

Article

Multi-Objective Optimal Configuration of Hydrogen Fuel Cell-Based Multi-Energy Microgrid System Considering Exergy

Ji Li ^{1,*}, Lei Xu ¹, Yang Kou ¹, Weile Liang ¹, Yunshan Wang ¹ and Zhi Yuan ^{2,*}¹ Electric Power Research Institute of State Grid Xinjiang Electric Power Co., Ltd., Urumqi 830011, China² Engineering Research Center of Renewable Energy Power Generation and Grid-Connected Control, Ministry of Education, Xinjiang University, Urumqi 830017, China

* Correspondence: lj24sg@163.com (J.L.); yz2019@xju.edu.cn (Z.Y.)

Abstract: Relying solely on electrical energy storage for energy regulation makes it difficult to provide a stable and efficient energy supply for microgrid systems currently. Additionally, the economic cost of microgrids and the rate of energy use present a challenge that must be addressed. A strategy for allocating capacity for multi-energy microgrids that takes energy efficiency and hydrogen energy into account is offered as a solution to the aforementioned issues. Initially, the construction of the multi-energy microgrid system takes into account the thermoelectric coupling properties of hydrogen energy devices. Second, the system's energy utilization level is measured using the exergy efficiency analysis. Next, the multi-objective capacity optimization allocation model of the multi-energy microgrid system is established, with the exergy efficiency and system economic cost serving as the objective functions. Lastly, the multi-objective model is solved using the ϵ -constraint approach to find the Pareto frontier, and Technique for Order Preference by Similarity to an Ideal Solution is employed for decision-making. The example results demonstrate that, when compared to a traditional microgrid using electric energy storage, the proposed model can effectively lower the system's economic cost and improve exergy efficiency. Additionally, multi-objective capacity optimization can be used to strike a balance between exergy efficiency and the system's economic cost. For relevant studies on the capacity allocation of multi-energy microgrids, this work can be a helpful resource.

Keywords: multi-energy microgrid; hydrogen; multi-objective optimization; exergy

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1. Introduction

Traditional energy systems are under pressure to change and improve due to the world's increasing energy demand and environmental issues. Combining hydrogen energy, an efficient and clean secondary energy source, with a multi-energy microgrid system can increase energy utilization efficiency as well as light and wind dissipation capabilities, which is crucial for achieving sustainable energy development [1,2].

Microgrids that combine many energy sources, conversion devices, and loads based on the energy source's properties and the load demand are known as multi-energy microgrids. The key to ensuring the steady and cost-effective operation of multi-energy microgrids is building a sensible configuration and scheduling plan. In [3], Liu et al. studied a multi-energy microgrid which examined the capacity allocation and combined advantages of hybrid electric–thermal shared energy storage inside a microgrid system from both economic and environmental viewpoints. In [4], Shen et al. built a multi-energy microgrid that is connected to gas, electricity, and heat, and suggested an ideal allocation strategy that considered the multi-energy coupled demand response. This enhances the system's economy and environmental friendliness. In [5], Lu et al. built a standalone multi-energy microgrid using electric storage, photovoltaic cells, an electric chiller, an electric boiler, and a wind turbine. They also suggested a two-stage hybrid decision-making approach to

determine how best to configure the microgrid. In [6], Chen et al. developed a coordinated scheduling and optimized scheduling model for a multi-energy microgrid that is based on cogeneration and P2G technology. This model increases the multi-energy microgrid's flexibility to satisfy a variety of energy demands. In [7], Chen et al. suggest the optimal scheduling model for a multi-energy microgrid system based on carbon capture and storage technologies. This effectively increases the multi-energy microgrid system's environmental friendliness and efficiency of energy use. The aforementioned reference delves further into the optimal configuration and dispatch of multi-energy microgrid systems to attain the synergistic interplay among diverse energy sources inside the system. Nevertheless, none of them gave thought to integrating hydrogen energy into a multi-energy microgrid. Combining hydrogen energy storage with multi-energy microgrids will benefit the system's economic cost and energy supply stability because of its lengthy storage cycles and large storage capacity [8–10].

A microgrid system with hydrogen–electric hybrid energy storage was created by Li et al. in [11], and the capacity configuration of the system's energy storage components was tuned to optimize the economy and dependability of the system. A two-tier optimal scheduling model for hydrogen-based microgrid systems is proposed by Nguyen et al. [12], which effectively lowers the carbon emissions and dispatch costs of microgrid systems. A microgrid system with hydrogen storage that is akin to cogeneration was created by Nojavan et al. in [13]. Simultaneously, an optimal dispatch strategy was suggested to address the uncertainty of renewable energy sources and loads, thereby improving the stability and flexibility of the microgrid system's energy supply. The aforementioned study did not take waste heat from the hydrogen fuel cell (HFC) and electrolyzer (EL) into account, even though it integrated hydrogen energy into a microgrid system. Currently, hydrogen energy systems have a low conversion efficiency. Because some energy is lost as heat in EL and HFC throughout the electricity–hydrogen–electricity conversion process, using waste heat becomes an effective technique to boost the conversion efficiency of hydrogen energy systems. By using an HFC-based cogeneration unit, the hydrogen-based multi-energy microgrid designed by Fang et al. [14] increases the microgrid system's energy utilization efficiency. In [15], Shi et al. take into account the thermal energy consumption of hydrogen energy devices and offer a multi-energy microgrid scheduling model that combines thermal energy and hydrogen energy storage. Nevertheless, the aforementioned research fails to maximize the microgrid system's energy usage efficiency, making it challenging to coordinate the system's economic costs and energy use.

The majority of current research on the energy utilization analysis of multi-energy flow systems focuses on energy efficiency analysis based on the first law of thermodynamics [16–19]. However, in multi-energy flow systems, different types of energy sources are coupled together. The energy efficiency analysis based on the first law of thermodynamics does not account for the varying quality of these energy sources, making it challenging to accurately assess each type of energy flow [20]. Improving energy quality is a more significant goal than preserving energy quantity when it comes to multi-energy flow system energy efficiency. The same quantity of energy might have distinct qualities since this quality differs among different sources of energy. Based on the second law of thermodynamics, exergy efficiency makes assessing the quality of energy easier by examining the most work that can be conducted with a given amount of energy. This approach considers both the “quality” and the “quantity” of the energy [21]. Exergy efficiencies have been used in research to assess and analyze multi-energy flow systems [22,23], but fewer studies have looked at exergy efficiencies in relation to the best way to allocate capacity in multi-energy microgrids.

In this paper, in order to solve the problems mentioned above and realize the efficient and stable energy supply of the multi-energy microgrid system with hydrogen storage, as well as the balance between the economic cost and energy utilization, firstly, a multi-energy microgrid system including a wind turbine, photovoltaic cells, hydrogen storage, a heat storage tank, an absorption chiller, and an electric chiller is established by considering the

application of EL and HFC waste heat. Second, taking into account the system's economic cost as well as the relationship between various energy sources, the multi-objective capacity optimization allocation model of a multi-energy microgrid system is established. The objective function is the system's economic cost and exergy efficiency. Once more, the Pareto frontier of the multi-objective optimization model is solved using the ε -constraint method, and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is used for decision-making. Ultimately, a case simulation is used to confirm the efficacy of the optimization technique presented in this research.

This paper's Section 2 gives the mathematical model of the multi-energy microgrid system. A multi-objective model of the system's capacity allocation is developed in Section 3. The solution approach for the multi-objective model is covered in Section 4. Section 5 describes the optimization findings. Lastly, Sections 6 and 7 offer a discussion section and conclusion.

2. Architecture and Mathematical Modeling of Multi-Energy Microgrid Systems

Figure 1 depicts the connected cold–heat–electricity–hydrogen multi-energy microgrid system built in this work. The system structure description and mathematical model construction are shown below.

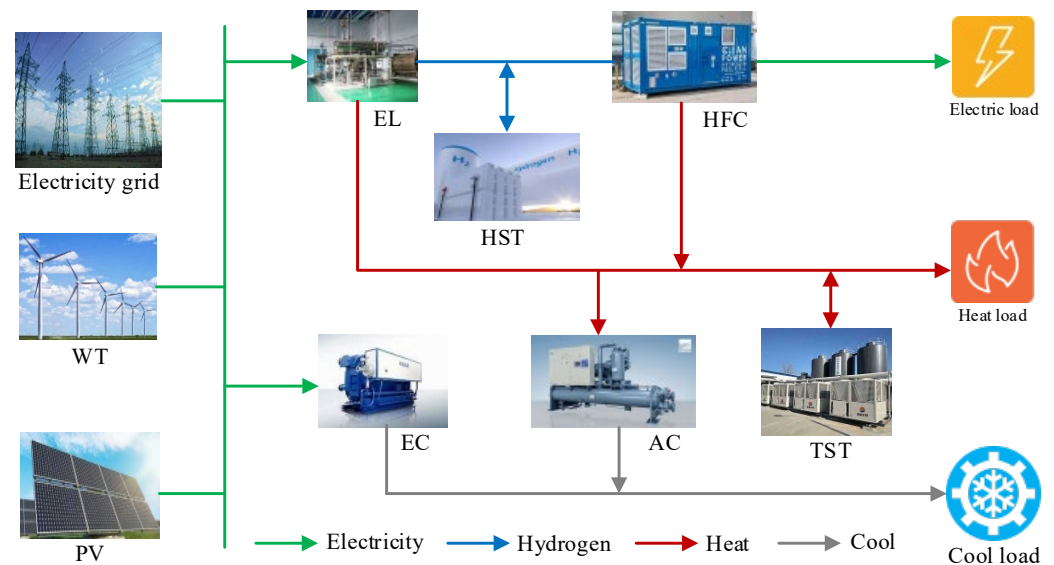


Figure 1. Multi-energy microgrid system architecture.

2.1. Multi-Energy Microgrid System Architecture

The photovoltaic (PV), wind turbine (WT), and upper grid connections provide the multi-energy microgrid system's electricity source. The system's primary energy conversion and storage components are the electric refrigerator (AR), thermal storage tank (TST), absorption chiller (AC), and a hydrogen energy storage system. Thermal, electrical, and cooling loads make up the system's loads.

Hydrogen storage systems include the EL, hydrogen storage tank (HST), and HFC. During the processes of electrolytic hydrogen production and HFC power generation, a significant amount of energy is dissipated as heat, resulting in low energy conversion efficiency for both EL and HFC. Therefore, utilizing the waste heat produced by HFC and EL is a crucial strategy for improving the overall energy conversion efficiency of the hydrogen storage system. The multi-energy coupling properties of EL and HFC may be fully realized by recovering the waste heat of EL and HFC through the waste heat recovery device. This also increases the system's efficiency in using energy and provides low-carbon clean electricity and heat energy [24].

2.2. Modeling of Equipment in Multi-Energy Microgrid Systems

The following displays the mathematical model for every device in the system.

2.2.1. Photovoltaic

The PV's output power can be obtained by measuring the present ambient temperature and the amount of solar energy that the panel has absorbed. The following formula expresses this relationship [25].

$$P_{PV}(t) = P_{sta} f_{PV} \frac{G(t)}{G_{sta}} \{1 + \alpha_T [T_a(t) - T_{a,sta}]\} \quad (1)$$

where $P_{PV}(t)$ is the output power of the PV panel; P_{sta} is the rated power of the PV under standard test conditions; f_{PV} is the attenuation coefficient of the power; $G(t)$ is the intensity of solar irradiation; G_{sta} is the intensity of solar irradiation under standard test conditions; α_T is the temperature coefficient of the PV; $T_a(t)$ is the temperature of the PV; and $T_{a,sta}$ is the ambient temperature under standard test conditions.

The temperature of the photovoltaic panel can be computed using the formula that follows.

$$T_a(t) = T(t) + \lambda G(t) \quad (2)$$

where $T(t)$ is the ambient temperature, and λ is the radiation temperature coefficient, which is 0.0256.

2.2.2. Wind Turbine

Wind energy can be converted by WT into electrical energy, and the wind speed at the unit's hub is what mostly influences its output power. For this reason, the formula for determining WT's output power is provided below [26].

$$P_{WT}(t) = \begin{cases} 0 & 0 < v < v_{in}, v_r < v \\ \frac{P_r(v-v_{in})}{v_{out}-v_{in}} & v_{in} < v < v_{out} \\ P_r & v_{out} \leq v < v_r \end{cases} \quad (3)$$

where $P_{WT}(t)$ is the power generated by WT; P_r is the rated generating power of the WT; v_{in} is the cut-in wind speed of the WT; v_r is the rated wind speed of the WT; and v_{out} is the cut-out wind speed of the WT.

2.2.3. Electrolyzer

Water is converted to hydrogen and oxygen using EL, a type of hydrogen production apparatus. It is assumed in this study that the effectiveness of the EL is constant. Considering the thermoelectric coupling characteristics of the EL, the thermoelectric power relation equation for the EL is presented as follows [27].

$$\begin{cases} M_{el}(t) = \rho \eta_{el} P_{el,e}(t) \\ P_{el,h}(t) = (1 - \eta_{el}) P_{el,e}(t) \end{cases} \quad (4)$$

where $M_{el}(t)$ is the quantity of hydrogen that the EL produces; ρ is the quantity of hydrogen generated for 1 kW·h that the EL uses to generate energy; η_{el} is the EL's efficiency; the EL's input power is denoted by $P_{el,e}(t)$; and $P_{el,h}$ is the heat production power of the EL.

2.2.4. Hydrogen Fuel Cell

HFC uses hydrogen as a raw material and converts it into electricity through a redox reaction. Since HFC produces a lot of heat energy when producing electricity, waste heat recovery technology can be used to realize HFC cogeneration, which can increase HFC's

energy consumption efficiency. Considering the thermoelectric effect of HFC, it is modeled using the following equation [27].

$$\begin{cases} P_{\text{hfc}, e}(t) = \frac{M_{\text{hfc}}(t)}{\rho} \eta_{\text{hfc}}, \\ P_{\text{hfc}, h}(t) = (1 - \eta_{\text{hfc}}) P_{\text{hfc}, e}(t) \end{cases} \quad (5)$$

where $P_{\text{hfc}, e}(t)$ is the power generated by HFC; $M_{\text{hfc}}(t)$ denotes the hydrogen consumption of the HFC; η_{hfc} is the HFC's efficiency; and $P_{\text{hfc}, h}(t)$ is the heat generation power of the HFC.

2.2.5. Hydrogen Storage Tank

The stable operation of hydrogen energy equipment in the microgrid system is dependent on the HST, which stores the hydrogen produced by the EL and supplies it to the HFC when required. The HST is modeled using the following equation [27].

$$M_{\text{hst}}(t) = M_{\text{hst}}(t-1) + \eta_{\text{hst}} M_{\text{el}}(t) - \frac{M_{\text{fc}}(t)}{\eta_{\text{hst}}} \quad (6)$$

where $M_{\text{ht}}(t)$ represents the amount of hydrogen stored in the tank at time t , and η_{hst} denotes the efficiency of HST.

2.2.6. Thermal Storage Tank

TST may efficiently increase the utilization rate of leftover heat from EL and HFC and prevent energy waste by storing heat when there is an excess of waste heat and releasing heat when there is a lack of waste heat. The modeling of TST follows a similar approach to that of HST, and its model is shown by the following formula [28].

$$H_{\text{tst}}(t) = (1 - \eta_{\text{loss}}) H_{\text{tst}}(t-1) + \eta^+ H_{\text{cha}}(t) - \frac{H_{\text{dis}}(t)}{\eta^-} \quad (7)$$

where $H_{\text{tst}}(t)$ represents the TST's overall heat storage capacity; η_{loss} is the TST's dissipation coefficient; η^+ is the heat charging and dissipation coefficient of the TST; $H_{\text{cha}}(t)$ is the TST's heat charging capacity; $H_{\text{dis}}(t)$ is the TST's exothermic capacity; and η^- is the exothermic heat dissipation coefficient of the TST.

2.2.7. Electric Coolers

EC is an electric-cooling coupling device that converts electrical energy into cooling energy according to the system's requirements for cooling load. The model is shown below [29].

$$P_{\text{ec}, c}(t) = \text{COP}_{\text{ec}} P_{\text{ec}, e}(t) \quad (8)$$

where $P_{\text{ec}, c}(t)$ is the EC's cooling power; COP_{ec} is the rated coefficient of performance of the EC; and $P_{\text{ec}, e}(t)$ is the electrical energy required by the EC for cooling.

2.2.8. Absorption Chillers

AC can utilize the waste heat from EL and HFC as the driving energy source. It employs water, ammonia, or Freon as the refrigerant and uses a condenser and evaporator to enable these substances to absorb heat energy for refrigeration purposes. The model for AC is calculated by the subsequent formula [29].

$$P_{\text{ac}, c}(t) = \text{COP}_{\text{ac}} P_{\text{ac}, h}(t) \quad (9)$$

where $P_{\text{ac}, c}(t)$ is the cooling power of AC; COP_{ac} is the rated coefficient of performance of the AC; and $P_{\text{ac}, h}(t)$ is the thermal energy required for AC to achieve cooling.

3. Multi-Objective Capacity Optimization Allocation Model for Multi-Energy Microgrid Systems

The multi-objective capacity optimization allocation model of the system contains an economic objective function and an exergy objective function, as shown below.

3.1. Economic Objective Function

The primary components of multi-energy microgrids' economic costs are those associated with initial construction, operation and maintenance, and power purchasing. Therefore, the economic cost objective function can be expressed as follows [30,31].

$$f_1 = C_{in} \frac{r(1+r)^l}{(1+r)^l - 1} + C_{om} + C_{gc} \quad (10)$$

where C_{in} is the initial construction cost of multi-energy microgrid system; r is the inflation rate; l represents the system's design service life, set at 20 years in this study; C_{om} is the system's operating and maintenance costs; and C_{gc} is the cost of power purchased from the grid.

The following formula can be used to determine the system's initial construction cost.

$$C_{in} = k_{pv}N_{pv} + k_{wt}N_{wt} + k_{hfc}N_{hfc} + k_{el}N_{el} + k_{ht}N_{ht} + k_{tst}N_{tst} + k_{ac}N_{e,ac} + k_{ec}N_{ec} \quad (11)$$

where k_x is the power cost factor for each piece of equipment and N_x is the configured capacity of each piece of equipment.

The following formula can be used to determine the system's operating and maintenance cost.

$$C_{om} = \sum_{t=1}^T (k_{pv,om}P_{pv}(t) + k_{wt,om}P_{wt}(t) + k_{hfc,om}P_{hfc}(t) + k_{el,om}P_{el}(t) + k_{ac,om}P_{ac}(t) + k_{ec,om}P_{ec}(t) + k_{hst,om}M_{hst}(t) + k_{tst,om}H_{tst}(t)) \quad (12)$$

where $k_{x,om}$ is the cost of maintenance and operation for each equipment per unit of power and P_x represents the device's real operational power.

The following is the formula that the system uses to determine how much it will cost to acquire power from the grid.

$$C_{gc} = \sum_{t=1}^T \alpha_e P_{e,buy}(t) \quad (13)$$

where α_e is the power tariff that was purchased and $P_{e,buy}(t)$ is the system's purchased electricity.

3.2. Exergy Objective Function

Multi-energy microgrid systems must maximize energy utilization while also considering economic costs when making capacity allocations. Considering that a coupled cold-heat-electricity-hydrogen multi-energy microgrid system encompasses multiple types of energy and that the quality of energy can vary among these different types, it is important to recognize that energy quality is not necessarily uniform across all energy streams. As a result, evaluating the quality of any kind of energy source is essential. Exergy can evaluate the energy-saving indices of multi-energy microgrid systems in terms of both "quality" and "quantity". This approach is particularly applicable to multi-energy flow systems with multi-energy coupling, providing a reliable basis for the economic configuration and energy-saving operation of such systems.

The exergy of solar energy is considered to be the thermal radiation at the temperature of the Sun and is typically calculated using the Petela formula [32]. The photovoltaic panel's area, solar radiation intensity, ambient temperature, and solar temperature are all related to

the exergy of solar energy, among other things. The expression for this exergy is shown in Equation (14).

$$E_{pv}^{in}(t) = I(t)S_{pv}\gamma(t)\Delta t/1000 \quad (14)$$

$$\gamma(t) = 1 + \frac{1}{3}\left(\frac{T_a(t)}{T_{sun}}\right)^4 - \frac{4}{3}\frac{T_a(t)}{T_{sun}} \quad (15)$$

where $I(t)$ is the solar irradiation intensity; S_{pv} is the area of the PV module; $T_a(t)$ is the ambient temperature; and T_{sun} is the solar temperature, taken as 5777 K in this paper.

The physical nature of wind energy is kinetic energy; therefore, its exergy is related to factors such as wind speed and the area swept by the blades. The calculation equation is shown below [33].

$$E_{wt}^{in}(t) = \frac{8}{27}\rho A_{wt}v_{wt}^3(t) \quad (16)$$

where $v_{wt}(t)$ is the wind speed; A_{wt} is the area swept by the wind through the blades of the fan, taken as 38.47 m²; and ρ is the air density.

The power purchase exergy of the system is shown in Equation (17).

$$E_e^{in}(t) = P_{e, buy}(t)\Delta t \quad (17)$$

where $P_{grid}^e(t)$ is the purchased power of the system and Δt is the operating period.

The exergy of the electrical load in the system is given by the following equation.

$$E_e^{out}(t) = P_{load, e}(t)\Delta t \quad (18)$$

where $P_{load, e}(t)$ represents the electrical load demand.

The following equation displays the exergy for the heat and cold loads.

$$\begin{cases} E_h^{out}(t) = (1 - \frac{T_a}{T_h})P_{load, h}(t)\Delta t \\ E_c^{out}(t) = (\frac{T_a}{T_c} - 1)P_{load, c}(t)\Delta t \end{cases} \quad (19)$$

where T_a is the ambient temperature, T_h is the heat source temperature, $P_{load, h}(t)$ is the heat load demand, T_c is the cooling source temperature, and $P_{load, c}(t)$ is the cooling load demand.

Exergy can effectively and accurately assess the overall energy efficiency of a multi-energy microgrid system. The exergy $E_x^{in}(t)$ input from the energy supply side of the microgrid system is introduced into the microgrid as payment exergy. It then undergoes a series of transmissions, conversions, and storage within the system, ultimately resulting in exergy $E_x^{out}(t)$ as output exergy. Payment exergy consists of $E_{pv}^{in}(t)$, $E_{wt}^{in}(t)$, and $E_e^{in}(t)$, and earnings exergy consists of $E_e^{out}(t)$, $E_h^{out}(t)$, and $E_c^{out}(t)$.

Exergy reflects the degree of matching between the system's energy supply and energy use at the energy level. The exergy of a multi-energy microgrid system can be calculated using the ratio of the system's input exergy to the output exergy. Thus, the system's exergy expression is as follows.

$$\varphi_e = \frac{E_e^{out}(t) + E_h^{out}(t) + E_c^{out}(t)}{E_e^{in}(t) + E_{pv}^{in}(t) + E_{wt}^{in}(t)} \quad (20)$$

To facilitate a solution for the optimization model, the inverse of exergy is used as the system exergy objective function, as shown in the following equation.

$$f_2 = \frac{1}{\varphi_e} \quad (21)$$

3.3. Constraint

The power-balancing constraints, equipment operation constraints, and energy storage equipment operation limitations are the three primary categories of system constraints.

3.3.1. Power Balance Constraints

The power balance constraints contain electrical power balance constraints, thermal power balance constraints, and cold power balance constraints, as shown in Equations (22)–(24).

$$P_{pv} + P_{wt} + P_{e, buy} + P_{hfc, e} - P_{el, e} - P_{ec, e} = P_{load, e} \quad (22)$$

$$P_{hfc, h} + P_{el, h} - P_{ac, h} + H_{dis} - H_{cha} = P_{load, h} \quad (23)$$

$$P_{ac, c} + P_{ec, c} = P_{load, c} \quad (24)$$

3.3.2. Equipment Operating Constraints

The operating constraints of the WT, PV, and other equipment are displayed in Equation (25).

$$\begin{cases} 0 \leq P_{pv}(t) \leq N_{pv} \\ 0 \leq P_{wt}(t) \leq N_{wt} \\ 0 \leq P_{el}(t) \leq N_{el} \\ 0 \leq P_{hfc}(t) \leq N_{hfc} \\ 0 \leq P_{ac}(t) \leq N_{ac} \\ 0 \leq P_{ec}(t) \leq N_{ec} \end{cases} \quad (25)$$

Equation (26) illustrates the operating constraints of the two energy storage devices in the system, HST and TST.

$$\begin{cases} \alpha_{hst} N_{hst} \leq M_{hst}(t) \leq N_{hst} \\ M_{hst, start} = M_{hst, end} \\ \alpha_{tst} N_{tst} \leq H_{tst}(t) \leq N_{tst} \\ H_{tst, start} = H_{tst, end} \end{cases} \quad (26)$$

where α_{hst} and α_{tst} represent the minimum energy storage ratio coefficients for the hydrogen storage tank and thermal storage tank, respectively, with a value of 0.05; $M_{hst, start}$ and $M_{hst, end}$ denote the amount of hydrogen in the hydrogen storage tanks at the beginning and end of each day, respectively; N_{hst} and N_{tst} indicate the configuration capacities of the hydrogen storage tanks and thermal storage tanks, respectively; $H_{tst, start}$ and $H_{tst, end}$ represent the amount of heat stored in the thermal storage tanks at the beginning and end of each day, respectively.

4. Solution Strategies and Evaluation Methods for Multi-Objective Optimization Models

In this section, the solution scheme of the system capacity optimization allocation model developed in the previous section is investigated. The Pareto frontier of the model is solved using the ϵ -constraint method, and TOPSIS is used for decision-making. The multi-objective solution process is illustrated in Figure 2.

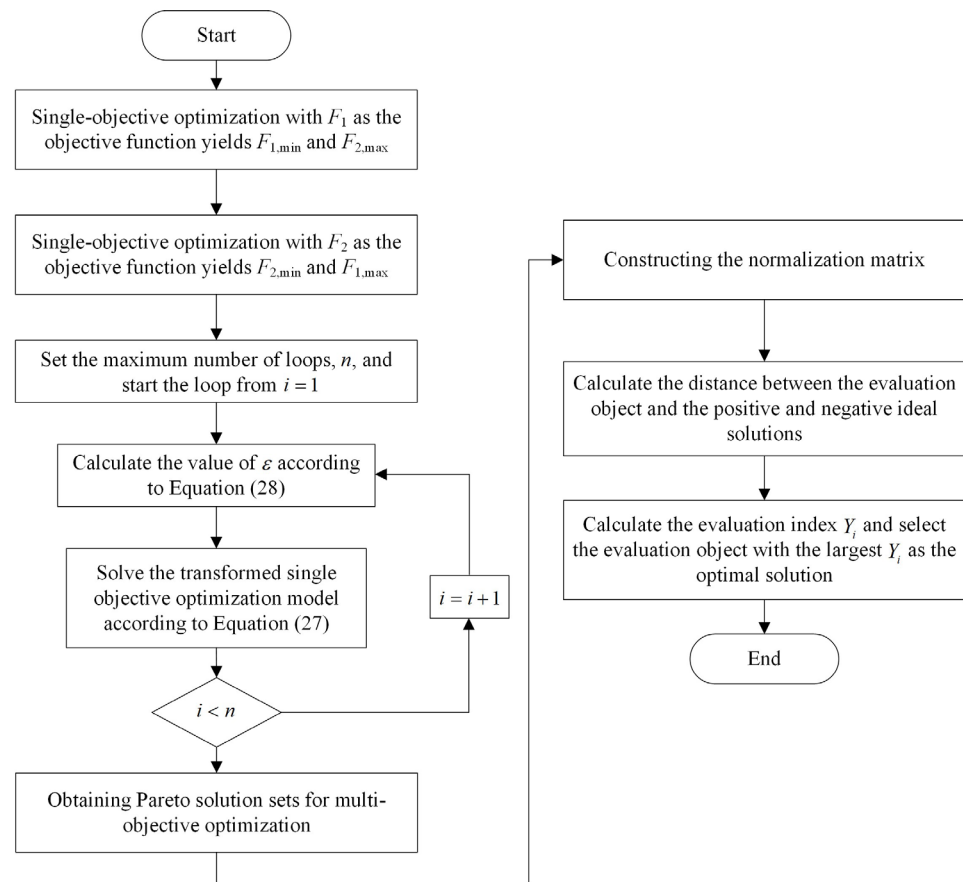


Figure 2. Multi-objective solution process.

4.1. Multi-Objective Solution Strategy

Traditional multi-objective optimization problems typically begin by transforming the multi-objective optimization model into a singular-objective one. This approach allows the multi-objective problem to be addressed by solving the resulting single-objective model. At the moment, the weighting approach and the ε -constraint method are the primary techniques for resolving multi-objective optimization issues [34]. The ε -constraint method is employed in this study to solve multi-objective optimization models due to its advantage of not requiring subjective weights and its ability to provide a complete set of solutions for the Pareto front.

The goal of the ε -constraint method is to convert an objective function in a multi-objective optimization model into a constraint. Then, by gradually altering the constraint's range of values, a multi-objective optimization problem can be converted into a sequence of single-objective optimization problems. This process is illustrated by the following equation [28,34].

$$\begin{cases} \min f_2 \\ \text{s.t.} \begin{cases} f_1 \leq \varepsilon \\ \text{eq. (22)} - \text{eq. (26)} \end{cases} \end{cases} \quad (27)$$

In Equation (27), ε represents the information gap parameter, and its value strategy is provided by Equation (28).

$$\varepsilon = f_{1,\max} - \frac{(f_{1,\max} - f_{1,\min})(i - 1)}{i_{\max} - 1}, \quad i = 1, 2, \dots, n \quad (28)$$

where $f_{1,\max}$ denotes the economic cost of the system when optimized with exergy as the single objective; $f_{1,\min}$ represents the value of the objective function when the system is

optimized with economic cost as the single objective; i indicates the number of cycles; and n is the maximum number of cycles.

The interval of ε ranges from the maximum to the minimum value of f_1 . By varying ε , different objective function values can be obtained, collectively forming the Pareto optimal solution set for the multi-objective problem.

4.2. Evaluation Methodology

Selecting the best possible solutions for the multi-objective optimization issue is necessary because, with the Pareto solution set acquired by the ε -constraint technique, each and every point in the solution set represents the best possible solution. In this paper, the TOPSIS is used to make decisions regarding the points in the Pareto optimal solution set. TOPSIS is a technique for comprehensive evaluation that compares the distances between sample values and ideal solutions. First, the greatest and worst spots in the space are established as reference points. Next, a distance calculation is made between each evaluation object and these reference points. If an object is located closer to the best point and farther from the worst point, it is said to have superior comprehensive qualities [35].

The specific steps required to use TOPSIS for decision-making are listed in the following list.

1. Construct the normalized decision matrix.

$$f'_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^n f_{ij}^2}} \quad (29)$$

where f'_{ij} is the normalized objective value, and f_{ij} is the actual value of the i -th solution for the j -th objective.

2. Determine the positive ideal solution f^+ and the negative ideal solution f^- .

$$\begin{cases} f^+ = \{\max f_{ij} | j = 1, 2, \dots, m\} \\ f^- = \{\min f_{ij} | j = 1, 2, \dots, m\} \end{cases} \quad (30)$$

3. Calculate the Euclidean distance between each evaluation object and both the positive and negative ideal solutions.

$$\begin{cases} D_i^+ = \sqrt{\sum_{j=1}^m (f'_{ij} - f_j^+)^2} \\ D_i^- = \sqrt{\sum_{j=1}^m (f'_{ij} - f_j^-)^2} \end{cases} \quad (31)$$

4. Calculation of evaluation indicators.

$$Y_i = \frac{D_i^-}{D_i^- + D_i^+} \quad (32)$$

The evaluation index Y_i is introduced, with a larger value of Y_i indicating a better program.

5. Calculus Analysis

CPLEX can swiftly determine the optimization model's best solution and solve linear programming problems with good accuracy and resilience. Consequently, the multi-energy microgrid system's optimal configuration model is solved in this study by using the Yalmip toolbox (version 20220204) in MATLAB 2022R with the CPLEX 12.10; the instance settings and scenario analysis are displayed below.

5.1. Instance Setting

To validate the model proposed in this paper, meteorological and load data from a specific location are used as inputs to the system, as shown in Figures 3 and 4. The tariff for purchasing electricity from the grid for the multi-energy microgrid is presented in Table 1. The investment costs and parameters of the equipment in the system are detailed in Table 2. The key parameters of the equipment within the multi-energy microgrid system are presented in Table 3.

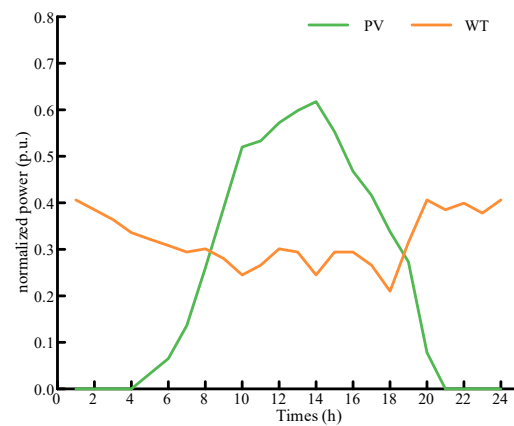


Figure 3. Wind and solar output factor.

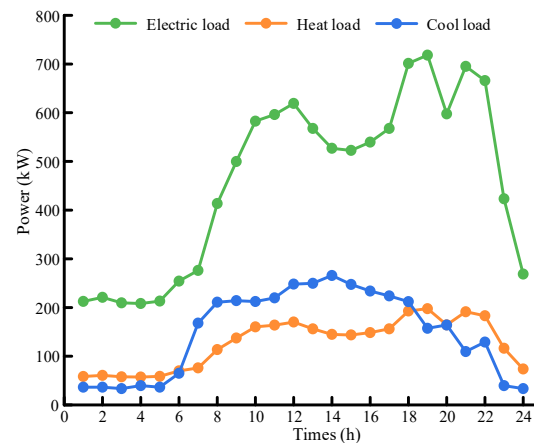


Figure 4. Heat and cool electrical loads in microgrid system.

This paper establishes four distinct scenarios for comparative analysis to examine the impact of the hydrogen energy storage system, considering the utilization of EL and HFC waste heat, on the capacity allocation outcomes of the multi-energy microgrid system, as well as on the multi-objective optimization of the system's performance.

Scenario 1: The capacity allocation is optimized with the best system economic cost using the microgrid model that is presented in this study in Section 2.1.

Scenario 2: In the microgrid model suggested in this study, the hydrogen storage system is replaced with battery electric storage (BES) and electric boiler (EB), and the capacity allocation is optimized with the best system economic cost.

Scenario 3: Capacity optimization with the objective of maximizing system exergy, using the microgrid model outlined in Section 2.1 of this paper.

Scenario 4: The microgrid model proposed in Section 2.1 is subjected to multi-objective optimization, considering both the economic cost and exergy of the system.

Table 1. Time-sharing tariff [36].

Times (h)	Price of Electricity (CNY/kW·h)
01:00–07:00 and 23:00–24:00	0.38
08:00–11:00 and 15:00–18:00	0.68
12:00–14:00 and 19:00–22:00	1.20

Table 2. Time-sharing tariff [29,30,36].

Equipment	Construction Cost (CNY)	Operation and Maintenance Cost (CNY)
PV	17,600	0.020
WT	12,000	0.070
EL	15,840	0.023
HFC	5000	0.060
HST	4928	0.014
TST	1760	0.141
EC	2200	0.160
AC	2502	0.152

Table 3. Key parameters of equipment within a multi-energy microgrid system [27,29,30,36,37].

Parament	Value	Parament	Value
f_{PV}	0.9	η_{el}	0.6
G_{sta}	1000 W/m ²	η_{hfc}	0.6
α_T	$-3.7 \times 10^{-3} \text{ } ^\circ\text{C}$	η_{hst}	0.9
$T_{a,sta}$	25 °C	η_{loss}	0.01
v_{in}	2.5 m/s	η^+, η^-	0.88
v_r	9.5 m/s	COP_{ec}	4.5
v_{out}	40 m/s	COP_{ac}	1.41

5.2. Analysis of Optimization Results for Scenario 1 and Scenario 2

The capacity optimization for Scenario 1 and Scenario 2 is conducted with the system economic cost as the objective. The results for the multi-energy microgrid system's cost and exergy are presented in Table 4, while the microgrid capacity configuration results are shown in Table 5.

As shown in Table 4, EL and HFC are used as thermoelectric coupling equipment in Scenario 1. The construction cost of Scenario 1 is CNY 1,485,800 higher than that of Scenario 2. Compared to Scenario 2, Scenario 1 has reduced operation and maintenance cost and power purchase costs by CNY 2,578,100 and CNY 532,800, respectively. The total cost of Scenario 1 is reduced by CNY 1,249,200 compared to Scenario 2, and exergy is improved by 0.22%.

Table 4. Optimization results for Scenario 1 and Scenario 2.

Item	Scenario 1	Scenario 2
Initial construction cost	6,244,200 CNY	4,758,400 CNY
Operation and maintenance cost	875,200 CNY	3,453,300 CNY
Power purchase cost	1,251,100 CNY	1,408,000 CNY
Total cost	8,370,500 CNY	9,619,700 CNY
Exergy	62.72%	61.91%

Table 5. Equipment capacity configuration results for Scenarios 1 and Scenario 2.

Equipment	Equipment Configuration Capacity	
	Scenario 1	Scenario 2
PV	1083.411 kW	1256.20 kW
WT	1376.79 kW	1191.40 kW
EL	808.15 kW	-
HFC	397.36 kW	-
HST	184.85 kW·h	-
TST	802.44 kW·h	84.87 kW
EC	300 kW	300 kW
AC	94.28 kW	94.28 kW
ESE	-	350.00 kW·h
EB	-	299.01 kW

As shown in Table 5, due to the discrepancy between the peak heat production hours of EL and HFC and the peak heat demand hours, excess heat produced by EL and HFC is stored in TST. This stored heat is then used during peak heat demand periods after the initial heat load demand has been met. Therefore, to ensure the reliability of the heat energy supply in the microgrid system, Scenario 1 requires larger TST configuration. In Scenario 2, the heat load demand is met by the electric boiler, which responds more quickly to heat load variations, thus necessitating a smaller configuration of TST.

5.3. Analysis of Multi-Objective Optimization Result Analysis

The results of the economic cost configuration and device capacities obtained from the optimization of scenarios 3 and 4 are presented in Tables 6 and 7.

Table 6. Optimization results for Scenario 3 and Scenario 4.

Item	Scenario 1	Scenario 2
Initial construction cost	6,244,200 CNY	4,758,400 CNY
Operation and maintenance cost	875,200 CNY	3,453,300 CNY
Power purchase cost	1,251,100 CNY	1,408,000 CNY
Total cost	8,370,500 CNY	9,619,700 CNY
Exergy	62.72%	61.91%

Table 7. Equipment capacity configuration results for Scenario 3 and Scenario 4.

Equipment	Equipment Configuration Capacity	
	Scenario 1	Scenario 2
PV	1083.411 kW	1256.20 kW
WT	1376.79 kW	1191.40 kW
EL	808.15 kW	-
HFC	397.36 kW	-
HST	184.85 kW·h	-
TST	802.44 kW·h	84.87 kW
EC	300 kW	300 kW
AC	94.28 kW	94.28 kW
ESE	-	350.00 kW·h
EB	-	299.01 kW

The total system cost for Scenario 4 increased by CNY 1,262,800 compared to Scenario 1, and its exergy improved by 3.81% relative to Scenario 1. Conversely, Scenario 4's total system cost is CNY 3,236,600 lower than that of Scenario 3, with a system exergy increase of 1.82% compared to Scenario 3.

As shown in Table 7, Scenario 3 focuses solely on optimizing system exergy. Consequently, the capacity configurations for each device obtained from Scenario 3 are higher

compared to those from Scenario 1 and Scenario 4 optimizations. Compared to Scenario 1, Scenario 4 has a higher configured capacity for EL and HFC. This suggests that Scenario 4 effectively leverages the thermoelectric coupling characteristics of EL and HFC. The increased capacity of these components enhances the system's ability to utilize wind energy and reduces the cost of purchasing power for the microgrid.

By dividing a day into 24 one-hour time intervals, the electrical, thermal, and cooling energy balance diagrams for Scenario 4 are presented in Figures 5–7. Power values greater than 0 in the graph represent power generation or heat production, while power values less than 0 indicate power consumption or heat absorption.

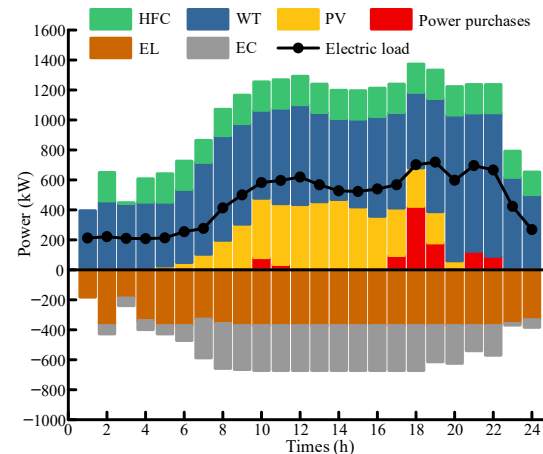


Figure 5. Power balancing in multi-energy microgrid system.

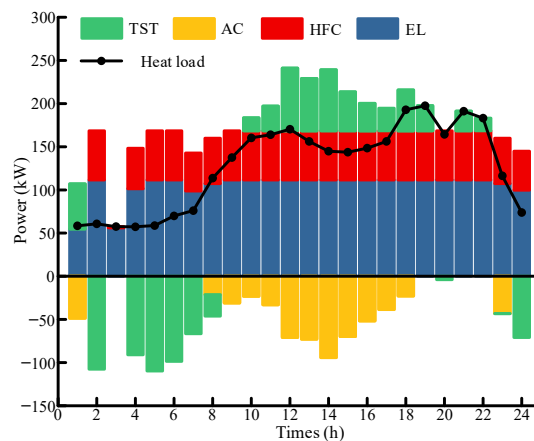


Figure 6. Thermal energy balance in multi-energy microgrid system.

As shown in Figure 5, the primary energy source for the microgrid system is the power generated by wind turbines and PV panels. The load demand peaks during the 10–11, 17–19, and 21–22 time periods. To maintain the stability of the system's energy supply, the system purchases power from the higher-level grid during these periods.

As shown in Figure 6, the heat load demand is low at moments 2 and 4–7. During these times, the excess heat energy, after meeting the heat load demand through EL and HFC, is stored by the TST. The heat load demand is high during the 18–19 and 21–22 time periods, when the TST releases thermal energy to compensate for the heat load deficit. As illustrated in Figure 7, the heat load demand is low, but the cooling load demand is high during the 13–15 time period. Consequently, during this period, the TST, along with EL and HFC, provides thermal energy to meet both the heat load and the cooling requirements of AC.

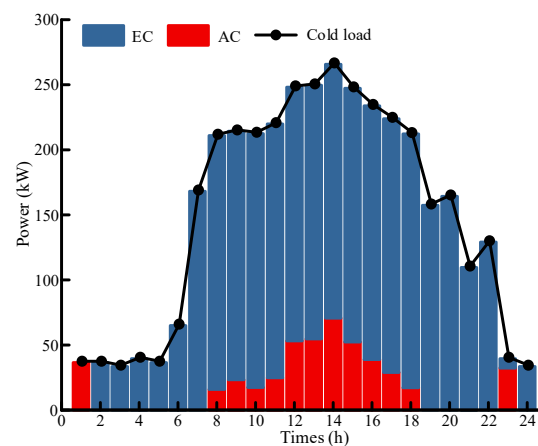


Figure 7. Cool energy balance in multi-energy microgrid system.

As shown in Figure 7, the cooling load demand in the system is met by both the EC and AC. The cooling load is higher during the 8–18 time period, during which the absorption chiller's power is utilized. The absorption chiller leverages low-grade thermal energy for cooling, in contrast to the EC, which uses high-quality electric energy. During these periods, the use of AC enhances the economic efficiency of energy supply and improves the system's exergy.

6. Discussion

In this research, a multi-energy microgrid system with combined cooling, heating, and power supply is realized by combining the operating waste heat of EL and HFC with EC and AC. Multi-objective capacity optimization is used to balance the microgrid system's energy efficiency and economic cost.

The multi-energy microgrid system built in Section 2.1 of this study has significantly increased economics and exergy efficiency when compared to the conventional microgrid system using BES and EG. The hydrogen storage system enhances the system's use of renewable energy sources and energy independence by converting excess electricity from wind power output into hydrogen energy that is stored in HST. This effectively controls the fluctuation of wind power generation. Thus, in comparison to the conventional microgrid system, the system built in this study has a CNY 532,800 lower power purchase cost, and a CNY 1,249,200 lower total economic cost. The exergy efficiency of the system built in this paper is improved by 0.22% when compared to the traditional microgrid system because the coupling of electricity–hydrogen–heat of hydrogen energy equipment is realized through the waste heat utilization of HFC and EL. This effectively improves the flexibility and reliability of energy supply on the load side.

Multi-objective optimization facilitates trade-offs and optimization among multiple objectives. A comparison of the results from multi-objective optimization with those from single-objective optimization reveals that single-objective optimization focused on economic cost can reduce the system's economic cost by CNY 1,622,800, albeit with a decrease in exergy efficiency of 3.81%. Conversely, optimizing solely for exergy efficiency results in an increase in economic cost by CNY 3,236,600 while improving exergy efficiency by 1.82%. Thus, economic cost and exergy efficiency represent conflicting optimization objectives. The optimal solution that accounts for both the economic cost and exergy efficiency of the microgrid system can be achieved through multi-objective optimization.

7. Conclusions

This paper presents the construction of a multi-energy microgrid system based on hydrogen energy with the goal of improving the system's energy supply reliability and resolving the conflict between the microgrid's economic cost and energy efficiency. With the goals of maximizing the system's energy efficiency and decreasing its economic cost, a multi-

objective optimal allocation strategy for the multi-energy microgrid is presented. Ultimately, the solution is solved using TOPSIS and the ε -constraint approach. An arithmetic simulation was used to confirm the efficacy of the suggested approach, and the following findings were made:

1. The operating waste heat of EL and HFC is efficiently utilized by the multi-energy microgrid system built in this paper. The economic cost of the system suggested in this study is CNY 1,249,200 less than the conventional multi-energy microgrid system, and its exergy efficiency is increased by 0.22%.
2. In this paper, we employ multi-objective optimization to determine the optimal configuration of the microgrid system, considering both economic cost and exergy efficiency. The results show that multi-objective optimization enhances the exergy efficiency of the multi-energy microgrid by 3.81% compared to the exergy efficiency achieved through single-objective optimization focused solely on economic cost. Additionally, the economic cost from the multi-objective optimization is reduced by CNY 3,236,600 compared to that derived from single-objective optimization aimed only at maximizing exergy efficiency.

Although this research offers sufficient references for the optimization analysis of multi-energy microgrid systems, several elements still require additional research and development. The impact of unknown variables like wind power and load demand on the system configuration outcomes will be the first thing we look further into in future studies. Second, by carefully modeling the energy conversion components of the system and accounting for both the system's energy loss and the dynamic properties of the components, we will create a thorough energy management plan for the multi-energy microgrid. To further improve the multi-energy microgrid system described in this paper's practical practicality and application, we will also carry out a thorough analysis of the multi-energy microgrid's off-grid state configuration and operation techniques.

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Nomenclature

Abbreviation	Full Name
HFC	hydrogen fuel cell
EL	electrolyzer
PV	photovoltaic
WT	wind turbine
TST	thermal storage tank
EC	electric chiller
AC	absorption chiller
HST	hydrogen storage tank
BES	battery electric storage
EB	electric boiler

References

- George, A.R.; Al-Hinai, A.; Margaret, V. A comprehensive review on energy management strategy of microgrids. *Energy Rep.* **2023**, *9*, 5565–5591.
- Verma, N.; Kumar, N.; Gupta, S.; Malik, H.; Márquez, F.P.G. Review of sub-synchronous interaction in wind integrated power systems: Classification, challenges, and mitigation techniques. *Prot. Control. Mod. Power Syst.* **2023**, *8*, 1–26. [\[CrossRef\]](#)
- Liu, L.; Yao, X.; Qi, X.; Han, Y. Low-carbon economy configuration strategy of electro-thermal hybrid shared energy storage in multiple multi-energy microgrids considering power to gas and carbon capture system. *J. Clean. Prod.* **2023**, *428*, 139366. [\[CrossRef\]](#)
- Shen, Y.; Hu, W.; Liu, M.; Yang, F.; Kong, X. Energy storage optimization method for microgrid considering multi-energy coupling demand response. *J. Energy Storage* **2022**, *45*, 103521. [\[CrossRef\]](#)
- Lu, Z.; Gao, Y.; Xu, C.; Li, Y. Configuration optimization of an off-grid multi-energy microgrid based on modified NSGA-II and order relation-TODIM considering uncertainties of renewable energy and load. *J. Clean. Prod.* **2023**, *383*, 135312. [\[CrossRef\]](#)
- Chen, J.J.; Qi, B.X.; Rong, Z.K.; Peng, K.; Zhao, Y.L.; Zhang, X.H. Multi-energy coordinated microgrid scheduling with integrated demand response for flexibility improvement. *Energy* **2021**, *217*, 119387. [\[CrossRef\]](#)
- Chen, H.; Yang, S.; Chen, J.; Wang, X.; Li, Y.; Shui, S.; Yu, H. Low-carbon environment-friendly economic optimal scheduling of multi-energy microgrid with integrated demand response considering waste heat utilization. *J. Clean. Prod.* **2024**, *450*, 141415. [\[CrossRef\]](#)
- Bhandari, R.; Adhikari, N. A comprehensive review on the role of hydrogen in renewable energy systems. *Int. J. Hydrogen Energy* **2024**, *82*, 923–951. [\[CrossRef\]](#)
- Qiu, Y.; Li, Q.; Ai, Y.; Chen, W.; Benbouzid, M.; Liu, S.; Gao, F. Two-stage distributionally robust optimization-based coordinated scheduling of integrated energy system with electricity-hydrogen hybrid energy storage. *Prot. Control. Mod. Power Syst.* **2023**, *8*, 1–14. [\[CrossRef\]](#)
- Salama, H.S.; Magdy, G.; Bakeer, A.; Vokony, I. Adaptive coordination control strategy of renewable energy sources, hydrogen production unit, and fuel cell for frequency regulation of a hybrid distributed power system. *Prot. Control. Mod. Power Syst.* **2022**, *7*, 1–18. [\[CrossRef\]](#)
- Li, J.; Xiao, Y.; Lu, S. Optimal configuration of multi microgrid electric hydrogen hybrid energy storage capacity based on distributed robustness. *J. Energy Storage* **2024**, *76*, 109762. [\[CrossRef\]](#)
- Nguyen, Q.M.; Nguyen, D.L.; Nguyen, Q.A.; Pham, T.N.; Phan, Q.T.; Tran, M.H. A Bi-level optimization for the planning of microgrid with the integration of hydrogen energy storage. *Int. J. Hydrogen Energy* **2024**, *63*, 967–974. [\[CrossRef\]](#)
- Nojavan, S.; Akbari-Dibavar, A.; Farahmand-Zahed, A.; Zare, K. Risk-constrained scheduling of a CHP-based microgrid including hydrogen energy storage using robust optimization approach. *Int. J. Hydrogen Energy* **2020**, *45*, 32269–32284. [\[CrossRef\]](#)
- Fang, X.; Dong, W.; Wang, Y.; Yang, Q. Multiple time-scale energy management strategy for a hydrogen-based multi-energy microgrid. *Appl. Energy* **2022**, *328*, 120195. [\[CrossRef\]](#)
- Shi, M.; Wang, H.; Lyu, C.; Xie, P.; Xu, Z.; Jia, Y. A hybrid model of energy scheduling for integrated multi-energy microgrid with hydrogen and heat storage system. *Energy Rep.* **2021**, *7*, 357–368. [\[CrossRef\]](#)
- Li, H.; Liang, F.; Guo, P.; He, C.; Li, S.; Zhou, S.; Deng, L.; Bai, C.; Zhang, X.; Zhang, G. Study on the biomass-based SOFC and ground source heat pump coupling cogeneration system. *Appl. Therm. Eng.* **2024**, *165*, 114527. [\[CrossRef\]](#)
- Zhang, Y.; Zhu, N.; Zhao, X.; Luo, Z.; Hu, P.; Lei, F. Energy performance and enviroeconomic analysis of a novel PV-MCHP-TEG system. *Energy* **2023**, *274*, 127342. [\[CrossRef\]](#)
- Kim, J.; Han, C.; Lee, S.; Kim, Y. Performance analysis of PEMFC-assisted renewable energy source heat pumps as a novel active system for plus energy buildings. *Energy Build.* **2024**, *319*, 114477. [\[CrossRef\]](#)
- Yuan, J.; Xiao, F.; Gang, W.; Zhang, Y.; Shi, J.; Zhang, Z.; Hao, X. Load allocation methods for the thermal and electrical chillers in distributed energy systems for system efficiency improvement. *Energy Convers. Manag.* **2023**, *292*, 117334. [\[CrossRef\]](#)
- Tong, C.; Zhang, H.; Liu, H.; Tian, W.; Wang, C. Study on energy efficiency improvement strategies of photovoltaic-hybrid energy storage DC microgrids under the concept of green energy conservation. *Appl. Math. Nonlinear Sci.* **2024**, *9*, 1–20. [\[CrossRef\]](#)

21. Meng, Z.; Wang, K.; Di, J.; Lang, Z.; He, Q. Energy analysis and exergy analysis study of a novel high-efficiency wind-hydrogen storage and power generation polygeneration system. *Int. J. Hydrogen Energy* **2024**, *57*, 338–355. [\[CrossRef\]](#)
22. Yang, S.; Wang, G.; Liu, Z.; Deng, C.; Xie, N. Energy, exergy and exergo-economic analysis of a novel SOFC based CHP system integrated with organic Rankine cycle and biomass co-gasification. *Int. J. Hydrogen Energy* **2024**, *53*, 1155–1169. [\[CrossRef\]](#)
23. Xu, A.; Yang, L.; Huang, W.; Zhang, Y.; Long, H.; Liu, Z.; Deng, C.; Yang, S. Exergy, economic, exergoeconomic and environmental (4E) analyses and multi-objective optimization of a PEMFC system for coalbed methane recovery. *Energy Convers. Manag.* **2023**, *297*, 117734. [\[CrossRef\]](#)
24. Yang, C.; Dong, X.; Wang, G.; Lv, D.; Gu, R.; Lei, Y. Low-carbon economic dispatch of integrated energy system with CCS-P2G-CHP. *Energy Rep.* **2024**, *12*, 42–51. [\[CrossRef\]](#)
25. Kohol , Y.W.; Ngouleu, C.A.W.; Fohagui, F.C.V.; Tchuen, G. Optimization of an off-grid hybrid photovoltaic/wind/diesel/fuel cell system for residential applications power generation employing evolutionary algorithms. *Renew. Energy* **2024**, *224*, 120131. [\[CrossRef\]](#)
26. Das, B.K.; Tushar, M.S.H.K.; Hassan, R. Techno-economic optimisation of stand-alone hybrid renewable energy systems for concurrently meeting electric and heating demand. *Sustain. Cities Soc.* **2021**, *68*, 102763. [\[CrossRef\]](#)
27. Sun, L.; Chen, L.; Xiong, Y.; Li, X.; Mei, W. Capacity optimization configuration of hydrogen energy storage cogeneration integrated energy system considering photothermal collector module. *Electr. Power Autom. Equip.* **2023**, *43*, 70–76.
28. Cao, Y.; Wang, Q.; Du, J.; Nojavan, S.; Jermisittiparsert, K.; Ghadimi, N. Optimal operation of CCHP and renewable generation-based energy hub considering environmental perspective: An epsilon constraint and fuzzy methods. *Sustain. Energy Grids Netw.* **2019**, *20*, 100274. [\[CrossRef\]](#)
29. Ma, X.; Liu, S.; Zhao, S.; Zong, Q.; Liu, H. The optimal configuration of distributed generators for CCHP micro-grid based on double-layer operation strategy and improved NSGA-III algorithm. *Energy Build.* **2023**, *293*, 113182. [\[CrossRef\]](#)
30. Han, Y.; Yu, S.C.; Li, L.Y.; Hou, Y.; Li, Q.; Chen, W. Low-carbon and economic configuration method for solar hydrogen storage microgrid including stepped carbon trading. *High Volt. Eng.* **2022**, *48*, 2523–2533.
31. Zhang, J.; Kan, S.; Hua, Y.; Zhang, X.; You, G.; Zhang, Z. Capacity Optimization of CHP Microgrid Based on Hydrogen Energy Storage. *Acta Energ Sol Sin.* **2022**, *43*, 428–434.
32. Chen, Y.; Guo, M.; Liu, Y.; Wang, D.; Zhuang, Z.; Quan, M. Energy, exergy, and economic analysis of a centralized solar and biogas hybrid heating system for rural areas. *Energy Convers. Manag.* **2023**, *276*, 116591. [\[CrossRef\]](#)
33. Ehyaei, M.A.; Ahmadi, A.; Rosen, M.A. Energy, exergy, economic and advanced and extended exergy analyses of a wind turbine. *Energy Convers. Manag.* **2019**, *183*, 369–381. [\[CrossRef\]](#)
34. Mohebi, P.; Roshandel, R. Optimal design and operation of solar energy system with heat storage for agricultural greenhouse heating. *Energy Convers. Manag. X* **2023**, *18*, 100353. [\[CrossRef\]](#)
35. Wang, X.; Henshaw, P.; Ting, D.S.K. Three-objective Optimization of a Concentrated Photovoltaic Thermoelectric System via Student Psychology-based Optimization Algorithm and an External Archive Strategy. *Energy* **2024**, *304*, 131915. [\[CrossRef\]](#)
36. Wu, Q.; Li, C. Modeling and operation optimization of hydrogen-based integrated energy system with refined power-to-gas and carbon-capture-storage technologies under carbon trading. *Energy* **2023**, *270*, 126832. [\[CrossRef\]](#)
37. Chen, Y.; Chen, J.; Zhang, W.; Ni, C.; Zhao, B. Optimal scheduling strategy of distributed electric-thermo-hydrogen system considering lifetime decay characteristics of electrolytic cell and battery. *Electr. Power Autom. Equip./Dianli Zidonghua Shebei* **2023**, *43*.

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