A fuzzy-based multi-objective robust optimization model for a regional hybrid energy system considering uncertainty

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Abstract  
Regional hybrid energy system (RHES) is an effective way to accommodate clean energy and reduce its uncertainty. It is also an important development direction for energy market reform, playing an important role in the field of energy supply and demand. Based on electricity price, thermal price, and the relationship between load supply and demand, the paper proposes an optimal scheduling model for regional energy systems to promote clean energy consumption. Firstly, the typical structure and system modules of the integrated regional energy system are introduced in detail, and the two subsystem operating models of electricity and heating are given. Secondly, a multi-objective function that combines the economics and stability of the system is constructed. The model maximizes the economic benefits and minimizes the net load fluctuations on the basis of maximizing the consumption of clean energy. The multi-objective singularity is realized by fuzzy membership function. The decision-making risk caused by the uncertainty of clean energy output is analyzed by introducing robust optimization theory. Finally, the effectiveness of the proposed model is verified based on a region in northwestern China. The results show that the proposed multi-objective model can combine different optimization demands together, maximize the economic characteristics of clean energy while properly controlling risks, and provide reasonable support for decision makers to develop optimal operation plans.

Keywords  
clean energy, fuzzy membership function, regional hybrid energy system, robust optimization

INTRODUCTION

Faced with the increasing prominence of fossil fuel shortages, environmental pollution, climate change, energy security, and other issues, traditional energy structures and utilization methods are unsustainable. In order to adapt to the future energy transformation situation, the development of renewable energy has become an important part of national energy strategies. By 2018, the global installed capacity of renewable energy power generation totaled 2391 GW, accounting for one-third of the total installed capacity of power generation in the world. Among them, the cumulative installed capacity of hydropower reached 1172 GW, accounting for 50%; wind and solar accounted for the remaining major share, with an
installed capacity of 564 GW (24%) and 486 GW (20%), respectively. The renewable energy power generation capacity of China is 729 GW, accounting for 38.4% of all domestic installed power capacity. According to the “China’s 2050 High Proportion of Renewable Energy Development Scenarios and Pathways” (China Energy Development Strategy), the proportion of renewable energy power generation will reach 85% by 2050, and the proportion of wind power and photovoltaics will achieve 63%, which means that while currently a supplementary energy, renewable energy is gradually changing to mainstream energy. However, limited by the uncertainties (intermittent, volatility, antipeaking, etc), large-scale on-grid connection for renewable energy will bring challenges to the stable operation of the grid, resulting in a serious power curtailment problem. In 2018, the abandoned wind and solar in China had reached 41.9 billion kilowatt-hours (kWh) and 7.3 billion kWh, respectively. Especially in the northwestern region, in the same year, the accumulated grid-connected capacity of wind power was 49.05 million kilowatts (kW), accounting for 19.43% of the total installed capacity of the whole network; the abandoned wind power was 16.837 billion kWh, and the abandoned rate of wind was 16.21%. The grid-connected capacity of photovoltaic was 5.463 million kW, which accounted for 16.0% of the total installed capacity of the whole network. The abandoned photovoltaic output was 4.714 billion kWh, and the abandoned rate of solar was 8.91%. How to eliminate the huge amount of abandoned wind power in the northwest region has become an obstacle for China to develop renewable energy and transform the national energy strategy.

The northwest of China is a vast area, and its energy consumption is characterized by regional agglomeration. The energy density and the load utilization hours are high. Due to the coal-based heating technology, the power curtailment is more serious in heating season and carbon emission is excessive. Therefore, it is important to utilize the abundant renewable energy to organically couple electric energy and thermal energy, so as to achieve the clean, efficient, and economical operation of energy in the region through energy conversion equipment or by means of different energy storage carriers. In this context, the design of the regional hybrid energy system (RHES) must combine the design object with the surrounding resource endowment, not only to meet the demand of electric heating load in the region stably, but also to realize the coordinated economic operation of different energy generating units. The selection of energy conversion and storage equipment is the key to the construction of a regional energy system, and also to solving the problem of the energy waste of renewable power generation in Northwest China Link.

The selection of energy storage equipment for RHES can refer to the operation experience of domestic field projects in recent years. The multi-energy complementary demonstration project of Haixi Prefecture in Qinghai Province has 100 megawatt-level energy storage (100 MWh), supporting wind power (400 MW), photovoltaic power (200 MW), and concentrated solar power (50 MW). Among them, the energy storage station is composed of 50 standard containers and 25 boxes of 35 kV battery subunits, which are connected to the 35 kV side of the Xinlu 330 kV collection station and sent out. In 2017, the first MW-level lithium storage power plant in Baoqing, Shenzhen, was put into operation. At the same time, referring to the Philippine off-grid SREC microgrid project invested in by Wenergy in Singapore, foreign countries combined photovoltaic power generation (1.4 MW), diesel power generation (1.2 MW), and 2.4 MWh battery energy storage to build the largest off-grid power plant in South-East Asia, which can solve the power supply of nearly 700 households. It can be seen that electrochemical energy storage has entered a large-scale development stage due to its high energy density and good economy.

Domestic and foreign scholars have carried out a lot of research on the accommodation of clean energy by regional energy systems. From the perspective of energy conversion, they consume the abandoned energy through equipment, such as electric heat transfer. The literature3 took the grid-connected microgrid including wind power plant, photovoltaics, combined heat and power systems, electric boiler, fuel cells, and energy storage system as an example, and compared two common electric heating scheduling methods. The result proved that the unified scheduling of combined heat and power coordinated electric heat transfer equipment can further reduce the operating cost of the microgrid while eliminating the abandonment. From the perspective of energy storage, literature4 analyzes the potential impacts of variability and intermittency in renewable resources on the design of standalone renewables-based energy systems incorporating storage.

The literature5 combines electrical energy and thermal energy to increase the flexibility of the system by adding energy storage devices, alleviating the rigid coupling relationship between the heating network and the power grid, and improving the wind power penetration rate. In Ref. 6, from the perspective of decoupling thermo-electric coupling constraints and improving the regulation ability of power systems, a coordinated wind-distribution scheduling model based on cogeneration units with heat storage and electric boilers is proposed. In the research of regional energy system modeling, wind power and economic dispatching often serve as two optimization targets, but existing research results often have two problems: On the one hand, for multi-objective optimization models, the weights of the two targets are difficult to quantify. Subjective valuation is biased, and the rationality of the optimization results depends on the parameter setting, which leads to an inconsistency between consumption and economics. On the other hand, the
Regional energy system constitutes a more complex cogeneration system, and in addition to the electric heating economic dispatch, the system also includes devices such as electricity storage, heat storage, and electric vehicles. The joint operation of electrical and heating does not consider the role of such equipment in improving energy efficiency and eliminating energy. In the regional energy system, there are many optimization variables and the expressions are complex. Therefore, the scheduling problem is a multidimensional nonlinear optimal problem. Some scholars constructed a comprehensive energy system economic model from the perspective of unified equipment-wide scheduling and proposed corresponding solutions. In Ref. 7, for a multi-objective optimization model of a microgrid with the lowest overall power generation cost, the best environmental benefit and the lowest battery loss were established. An improved multi-objective particle swarm optimization algorithm is introduced to solve the model. In Ref. 8, a bicriteria problem of capital cost minimization and reliability maximization is solved for two cases of remotely located mining operations in Chile and Canada to demonstrate the capabilities of the methodology. Approximations of the pareto-optimal fronts were generated using a multi-objective genetic algorithm (NSGA-II). In Ref. 9, a residential model of South Australia was used as an example to construct a mathematical model of an integrated energy microgrid. The economic scheduling model was established based on mixed-integer linear programming under the premise of meeting different types of energy requirements. In Ref. 10, an electrothermal coupled integrated energy microgrid was constructed. The problem of uncertainty in the microgrid is addressed by the rolling horizon Markov decision process (MDP). A real-time scheduling method for integrated energy microgrid is proposed.

The above research shows that the current research on regional energy systems with clean energy mainly focuses on configuring different energy conversion storage devices and coordinated scheduling strategies. There are fewer studies that take into account the negative impacts of the volatility of wind power and photovoltaic power generation to the system. In the regional energy system, on the one hand, energy conversion and storage equipment can effectively promote the consumption of renewable energy; hence, how to improve the benefit and reduce operating costs is the primary problem facing the system. On the other hand, due to the uncertainty of renewable energy power generation, how to coordinate multi-energy and energy conversion storage devices, and rationally arrange scheduling strategies to reduce system operation risks and improve stability is another important question. Therefore, the specific innovations of this paper are as follows:

1. Establish a multi-objective electrothermal joint scheduling model and construct a stochastic scheduling optimization model with the objective of maximizing economic benefit of RHES and minimizing system load volatility.

2. In the model processing, the power output and cost function are linearized, and the fuzzy membership function is used to process the multi-objective function. The multi-objective unit combination optimization problem is changed into mixed-integer programming (MIP) problem, which can be quickly solved by software GAMS.

3. Using the robust optimization theory to analyze the influence of wind and solar uncertainty on system stability, which effectively reduce the decision-making risk of decision makers.

4. Taking a certain area in northwestern China as an example, it is analyzed, and the optimal operation plan of each unit formulated, taking into account the economics and stability of multi-energy coordinated operation in the region, and the utilization efficiency of resources maximized.

The rest of the paper is arranged as follows: Section 2 designs the basic structure of RHES and the operational characteristics of each unit; Section 3 builds a multi-objective function to establish a scheduling optimization model and processes the model; Section 4 introduces a robust optimization theory to overcome the instability of system operation; Section 5 validates the validity and practicability of the model through a case study; and Section 6 describes the conclusions of this paper.

2 | RHES DESCRIPTION

2.1 | System structure

This paper constructs a grid-connected regional hybrid energy system (RHES) based on the electric load and clean energy output characteristics of a certain area in western Inner Mongolia. The structure of RHES is shown in Figure 1. The system is driven by wind energy, solar energy, and natural gas, including two subsystems, namely a power system and thermal system. The system includes a small wind power generation group, a photovoltaic power generation group, a wind power plant (WPP), a photovoltaic (PV), a conventional gas turbine (CGT), an electric boiler (EB), solar collectors (SCs), electrical energy storage (EES) composed of lithium iron phosphate battery, and thermal energy storage (HES) composed of heat storage tank. The RHES exchanges energy with the distribution network via the tie line, and the units in the network are uniformly controlled and transmitted by the RHES central controller. Specific parameter settings are shown in Table 1:

2.2 | Operating characteristics

In RHES, combined with the western region and climate characteristics of Inner Mongolia, the maximum power-tracking
mode is adopted to make full use of clean energy, such as wind energy and solar energy, and natural gas is used as the backup energy source. Among them, WPP and PV are mainly used to meet the demand of electric load, and CGT provides the backup for RHES by taking advantage of its fast start-up–shutdown speed. According to clean energy output and the reverse distribution characteristics of load demand, the abandoned wind and solar in the valley period can be converted into heat or electric energy. The heating load is partially satisfied by the SC, and most of them are converted by the EB using the abandoned energy or the natural gas, and a certain capacity of the heat storage device is arranged to store the heat energy converted from electricity. The RHES is connected with the external network and selects to power or heating supply or energy storage according to the relationship of real-time electricity price and gas price. RHES can use EB, CGT, gas boilers, and clean energy to coordinately meet the demand of electric and heating load, realize the economic dispatch of electricity and heat in the regional power grid, and improve the comprehensive utilization efficiency of clean energy.

**TABLE 1** Key operating parameters of each device

| Types | Parameters                    | Unit   | Types           | Parameters        | Unit   |
|-------|-------------------------------|--------|-----------------|-------------------|--------|
| WPP   | Cut-in speed                  | m/s    | EB              | Heating efficiency| —      |
|       | Cut-out speed                 | m/s    |                 | Ramp rate         | yuan/kWh|
|       | Rated speed                   | m/s    |                 | Start–stop cost   | yuan/kWh|
| PV    | $\alpha$                      | —      |                 | Scheduling time   | —      |
|       | $\beta$                       | —      |                 | Initial capacity  | MWh    |
| CGT   | Ramp rate                     | MW/h   |                 | Max capacity      | MWh    |
|       | Slope coefficient of cost     | yuan/kWh |      | Charge discharge power | MW |
|       | curve                         |        |                 | Cost              | yuan/kWh|
|       | Start–stop cost               | yuan/kWh |      | $\eta_{ele}$-$\eta_{heat}$ | —   |
|       | Start–stop time               | h      | Supply heat     | Supply heat       | yuan/kWh|
2.3 | Energy output model

2.3.1 | Power source output model

In the proposed RHES, power source mainly includes WPP, PV, and CGT. The section mainly introduces output models of WPP and PV. Literature 13 and 14 have confirmed that the Rayleigh distribution function and the beta distribution function can be used to simulate wind speed and solar irradiance.

**WPP output model**

Limited by the technical parameters of the wind turbine, the output of wind power shows a phased characteristic with the change of wind speed, namely:

\[
 g_{\text{WPP},t} = \begin{cases} 
 0, & v_t < v_{\text{in},t} \\
 0.5 C_w \rho A_{WT} v_t^3, & v_{\text{in},t} \leq v_t \leq v_{\text{rated},t} \\
 g_{\text{WPP},t}^{\text{rated}}, & v_{\text{rated},t} \leq v_t \leq v_{\text{out},t} 
\end{cases},
\]

where \( C_w \) is the performance parameter of wind turbine; \( \rho \) is the air density; \( A_{WT} \) is the projection of wind turbine blade sweeping area on vertical plane of wind speed; \( v_t \) is the real-time wind speed of WPP at the time \( t \); \( v_{\text{in}} \), \( v_{\text{rated}} \), and \( v_{\text{out}} \) represent the cut-in wind speed, the rated wind speed, and the cut-out wind speed, respectively; \( v_{\text{rated}} \) is the rated power of the wind turbine; when the wind speed is lower than the cut-in wind speed or higher than the cut-out wind speed, the wind turbine will stop working.

If the wind speed is between the rated wind speed \( v_{\text{rated}} \) and the cut-out wind speed \( v_{\text{out}} \), the wind turbine will have an output at the rated power \( g_{\text{WPP},t}^{\text{rated}} \). In other cases, the output of the wind turbine depends on the wind speed.

Since the wind speed varies at different heights, the wind speed at a particular altitude is converted to the actual wind speed at the height of the wind turbine tower.

\[
f(v_t') = \left( \frac{h}{h'} \right)^\beta v_t',
\]

where \( v_t' \) is the measured wind speed at the height \( h' \); \( f(v_t') \) is the wind speed measured by the wind turbine at the tower height \( h \), and \( \beta \) is the coefficient of measurement.

**PV output model**

Photovoltaic power generation is based on the photovoltaic effect of the semiconductor interface, which directly converts the solar energy absorbed by the semiconductor into electrical energy. Assuming that the PV equipment is equipped with a maximum power point tracking system, the PV power output can be expressed as follows:

\[
g_{PV,t} = \left[ 1 - \gamma \left( C_{\text{air}} + \frac{C_v - 20}{800} \theta_t - C_{\text{ref}} \right) \right] \eta_{PV} S_{PV} N_{PV},
\]

where \( \gamma \) represents the photovoltaic conversion efficiency of the photovoltaic panel, \( C_{\text{air}} \) is the atmospheric ambient temperature, \( C_v \) is the normal working temperature, \( C_{\text{ref}} \) is the reference temperature, \( \eta_{PV} \) is the reference efficiency, \( \theta_t \) is the optical radiation intensity at time \( t \), \( S_{PV} \) is the individual panel area, and \( N_{PV} \) is the number of photovoltaic panels.

Photovoltaic power generation also has characteristics of randomness, intermittence, and volatility, etc. Its output intensity is related to the intensity of light radiation. The beta distribution function is commonly used to describe the solar radiation intensity. The specific formula is as follows:

\[
f(\theta) = \frac{\theta^{\alpha-1} (1-\theta)^{\beta-1}}{\int_0^1 \theta^{\alpha-1} (1-\theta)^{\beta-1} d\theta},
\]

where \( \theta \) indicates solar radiation; \( \alpha \) and \( \beta \) are shape parameters of beta distribution.

Based on historical data on the intensity of the illuminating radiation, after obtaining the expected value \( \mu \) and variance \( \sigma \) of the radiant radiance, the values of \( \alpha \) and \( \beta \) are as follows:

\[
\beta = (1-\mu) \times \left( \frac{\mu \times (1+\mu)}{\sigma^2} - 1 \right),
\]

\[
\alpha = \frac{\mu \times \beta}{1-\mu},
\]

where \( \mu \) and \( \sigma \) represent the expected value and standard deviation of the solar photovoltaic radiation intensity, respectively.

Therefore, the intensity distribution function of solar photovoltaic radiation is as follows:

\[
P(\theta) = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} f(\theta) d\theta,
\]

where \( \theta_{\text{max}} \) and \( \theta_{\text{min}} \) are the upper and lower limits of solar radiation intensity, respectively.

**CGT output model**

The gas turbine generates steam by burning natural gas to drive the rotor of the generator to rotate at a high speed to generate alternating current, and the waste heat is recovered by the waste heat boiler, and a certain amount of heat energy is generated by the conversion device of steam and hot water. As the main power generation equipment of RHES, its power generation efficiency is greatly affected by the output
power. In a certain range, the power generation efficiency and the output power are positively correlated. The heat recovery amount of exhaust gas of the gas engine is related to the electric load rate \( \lambda \) of the unit. The power generation of gas turbine is as follows:

\[
g_{\text{CGT},t} = \eta_c L_{\text{NG}} V_{\text{NG}}, \quad (9)
\]

\[
\eta_e = (a \lambda^3 + b \lambda^2 + c \lambda + d) \eta_e^E, \quad (10)
\]

where \( g_{\text{CGT},t} \) is the power generation of gas turbine at time \( t \); \( \eta_c \) is the power generation efficiency of the gas turbine; \( L_{\text{NG}} \) is the calorific value of natural gas, generally taking 9.7 KWh/m\(^3\); \( V_{\text{NG}} \) is the amount of natural gas consumed by gas turbine during operation; \( Q_r \) is the heat recovery amount of gas turbine exhaust gas; \( \eta_e \) is the heat recovery amount of gas turbine; \( \eta_e^E \) is the rated power generation efficiency of gas turbine; and \( a, b, c, d \) are coefficients.

### 2.3.2 Heat source output model

#### SC operation model

SC is used as a main energy source to supply heat to the system. The SC mainly collects the solar radiation by the compound parabolic collector (CPC). Because CPC achieves higher concentration for large acceptance angle, it requires only intermittent sun tracking. In addition, the CPC can achieve a higher temperature than the flat plate collector for power generation. Because SC has a large acceptance angle, CPC could both accept both beams and diffuse radiation. Equation (11) calculates the total effective flux absorbed at the absorber surface:

\[
S_t = \left[ I^B_t R^B_t + I^d_t / C \right] \tau \rho a, \quad (11)
\]

where \( S_t \) is total effective flux absorbed at time \( t \) at the absorber surface. \( I^B_t \) is the hourly radiation of the beam at time \( t \). \( R^B_t \) is the tilt factor of the beam at time \( t \). \( I^d_t \) is the diffuse radiation at time \( t \). \( C \) is the concentration ratio. \( \rho \) is the absorptivity of the absorber surface. \( a \) is the effective reflectivity of the concentrator surface for all radiation. \( \tau \) is the transmissivity of the cover. The detailed calculation process about the operation model of CPC can be seen in the literature.\(^14\) Then, the useful heat gain can be given by Equation (12):

\[
Q_{\text{SC},t} = F_R WL \left[ S_t - \frac{U_{\text{lo}}}{C} (T^a - T_{\text{air}}) \right], \quad (12)
\]

where \( Q_{\text{SC},t} \) is the useful heat gain of the SC at time \( t \); \( W \) and \( L \) are the length and width of tube, respectively; \( T^a \) is the temperature of the SC’s inlet at time \( t \); \( T_{\text{air}} \) is the environment temperature at time \( t \); \( U_{\text{lo}} \) is the overall loss coefficient of the SC; and \( F_R \) is the operation ratio of SC, and the detailed calculation method is in the literature.

#### Electric boiler operation model

An electric boiler is simple to install, flexible to control, and easy to repair and replace, so it is widely used in microgrids. The electric boiler can cooperate with the CHP system under the guidance of electricity price to meet the heat load demand and increase the electricity consumption during the valley period. Therefore, the introduction of the electric boiler can realize the conversion of electricity and heat, and coordinate the electric and heating load in peak and valley periods. The output model is as follows:

During the period of low output of the SC, the abandoned wind power is used to drive the electric boiler to meet the main heating load requirements of the system; the heating power of the electric boiler is as follows:

\[
Q_{\text{EB},t} = 3.6 \eta_{\text{ele}} \delta_{\text{EB},t}, \quad (13)
\]

where \( Q_{\text{EB},t} \) is the heat output power of the electric boiler, \( Qf/h \); \( \delta_{\text{EB},t} \) is the electric power consumed by the electric boiler, MW; \( \eta_{\text{ele}} \) is the heat conversion efficiency of the electric boiler.

### 2.4 ESS operation model

The energy storage system is capable of decoupling the production and consumption of energy over time, thereby achieving energy conversion across time to coordinate the imbalance of regional power supply and load. The energy storage in the electric heat–combined dispatching includes electrical energy storage and thermal energy storage.

#### 2.4.1 Electrical energy storage

Electrical energy storage is beneficial for peak load shifting and operating cost reduction. The electric storage includes energy type (battery) and power type (supercapacitor), and energy storage mode is adopted when the scheduling period is long. Simultaneous operation of power storage and heat storage is conducive to smoothing the charging and discharge curve of heat storage equipment and prolonging the service life. The energy storage capacity is related to the power and the efficiency of charging and discharging. The mathematical model can be expressed as follows:

\[
E_{\text{EES},t} = \begin{cases} E_{\text{EES},t-1} + \theta \delta_{\text{EES},t} - (1 - \theta) \frac{1}{\eta_{\text{dis}}} \\ E_{\text{EES},0}, \quad t > 1 \end{cases} \quad (14)
\]
where $E_{\text{ESS},t}$ is the storage capacity at time $t$, $g_{\text{ESS},t}^{\text{cha}}$ and $g_{\text{ESS},t}^{\text{dis}}$ represent the charge and discharge power of the energy storage system at time $t$, respectively; $\eta_{\text{ele}}^{\text{cha}}$ and $\eta_{\text{ele}}^{\text{dis}}$ represent the charge and discharge efficiency of the energy storage system, respectively. $\theta$ is a 0-1 variable: 1 represents charging and 0 represents discharging. When $t=1$, EES is the initial heat storage, and the value is 0.

### 2.4.2 Thermal energy storage

Due to the mismatch of the size and distribution between thermal load and power load, when the demand of thermal energy is low and the demand of electric energy is high, some cogeneration units will be limited by thermal energy and cannot be fully put into operation; otherwise, when the thermal energy demand is high and the electric energy demand is low, surplus power will not be able to feed into the grid, or will feed into the grid uneconomically, and thus, electric heating scheduling cannot be efficient and economical. The time-dependent transfer of heat load using thermal energy storage can alleviate the contradiction between the electric and heating load in the grid and the electric-heat ratio of the cogeneration system, and realize the unified coordination and management of electricity and heat.

The storage characteristics of thermal energy storage indicate the relationships between storage capacity, output and input power, and thermal efficiency. The mathematical model can be expressed as follows:

$$
H_{\text{TES},t} =
\begin{cases}
H_{\text{TES},t-1} + \delta \eta_{\text{heat}} Q_{\text{cha}}^{\text{heat}} - (1 - \delta) \eta_{\text{heat}} Q_{\text{dis}}^{\text{heat}}, & t > 1 \\
H_{\text{TES},0}, & t = 1,
\end{cases}
$$

where $H_{\text{TES},t}$ is the heat storage capacity at time $t$; $Q_{\text{cha}}^{\text{heat}}$ and $Q_{\text{dis}}^{\text{heat}}$ are the heat charge and discharge power at time $t$; $\eta_{\text{heat}}^{\text{cha}}$ and $\eta_{\text{heat}}^{\text{dis}}$ are the heat charge and discharge efficiency of the heat storage system, respectively. $\delta$ is a 0-1 variable: 1 is when storing heat and 0 is when releasing heat, for $t \geq 1$. When $t = 1$, HES is the initial heat storage, and the value is 0.

Capacity constraints of energy storage equipment are as follows:

$$
\begin{align*}
E_{\text{ESS},\text{min}} & \leq E_{\text{ESS},t} \leq E_{\text{ESS},\text{max}}, \\
H_{\text{TES},\text{min}} & \leq H_{\text{TES},t} \leq H_{\text{TES},\text{max}},
\end{align*}
$$

where $E_{\text{ESS},\text{min}}$, $E_{\text{ESS},\text{max}}$, $H_{\text{TES},\text{min}}$, and $H_{\text{TES},\text{max}}$ are the upper and lower limits of the capacity of power storage and heat storage, respectively. Since the energy storage also satisfies the power constraints and the power constraints are of the same form, the power constraints are represented by the same power symbol in this paper:

$$
\begin{align*}
\mu_{\text{ESS},t}^{\text{cha}} E_{\text{ESS},\text{min}} & \leq g_{\text{ESS},t}^{\text{cha}} E_{\text{ESS},t} \leq \mu_{\text{ESS},t}^{\text{cha}} E_{\text{ESS},\text{max}}, \\
\mu_{\text{ESS},t}^{\text{dis}} E_{\text{ESS},\text{min}} & \leq g_{\text{ESS},t}^{\text{dis}} E_{\text{ESS},t} \leq \mu_{\text{ESS},t}^{\text{dis}} E_{\text{ESS},\text{max}}
\end{align*}
$$

where $g_{\text{ESS},t}^{\text{cha}}$, $g_{\text{ESS},t}^{\text{dis}}$, $\mu_{\text{ESS},t}^{\text{cha}}$, and $\mu_{\text{ESS},t}^{\text{dis}}$ represent the state of energy storage device at time $t$ and satisfy:

$$
\begin{align*}
\mu_{\text{ESS},t}^{\text{cha}} &= \{0, 1\}, \\
\mu_{\text{ESS},t}^{\text{dis}} &= \{0, 1\},
\end{align*}
$$

where 1 means that the energy storage device is in working state, and 0 means not working. Meanwhile, it is considered that the energy storage device cannot be charged and discharged simultaneously in one cycle.

### 3 MULTI-OBJECTIVE FUZZY SCHEDULING MODEL

#### 3.1 Model assumption

In the current day, electric heat scheduling plan of a regional energy system with a certain proportion of clean energy, the objective function needs to take into account the economic benefits and stability of the system, while meeting the energy balance, operating constraints, and backup constraints of each unit. Therefore, the problem of clean energy output uncertainty and multi-objective function solving are the key issues for the optimal operation of RHESS. First, the decision makers have a large deviation risk based on the predicted values of WPP, PV, and SC. The robust parameters of probability distribution function of the obtained wind and solar output scene are set, and the robust stochastic optimization theory is used to solve the uncertainty risk. Secondly, the optimization direction of the two objectives of maximum economic benefit and minimum system load fluctuation is opposite, the dimension level is different, and it cannot be directly weighted. At the same time, the existence of nonlinear objective function and constraints makes the proposed model a mixed-integer nonlinear programming (MINLP) model. If the solution is directly solved, the solution time may be long and the optimization level of the result may not be high. In this paper, the nonlinear objective function and constraints are linearized, and the MINLP model is transformed into the
mixed-integer programming (MIP) model. Then, the fuzzy dimension theory is used to deal with the different dimensions and optimization directions of the objective function to achieve the consistency of the objective function. Finally, the weighted multi-objective model is set as a single-objective model by setting a reasonable weight coefficient, and then, the mathematical model is solved. Finally, it provides an effective decision-making tool of different risk categories for decision makers.

3.2 | Model construct

3.2.1 | Objective function

The revenue maximization objective function in the system is as follows:

Objective of maximum economic efficiency

\[
\text{max } \text{obj}_1 = \sum_{t=1}^{T} \left( \left( \frac{R_{WPP,t} + R_{PV,t} + R_{SC,t}}{C_{CGT,t}} + C_{PGL,t} + C_{EB,t} \right) \right),
\]

where \( R_{WPP,t} \), \( R_{PV,t} \), \( R_{SC,t} \), \( R_{CGT,t} \), and \( R_{EB,t} \) represent the revenues of WPP, PV, SC, CGT, and EB at time \( t \), respectively; \( C_{CGT,t} \) represents the operating cost of CGT at time \( t \); \( C_{PGL,t} \) is the product of the purchase price of RHES from the public grid and the purchased amount; \( C_{EES,t} \) and \( C_{TES,t} \) indicate the cost of electricity storage and heat storage at time \( t \). The marginal costs of the energy supply of WPP, PV, and SC are almost zero, so its operating income is equal to the product of the quantity and price of energy supply. Since EB mainly uses abandoned wind and solar power to convert electricity into heat energy, the electricity cost of EB is zero; when the abandoned wind is insufficient, the power of public grid stored at low valley is used to convert thermal energy.

For CGT, its operating costs include fuel costs and start-up–shutdown costs. The specific costs are calculated as follows:

\[
C_{CGT,t}^f = a_1 g_{CGT,t}^2 + b_1 g_{CGT,t} + c_1,
\]

\[
C_{CGT,t}^{sd} = \left[ \mu_{CGT,t}^u \left( 1 - \mu_{CGT,t-1}^u \right) \right] C_{CGT,t}^u + \left[ \mu_{CGT,t}^d \left( 1 - \mu_{CGT,t+1}^d \right) \right] C_{CGT,t+1}^d,
\]

where \( C_{CGT,t}^f \) and \( C_{CGT,t}^{sd} \) are fuel cost and start-up–shutdown cost of CGT at time \( t \), respectively, \( t \) and \( s \) are the indexes for time, \( t \neq s \); \( a_1, b_1, \) and \( c_1 \) are the cost coefficients of CGT power generation; \( C_{CGT,t}^u \) is the start-up–shutdown cost of CGT at time \( t \); \( \mu_{CGT,t}^u \) and \( \mu_{CGT,t}^d \) are the operation status of CGT at time \( t \), 0-1 variables; \( C_{CGT,t}^u \) and \( C_{CGT,t+1}^{sd} \) are the start-up–shutdown costs of CGT at times \( t \) and \( s + 1 \), respectively.

Objective of minimum operational risk

The output of wind power and solar energy has characteristics of volatility and intermittence, and it is necessary to reasonably control the uncertainty factors brought by the RHES to the stable operation of the main network. Therefore, the risk balance and system benefits are considered, and the minimum net load fluctuation of the system selected as an optimization objective. The specific objective function is as follows:

\[
\text{min } \text{obj}_2 = \left\{ \sum_{t=1}^{T} \left[ \left( g_{WPP,t} + g_{PV,t} + g_{CGT,t} - g_{EB,t} - g_{PG,t} \right) - \bar{G} \right] / T \right\}^{\frac{1}{2}},
\]

where \( \text{obj}_2 \) is the load fluctuation value caused by WPP and PV access to RHES, which is the standard deviation of load fluctuation; and \( \bar{G} \) is the average value of load fluctuation of MES throughout the scheduling period.

3.2.2 | Restrictions

The RHES mainly meets the energy balance constraints and the operating constraints of each unit during operation.

Energy supply and demand balance constraints

In order to ensure the safe and reliable operation of the RHES, it is necessary to consider the energy supply and demand balance constraint, the rotation reserve constraint, and the load fluctuation constraint.

\[
\sum_{w=1}^{W} g_{W,t} (1 - \varphi_{W}) + \sum_{p=1}^{P} g_{PV,t} (1 - \varphi_{PV}) + \sum_{e=1}^{ES} \left( g_{EES,t}^{dis} - g_{EES,t}^{cha} \right) + \sum_{c=1}^{C} g_{CGT,t} (1 - \varphi_{CGT}) + g_{PD,t} - \sum_{e=1}^{E} g_{EB,t} = L_t,
\]

where \( L_t \) is the load demand at time \( t \). \( g_{WPP,t}, g_{PV,t}, \) and \( g_{CGT,t} \) are the output of WPP, PV, and CGT at time \( t \). \( W, P, G, C, \) and \( E \) represent the total number of wind turbines, photovoltaic units, energy storage, and gas and electric heating generator sets, respectively. \( \varphi_{WPP}, \varphi_{PV}, \varphi_{CHP}, \) and \( \varphi_{CGT} \) are the factory power consumption rates of WPP, PV, CHP, and CGT, respectively. \( g_{EB,t} \) is the electric power consumed by the electric boiler at time \( t \). \( g_{PD,t} \) is the electricity purchased from external online at time \( t \).
where \( Q_t \) is the thermal load demand at time \( t \). \( Q_{EB,t} \) is the heat supply of electric boiler at time \( t \). \( Q_{dis,t}^{\text{ins}} \) and \( Q_{heat,t}^{\text{sha}} \) are the discharge and charge quantities of heat storage equipment.

System reserve constraint

\[
\begin{align*}
\Delta g_{\text{HES},t}^\text{max} - \Delta g_{\text{HES},t}^\text{min} & \geq r_1 \cdot L_t + r_2 \cdot g_{\text{WPP},t} + r_3 \cdot g_{\text{PV},t},
\end{align*}
\]  

(26)

\[
\begin{align*}
\Delta g_{\text{HES},t}^\text{min} - \Delta g_{\text{HES},t}^\text{max} & \geq r_4 \cdot g_{\text{WPP},t} + r_5 \cdot g_{\text{PV},t},
\end{align*}
\]  

(27)

where \( \Delta g_{\text{HES},t}^\text{max} \) and \( \Delta g_{\text{HES},t}^\text{min} \) represent the maximum and minimum available output of RHES at time \( t \). \( \Delta g_{\text{HES},t} \) represents the output of RHES at time \( t \). \( r_1, r_2, \) and \( r_3 \) represent the upper rotation reserve factors of load, WPP and PV. \( r_4 \) and \( r_5 \) are the lower rotation reserve factors of WPP and PV, respectively.

3.3 | MINLP model solution

3.3.1 | Linearization

Equation (19) determines the objective function of RHES. Decision variables include continuous variables and 0-1 variables, which are mixed-integer nonlinear programming (MINLP). Among them, the unit output is used as the decision variable, the power of WPP and wind speed are power functions, and the operating cost of CGT is the quadratic equation. For the complex solution of the model, the calculation is large, and it is difficult to obtain the optimal solution. In this paper, the objective function and the nonlinear factor are linearized before solving the model.

**Power function processing**

According to the power function formula \( y_i = ax_i^{b}e^{c} \), the logarithm of both sides is taken to get \( y_i' = \ln y_i \), let \( \ln y_i = \ln a + b \ln x_i + u_i \), \( a^* = \ln a \), and \( x_i^* = \ln x_i \), and then, the above expression is expressed as \( y_i'^* = a^* + bx_i^* + u_i^* \); the variables \( y_i^* \) and \( x_i^* \) are linear relationships. Similarly, after taking the logarithm of the WPP running model \( \ln g_{\text{WPP},t} = \ln C_w \rho A_{WT} + 3 \ln v_i - 0.69 \) \((v_{in} \leq v_i \leq v_r)\), it is converted into a linear equation:

\[
y_i'^* = 3x_i'^* + \ln C_w \rho A_{WT} - 0.69.
\]  

(28)

**Quadratic equation processing**

By dividing the quadratic function \( f(g) = ag^2 + bg + c \) into \( N \) segments, the quadratic function can be expressed as a piecewise function \( f(g) \). For \( g \in [g_{\text{min}} + n\Delta,g_{\text{min}} + (n+1)\Delta], n = 0,1,...,N-1 \), \( \Delta \) is the length of each segment of the piecewise function, \( \Delta = (g_{\text{max}} - g_{\text{min}})/N \), as shown in Figure 2.

\[
F(g) = f(g_{\text{min}} + n\Delta) + (g - g_{\text{min}} - n\Delta) * \left[b + (2n+1)c\Delta + 2cg_{\text{min}}\right].
\]  

(29)

Similarly, the linear equation of CGT after segmentation is expressed as follows:

\[
f'(C_{\text{CGT},t}) = f'(C_{\text{CGT},t} - n\Delta C_{\text{CGT}}) + (C_{\text{CGT},t} - g_{\text{min}} - n\Delta C_{\text{CGT}}) \times \left[b + (2n+1)c\Delta C_{\text{CGT}} + 2cg_{\text{min}}\right].
\]  

(30)

\[
C_{\text{CGT},t} \in [C_{\text{CGT},t} + n\Delta C_{\text{CGT}}, C_{\text{CGT},t} + (n+1)\Delta C_{\text{CGT}}].
\]  

(31)

herein, \( n = 0,1,...,N-1 \) and \( \Delta C_{\text{CGT}} = (C_{\text{max}} - C_{\text{min}})/N \).

3.3.2 | Fuzzy processing

In RHES, there are two objective functions that maximum the operating benefit and minimum the system risk. How to obtain the optimal solution while satisfying the operation constraints of RHES is the key to solving the model. For the multi-objective optimization problem, the multi-objective function needs to be transformed into a single-objective function to solve the mathematical model.\(^{14,15}\) However, multi-objective functions have different dimensions and...
optimization directions, which are difficult to directly weight and require preprocessing. Fuzzy satisfaction theory can transform numerical optimization into degree optimization by analyzing the distance between the objective function value and the ideal value. Here, the semi-linear membership function is selected to handle the objective of maximum operating profit. The semi-gradient membership function is selected to handle the objective of minimum operating risk. The specific process is as follows:

The membership function of economic benefit maximization objective is as follows:

\[
\mu(\text{obj}_1) = \begin{cases} 
1 & \text{obj}_1 \geq \text{obj}_1^* \\
(\text{obj}_1 - \text{obj}_1^* + \delta_1)/\delta_1 & \text{obj}_1^* - \delta_1 \leq \text{obj}_1 < \text{obj}_1^* \\
0 & \text{obj}_1 < \text{obj}_1^* - \delta.
\end{cases}
\]

(32)

The membership function of the operating risk minimization objective is as follows:

\[
\mu(\text{obj}_2) = \begin{cases} 
1 & \text{obj}_2 \leq \text{obj}_2^*
\\
\text{obj}_2^* + \delta_2 - \text{obj}_2/\delta_2 & \text{obj}_2^* - \delta_2 \leq \text{obj}_2 < \text{obj}_2^* + \delta_2 \\
0 & \text{obj}_2 > \text{obj}_2^* + \delta.
\end{cases}
\]

(33)

Among them, \(\text{obj}_1\) is the value of the first objective function; \(\text{obj}_1^*\) is the ideal value of the first objective function; and \(\delta_1\) is the added value of the first objective function acceptable to the decision maker, which serves to perform a certain expansion and contraction of the target. The membership function is as shown in Figure 3:

3.3.3 The model flow of multi-objective fuzzy optimization scheduling

This paper establishes the objective functions of maximizing economic benefits and minimizing operational risks. Because the marginal cost of the output of wind and solar is low and the economy is optimal, when the economic benefits of RHES are optimal, the power on-grid of WPP, PV, and SC (the highest utilization rate) is large, and the system operation risk is relatively large; when the risk of the system is lowest, CGT reduces the amount of on-grid clean energy taking advantage of its characteristics of fast start-up speed and stable output, and has relatively low economic performance. In order to balance the relationship between the two, the fuzzy goal is used to convert the multi-objective into a single-objective function, which is solved in four steps.

1. Input raw data, including forecast output and parameters of wind and solar power; the output, climbing rate, start-up, and shutdown limits of turbine engines; the

positive and negative rotation backup demand of the system; output limits of electric boiler.

2. Take the maximum economic benefits as the objective, solve the RHES operation optimization model, and obtain the economic optimal value \(\text{obj}_1^*\) and the operational risk value \(\text{obj}_2\) at this time.

3. Take the minimum operating risk as the objective, solve the RHES operation optimization model, and obtain the lowest operating risk value \(\text{obj}_2^*\) and the economic benefit value \(\text{obj}_1\) at this time.

4. Stretch the individual target values and determine \(\delta_1\) and \(\delta_2\). Since it is double target fuzzy optimization, the optimization result cannot be lower than \(\text{obj}_2^*\) and cannot exceed \(\text{obj}_1^*\), and the optimization results of \(\delta_1\) and \(\delta_2\) are ranges from \(0 \leq \delta_1 \leq \text{obj}_1^* - \text{obj}_1\) and \(0 \leq \delta_2 \leq \text{obj}_2 - \text{obj}_2^*\), respectively. According to the will and preference of the decision maker, the degree of expansion and contraction is different.

5. Bring \(\delta_1\) and \(\delta_2\) into the following formula and get the expression of each objective function.

Let \(\mu\) be the minimum of all target membership functions, which can be used to indicate the satisfaction degree of the decision. The satisfaction index is as follows: \(\chi = \min \{ \mu(\text{obj}_1), \mu(\text{obj}_2) \} \). The original problem is transformed into a single-objective nonlinear optimization problem, maximizing the satisfaction index \(\chi\), which satisfies all constraints:

\[
\begin{align*}
\text{max} & \quad \chi \\
\text{s.t} & \quad \mu(\text{obj}_1) \geq \chi \\
& \quad 0 \leq \chi \leq 1 \\
& \quad \text{eq}(1) - (19).
\end{align*}
\]

(34)

Through the linearization fuzzification process, the above multi-objective unit combination optimization problem becomes a MIP problem, which can be quickly solved by the software GAMS.

4 ROBUST-BASED MIP MODEL

4.1 Uncertainty analysis

Both wind and photovoltaic power generation have randomness and volatility. Wind power is subject to seasonal and time constraints. The number of hours of photovoltaic power generation is low. The control requirements for RHES are relatively high when the two unstable energy sources are used together. In addition, the expected values of available power from wind and solar sources can be calculated according to the scene simulation. It is impossible
to formulate an accurate power output plan in advance, so the uncertainty risk of the wind and solar cannot be ignored.

Regional hybrid energy system must maintain the dynamic balance of supply and demand of power load at all times. The uncertainty of wind power and photovoltaic output makes it difficult to maintain the balance of the system, but gas turbine power generation is relatively stable, and related technologies are relatively mature. In this paper, the robust stochastic optimization theory is used to overcome the disadvantages caused by the uncertainty of wind and solar. The robust stochastic optimization theory can formulate different scheduling schemes according to the requirements of the risk tolerance of RHES and achieve optimal economic benefits under specific risk tolerance.

4.2 Robust stochastic optimization model

The system operates stably when the load is fully borne by the gas turbine, but the operating cost is high, and the environment is seriously damaged. Due to the intermittent and random nature of wind power and photovoltaic power, the large number of grid-connected wind power and photovoltaic power will inevitably hinder the stable operation of the system. According to the robust stochastic optimization theory, the constraint is modified by the robust coefficient $\Gamma$, with free regulation performance to increase its uncertainty. The actual amount of wind and solar power generation cannot be accurately predicted, but it can be turned into intervals to improve prediction accuracy:

$$\tilde{g}_{\text{wpp},t} = g_{\text{wpp},t} + \eta_i e_{\text{wpp},t} \delta_{g,\text{wpp},t}, \eta_i \in [-1, 1],$$

$$\tilde{g}_{\text{pv},t} = g_{\text{pv},t} + \gamma_i e_{\text{pv},t} \delta_{g,\text{pv},t}, \eta_i \in [-1, 1].$$

Then, the power fluctuation interval is as follows:

$$\tilde{g}_{\text{wpp},t} \in [(1 - e_{\text{wpp},t})g_{\text{wpp},t}, (1 + e_{\text{wpp},t})g_{\text{wpp},t}],$$

$$\tilde{g}_{\text{pv},t} \in [(1 - e_{\text{pv},t})g_{\text{pv},t}, (1 + e_{\text{pv},t})g_{\text{pv},t}].$$

where $\tilde{g}_{\text{wpp},t}$ and $\tilde{g}_{\text{pv},t}$ are the uncertain forms of WPP and PV power generation, respectively; $e_{\text{wpp},t}$ and $e_{\text{pv},t}$ are the error coefficients of WPP and PV power generation, respectively.

The equation constraint (24) is transformed into an inequality constraint as follows:

$$\tilde{g}_{\text{wpp},t}(1 - \varphi_{\text{wpp}}) + \tilde{g}_{\text{pv},t}(1 - \varphi_{\text{pv}}) + g_{\text{CGT},t}(1 - \varphi_{\text{CGT}}) + g_{\text{PD},t} \geq L_t + g_{\text{EB},t} - (g_{\text{EES},t} - g_{\text{cha},t}).$$

Then, set $H_t$ is the net load of system, which can be calculated as follows:

$$H_t = g_{\text{CGT},t}(1 - \varphi_{\text{CGT}}) + g_{\text{PD},t} - (L_t + g_{\text{EB},t}) - (g_{\text{EES},t} - g_{\text{cha},t}).$$

According to the formula (35), the constraint condition (16) can be converted, and the constraint after the conversion is as follows:

$$-\tilde{g}_{\text{wpp},t}(1 - \varphi_{\text{wpp}}) - \tilde{g}_{\text{pv},t}(1 - \varphi_{\text{pv}}) \leq H_t,$$

which is as follows:

$$-(g_{\text{wpp},t} + \eta_i e_{\text{wpp},t} \delta_{g,\text{wpp},t})(1 - \varphi_{\text{wpp}})$$

$$-(g_{\text{pv},t} + \gamma_i e_{\text{pv},t} \delta_{g,\text{pv},t})(1 - \varphi_{\text{pv}}) \leq H_t.$$
On the basis of taking into account the economic benefits and system risks of RHES, in order to overcome the uncertainty of wind power and photovoltaic power generation, the robust stochastic optimization theory is introduced and the robust stochastic optimization scheduling model of RHES is constructed. By setting the prediction error, the impact of different robust coefficient settings on the scheduling results of RHES is discussed to meet the different risk preferences of decision makers.

5 | ILLUSTRATIVE EXAMPLE

5.1 | Basic data

In this section, a hybrid integrated energy system is modeled to verify the validation of the optimization model. In this paper, the RHES project of the regional grid in northern China in winter is selected, which mainly contains small wind power clusters, small photovoltaic power generation clusters, CGT units, etc. Simplified diagram of RHES operation principle is shown in Figure 4. The equipment capacity and key operating parameters of RHES are shown in Tables 2 and 3.

This hybrid energy system could comprehensively regulate the electricity and thermal power in the district, and at the same time, it could operate in a flexible structure according to energy storage, to meet the need of electric and thermal loads.

5.1.1 | Load Data

The typical day of the system is shown as follows: In this part, a typical daily data for the winter heating season in Bayannaoer of Inner Mongolia is selected, and the time interval of data acquisition is one hour. The electric and the heating load of this RHES project in a typical day is shown in Figure 5.

5.1.2 | The Energy Price Data

The price of energy has a great impact on the overall economy of the system. According to the actual situation, the price of electricity and natural gas of the main grid adopts the time-of-use price and divides the peak, flat, and valley period. See Figure 6 for details. The on-grid electricity price of WPP, PV, and CGT is set to be 0.49 ¥/kWh, 0.65 ¥/kWh, and 0.65 ¥/kWh,16,17 respectively, and the heating price of the system is 0.25 ¥/kWh.

5.1.3 | The Energy Output and Storage Data

In order to obtain the available output of WPP and PV, referring to,18 the wind power parameters are set as...
v_{in} = 3 \text{ m/s}, v_{rated} = 14 \text{ m/s}, v_{out} = 25 \text{ m/s}, and the PV illumination intensity parameters, \alpha and \beta, set to 0.39 and 8.54, respectively. Referring to literature, and according to the solar thermal intensity distribution data of the region, the thermal power of SC is obtained. In this paper, through the scene simulation method, 50 sets of simulation scenes are generated by using the above parameters and reduced to 10 typical scenes by the method of Ref. 20 and finally, the scene with the highest probability of occurrence is used as output data. Typical daily power output is shown in Figure 7.

5.2 | Simulation result

5.2.1 | Optimal Weight Determination

In order to analyze the impact of different optimization objectives on the operation of the system, the scheduling results in
different optimization objective functions are solved, respectively. Firstly, the optimal operation strategy of the RHES is obtained by taking the economic benefit optimization as the target (obj1 mode). At this time, the value of operation revenue and net load fluctuations is $68.50 \times 10^3 ¥$ and 0.056, respectively. Figure 8 and Figure 9 show the scheduling results of the RHES operation in obj1.

According to Figures 8 and 9, in order to maximize economic benefits, RHES will give priority to WPP, PV, and SC to meet the demand of electrical load and heat load. CGT utilizes its own fast start-up and shutdown speeds to provide backup for WPP, PV, and SC, realizing the coordinated and complementary operation. The total output of WPP, PV, and SC is 93.33, 14.93, and 10.40 MWh; the output of CGT is 10.94 MWh. Some of them use EB to convert to thermal energy to supply heating for SC, which is up to 70.12 MWh; the electricity purchased from external network is 4.84 MWh. In the pursuit of maximizing economic efficiency, according to the real-time electricity price, gas price, thermal price, purchase and sale price of external grid, and energy storage cost, RHES will not be able to use wind and solar at one time to realize energy conversion, storage, and utilization. Among them, at 06:00-07:00 and 16:00-17:00, EES discharged 2.86 MWh, and during 19:00-21:00, EES stores 3.16 MWh. The electrical storage, heat storage, and the abandoned energy accumulate up to 6.02 MWh, 0 MWh, and 11.07 MWh, respectively. The obj1 refers to the peak period of thermal load, the valley period of renewable energy output, and the priority of renewable energy output under the goal of economic benefit maximization. The insufficient part is converted to heat or heat storage energy by the electric boiler purchased from the external network; the valley period of thermal load, the peak period of renewable energy output, satisfies the balance of electric quantity, and under the constraint of heat energy balance (Equations 24 and 25), according to the real-time electricity prices, heat prices, and power storage income. The relationship between heat storage benefits determines the storage or disposal of surplus renewable energy. Under this objective function, renewable energy will try its best to produce its output. When the renewable energy is insufficient, the cost of electricity purchase in the external network is lower than the cost of heat energy storage. At this time, HES is 0, and the system purchases 4.84 MW from the external grid and has certain energy abandonment.

However, in the regional power grid, the high permeability of intermittent energy causes the random power output, and the high-power load switching causes the...
imbalance of active power supply and demand, which brings great challenges and risks to the stable operation of RHES. When discussing the optimal operation strategy of RHES, it also needs to analyze the risks brought to the system by WPP, PV, and SC. That is, the net load fluctuation of the system is used to measure the stability level of the grid with high-permeability intermittent energy. Unlike the optimal operation strategy of the objective function, the minimum load fluctuation is calculated. At this time, the value of operation revenue is \( 58.91 \times 10^3 \) ¥ and the net load fluctuation is relatively balanced. When \( \mu (obj_1) \in [0.2,0.5] \), the value of objective function \( obj_1 \) increases faster; when \( \mu (obj_2) \in [0.5,0.8] \), the value of objective function \( obj_2 \) reaches a relatively stable state; when \( \mu (obj_2) \in [0.3,0.5] \), the value of \( obj_2 \) increases faster; when \( \mu (obj_2) \in [0.5,0.7] \), the value of \( obj_2 \) reaches a relatively stable state. When \( \chi = 0.576 \), the value of objective function has reached a steady state. The maximum and minimum satisfaction functions can be used to indicate the satisfaction degree of the decision, which means that the optimal weight coefficient is distributed in the interval. Therefore, we chose 0.576 as the value of \( \chi \) and give the comprehensive result of the scheduling result of RHES.

According to Figures 10 and 11, when the minimum net load fluctuation is the optimal target, RHES will reduce the output of WPP, PV, and SC, and preferentially utilize CGT and EB to meet the electrical load and heating load. The total output of WPP, PV, and SC is 90.95 MWh, 14.27 MWh, and 10.40 MWh, respectively, and the power output of CGT is 12.24 MWh, which is increased by 1.32 MWh compared with mode 1. At the same time, CGT converts 67.64 MW of thermal energy through EB, and SC only provides 10.40 MWh. In the mode of pursuing the minimum risk, the energy storage system discharges 3.49 MWh during 05:00-08:00 and 16:00-18:00, 3.15 MWh of storage power during 12:00-15:00 and 19:00-20:00, storage heat of 1.14 MWh at 02:00, 04:00, 07:00, and 10:00, and releases 0.98 MWh of heat during 16:00-17:00. The system has abandoned energy of 12.26 MWh, which is 1.19 MWh more than mode 1. At the same time, heat storage participates in energy exchange, indicating that, under the target of minimum system fluctuation, energy storage regulates the volatility of uncertain energy output.

In the above, the economic benefits and net load fluctuations under different targets are solved separately. In order to make the optimal operation strategy consider the optimization appeals of different objective functions at the same time, it is necessary to consider the maximum and minimum values of the two, and the maximum and minimum satisfaction methods used to convert the multi-objective function into a single-objective function combined with a membership function. The ideal value of \( obj_1^* \) is 68 495, of \( obj_1 + \delta_1 \) is 59 980, of \( obj_2^* \) is 0.33, and of \( obj_2 + \delta_2 \) is 0.049. The multi-objective optimization results of economic benefits and net load fluctuations are shown in Table 4.

Let \( \mu \) be the minimum value in the membership function of all objective functions, \( \chi = \min \{ \mu (obj_1), \mu (obj_2) \} \), when \( \chi \) is the maximum of 0.576, the operating benefit is 65 867 ¥, and the net load fluctuation of the system is 0.037. According to Table 1, when \( \chi = 0.517 \), the value of revenue and system fluctuations is relatively balanced. When \( \mu (obj_1) \in (0.2,0.5) \), the value of objective function \( obj_1 \) increases faster; when \( \mu (obj_2) \in [0.5,0.8] \), the value of objective function \( obj_2 \) reaches a relatively stable state; when \( \mu (obj_2) \in [0.3,0.5] \), the value of \( obj_2 \) increases faster; when \( \mu (obj_2) \in [0.5,0.7] \), the value of \( obj_2 \) reaches a relatively stable state. Therefore, we chose 0.576 as the value of \( \chi \) and give the comprehensive result of the scheduling result of RHES.

According to Figures 12 and 13, it can be seen that when the equilibrium economic benefit and the net load fluctuation of the system reach equilibrium, the total output of WPP, PV, and SC is 91.86 MWh, 14.57 MWh, and 11.38 MWh, respectively, and the power output of CGT is 10.93 MWh, while CGT converts 72.22 MWh of thermal energy by EB. In the RHES equalization mode, the accumulative charge and discharge quantity of the energy storage system reaches 10.05 MWh, and the charge and discharge of heat reaches 6.42 MWh. The system’s abandoned energy is 9.49 MWh. Energy storage and heat storage are also involved in energy exchange, indicating that energy storage plays an important role in the balanced operation of the system.

### 5.2.2 Effectiveness analysis of robust stochastic optimization theory

In the former part of this paper, the RHES scheduling model is solved using a single target to obtain the optimal scheduling.
result set. Then, the fuzzy satisfaction theory is considered\textsuperscript{21} and the optimization appeals of different objective functions are taken into account, which solves the problem of multi-objective optimization and realizes the overall optimization operation. In order to discuss the uncertain effects of wind and solar output on the system, a robust stochastic optimization theory is introduced to construct a robust stochastic optimization model for RHES, and the empirical error coefficients are predetermined as $e_{\text{WPP}} = e_{\text{PV}} = 0.05$. The scheduling optimization situations of RHES are discussed when the robust coefficient $\Gamma_{\text{WPP}} = \Gamma_{\text{PV}} = 0.5$ and $\Gamma_{\text{WPP}} = T_{\text{PV}} = 0.9$. The values of $\Gamma$ in the robust optimization theory can reflect the ability of the system to cope with risk.\textsuperscript{22} When $\Gamma$ is 0.5, it means that the system’s ability to deal with risk is medium; when the value is 0.9, it means that the system has a high ability to deal with risk. Table 5 shows the scheduling scheme of the RHES with different robustness coefficients.

In comparison with $\Gamma = 0$, when the robustness coefficient is 0.5, the system scheduling scheme changes due to the randomness of wind power; the grid-connected wind power is reduced from 91.86 MWh to 90.23 MWh, and the amount of abandoned wind power is increased from 9.49 MWh to 11.81 MWh. In addition, both the economic benefits of the system and the load volatility are reduced. This means that if the random characteristics of wind power are not considered, the system will arrange a scheduling scheme according to its predicted power. Although the grid-connected power may increase, the corresponding risks need to be taken. Figure 14, respectively, show the output schemes of each unit when the robustness coefficient is 0 or 0.5. At 9 hours, the grid-connected clean energy is further reduced, the output of CGT is increased, and the load fluctuation value of system is close to the lowest point of the single-objective function.

Therefore, the introduction of the robustness coefficient can reflect the risk attitude of the decision maker. The larger the value, the lower the risk tolerance of the decision maker. In order to minimize the operating risk, the system will reduce the grid-connected power generation of clean energy.

### 6 | CONCLUSIONS

In this paper, an optimization model of an RHES consisting of WPP, PV, SC, CGT, EB, and energy storage is built, which aims to obtain the economic benefits while considering the system stability. Then, a multi-objective optimization model for RHES operation is constructed based on device models under two objective functions, namely the maximum economic revenue and minimum load fluctuation functions. Finally, the regional power grid of Bayannaoer, Inner Mongolia, China, is taken, in winter, as an example object; the conclusions can be summarized as follows:

1. The paper built a regional hybrid energy system to fully utilize the complementary advantages of clean energy and synergistically meet the needs of users’ electrical
and heating loads. For WPP, PV, SC, CGT, EB, and other integrated electric–thermal complementary hybrid energy systems, CGT provided backup when clean energy was insufficient, and coordinated power generation and energy storage according to different gas and electricity prices in different periods; electric boilers used abandoned wind and solar energies in the valley time to convert into heat energy, which complements the SC to meet the heat load demand.

2. The multi-objective optimization scheduling model established in this paper could take into account the optimization requirements of different objective functions, and reasonably control the stability of the system while pursuing the maximum operating efficiency of RHES, and achieve an overall balanced operation. In OBJ mode, compared with the economic benefit optimization mode, RHES would reduce the output of WPP and PV power generation, increase the power generation of CGT or the external power grid, and enhance the stability of the system through the peaking backup of EES and RHES. Compared with the load volatility minimization mode, RHES would use WPP, PV, and SC more, and use them as the backup for power generation or heating during the peak period, which can both suppress the uncertainty risk of WPP and PV and release the peaking capacity of CGT, TES, and EES to promote the integration of clean energy and increases in its operating income.

3. The paper used the fuzzy membership function to analyze the distance between the objective function value and the ideal value, converted the numerical optimization into degree optimization, selected the semi-linear membership function to process the objective of maximum the operating revenue, and selected the semi-gradient membership function to process the objective of minimum operating risk. The maximum and minimum satisfaction method is adopted to convert the multi-objective function into a single-objective function combined with the membership function according to the degree of satisfaction of the decision maker (i.e., the optimal weight coefficient distribution interval), and the operation situation of RHES in the equilibrium mode is solved.

4. This paper used robust stochastic optimization to describe the uncertainty brought by WPP, PV, and SC to RHES. By setting the robustness coefficient, this paper provides risk avoidance tools for different types of decision makers to ensure the safe and stable operation of RHES. With the increase in the robust coefficient Γ, the sensitivity of decision makers to the uncertainty risk is increasing, the output of WPP, PV, and SC is gradually decreasing, and the value of income is gradually decreasing. If policy makers want to pursue the economic benefits of WPP, PV, and SC, they must sacrifice the stability of the system. At the same time, in the peak and valley periods, due to the tight relationship between supply and demand of load, with the increase in Γ, the scheduling scheme of RHES has a large change range. In the flat period, the scheduling scheme has a small change range. In the future, with the decline in energy storage costs, the application promotion space will gradually increase, and how to achieve the accumulation of clean energy by optimizing system capacity allocation is the focus of research.

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