Research Article

Distributionally Robust Optimal Dispatching of CHP Microgrid considering Concentrating Solar Power and Uncertainty

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In order to solve the problem of diversified low-carbon energy supply with renewable energy as the main body, concentrating solar power (CSP) stations are introduced to act as cogeneration units. Taking full advantage of the flexible coupling and multienergy complementarity of electric, heat, and gas, an economic dispatch method for combined heat and power microgrid systems (CHP microgrid) with interconnected electric, heat, and gas is proposed. First, build the CSP-CHP microgrid structure and model the main equipment. Then, aiming at the minimum operating cost of the system, a regular scheduling model of the CSP-CHP microgrid system is established. On this basis, in order to deal with the uncertainty of renewable energy output, a distributionally robust optimization (DRO) model is introduced. In the DRO model, the Kullback–Leibler (KL) divergence is used to construct an ambiguity set about the predicted error of renewable energy output, and finally, the CSP-CHP microgrid DRO economic dispatch model is established. Finally, the system is simulated and analyzed in a typical CSP-CHP microgrid system, and the feasibility and effectiveness of the proposed method are verified by analysis. In addition, the necessity of introducing CSP and the advantages of the DRO model is further explained by comparison.

1. Introduction

With the vigorous rise of a new round of energy revolution in the world, clean and low carbonization has become the development goal of a new round of energy revolution [1, 2]. The energy Internet can change the independent operation of traditional energy sources and achieve the goal of the multisource coordinated and complementary operation. The combined heating and power (CHP) microgrid system breaks the operating barriers of the traditional energy system, realizes the mutual coupling, substitution, and supplementation of multiple energy forms, and promotes the diversified utilization of energy [3, 4].

In the CHP microgrid, the energy demand periods of electricity and heat loads in the dispatch cycle do not match, and the renewable energy generation has strong randomness [5]. In most cases, traditional coal-fired or gas-fired units are used as the core units in the CHP microgrid. However, both units are constrained by “determining power by heat”, which limits the energy utilization capacity and flexible operation capacity of the system [6, 7]. Some experts propose to use thermal storage equipment to break the rigid operation limit of CHP units [8, 9], but the two-way conversion of energy cannot be realized during operation. Therefore, choosing a new type of green, flexible, and controllable CHP unit is the basic way to solve the emission problem and limited operation mode of traditional units.

Concentrated solar power (CSP) is a new power generation form equipped with a large capacity heat storage system, which can realize the power conversion between “solar-heat-electricity” and has the ability of long-term operation [10]. At present, most of the research focuses on multienergy system collaborative power generation. Morenne P et al. [11] provide fuel for the traditional biomass boiler and the centralized CSP system composed of parabolic trough collector. The results show that biomass/solar hybrid
can reduce biomass consumption, increase the maximum operating hours, and improve the system efficiency. Yang J et al. [12] propose a hybrid renewable energy system, including photovoltaic (PV), wind power, CSP station, battery, and electric heater, and design a system optimization operation strategy composed of a variety of energy storage technologies and flexible power supply. The results show that the combination of CSP and photovoltaic power stations is an effective way to economically improve the reliability of power generation. Guo S et al. [13] propose an optical wind-water hybrid power generation system with pumped storage CSP dual energy storage and study the optimal coordinated operation strategy and multiobjective selection. However, the potential of CSP as a core unit to participate in CHP microgrid operation is ignored.

The traditional CSP faces the problem of a single heat storage source, which cannot give full exert its flexible operation capabilities. An electric boiler is important thermolectric conversion equipment, which can realize one-way and efficient conversion of thermolectric energy [14, 15]. The combined operation of the electric boiler and CSP can realize the bidirectional conversion of electric energy and thermal energy [16]. It can not only use the time-of-use electricity price to obtain low-cost heat storage but also further improve the operational flexibility and energy supply sustainability of the CSP station, making the CSP station have the capability of cogeneration and the potential to replace traditional units.

As an important device in CHP microgrid, energy storage has the advantages of promoting renewable energy consumption, rapid response, and reducing operating costs, and the application of energy storage is becoming more and more extensive [17]. Mohamad F et al. [18] study the impact of energy storage systems on the reliability of power systems, and the results show that the utilization of energy storage in power systems is of great significance for improving system reliability and minimizing costs. Xie C et al. [19] propose a two-layer optimization strategy that considers dispatching energy storage systems in smart microgrids with high photovoltaic penetration, and the results show that the addition of energy storage can effectively reduce the system cost. With the development of the multienergy system, energy storage has gradually changed from single electric energy storage to multienergy storage. Mirzaei M A et al. [20] propose a concept of multienergy cooperation considering multiple types of energy storage to meet consumers’ electricity, natural gas, and thermal energy demands at the lowest operating cost. Multienergy energy storage can effectively improve the performance of generator sets under the constraints of multienergy distribution networks and reduce the total operating cost by 15%. Li et al. [21] adopt the multicycle prediction method of renewable energy generation and load based on automatic reinforcement learning and propose an optimal dispatching model of the isolated microgrid. Dong H et al. [22] propose an integrated energy system optimization technique, including accurate prediction models and multiple forms of energy storage, to improve the load forecasting accuracy and coordinated control of various energy sources in the current integrated energy system. In addition, demand response is also an important factor to be considered in the operation of the microgrid. In the dispatching model, Li et al. [23] promote the balance between energy supply and demand through the comprehensive demand response plan and maintain the comprehensive satisfaction of users within an acceptable range. Chen et al. [24] developed an integrated demand response (IDR) model including power and natural gas demand response in the microgrid. At the same time, the IDR model also considers customer satisfaction.

In order to solve the problem of the random output of renewable energy in CHP microgrid system, in addition to introducing energy storage equipment, stochastic optimization (SO) [25–27] and robust optimization (RO) [28–30] methods are widely used. However, with the increase of the number of scenarios, the SO may lead to the disaster of data dimension and increase the difficulty of calculation. In the robust optimization solution, the results are too conservative due to the low probability of the worst case.

In view of the shortcomings of the above two methods, distributionally robust optimization (DRO), as a new uncertainty optimization method, has become a research hotspot in recent years [31]. At present, there have been many studies on the application of DRO in the operation of the energy system, including the unit commitment problem [32, 33] and economic dispatching problem [34, 35]. Chen G et al. [36] present a fast power DRO dispatching model for multifzone heating, ventilation, and air conditioning (HVAC) systems. Wasserstein distance is used to construct ambiguity sets to deal with the uncertainty from prediction error, so as to improve the optimality of the solution. Zhang Y et al. [37] propose a data-driven distributionally robust optimization (DDRO) model for multienergy coupled systems. In this model, the ambiguity set of wind power output is constructed according to the moment information used in the probability distribution of the wind power scenario.

According to the above literature analysis, the following is obtained. (1) At present, in the cooperative operation of multiple energy sources, the CSP station is not taken as the core unit. Therefore, it cannot fully play its role in the “solar-thermal-electricity” conversion. (2) Although DRO has been successfully used in the operation of various energy systems, this method has not been used in the study of CHP microgrids including CSP. Besides, the DRO model based on Kullback–Leibler (KL) divergence can be transformed into a deterministic mixed-integer linear optimization model through correlation transformation, which can be solved directly by a commercial solver [38]. Therefore, it is necessary to study the related problems of constructing the CHP microgrid operation model including CSP based on the DRO method.

Based on this, the contribution of this study is as follows:

(1) The concentrated solar power station is introduced into the cogeneration system and used as the core unit to realize the efficient energy conversion between the “solar-thermal-electricity” of the system.
The electric boiler is added to the system to improve the operational flexibility and energy supply sustainability of the concentrated solar power station. Finally, the CSP-CHP microgrid joint system is formed.

(2) Aiming at the lowest total operation cost of the system, the conventional dispatch model of the CSP-CHP microgrid system is constructed. At the same time, in order to deal with the uncertainty of renewable energy output in the system, the distributionally robust optimization model is introduced into the conventional dispatching model, and the KL divergence is used to describe the prediction error of renewable energy output.

(3) The simulation is carried out in a typical CSP-CHP microgrid system. The simulation results show that the introduction of the CSP station can effectively reduce the CSP-CHP microgrid system operation cost and improve operational efficiency. In addition, it also verifies the advantages of the distributionally robust optimization model in dealing with renewable energy output, improving solution efficiency, and reducing operating costs.

The rest of this study is organized as follows. The structure of CHP microgrid containing CSP is analyzed in Section 2. Section 3 introduces and models the main equipment in the CSP-CHP microgrid system. In Section 4, the conventional dispatching model and distributionally robust dispatching model of the CSP-CHP microgrid system are established. A system simulation is performed in Section 5, and some main conclusions are presented in Section 6.

2. System Description

In a traditional CHP microgrid, conventional power generation limits its operational flexibility and efficiency due to its working mode of “determining power by heat” and usually needs to be equipped with energy storage to realize thermoelectric decoupling. Secondly, traditional CHP microgrid is limited by the independent operation of various energy forms of electricity, heat, and gas. Although the conversion of different energy forms can be realized by configuring energy conversion equipment, only one-way conversion of energy can be realized.

In view of the above problems, by optimizing and adjusting the traditional system structure, a CHP microgrid structure including CSP, energy storage, and multienergy two-way interconnection is constructed, as shown in Figure 1.

The CSP replaces the traditional cogeneration unit as the core energy supply equipment of the system, and the electric boiler cooperates with the CSP to realize the bidirectional conversion of electricity and heat energy. The power-to-gas (P2G) device and the gas turbine realize the bidirectional conversion of electricity-gas energy, that is, the CSP-CHP microgrid realizes the interconnection between different energies through the energy conversion equipment. The energy storage device realizes the high-value utilization of energy across time periods through the energy time-shift characteristic, which effectively improves the operating flexibility and economy of the system.

A variety of clean power generation energy sources on the power supply side can realize coordinated operation and mutual backup, ensuring the stable and efficient operation of the CSP-CHP microgrid. However, the renewable energy inside the CSP-CHP microgrid system has the characteristics of output uncertainty, which adversely affects the stability of the system.

3. Main Equipment Models in CSP-CHP Microgrid

3.1. Model of Energy Supply Equipment

3.1.1. Concentrated Solar Power (CSP). The composition of the CSP includes 3 parts: concentrating heat-collecting mirror field, generator, and thermal storage system. The input thermal power of the CSP station can be represented by the thermal power converted and collected by the concentrating heat-collecting mirror field through solar radiation. The output $P^t_{\text{CSP}}$ of the CSP station in period $t$ is

$$P^t_{\text{CSP}} = \eta_{\text{csp}} (Q_{\text{m2g}} + Q_{\text{e2g}}),$$

where $\eta_{\text{csp}}$ is the thermoelectric conversion efficiency, $Q^t_{\text{m2g}}$ is the heat supplied by the mirror field to the generator, and $Q^t_{\text{e2g}}$ is the heat supplied by the thermal storage energy to the generator.

The thermal provided by the mirror field to the thermal storage system at time $t$ is

$$Q^t_{\text{m2f}} = (1 - \eta_{\text{m2e}}) (Q^t_{\text{mf}} - Q^t_{\text{m2f}} - Q^t_{\text{m2g}}),$$

where $\eta_{\text{m2e}}$ is the loss degree of heat transmission, $Q^t_{\text{mf}}$ is the heat collected by the concentrating heat-collecting mirror field, and $Q^t_{\text{m2f}}$ is the heat that cannot be used by the CSP station.

In addition, the thermal storage system in the CSP station should also satisfy the following equation constraints at each time period:

$$Q^t_e = (1 - \tau) Q^{t-1}_e + \eta_{\text{tes}}^{\text{ch}} N_{\text{tes}}^{\text{ch}} \Delta t - \frac{N_{\text{tes}}^{\text{dis}}}{\eta_{\text{tes}}} \Delta t,$$

$$N_{\text{tes}}^{\text{dis}} = Q_{\text{e2g}} + Q_{\text{tes}}^{\text{ch}},$$

where $Q^t_e$ is the stored heat of thermal energy storage, $\tau$ is the heat loss degree of thermal energy storage, $\eta_{\text{tes}}^{\text{ch}}$ and $\eta_{\text{tes}}^{\text{dis}}$ are the heat storage and heat release efficiency of the thermal storage system, respectively, $N_{\text{tes}}^{\text{ch}}$ and $N_{\text{tes}}^{\text{dis}}$ are the heat storage and heat release power of the thermal storage system, respectively, and $Q_{\text{tes}}^{\text{ch}}$ is the amount of heat supplied by the thermal storage system to the heat load.

When the CSP station participates in the dispatching operation, the generator and thermal storage system will generate operation and maintenance costs. The operation and maintenance costs $C_{\text{CSP}}$ are
3.1.2. Gas Turbines (GT) and Waste Heat Boiler (WH).
In CSP-CHP microgrid, GT units are the only equipment with nonnegligible carbon emissions. Under the carbon trading mechanism, the penalty mechanism for exceeding carbon emission quotas is adopted, and the carbon emission expenditure of GT units $C_{\text{gt}}$ is

$$C_{\text{gt}} = c_{\text{em}} \left( e_{\text{gt}} - e_{\text{m}} \right) P_{\text{gt}}^t,$$

where $c_{\text{em}}$ is the operation and maintenance cost coefficient of thermal energy storage and generator, respectively.

The GT unit provides energy by burning natural gas, so the relationship between power generation $P_{\text{gt}}^t$ and natural gas consumption $V_{\text{gt}}^t$ is as follows:

$$P_{\text{gt}}^t = \frac{V_{\text{gt}}^t \eta_{\text{gt}} L_N}{M},$$

where $\eta_{\text{gt}}$ is the power generation efficiency of GT, $L_N$ is the low calorific value of GT, and $M$ is the conversion value of calorific value and power, taking 3.6.

Operation and maintenance costs $C_{\text{gt}}$ will be incurred when GT unit participate in the dispatching operation, which are as follows:

$$C_{\text{gt}} = u_{\text{gt}}^t c_{\text{om}}^t P_{\text{gt}}^t,$$

where $u_{\text{gt}}^t$ is a 0–1 variable, indicating the operating state of GT, and $c_{\text{om}}^t$ is the operation and maintenance cost coefficient of GT.

The heat generated by the GT unit during power generation can be recovered by the WH for secondary use. The heat collected $Q_{\text{wh}}^t$ by the WH in the $t$ period is

$$Q_{\text{wh}}^t = \eta_{\text{wh}} \left( \frac{L_N V_{\text{gt}}^t}{M} - P_{\text{gt}}^t \right),$$

where $\eta_{\text{wh}}$ is the heat recovery efficiency of the waste heat boiler and $Q_{\text{wh}}^{\text{max}}$ is the maximum heat collection of the waste heat boiler.

### Figure 1: CSP-CHP microgrid structure.
The relationship between the volume \( V_{p2g}^{\text{ch4}} \) of methane produced by the power-to-gas device and the power consumption \( P_{p2g}^{\text{ch4}} \) is
\[
V_{p2g}^{\text{ch4}} = \frac{3.6 \eta_{p2g} P_{p2g}^{\text{th}}}{L_N}\]
(9)
where \( \eta_{p2g} \) is the conversion efficiency of P2G.

The volume of methane produced by P2G is equal to the volume of carbon dioxide consumed by the reaction; then,
\[
V_{p2g}^{\text{ch4}} = \frac{R_{p2g}}{\rho_{co2}}\]
(10)
where \( R_{p2g} \) is the mass of CO\(_2\) required for the operation of the P2G and \( \rho_{co2} \) is the gaseous density of CO\(_2\).

According to the operation of P2G, the cost is divided into three parts: carbon transaction cost, CO\(_2\) purchase cost, and operation and maintenance cost. In addition, the P2G has the ability to reduce carbon during production and operation and can be directly sold in the carbon trading market for economic benefits. Based on this, the carbon transaction cost \( C_{t,c}^{\text{co2}} \) of P2G can be expressed as
\[
C_{t,c}^{\text{co2}} = \eta_{co2} \frac{e_{p2g} - e_{p}}{P_{p2g}^{\text{th}}}\]
(11)
where \( e_{p2g} \) is the amount of CO\(_2\) absorbed when P2G consumes unit electric power, which can be solved by equations (9) and (10), and \( e_{p} \) is the carbon emission allocation for P2G, which takes a value of 0.

When the P2G is operation, CO\(_2\) needs to be purchased from the carbon trading market; then, the cost of purchasing CO\(_2\) \( C_{t,buy}^{\text{co2}} \) is
\[
C_{t,buy}^{\text{co2}} = \eta_{co2} R_{p2g}^{\text{th}} P_{p2g}^{\text{th}},
\]
(12)
where \( \eta_{co2} \) is the price per unit mass of CO\(_2\) purchased from the carbon trading market.

The P2G needs maintenance during operation, and the maintenance cost of P2G is
\[
C_{t,\text{om}}^{\text{p2g}} = \epsilon_{p2g} P_{p2g}^{\text{th}},
\]
(13)
where \( \epsilon_{p2g} \) is the operation and maintenance cost coefficients of P2G.

### 3.2.2. Electric Boiler (EB).
As an important electric heat conversion equipment in CPS-CHP microgrid, the operation efficiency of electric boiler is close to 100%. In this CPS-CHP microgrid, the EB, thermal storage system, and WH provide heat to improve the flexibility of operation of the whole system.

The output \( Q_{eb}^{\text{th}} \) model of EB is
\[
Q_{eb}^{\text{th}} = \eta_{eb} P_{eb}^{\text{th}},
\]
(14)
where \( \eta_{eb} \) is the conversion efficiency of EB, \( P_{eb}^{\text{th}} \) is the electric energy consumed by the EB, and \( Q_{eb}^{\text{th}} \) is the upper limit of thermal power output of EB.

### 3.2.3. Energy Storage (ES).
Both gas energy storage and electric energy storage are energy storage equipment, so the mathematical model is very similar. A unified mathematical model can be established to describe
\[
P_{t}^{\text{es}} = P_{0}^{\text{es}} + \sum_{i=1}^{T} E_{t}^{\text{ch}} \eta_{ch} \Delta T - \sum_{i=1}^{T} E_{t}^{\text{dis}} \eta_{dis} \Delta T, P_{t}^{\text{es}} = P_{0}^{\text{es}}, 0 \leq E_{t}^{\text{ch}} \leq s_{ch,t} E_{t}^{\text{ch,max}}, 0 \leq E_{t}^{\text{dis}} \leq s_{dis,t} E_{t}^{\text{dis,max}}, 0 \leq s_{ch,t} + s_{dis,t} \leq 1,
\]
(15)
where \( P_{t}^{\text{es}} \) denotes the energy stored in ES, \( P_{0}^{\text{es}} \) is the initial state of ES, \( \eta_{ch} \) and \( \eta_{dis} \) represent the charging and discharging efficiency, respectively, \( E_{t}^{\text{ch,max}} \) and \( E_{t}^{\text{dis,max}} \) represent the maximum charging and discharging power, respectively, and \( s_{ch,t} \) and \( s_{dis,t} \) are the binary variables.
4. Economic Dispatch Model of CSP-CHP Microgrid

4.1. Conventional Dispatching Model

4.1.1. Objective Function. The dispatching operation goal of CSP-CHP microgrid is to minimize system operating costs, including interaction costs of CSP-CHP microgrid and external network $C_{\text{inter}}^t$, CSP-CHP microgrid operation and maintenance costs $C_{\text{om}}^t$, and CSP-CHP microgrid carbon trading costs $C_{\text{tr}}^t$. Then, the conventional optimization model of the CSP-CHP microgrid is

$$
C_{\text{om}} = \sum_{t=1}^{T} (C_{\text{inter}}^t + C_{\text{om}}^t + C_{\text{tr}}^t),
$$

$$
C_{\text{inter}}^t = (c_{\text{buy}}^t P_{\text{buy}}^t - c_{\text{sell}}^t P_{\text{sell}}^t) + (\lambda_{\text{buy}}^t V_{\text{buy}}^t - \lambda_{\text{sell}}^t V_{\text{sell}}^t),
$$

$$
C_{\text{om}}^t = c_{\text{em}}^{t, \text{om}} + c_{\text{om}}^{t, \text{om}} + \lambda_{\text{ch}}^t Q_{\text{ch}}^t + \lambda_{\text{eh}}^t Q_{\text{eh}}^t + \lambda_{\text{dis}}^t (E_{\text{dis}}^t - E_{\text{ch}}^t),
$$

where $c_{\text{buy}}^t$ and $P_{\text{buy}}^t$ are the price and quantity of electricity purchased by CSP-CHP microgrid from the external grid, respectively, and $c_{\text{sell}}^t$ and $P_{\text{sell}}^t$ are the price and quantity of electricity sold by CSP-CHP microgrid to the external grid, respectively. Gas purchases are similar to electricity purchase variables. $c_{\text{om}}^{t, \text{em}}$, $c_{\text{om}}^{t, \text{om}}$, and $c_{\text{om}}^{t, \text{em}}$ are the operation and maintenance cost coefficients of WH, EB, and ES.

4.1.2. Equipment Operation Constraint

(1) Power balance constraints:

$$
P_{\text{CSP}}^t + P_{\text{GT}}^t + P_{\text{buy}}^t + P_{\text{dis}}^t = P_{\text{ch}}^t + E_{\text{ch}}^t + P_{\text{sell}}^t + P_{\text{L}},
$$

$$
N_{\text{ch}}^{\text{dis}} + Q_{\text{ch}}^t + Q_{\text{eh}}^t = Q_{\text{chb}}^t + Q_{\text{ehb}}^t + Q_{\text{L}},
$$

$$
V_{\text{buy}}^t + V_{\text{ch}}^{\text{ch}} + V_{\text{dis}}^t = E_{\text{ch}}^t + V_{\text{gt}}^t + G_{\text{L}},
$$

where $E_{\text{ch}}^t$ and $P_{\text{dis}}^t$ are the charging and discharging power of the ES, respectively, $P_{\text{L}}$, $Q_{\text{L}}$, and $G_{\text{L}}$ are the electric load, thermal load, and gas load, $Q_{\text{chb}}^t$ and $Q_{\text{ehb}}^t$ are the heat transferred from the electric boiler and waste heat boiler to the thermal storage system, respectively, $E_{\text{ch}}^t$ and $E_{\text{dis}}^t$ are the charging and discharging power of the gas ES, respectively, and $N_{\text{ch}}^{\text{dis}}$ is the heating power supplied by the thermal storage system to the thermal load. Equations (17)–(19) represent the power balance of electric energy, thermal energy, and natural gas, respectively.

(2) CSP operation constraints:

(1) Thermal power balance constraints:

$$
Q_{m,f}^{\text{ex}} = (1 - \eta_{m,2}) (Q_{m,f}^t - Q_{m,f}^{\text{loss}} - Q_{m,2}^t), \quad Q_{m,2}^t \geq 0,
$$

$$
Q_{m,f}^{\text{ex}} = (1 - \eta_{m,2}) (Q_{m,f}^t - Q_{m,f}^{\text{loss}} - Q_{m,2}^t), \quad Q_{m,2}^t \geq 0.
$$

(2) Thermal storage system constraints:

$$
Q_{\text{chb}}^t + Q_{\text{ehb}}^t + Q_{\text{chb}}^t = N_{\text{ch}}^{\text{ch}},
$$

$$
Q_{\text{chb}}^t + N_{\text{ch}}^{\text{dis}} = N_{\text{ch}}^{\text{max}}, \quad 0 \leq N_{\text{ch}}^{\text{max}}, \quad 0 \leq N_{\text{ch}}^{\text{dis}},
$$

(3) Generator unit constraints:

$$
P_{\text{CSP}}^\text{min} \leq P_{\text{CSP}}^t \leq P_{\text{CSP}}^\text{max},
$$

$$
-r_d \leq P_{\text{CSP}}^t - P_{\text{CSP}}^{t-1} \leq r_d,
$$

where $r_d$ and $r_d$, respectively, represent the up and down climbing power limits of the generator unit. Equations (20)–(21) are the heat balance constraints inside the CSP. Equation (24) is the heat charging and discharging constraint of the thermal storage system. Equations (25) and (26) are the output and climbing constraints of the generator unit, respectively.

(3) Gas turbines’ constraints:

(1) GT reserve constraints: reserve is the additional capacity of the power system that needs to be added to ensure stable operation under the influence of uncertain variables. Regulating reserves (RR) can be used to deal with forecast errors of renewable energy output, and spinning reserves (SR) can be used to deal with emergencies:

$$
S_{\text{R}} \geq P_{\text{R}}^t, \quad S_{\text{S}}^t \geq P_{\text{S}}^t,
$$

$$
0 \leq S_{\text{R}} \leq r_{\text{GT}} T_{\text{R}},
$$

$$
0 \leq S_{\text{S}}^t \leq r_{\text{GT}} T_{\text{S}},
$$

$$
-S_{\text{R}} \leq \xi \leq S_{\text{R}},
$$

where $S_{\text{R}}^t$ and $S_{\text{S}}^t$ are the RR and SR capacity of GT, respectively, $P_{\text{R}}^t$ and $P_{\text{S}}^t$ are the total requirements for RR and SR, respectively, $r_{\text{GT}}$ is the ramp rate of the GT, $T_{\text{R}}$ and $T_{\text{S}}$ are the response times required for RR and SR, respectively, $\xi$ is the output forecast error of
renewable energy, which is an uncertain variable. Equation (27) represents the reserve demand of gas turbine. In order to balance the uncertain prediction error of renewable energy output, the regulation reserve shall meet the constraints of (30).

(2) GT operation constraints:

\[ P_{gt}^d + S_t^r + S_t^s \leq P_{gt}^{\text{max}}, \]  
\[ P_{gt}^{\text{min}} \leq P_{GT,t} - S_t^r, \]  
\[ -r_{GT} \leq P_{gt}^d - P_{gt}^{d-1} \leq r_{GT}, \]

where \( P_{gt}^{\text{max}} \) and \( P_{gt}^{\text{min}} \) are the maximum and minimum output of the GT. Equations (31)–(33) are the output and climbing constraints of GT unit, respectively.

(4) Other unit constraints: constraints such as wind turbine (WT), photovoltaics (PV), interaction with the electricity market (EM), and interaction with the gas market (GM) are as follows:

\[ \Phi_t^{\text{min}} \leq \Phi_t \leq \Phi_t^{\text{max}}, \]

where \( \Phi = \{ \text{WH, EB, P2G, WT, PV, EM, GM} \} \), \( \Phi_t^{\text{min}} \) is the minimum output of the equipment. \( \Phi_t^{\text{max}} \) is the maximum output of the equipment.

4.2. Distributionally Robust Transformation of the CSP-CHP Microgrid Model. It can be seen from Figure 1 that the CSP-CHP microgrid system includes wind turbines and photovoltaics, but its output has random fluctuations, which will affect the stable operation of the CSP-CHP microgrid system.

4.2.1. DRO Model Reorganization. For clear representation, the CSP-CHP microgrid dispatching model constructed above can be abbreviated as follows:

\[ \min_{x \in X} f(x), \]  
\[ \text{s.t. } F(x, \xi) \leq 0, \]

where \( x \) represents the decision variable, \( \xi \) represents the uncertainty variable, and \( X \) is the feasible region of \( x \).

Since constraint (30) contains the uncertainty variable \( \xi_t \), the model is difficult to solve directly. Therefore, this study adopts the distributionally robust optimization method to deal with the model. It can be rewritten in the form of robust opportunistic constrained optimization:

\[ \min_{x \in X} f(x), \]  
\[ \text{s.t. } P_r \{ F(x, \xi) \leq 0 \} \geq 1 - \alpha, \]

where \( P \) is the distribution function of \( \xi, \Omega_P \) is the ambiguity set of \( P, P_r \) is the probability of the distribution function, and \( \alpha \) is the significance level. The robust chance constraint in (38) describes that even if \( \xi \) is under the worst distribution of \( \Omega_P \), the constraint is still satisfied with a probability of not less than \( 1 - \alpha \).

4.2.2. Ambiguity Set. In order to solve the constructed DRO model, the ambiguity set of \( P \) needs to be constructed first. Based on the above analysis, this study adopts the method based on the KL divergence to construct the ambiguity set. That is, the KL divergence is used as a measure of the distance between the distribution function \( P \) and the reference distribution function \( P_0 \), and the size of the distance represents the similarity between the two distribution functions:

\[ D_{KL}(PP_0) = \int f(\omega) \frac{f(\omega)}{f_0(\omega)} d\omega, \]

where \( f(\omega) \) is the density function of \( P \) and \( f_0(\omega) \) is the density function of \( P_0 \).

The closer the distance between the two distributions, the higher the similarity. Considering all distribution functions whose distance from \( P_0 \) does not exceed \( d \), the following ambiguity set of distribution functions is constructed:

\[ \Omega_P = \{ P | D_{KL}(PP_0) \leq d \}. \]

When \( d \) is 0, there are countless qualified distribution function in \( \Omega_P \). Different \( d \) corresponds to different ambiguity sets, and the size of decision risk is also different. The DRO model transformation and solution process are detailed in [36].

5. System Simulation

The basic operation result analysis is to verify the operation feasibility of introducing the CSP and DRO method (that is, whether the scheme satisfies the balance of supply and demand in each dispatch period). On this basis, different operation scenes are compared from the perspectives of CSP and uncertainty method to verify the effectiveness of this scheme in reducing system operating costs. At the same time, it can provide dispatching decision-making basis for scheduling decision makers.

5.1. Parameters and Scene Settings. The internal basic structure of CSP-CHP microgrid used in the calculation example is shown in Figure 1. The maximum ramp rate of the P2G equipment is 90 kW/h, and the maximum operating power is 240 kW. The carbon emission price factor is 0.18 DKK/kg. The operation and maintenance cost of GT unit is 0.09 DKK/(kW · h), the upper limit of its output power is 200 kW, and its carbon emission intensity is 0.51 kg/(kW · h). The energy conversion efficiency of the EB is taken as 0.98, the upper limit of its output thermal power is 650 kW, and the maintenance cost of the electric heater is taken as 0.06 DKK/kW. Other parameters are detailed in Table 1.

The forecast data of wind power and photovoltaic output are shown in Figure 3. The electrical load and thermal load
data in the system are shown in Figure 4(a), and the gas load are shown in Figure 4(b). The time-of-use tariff mechanism is adopted when the system interacts with the external network, and the time-of-use price at different time periods is shown in Figure 5(a). The purchase price of gas at different time periods is shown in Figure 5(b).

### 5.2. Analysis of Basic Operating Results

#### 5.2.1. Electric Energy Dispatching Results

Electric energy storage utilizes its storage/discharge characteristics to realize the time transfer and value enhancement of electric energy. The dispatching results of electric energy storage are shown in Figure 7.

It can be seen from Figure 5(b), it can be seen that the electricity price is relatively low at this time. Electric energy storage discharges at 8:00–10:00, 20:00, and 22:00, and the electricity market price is relatively high at this time. In this way, the purpose of “charging at a low price and discharging at a high price” is achieved so that the total cost of the system is lower. In addition, the reasonable dispatching of the CSP-CHP microgrid system is realized through the DRO model so that there is no abandonment of wind power and PV in the system.

#### 5.2.2. Thermal Energy Dispatching Results

The thermal energy consumption of the CSP-CHP microgrid system is mainly thermal load, thermal storage system, and CSP station. The thermal energy dispatching of the system is shown in Figure 8.

It can be seen from Figure 8 that the system can meet the thermal demand of the system. It can be seen from Figure 8 that the system can meet the thermal demand of the system. During the period of 00:00–07:00, most of the system heat energy comes from the electric boiler. From 07:00, the thermal storage system will collect the heat from the mirror field and store some of the heat supplied by the electric boiler. During the period from 08:00 to 22:00, with the continuous supply of heat energy from the waste heat boiler and the electric boiler and the heat release from the thermal storage system, the system can meet the heat load. The heat collected by the mirror field and part of the heat released by the thermal storage system realize the conversion of heat-electric energy through the CSP station, thereby meeting the electricity demand of the system.

During this dispatch period, the thermal storage system cooperates with the electric boiler to achieve the goal of low-cost heat storage of the thermal storage system based on the time-of-use electricity price. The thermal storage system uses its heat storage/release characteristics to realize the time transfer and value enhancement of thermal energy, improve the flexibility of the heat storage system and the power generation capacity of the CSP station, and deeply tap the flexible operation potential of the CSP station. At the same time, the electric boiler and the CSP station cooperate with each other to realize the two-way flow of “electricity-heat” energy, which greatly improves the energy conversion capability and operational flexibility of the system.

#### 5.2.3. Gas Dispatching Results

The natural gas consumption of the CSP-CHP microgrid system is mainly gas load, GT, and gas storage energy. The gas supply and gas consumption of the system is shown in Figure 9.

It can be seen from Figure 9 that the system can meet the gas demand of each period. The gas load demand is mainly met by the natural gas market, while the remaining out-sourced natural gas and the natural gas produced by the P2G are stored in gas storage energy. When the GT unit is in the “cogeneration” mode, the cost of gas purchase and operation and maintenance per unit of electricity/heat energy is lower

| Table 1: Basic parameters. |
|-----------------------------|
| Parameters | Value | Parameters | Value |
| $\eta_{\text{csp}}$ | 0.4 | $\eta_{\text{elec}}$ | 0.01 |
| $\tau_{\text{csp}}$ | 0.0001 | $\tau_{\text{elec}}$ | 0.97 |
| $\eta_{\text{dis}}$ | 0.97 | $\eta_{\text{om}}$ | 0.05 DKK/kW |
| $N_{\text{om,max}}$ | 350 kW | $N_{\text{om}}$ | 0.12 DKK/kW |
| $N_{\text{om}}$ | 80 kW | $N_{\text{om},\text{max}}$ | 0.12 DKK/kWh |
| $c_{\text{om},\text{gas}}$ | 0.09 DKK/kWh | $c_{\text{om},\text{gas}}$ | 0.09 DKK/kWh |
| $c_{\text{om},\text{es,g}}$ | 85 kWh | $c_{\text{om},\text{gas}}$ | 200 kWh |
| $\eta_{\text{om}}$ | 0.78 | $\eta_{\text{dis}}$ | 0.78 |
than that of purchased electricity, so the GT unit has been in a gas-consuming operation. During the period from 05:00 to 16:00, the venting of gas storage energy and purchasing natural gas from the market jointly meet the gas demand of the system and solve the risk of insufficient gas supply caused by the restriction of gas purchase flow. In this dispatching cycle, the gas storage energy stores gas in the low-price period of gas purchase and deflects gas in the high price.
period of gas purchase, realizing the cross-period use and value improvement of natural gas.

5.2.4. Operation Results’ Analysis. The system will incur multiple costs during dispatch, including electricity purchase cost, gas purchase cost, operation and maintenance cost, and carbon cost. The operating results of the CSP-CHP microgrid system are shown in Table 2.

It can be seen from Table 2 that the cost of interaction with external network accounts for about 72.35% of the total operation cost, while only the cost of gas purchase accounts for about 56.14%. At the same time, according to Figure 6, the total electricity purchase of the system in this dispatching period is 6007.02 kW·h, accounting for about 31.9% of the total electricity consumption. According to Figure 7, the total gas purchase volume of the system is 1208.32 m³, accounting for about 68.93% of the total gas consumption. The carbon emission cost is 68.93 DKK, accounting for 0.88% of the total cost, indicating that the system has less carbon emission and realizes the low-carbon operation of the system. This shows that the system is highly dependent on the external network. In order to ensure the balance of supply and demand of electricity, heat, and gas energy, the system must maintain real-time interaction with the external network at each time period.

5.3. Model Validity Analysis

5.3.1. Effectiveness Analysis of Introducing CSP Station. In order to verify the effectiveness of the introduction of the CSP station, four operating scenes are set up in this section for comparative analysis.

Scene 1: Dispatched and operation with the model constructed in this study.
Scene 2: The CSP station is replaced by wind power with the same installed capacity to participate in the system operation.

Scene 3: The CSP station adopts the traditional operation mode to participate in the system operation (that is, the electric boiler does not cooperate with the thermal storage system).

Scene 4: The gas turbine is used instead of the CSP station to participate in the system operation.

The operation results of the CSP-CHP microgrid under different scenes are shown in Table 3.

It can be seen from Table 3 that the total operating cost of Scene 1 is reduced by about 27.97%, 14.98%, and 7.74% compared with Scene 2, Scene 3, and Scene 4, respectively, indicating that the introduction of CSP station and the electric boiler has good economics. Compared with Scene 1, Scene 4 uses gas turbines instead of CSP station. GT has the limitation of “determining electricity by heat” so that when the supply and demand do not match, the GT operating output needs to be increased to meet single energy demand. Electricity surplus is sold out immediately, so it is impossible to maximize the revenue from electricity sales through TOU price. In addition, the gas purchase cost of the system is high and the operation economy of the system is low.

In scene 1, the CSP station is equipped with a high-capacity thermal storage energy system, and the thermal storage energy cooperates with the electric boiler to convert the low-cost electric energy in the valley period into heat energy and store it in the thermal storage energy. This expands the heat source of the thermal storage energy, makes the operation of the thermal storage energy more flexible, and can realize two functions of heating and power generation. In addition, the “electricity-thermal-electricity” energy cycle is also realized in Scene 1, which greatly improves the power generation capacity and operational flexibility of the CSP station and effectively reduces the operation cost by using the electricity price mechanism.

5.3.2. Effectiveness Analysis of the DRO Model.
Comparative analysis of different dispatching methods: aiming at the uncertainty of renewable energy output, the
commonly used methods are stochastic optimization (SO) and robust optimization (RO). In order to verify the advantages of the DRO method adopted in this study, DRO is compared with SO and RO.

This study assumes that the output forecast error of renewable energy follows a normal distribution with a mean of 0 and a standard deviation of 10% of the predicted value. For the parameters $d$ and $a$ in the DRO model, both values are 0.05. The parameter $\bar{a}$ involved in SO takes a value of 0.05. The upper limit of the prediction error of renewable energy output in RO is 3 times the standard deviation of the reference distribution, and the lower limit is the opposite. The calculation results under the three dispatching methods are shown in Table 4, and the required backup conditions in each dispatch method are shown in Figure 10. In addition, when the uncertainty of renewable energy output is not considered, it is deterministic optimization. At this time, the dispatching basis is the predicted output of the energy.

Comparing the operating results of the three methods for dealing with uncertain problems, it can be seen that the operating cost of DRO is between RO and SO, but the DRO method has the shortest solution time and the lowest operating cost of the CSP-CHP microgrid system. DRO reflects the risk preference of the decision maker. In DRO, the uncertainty of renewable energy output is not considered during dispatching, the operating cost and solution time of the system are both low. However, it has resulted in a large rate of renewable energy abandonment. If the energy abandonment penalty system is considered, the total operating cost of the system will increase significantly. Therefore, the uncertainty of renewable energy output cannot be ignored during system dispatching.

Through the comparison of different methods, it can be seen that when dealing with uncertainty, the more conservative the method used is, the more adjustment reserves are used to balance the predicted error of renewable energy output, and the operating cost will also increase accordingly. The distributionally robust optimization model used in this study is more robust. Compared with the RO method that only considers the worst case, the conservativeness of the DRO method is greatly reduced. Compared with SO, the DRO method does not need to consider too many scenes, which greatly saves the solution time of the system. In addition, from the energy abandonment rate of renewable energy, it can be seen that the DRO method has the lowest energy abandonment rate, while the stochastic optimization has the highest energy abandonment rate.

In addition, using different dispatching methods, the adjustment backup situation that needs to be arranged is also different, as shown in Figure 10.

From Figure 10, we can know that the SO needs to arrange the least amount of adjustment reserve, followed by the DRO, and the RO is the most. The main reason is that RO often considers the worst cases and is highly conservative. Therefore, the greatest amount of regulation reserve is required to balance the predicted error of renewable energy output, which also leads to higher operating costs. When using SO for scheduling, only the reference distribution needs to be considered, and the conservativeness is the lowest. Therefore, there is a minimum amount of regulation reserve requirements in the CSP-CHP microgrid system. The DRO method has a good balance between economy and robustness, which is also the advantage of the DRO method.

Comparison analysis of different risk preferences: the confidence level $1 - \alpha$ and ambiguity set parameter $d$ in DRO reflect the risk preference of the decision maker. In order to analyze the role of these two parameters, this section will select different parameter values and calculate the operating cost of the CSP-CHP microgrid system. The operating costs of the system under different parameters are shown in Table 5.

As can be seen from Table 5, the increase of $1 - \alpha$ or $d$ will lead to an increase in the total cost of CSP-CHP microgrid system operation. This is because the confidence level becomes larger, policymakers become conservative about the system’s response to uncertainty, and their preference for risk decreases. At this time, the more the reserve demand for regulation to balance the predicted error of renewable energy output inside the CSP-CHP microgrid system will increase accordingly.
system, the more natural gas consumed and the cost of operation and maintenance.

### 6. Conclusion

In order to improve the flexibility and economy of the cogeneration system, this study optimizes and adjusts the traditional CHP microgrid structure, introduces the CSP station to participate in the optimal operation of the CHP microgrid, and builds the CSP-CHP microgrid architecture. On this basis, the CSP-CHP microgrid conventional dispatching model is established. At the same time, in order to deal with the uncertainty in the CSP-CHP microgrid system, the DRO model is introduced. Finally, the CSP-CHP microgrid DRO economic dispatch model considering the uncertainty of renewable energy output is established. The following conclusions can be drawn from the simulation analysis:

1. The introduction of CSP stations to participate in the optimal operation of CSP-CHP microgrid can meet the multienergy requirements of electricity, thermal, and gas of the system and realize multienergy interconnection. However, the cost of purchasing energy for this system is relatively high, indicating that it is highly dependent on the external network. It is necessary to maintain interactive transactions with the external network in real time to ensure the security of the internal operation of the CSP-CHP microgrid system.

2. The CSP station acts as a combined heat and power unit to break the operating limitations of traditional units. Moreover, the thermal storage system and the electric boiler cooperate with each other to provide a low-cost thermal energy source for the heat storage system, making the operation of the heat storage system more flexible. This also expands its application avenues for CSP and improves the power generation potential of CSP station. And the CSP-CHP microgrid system realizes the “electricity-thermal-electricity” energy conversion, effectively using the electricity price mechanism to reduce the operating cost.

3. Energy storage (electricity ES, thermal ES, and gas ES) utilizes its energy transfer characteristics to store energy during low-price periods and release energy during high price periods, realizing the cross-period and high-value time-shift utilization of electricity, heat, and gas, and improving the economy and flexibility of the system.

### Table 4: Calculation results of different dispatching methods.

| Method               | Total cost (DKK) | Computing time (s) | Abandonment rate of renewable energy (%) |
|----------------------|------------------|--------------------|------------------------------------------|
| DRO method           | 7824.08          | 36.43              | 0.13                                      |
| SO method            | 6934.54          | 633.62             | 16.72                                     |
| RO method            | 8392.18          | 84.83              | 2.25                                      |
| Deterministic optimiz| 6799.03          | 37.65              | 19.23                                     |

### Table 5: Operating results under different risk preferences.

| $1 - \alpha$ | $d = 0.1$ | $d = 0.05$ | $d = 0.01$ |
|--------------|-----------|-----------|-----------|
| 0.9          | 7789.35   | 7786.39   | 7780.92   |
| 0.95         | 7914.65   | 7824.08   | 7783.02   |
The introduction of the DRO method effectively solves the problem of the uncertainty of renewable energy output in the CSP-CHP microgrid system. Distributionally robust optimization is more robust than SO, more economical than traditional RO, and achieves a better balance between the two methods. In addition, the higher the risk preference of decision makers, the lower the operating cost of the optimization results, but it also means that the robustness of the decision-making scheme is reduced accordingly. Therefore, the values of these two parameters should be appropriately selected according to actual requirements.

This study only considers the uncertainty of the output of renewable energy. In fact, there are many uncertain factors affecting the operation of CHP microgrid, such as the user’s electrical load and thermal load. In the follow-up, we will study the impact of uncertain factors on system operation from the perspective of supply and demand.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Huiru Zhao guided the research, established the model, and implemented the simulation; Zhao Ma wrote this article; Xuejie Wang and Qun Su checked the language; Guanglong Xie provided relevant research data.

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