNG cold energy utilization and flue gas waste heat recovery with CO₂ capture. *Energy* **2020**, *190*, 116201. [\[CrossRef\]](#)
50. Chu, C.; Wang, X.; Niu, Y. Capacity optimization of multi-energy complementary distributed energy system with seasonal thermal energy storage. *Dist. Heat.* **2022**, *1*, 127–136.
51. Wang, Y.; Chen, H.; Wang, H.; Xu, G.; Lei, J.; Huang, Q.; Liu, T.; Li, Q. A novel carbon dioxide capture system for a cement plant based on waste heat utilization. *Energy Convers. Manag.* **2022**, *257*, 115426. [\[CrossRef\]](#)
52. Li, Y.; Liu, Y.; Zhang, G.; Yang, Y. Thermodynamic analysis of a novel combined cooling and power system utilizing liquefied natural gas (LNG) cryogenic energy and lowtemperature waste heat. *Energy* **2020**, *199*, 117479. [\[CrossRef\]](#)
53. Wang, Y.; Ying, C.; Kai, W.; Xuefei, L. Performance evaluation and thermal analysis of heat pipe flue gas waste heat utilization system. *Energy Rep.* **2022**, *8*, 210–217. [\[CrossRef\]](#)
54. Wang, Y.; Shen, C.; Sun, P.; Li, C.; Zhang, C. Utilization of waste heat from commercial kitchen exhaust for water heating and dish drying. *Build. Eng.* **2020**, *32*, 101788. [\[CrossRef\]](#)
55. Song, W.; Chen, X.; Huang, Y.; Jiang, R.; Zhou, J. Thermal analysis technology to utilize waste biomass and waste heat to produce high-quality combustible gas through simulations and experiments. *Sci. Total Environ.* **2023**, *892*, 163970. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Wallin, A.; Thomasson, T.; Abdurafikov, R. Urban low-to-medium deep borehole field regeneration with waste heat from energy efficient buildings: A techno-economic study in Nordic climate. *Energy Build.* **2023**, *300*, 113628. [\[CrossRef\]](#)
57. Wang, L.; Huang, X.; Babaei, M.; Liu, Z.; Yang, X.; Yan, J. Full-scale utilization of geothermal energy: A high-efficiency CO₂ hybrid cogeneration system with low-temperature waste heat. *Clean. Prod.* **2023**, *403*, 136866. [\[CrossRef\]](#)
58. Wang, F.; Wang, L.; Zhang, H.; Xia, L.; Miao, H.; Yuan, J. Design and optimization of hydrogen production by solid oxide electrolyzer with marine engine waste heat recovery and ORC cycle. *Energy Convers. Manag.* **2021**, *229*, 113775. [\[CrossRef\]](#)
59. Lan, Y.; Lu, J.; Mu, L.; Wang, S.; Zhai, H. Waste heat recovery from exhausted gas of a proton exchange membrane fuel cell to produce hydrogen using thermoelectric generator. *Appl. Energy* **2023**, *334*, 120687. [\[CrossRef\]](#)
60. Valant, M.; Luin, U. Chemistry of the iron-chlorine thermochemical cycle for hydrogen production utilizing industrial waste heat. *J. Cleaner Prod.* **2024**, 140681. [\[CrossRef\]](#)
61. Mu, L.; Wang, S.; Lu, J.; Li, C.; Lan, Y.; Liu, G.; Zhang, T. Effect of hydrogen-enriched natural gas on flue gas waste heat recovery potential and condensing heat exchanger performance. *Energy* **2024**, *286*, 129591. [\[CrossRef\]](#)
62. Zhao, X.; Chen, H.; Li, J.; Pan, P.; Gui, F.; Xu, G. Thermodynamic and economic analysis of a novel design for combined waste heat recovery of biogas power generation and silicon. *Prod. Energy* **2024**, *290*, 130272. [\[CrossRef\]](#)
63. Takaaki, A.; Takumi, T.; Toyokazu, T.; Takayuki, A. Development of compact hydrogen production systems for H₂ refueling stations. *Jpn. Soc. Mech. Eng.* **2005**, *54*, 31–32.
64. GB/T 51350; The State Standard of the People's Republic of China. Technical Standard for Nearly Zero Energy Buildings. China Building Industry Press: Beijing, China, 2019.
65. Liu, Z.; Cui, Y.; Wang, J.; Yue, C.; Agbldjan, Y.S.; Yang, Y. Multi-objective optimization of multi-energy complementary integrated energy systems considering load prediction and renewable energy production uncertainties. *Energy* **2022**, *254*, 124399.

66. Liu, X.; Chang, Y.; Yu, J.; Qi, G. Discussion on calculation method of utilization ratio of waste heat for gas pass heat recovery boiler. *Regul. Stand.* **2021**, *37*, 26–30.
67. Calculation Formula of Solar Electricity Generation. Available online: <https://www.Everenergy.com.cn/archives/321> (accessed on 6 June 2023).
68. Hydrogen Fuel Cell Performance. Available online: <https://news.panasonic.com/jp/press/jn211001-3> (accessed on 1 June 2023).
69. Meteorological Data of China. Available online: <https://xihe-energy.com/#climate> (accessed on 6 January 2023).
70. Tian, J.; Xu, S. A morphology-based evaluation on block-scale solar potential for residential area in central China. *Sol. Energy* **2021**, *221*, 332–347. [[CrossRef](#)]

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