Dispatch Models for Electricity-Heat-Gas Systems With Concentrating Solar Power Plants Using Info-Gap Theory and Analytic Hierarchy Process

Hualong Liu, Wenyuan Tang
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, USA
{hliu37, wtang8}@ncsu.edu

***Abstract*—In order to further analyze the flexible coupling and complementary characteristics of various energy resources in the integrated energy system (IES) and increase the absorption capacity of renewables, concentrating solar power (CSP) plants and generalized energy storage (GES), such as electric energy storage systems, heat storage systems, and natural gas storage systems, are introduced into the IES. First, the framework of the electricity-heat-gas integrated energy system (EHGIES) structure is built, and the main equipment models are constructed. Second, the deterministic dispatch model for the EHGIES is established by minimizing the operating cost of the system. Third, info-gap decision theory is leveraged to effectively handle the uncertainties of photovoltaic, wind generation, electric, thermal, and gas loads. Based on two different risk preferences of risk aversion and risk seeking (opportunity seeking), multi-objective dispatch models under opportuneness and robustness strategies are established, and these multi-objective models are further transformed into single-objective models through the analytic hierarchy process. Finally, the feasibility, effectiveness, and superiority of the proposed models are verified by case studies.**

***Index Terms*—Info-gap decision theory, integrated energy system, multi-objective, optimal dispatch, renewables, uncertainty.**

I. Introduction

A. Research Motivation

In order to further reduce carbon emissions, the scale of grid-connected renewables, such as photovoltaic (PV) and wind generation, has been constantly expanding. However, the uncertainty, volatility, and intermittency of renewables have brought great challenges to the stable operation of the power grid. To solve the aforementioned problems, concentrating solar power (CSP) plant technologies [1], [2] have received extensive attention. The CSP plant with the thermal energy storage (TES) system can use the heat generated by concentrating solar radiation to produce steam to drive a turbine to generate electricity and store heat in the TES unit during the periods of low loads. During the periods of peak loads, the collected solar heat and the heat stored in TES are used to generate electricity so as to achieve continuous, stable, and reliable power output. The CSP plant resolve the problem that the traditional PV generation cannot generate electricity at night. The CSP plant has flexible output, strong controllability, and less carbon emissions, and can be used as the dispatchable source to coordinate PV and wind generation and improve the consumption level of renewables and the ability of power systems to cope with load changes. The CSP plant can consume renewables with renewables when it can be connected to the grid with PV and wind generation.

Due to the limited level of renewable consumption in the power grid, a large quantity of wind and light is abandoned. The integrated energy system (IES) breaks the structure and configuration of single network operation, and connects a variety of energy networks through coupling devices. The overall planning and dispatch of the IES network can cascade energy utilization, greatly improve the system's absorption capacity of renewables and energy conversion efficiency and the stability of power grid operation, and reduce energy waste and environmental pollution caused by a single energy supply system. Carbon capture, utilization, and storage (CCUS) [3] has the characteristics of achieving near-zero carbon emissions, and the CO_2 captured and stored in the CCUS device can be used as the carbon source required in the power-to-gas (P2G) reaction process. The integrated development of the vanilla IES and the CCUS device provides an opportunity for the low-carbon economic operation of the IES. Energy storage equipment has the advantages of promoting the consumption of renewables, rapid responses, and reducing operating costs, but with the diversification of energy supply demand, the scope of energy storage is becoming more and more extensive. The operational flexibility of the thermal storage system can improve the adjustment ability of the IES, and the introduction of gas storage equipment broadens the energy adjustment means of the IES. Therefore, electricity storage systems, heat storage systems, and gas storage systems can be regarded as generalized energy storage (GES) and participate in IES operation.

To sum up, it is of great theoretical and practical significance to study the electricity-heat-gas integrated energy system (EHGIES) with the CSP plants and GES systems while considering the uncertainties of renewables and loads.

B. Literature Review

Researchers have conducted a lot of studies on the IES. However, in most studies, traditional gas units or coal-fired units are used as core units, the demand periods of electricity and heat loads in the scheduling cycle do not match, and combined heat and power (CHP) are constrained by "heat to power (determining electricity by heat)", which limits the energy utilization and flexible operation capacity of the system, resulting in the abandonment of light and wind. As a new type of green, flexible, and controllable generator unit, the CSP plant is an important way to solve the limited operation mode and the carbon emission problem of traditional units. The optimal scheduling of the regional IES considering economy and environment was described in [4]. Reference [5] proposed a planning model of the IES with electricity, heat and gas using particle swarm optimization. The cost-benefit of IES planning considering demand response was analyzed in [6]. Reference [2] studied the modeling of the CSP plant. A distributionally robust coordinated expansion planning model for generation, transmission, and demand side resources considering the benefits of CSP plants was discussed in [7]. A look-ahead stochastic unit commitment model for a high renewable penetrated power system with CSP plants was proposed in [8]. Reference [9] presented the profit-sharing mechanism for aggregation of wind farms and CSP. In [1], a risk-constrained stochastic optimization method of a CSP plant was proposed. Reference [10] discussed the thermal energy storage systems for CSP plants. These studies are limited to collaborative power generation, ignoring the potential of the CSP as the core unit to participate in IES planning and operation. Furthermore, most of these studies only consider the storage of electric energy, and seldom consider the storage of heat and gas. Moreover, there are few researches on the integration of GES and CSP plants into the IES system.

There are four main methods to handle uncertainty in energy systems, namely stochastic programming [11], [12], robust optimization [13], [14], fuzzy optimization [15], [16], and interval methods [17], [18]. Stochastic programming is an analysis method based on probability theory, and relies on the probability models of uncertain variables, which are difficult to obtain accurately. In addition, scenario-based stochastic programming methods need to set plenty of scenarios, which lead to large calculation scale and low solving efficiency. Robust optimization makes decisions under worst conditions on the basis of given fluctuation ranges of uncertain variables, which often leads to conservative results and poor economy. Fuzzy optimization selects the membership function to describe uncertainty and its possible consequences, which is strongly subjective. Interval methods assume that the prediction errors of uncertain variables are within specific interval ranges; however, such ranges are demanding to obtain accurately. Compared with the above four methods, info-gap decision theory [19] is a relatively new approach to cope with uncertainty, and info-gap theory can still quantify uncertainty when the exact probability distributions or uncertainty intervals of uncertain variables are unknown. It has the advantages of strong applicability and high calculation efficiency. To a certain degree, researchers have applied info-gap decision theory to reactive power planning [20], voltage management [21], optimal power flow [22], market bidding strategies [23], unit commitment [24], and energy scheduling [25], [26]. Nonetheless, info-gap theory has few applications in the IES, especially in the EHGIES, which means the application of info-gap theory in the IES remains to be studied. Furthermore, in the existing info-gap theory models, only one uncertainty is usually considered in modeling, such as only load or wind or PV generation uncertainty. Only the uncertainty of wind generation was taken into account in the corresponding problems of References [22]–[24]. Only the uncertainty of loads was considered based on info-gap decision theory in [27]. Moreover, info-gap theory has two performance requirements for uncertainty, namely robustness and opportuneness; however, the current research generally only considers robustness and ignores opportuneness. References [27]–[30] only take into consideration robustness.

C. Contributions

To bridge the gaps mentioned in Sections I-A and I-B, this paper is aimed at exploring the optimal operation of the IES including the CSP plant and GES. Specifically, the main contributions of this paper are summarized as follows.

1) An EHGIES including the CSP plant and GES is established, and a deterministic optimal operation model of the EHGIES minimizing the operating costs is formulated.
2) Based on info-gap theory, the uncertainties of PV, wind generation, electric loads (ELs), thermal loads (TLs), and gas loads (GLs) are comprehensively considered in optimal EHGIES dispatch. According to decision makers' preference for risk, both a robust operation strategy for risk aversion (RA) and an opportunistic operation strategy for opportunity seeking (OS), or risk seeking, are established, and two different dispatch schemes from different decision-making perspectives are obtained.
3) Multi-objective models for the optimal operation of the EHGIES based on info-gap theory under opportuneness and robustness strategies are proposed. Then, these multi-objective models are further transformed into single-objective models through the analytic hierarchy process (AHP). These models can provide decision makers with operation schemes for uncertainties of different ranges under different risk attitudes.
4) The correctness, feasibility, superiority, and effectiveness of the proposed models are verified by a series of numerical examples.

II. The Architecture of the EHGIES and the Mathematical Models of Main Equipment

A. The Architecture of the EHGIES

By optimizing and adjusting the traditional IES structure, we construct the EHGIES containing CSP plants and GES systems. The basic architecture and energy flow of the EHGIES are shown in Fig. 1. The EHGIES includes gas boilers (GBs), gas storage systems (GSSs), power-to-gas (P2G) equipment, CCUS systems, gas turbines (GTs), heat recovery units (HRUs), solar fields (SFs), heat transfer fluids (HTFs), generators, thermal energy storage (TES) systems, electric boilers (EBs), PV panels, wind turbines (WTs), battery energy storage systems (BESSs). The loads encompass ELs, TLs, and GLs. In addition, the system can exchange energy with the external power grid (EPG) and the external gas network (EGN).

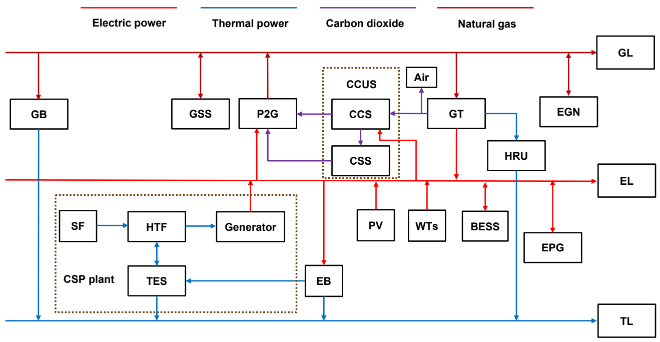

Fig. 1. Basic architecture and schematic energy flow of the EHGIES.

B. The Mathematical Models of Main Equipment

1) CSP Plants: As shown in Fig. 1, a CSP plant is an indirect solar thermal power generation station. The CSP consists of three modules, namely an SF, a generator, and a TES system. The SF gathers solar irradiation to the receiver through the reflector, and the collector uses the received solar energy to heat HTFs to convert solar energy to thermal energy. HTFs pass through these modules to transfer heat. Part of HTFs flow into the TES system, and some HTFs flow into the generation system to generate electricity. The encapsulated TES system can also transport heat to the heat network through the heat exchange platform to supply TLs. When the solar irradiation intensity is high, the TES will store the excess heat; during the periods of peak loads, the CSP plant increases power generation by invoking the heat stored by the TES system, which shifts the heat collected by the SF. Therefore, the CSP is dispatchable at a certain extent. The combination of the CSP and EBs expands the output range of the CSP. The EB converts electric energy from the grid into thermal energy and stores it in TES for the CSP to use when needed.

By thinking of the HTF as a node, we can obtain the thermal power balance relationship inside the CSP is as follows:

$$P_t^{\mathrm{SF}} + P_t^{\mathrm{TES,dis}} = P_t^{\mathrm{HCSP}} + P_t^{\mathrm{TES,ch}}, \quad \forall t, \tag{1}$$

where, P_t^{SF} is the thermal power transmitted by the SF to the HTF at time period t. $P_t^{\mathrm{TES,ch}}$ is the thermal power flowing from the HTF to the TES system at time t, $P_t^{\mathrm{TES,dis}}$ is the thermal power flowing from the TES to the HTF, and P_t^{HCSP} is the thermal power flowing into the generator.

The electric power P_t^{CSP} generated by the CSP at time period t is

$$P_t^{\mathrm{CSP}} = \eta^{\mathrm{H2P}} P_t^{\mathrm{HCSP}}, \quad \forall t, \tag{2}$$

where η^{H2P} is the the conversion efficiency of heat to electricity.

2) CCUS Systems: The CCUS system is comprised of the carbon capture and utilization (CCU) system and the carbon storage system (CSS). The amount of the CO_2 emission of the gas turbine (GT) is given by

$$E_t^{\mathrm{GT}} = \xi_1^{\mathrm{GT}} P_t^{\mathrm{Gen}} + \xi_2^{\mathrm{GT}} P_t^{\mathrm{HGen}}, \quad \forall t, \tag{3}$$

where ξ_1^{GT} and ξ_2^{GT} are the emission coefficients of the GT.

The carbon dioxide flow process in the GT-CCUS system can be represented by

$$E_t^{\mathrm{GT}} = E_t^{\mathrm{CCS}} + E_t^{\mathrm{air}}, \quad \forall t, \tag{4}$$

$$E_t^{\mathrm{CCS}} = E_t^{\mathrm{CSS,ch}} + E_t^{\mathrm{2P2G}}, \quad \forall t, \tag{5}$$

where E_t^{CCS}, E_t^{air}, $E_t^{\mathrm{CSS,ch}}$, and E_t^{2P2G} are the amount of CO_2 captured by CCS, the amount of CO_2 directly emitted to the atmosphere, the amount of CO_2 charged to CSS, and the amount of CO_2 transported by CCS to P2G, respectively.

The relationship between the CO_2 captured by CCS and the electric power consumed by CCS is as follows:

$$P_t^{\mathrm{CCS}} = \beta E_t^{\mathrm{CCS}}, \quad \forall t, \tag{6}$$

where β represents the corresponding coefficient between P_t^{CCS} and E_t^{CCS}.

3) P2G Systems: P2G can convert the electricity from PV and wind generation, which are sometimes difficult to consume, into natural gas, and GTs can use natural gas generated by P2G to generate electricity when the electricity loads are high. P2G mainly includes two processes, i.e., electrolysis of water and methanation. Oxygen and hydrogen are produced by electrolysis of water. Hydrogen is explosive, difficult to store and to transport over long distances, and natural gas has a higher energy density than hydrogen. Natural gas is easier to store and transport and more environmentally friendly, and the generated natural gas can be easily injected directly into natural gas pipelines. Therefore, the hydrogen generated by electrolysis is further synthesized into natural gas with carbon dioxide. The two processes of P2G are as follows:

$$2\,\mathrm{H_2O} \xrightarrow{\text{electrolysis}} 2\,\mathrm{H_2} + \mathrm{O_2}, \tag{7}$$

$$\mathrm{CO_2} + 4\,\mathrm{H_2} \longrightarrow \mathrm{CH_4} + 2\,\mathrm{H_2O}. \tag{8}$$

$$V_t^{\mathrm{P2G}} = \frac{\eta^{\mathrm{P2G}} P_t^{\mathrm{P2G}}}{H^{\mathrm{CH_4}}}, \quad \frac{E_t^{\mathrm{P2G}}}{M^{\mathrm{CO_2}}} = \frac{V_t^{\mathrm{P2G}}}{V_m}, \quad \forall t, \tag{9}$$

where η^{P2G} is the conversion efficiency of P2G, V_t^{P2G} is the volume of synthesized natural gas. P_t^{P2G} is the electricity consumed by P2G during time period t. E_t^{P2G} is the amount of CO_2 required by P2G, $H^{\mathrm{CH_4}}$ represents the calorific value of CH_4, $M^{\mathrm{CO_2}}$ denotes the molar mass of CO_2. V_m denotes the molar volume of CH_4.

The carbon dioxide balance equation of P2G is

$$E_t^{\mathrm{P2G}} = E_t^{\mathrm{CSS,dis}} + E_t^{\mathrm{2P2G}}, \quad \forall t, \tag{10}$$

where $E_t^{\mathrm{CSS,dis}}$ is the amount of CO_2 discharged to P2G.

III. DETERMINISTIC DISPATCH MODEL OF THE EHGIES

A. Optimization Objective

By minimizing the system operating cost, the objective function can be constructed as follows:

$$\min C = C_{\mathrm{OM}} + C_{\mathrm{imp}} + C_{\mathrm{CO_2}} - C_{\mathrm{exp}}, \tag{11}$$

$$C_{\mathrm{OM}} = \sum\nolimits_{t=1}^{T} \sum\nolimits_{k\in\Omega} \rho^k P_t^k, \tag{12}$$

$$C_{\mathrm{imp}}=\sum\nolimits_{t=1}^{T}\sum\nolimits_{i\in\mathcal{N}}\pi_t^{\mathrm{imp},i}P_t^{\mathrm{imp},i}, \tag{13}$$

$$C_{\mathrm{CO_2}}=\zeta\left(E^{\mathrm{CO_2}}-E_0^{\mathrm{CO_2}}\right), \tag{14}$$

$$E^{\mathrm{CO_2}}=\sum\nolimits_{t=1}^{T}\sum\nolimits_{l\in\Omega_{\mathrm{emi}}}\xi^l P_t^l-\sum\nolimits_{t=1}^{T}E_t^{\mathrm{CCS}}, \tag{15}$$

$$E_0^{\mathrm{CO_2}}=\sum\nolimits_{t=1}^{T}\sum\nolimits_{l\in\Omega_{\mathrm{emi}}}\gamma P_t^l, \tag{16}$$

$$\begin{aligned}\Omega=&\{\mathrm{CSP},\mathrm{PV},\mathrm{WT},\mathrm{GT},\mathrm{GB},\mathrm{EB},\mathrm{GES},\\&\mathrm{P2G},\mathrm{CCS},\mathrm{CSS}\},\quad \mathcal{N}=\{\mathrm{electricity},\mathrm{CH_4}\},\end{aligned} \tag{17}$$

where C, C_{OM}, C_{imp}, $C_{\mathrm{CO_2}}$, C_{exp} are the total cost, the operation and maintenance (OM) cost of devices, the cost of importing electricity and gas, the CO_2 trading cost, and the revenue from exporting electricity and natural gas, respectively. P_t^k is the generated electric power or thermal power of device k. ρ^k is the OM factor of device k. $\pi_t^{\mathrm{imp},i}$ is the electricity or gas price. $P_t^{\mathrm{imp},i}$ is the imported electric power or gas power. ζ is the cost coefficient of CO_2 trading. $E^{\mathrm{CO_2}}$ and $E_0^{\mathrm{CO_2}}$ are the CO_2 emissions of the EHGIES and the CO_2 emission quota of the EHGIES, respectively. l is the index of the devices producing CO_2. ξ^l is the emission coefficient of device l. P_t^l is the electric power or thermal power generated by device l. γ is the carbon emission quota factor. $\Omega_{\mathrm{emi}}=\{\mathrm{GT},\mathrm{GB},\mathrm{electricity}\}$

B. Constraints

1) Electric Power Balance Constraint:

$$\begin{aligned}&P_t^{\mathrm{PV}}+P_t^{\mathrm{WT}}+P_t^{\mathrm{imp,elec}}+P_t^{\mathrm{GT}}\\&+P_t^{\mathrm{CSP}}+P_t^{\mathrm{dis,BESS}}=P_t^{\mathrm{EL}}+P_t^{\mathrm{exp,elec}}+\\&P_t^{\mathrm{ch,BESS}}+P_t^{\mathrm{EB}}+P_t^{\mathrm{P2G}}+P_t^{\mathrm{CCS}},\quad\forall t,\end{aligned} \tag{18}$$

where P_t^{PV}, P_t^{WT}, P_t^{GT}, $P_t^{\mathrm{dis,BESS}}$, P_t^{EL}, $P_t^{\mathrm{ch,BESS}}$, and P_t^{EB} are the electric power generated by PV, the electric power generated by WTs, the electric power generated by the GT, the discharging power of the BESS, the power of the EL, the charging power of the BESS, and the power consumed by the EB, respectively.

2) Thermal Power Balance Constraint:

$$\begin{aligned}&P_t^{\mathrm{HGT}}+P_t^{\mathrm{HGB}}+P_t^{\mathrm{HEB,load}}+P_t^{\mathrm{HCSP,load}}\\&\qquad=P_t^{\mathrm{TL}},\quad\forall t,\end{aligned} \tag{19}$$

P_t^{HGT} and P_t^{HGB} are the thermal power generated by the GT at time t and the thermal power generated by the GB, respectively. P_t^{HEB} is the part of the thermal power generated by the EB that supplies the TL. P_t^{HCSP} is the part of the thermal power generated by the CSP that supplies the EL. P_t^{TL} is the power of the EL.

3) Natural Gas Balance Constraint:

$$\begin{aligned}V_t^{\mathrm{dis,GSS}}+V_t^{\mathrm{P2G}}+V_t^{\mathrm{imp,CH_4}}&=V_t^{\mathrm{exp,CH_4}}+V_t^{\mathrm{ch,GSS}}\\&+V_t^{\mathrm{GB}}+V_t^{\mathrm{GT}}+V_t^{\mathrm{GL}},\quad\forall t,\end{aligned} \tag{20}$$

where $V_t^{\mathrm{dis,GSS}}$, $V_t^{\mathrm{ch,GSS}}$, V_t^{GB}, V_t^{GT}, and V_t^{GL} are the discharging power of the GSS at time t, the charging power of the GSS, the gas consumed by the GB, the gas consumed by the GT, and the power of the GL, respectively.

4) CSP Constraints: The CSP generator set and the TES must meet the following operating constraints:

$$P_{\min}^{\mathrm{CSP}}\le P_t^{\mathrm{CSP}}\le P_{\max}^{\mathrm{CSP}},\quad\forall t, \tag{21}$$

$$-R_{\mathrm{down}}^{\mathrm{CSP}}\le P_t^{\mathrm{CSP}}-P_{t-1}^{\mathrm{CSP}}\le R_{\mathrm{up}}^{\mathrm{CSP}},\quad\forall t, \tag{22}$$

$$\begin{aligned}E_t^{\mathrm{TES}}=&(1-\sigma_{\mathrm{TES}})E_{t-1}^{\mathrm{TES}}+\eta_{\mathrm{TES}}^{\mathrm{ch}}P_t^{\mathrm{TES,ch}}\\&-P_t^{\mathrm{TES,dis}}/\eta_{\mathrm{TES}}^{\mathrm{dis}}+\eta_{\mathrm{HEB,TES}}P_t^{\mathrm{HEB,TES}}\\&-P_t^{\mathrm{TES2L}}/\eta_{\mathrm{TES2L}},\quad\forall t,\end{aligned} \tag{23}$$

$$0\le P_t^{\mathrm{TES,dis}}\le B_t^{\mathrm{TES,dis}}\eta_{\mathrm{TES}}^{\mathrm{dis}}P_{\max}^{\mathrm{TES,dis}},\quad\forall t, \tag{24}$$

$$0\le P_t^{\mathrm{TES,ch}}\le(1-B_t^{\mathrm{TES,dis}})P_{\max}^{\mathrm{TES,ch}}/\eta_{\mathrm{TES}}^{\mathrm{ch}},\quad\forall t, \tag{25}$$

$$E_{\min}^{\mathrm{TES}}\le E_t^{\mathrm{TES}}\le E_{\max}^{\mathrm{TES}},\quad\forall t, \tag{26}$$

$$0\le P_t^{\mathrm{TES2L}}\le B_t^{\mathrm{TES2L}}\eta_{\mathrm{TES2L}}P_{\max}^{\mathrm{TES2L}},\forall t, \tag{27}$$

$$0\le P_t^{\mathrm{HEB,TES}}\le B_t^{\mathrm{EB}}\eta_{\mathrm{HEB,TES}}P_{\max}^{\mathrm{HEB,TES}},\quad\forall t, \tag{28}$$

$$0\le P_t^{\mathrm{HEB,TES}}+P_t^{\mathrm{TES,ch}}\le P_{\max}^{\mathrm{TES,ch}}/\eta_{\mathrm{TES}}^{\mathrm{ch}},\quad\forall t, \tag{29}$$

$$0\le P_t^{\mathrm{TES2L}}+P_t^{\mathrm{TES,dis}}\le\eta_{\mathrm{TES}}^{\mathrm{dis}}P_{\max}^{\mathrm{TES,dis}},\quad\forall t, \tag{30}$$

$$B_t^{\mathrm{TES2L}}+B_t^{\mathrm{EB}}\le 1,\quad\forall t, \tag{31}$$

where $P_{\min}^{\mathrm{CSP}}$ and $P_{\max}^{\mathrm{CSP}}$ are the minimum and maximum output power of the CSP, respectively. $R_{\mathrm{down}}^{\mathrm{CSP}}$ and $R_{\mathrm{up}}^{\mathrm{CSP}}$ are the ramp down and ramp up rates of the CSP, respectively. σ_{TES} is the self-discharging rate of the TES. $\eta_{\mathrm{TES}}^{\mathrm{ch}}$ and $\eta_{\mathrm{TES}}^{\mathrm{dis}}$ are the charging and discharging efficiency of the TES, respectively. $P_t^{\mathrm{TES,ch}}$ and $P_t^{\mathrm{TES,dis}}$ are the the charging and discharging power of the TES at time t, respectively. $\eta_{\mathrm{HEB,TES}}$ is the charging efficiency of the EB to the TES. $P_t^{\mathrm{HEB,TES}}$ the charging thermal power of the EB to the TES. η_{TES2L} the discharging efficiency of the TES to TLs. P_t^{TES2L} the discharging power of the TES to ELs. $B_t^{\mathrm{TES,dis}}$ is the discharging binary decision variable for the TES. $P_{\max}^{\mathrm{TES,dis}}$ and $P_{\max}^{\mathrm{TES,ch}}$ are the maximum allowable discharging and maximum allowable charging power of the TES. $E_{\min}^{\mathrm{TES}}$ and $E_{\max}^{\mathrm{TES}}$ are the lower and upper limits of the TES, respectively. B_t^{TES2L} is the discharging binary decision variable for the TES supplying TLs. $P_{\max}^{\mathrm{TES2L}}$ is the maximum allowable discharging power of the TES supplying TLs at time t. B_t^{EB} is the discharging binary decision variable for the EB supplying the TES. $P_{\max}^{\mathrm{EB}}$ is the maximum allowable discharging power of the EB supplying the TES.

5) GES and CSS Constraints: GES and CSS must meet the following constraints during operation:

$$\begin{aligned}E_t^g=&(1-\sigma_g)E_{t-1}^{\mathrm{g}}+\eta_g^{\mathrm{ch}}P_t^{g,\mathrm{ch}}\\&-P_t^{g,\mathrm{dis}}/\eta_g^{\mathrm{dis}},\quad\forall t,\forall g,\end{aligned} \tag{32}$$

$$0\le P_t^{\mathrm{g,dis}}\le B_t^{\mathrm{g,dis}}\eta_{\mathrm{g}}^{\mathrm{dis}}P_{\max}^{\mathrm{g,dis}},\quad\forall t,\forall g, \tag{33}$$

$$0\le P_t^{\mathrm{g,ch}}\le(1-B_t^{\mathrm{g,dis}})P_{\max}^{\mathrm{g,ch}}/\eta_{\mathrm{g}}^{\mathrm{ch}},\quad\forall t,\forall g, \tag{34}$$

$$E_{\min}^{\mathrm{g}}\le E_t^{\mathrm{g}}\le E_{\max}^{\mathrm{g}},\quad\forall t,\forall g, \tag{35}$$

$$E_0^{\mathrm{g}} = E_T^{\mathrm{g}}, \quad \forall t, \forall g, \tag{36}$$

where $g \in \{\mathrm{BESS}, \mathrm{GSS}, \mathrm{CSS}\}$.

6) Other Constraints:

$$0 \leq P_t^k \leq \tilde{P}_t^k, \quad \forall t, \forall k \in \{\mathrm{PV}, \mathrm{WT}\}, \tag{37}$$

$$P_{\min}^k \leq P_t^k \leq P_{\max}^k, \forall t, \forall k \in \{\mathrm{GT}, \mathrm{EB}, \mathrm{GB}, \mathrm{P2G}\}, \tag{38}$$

$$R_{\mathrm{down}}^k \leq P_t^k - P_{t-1}^k \leq R_{\mathrm{up}}^k, \quad \forall t, , \forall k \in \{\mathrm{GT}, \mathrm{P2G}\}, \tag{39}$$

$$P_t^k = \eta_{\mathrm{gen}}^k P_t^{k,\mathrm{CH_4}}, \quad \forall t, , \forall k \in \{\mathrm{GT}, \mathrm{EB}, \mathrm{GB}\}, \tag{40}$$

$$P_t^{\mathrm{HGT}} = \eta_{\mathrm{HR}} P_t^{\mathrm{GT}}, \quad \forall t, \tag{41}$$

$$0 \leq P_t^{\mathrm{imp},i} \leq B_t^{\mathrm{imp},i} P_{\mathrm{PCC,max}}^i, \quad \forall t, \forall i \in \mathcal{N} \tag{42}$$

$$0 \leq P_t^{\mathrm{exp},i} \leq \left(1 - B_t^{\mathrm{imp},i}\right) P_{\mathrm{PCC,max}}^i, \quad \forall t, \forall i \in \mathcal{N} \tag{43}$$

where $\tilde{P}_t^k$ is the forecasted values of PV and wind generation. P_t^k denotes the electric power or thermal power generated by device k. $P_t^{k,\mathrm{CH_4}}$ represents the gas power consumed by device k. η_{gen}^k is the energy conversion efficiency of device k. P_t^{HGT} is the thermal power generated by the GT. η_{HR} is the corresponding coefficient between the electric power and thermal power generated by the GT. $P_{\mathrm{PCC,max}}^i$ is the maximum power allowed to be traded at the point of common coupling (PCC). $B_t^{\mathrm{imp},i}$ is the binary purchase decision variable.

7) Deterministic EHGIES Dispatch Model: The deterministic EHGIES dispatch model can be formulated as follows:

$$\begin{aligned} \min \quad & C = C_{\mathrm{OM}} + C_{\mathrm{imp}} + C_{\mathrm{CO_2}} - C_{\mathrm{exp}}, \\ \text{s.t.} \quad & (1)\text{–}(6), (9)\text{–}(10), (12)\text{–}(43). \end{aligned} \tag{44}$$

IV. Multi-objective Models for Optimal EHGIES Dispatch Based on Info-Gap Theory and AHP

The info-gap method can effectively deal with uncertainty without needing probability distributions and uncertain intervals. Info-gap theory includes system models, uncertainty modeling, and performance requirements. The total cost C can be regarded as the system model of the EHGIES. Performance requirements evaluate the level of robustness or opportuneness of the decisions against uncertainty. The model in Section III supposes that the prediction of PV, wind generation, and load demand is accurate, and it takes the forecasted value as the basis for the optimal operation of the EHGIES. However, PV, wind generation, and load demand have serious uncertainties in practice, and the actual value may seriously deviate from the predicted value. Therefore, the dispatch based on the predicted value will cause economic losses. These make the deterministic model in Section III unreasonable. Therefore, this paper employs info-gap theory to study uncertainty.

A. Modeling Uncertainty by Info-Gap Theory

Info-gap theory is a non-probabilistic and non-fuzzy optimization method to deal with uncertainty, which studies the possible effects of uncertain variables under the premise of satisfying the acceptable range of the preset target. Uncertainty modeling describes the gap between the forecasted values and other possible values. The uncertainties are modeled as imprecise sets in info-gap theory, which is totally different from rigorously exact sets of upper and lower bounds in robust optimization. The uncertainty sets of wind, PV generation, and loads can be expressed as

$$\mathcal{U}(\alpha_k, \tilde{P}_t^k) := \left\{ P_t^k \middle| \left| P_t^k - \tilde{P}_t^k \right| \leq \alpha_k \tilde{P}_t^k \right\}, \quad \forall t, \forall k, \tag{45}$$

$$\alpha_k \geq 0, \quad \forall k, \tag{46}$$

where P_t^k is the actual values of PV, wind generation, ELs, TLs, and GLs. $\tilde{P}_t^k$ is the forecasted values of PV, wind generation, ELs, TLs, and GLs. α_k is the radii (horizons) of the uncertainties of PV, wind generation, ELs, TLs, and GLs. $k \in \{\mathrm{PV}, \mathrm{WT}, \mathrm{EL}, \mathrm{TL}, \mathrm{GL}\}$.

The fluctuation ranges of the uncertain variables are

$$P_t^k \in \mathcal{U}(\alpha_k, \tilde{P}_t^k), \quad \forall t, \forall k. \tag{47}$$

By taking into consideration that the risk attitudes of decision makers will influence the dispatch plans, this paper proposes a multi-objective robustness model (RM) with RA for decision makers with more conservative decision intentions and a multi-objective opportunity model (OM) with OS for decision makers with more speculative decision intentions.

B. A Multi-objective RM With RA

The RM model maximizes uncertainty based on the premise that the decision cost does not exceed the expected cost, that is, the RA model achieves the robustness while ensuring the basic economy. For the RM model, the greater the value of uncertainty, the greater the RM ability and the corresponding dispatch cost. We obtain the ability to avoid risks at the cost of more dispatch costs. The multi-objective RM model with RA is summarized as follows:

$$\begin{aligned} \max \quad & (\alpha_{\mathrm{PV}}, \alpha_{\mathrm{WT}}, \alpha_{\mathrm{EL}}, \alpha_{\mathrm{TL}}, \alpha_{\mathrm{GL}}) \\ \text{s.t.} \quad & \max C \leq (1+\delta) C_0 \\ & \text{s.t.}(1)\text{–}(6), (9)\text{–}(43), (45)\text{–}(47), \end{aligned} \tag{48}$$

where δ is the robust level factor, and C_0 is the base cost. δ is proportional to the risk avoidance degree. In (48), α_{PV}, α_{WT}, α_{EL}, α_{TL}, and α_{GL} are maximized simultaneously, so Problem (48) is a multi-objective optimization problem. C_0 is the optimal dispatch cost when the uncertain variables in Problem (44) take the predicted value, that is, C_0 is the optimal solution to Problem (44). The RM is better than the traditional robust optimization. Because the RM sets the expected cost or profit index, system robustness and basic economy can be guaranteed simultaneously. The RM denotes the degree to which the EHGIES system can resist increasing uncertainties of uncertain variables.

C. A Multi-objective OM With OS

The OM thinks that uncertainty can benefit the dispatch of the system. In the OS strategy, the objective is to minimize the uncertainties of uncertain variables while ensuring that the obtained limit values of uncertain variable fluctuations make the total dispatch cost of the EHGIES not greater than the expected cost. The multi-objective OM model can be formulated as follows:

$$\begin{aligned} \min \quad & (\alpha_{\mathrm{PV}}, \alpha_{\mathrm{WT}}, \alpha_{\mathrm{EL}}, \alpha_{\mathrm{TL}}, \alpha_{\mathrm{GL}}) \\ \text{s.t.} \quad & \min C \leq (1-\kappa)\, C_0 \\ & \text{s.t.}(1)\text{–}(6),\ (9)\text{–}(43),\ (45)\text{–}(47), \end{aligned} \tag{49}$$

where κ is the opportunistic level factor.

The OM determine how the EHGIES system can benefit from the possible reduction of the uncertainties of uncertain variables.

D. Model Solving Method

1) RM: we let

$$\alpha_k = \omega_k \alpha, \quad \forall k \in \{\mathrm{PV}, \mathrm{WT}, \mathrm{EL}, \mathrm{TL}, \mathrm{GL}\}, \tag{50}$$

where α is the comprehensive equivalent radius of the uncertainty of the system. ω_k is the weights of fluctuation amplitudes of uncertain variables of PV, wind generation, ELs, TLs, and GLs.

We use the AHP to determine the weights. See [31] for the details of the AHP. Then, Problem (48) can be converted into

$$\begin{aligned} \max \quad & \alpha \\ \text{s.t.} \quad & \max C \leq (1+\delta)\, C_0, \\ & \text{s.t.}(1)\text{–}(6),\ (9)\text{–}(43),\ (45)\text{–}(47),\ (50), \end{aligned} \tag{51}$$

2) OM: In the same logic, we can transform Problem (49) into the following single objective optimization problem:

$$\begin{aligned} \min \quad & \alpha \\ \text{s.t.} \quad & \min C \leq (1-\kappa)\, C_0, \\ & \text{s.t.}(1)\text{–}(6),\ (9)\text{–}(43),\ (45)\text{–}(47),\ (50), \end{aligned} \tag{52}$$

V. CASE STUDIES

The basic structure of the used EHGIES is shown in Fig. 1. The operating parameters of CSP and CCUS are shown in Table I. The maximum electric power of P2G is 250 kW. The OM cost of the GT is \$0.0208/kWh, its maximum electric power output is 1000 kW, its ramp down and up rates are both 100 kW/h, and its carbon emission coefficient is 0.55 kg/kWh. The GSS capacity is $800\,\mathrm{m}^3$, and the maximum gas charging and discharging power are both $200\,\mathrm{m}^3$/h. The BESS capacity is 800 kWh; its maximum discharging and charging power are both 200 kW. The OM costs of PV and wind generation are both \$0.0069/kWh. The maximum electric power exchange between the system and the external grid is 800 kW. The maximum gas power exchange between the system and the external gas network is $1400\,\mathrm{m}^3$. The carbon emission quota factor is 0.424 kg/kWh. The cost coefficient of CO_2 trading is \$0.0167/kWh. Other used parameters are from [32]. Simulations and computations are performed using the solver of CPLEX on a desktop with an Intel i9 CPU, 3.60 GHz (16 CPUs), and 64 GB RAM in MATLAB/YALMIP.

TABLE I
KEY PARAMETERS OF THE CSP AND CCUS

Parameter	Value	Parameter	Value
η_{H2P}	45%	$P_{\max}^{\mathrm{TES,ch}}$	500 kW
σ_{TES}	0.03%	$P_{\max}^{\mathrm{TES,dis}}$	500 kW
$\eta_{\mathrm{TES}}^{\mathrm{ch}}$	98%	$E_{\min}^{\mathrm{TES}}$	400 kWh
$\eta_{\mathrm{TES}}^{\mathrm{dis}}$	98%	$E_{\max}^{\mathrm{TES}}$	1800 kWh
$\eta_{\mathrm{TES2L}}^{\mathrm{dis}}$	98%	β	0.5 kWh/kg

A. Deterministic Dispatch Results

C_0 and other results are shown in Table II. The supply and consumption of electric power, the supply and consumption of thermal power, and the supply and consumption of gas in the whole dispatch period are shown in Figs. 2–5. From Figs. 2–5, it can be seen that the EHGIES has a certain degree of external dependence. In order to ensure the supply and demand balance of the system's electricity, heat, and gas, the system must maintain real-time interaction with the external networks at all times. The integration of the CSP plant improves the economy of the system and reduces the emission of CO_2. After the introduction of GES, the energy storage makes use of its energy transfer characteristics to store energy at low price periods and release energy at high price periods, realizing the cross-time and high-value time-shift utilization of electricity, heat, and gas, and improving the economy and flexibility of the system. That is, GES improves the operating economy and flexibility of the system by coordinating the sources and the load side.

TABLE II
DETERMINISTIC DISPATCH RESULTS

Total cost (\$)	CO_2 trading cost (\$)
3607.5	71.7

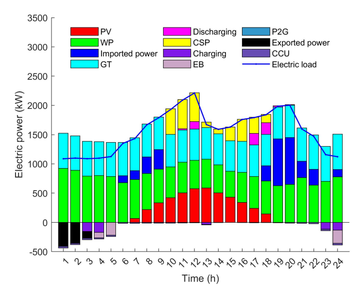

Fig. 2. The supply and consumption of electric power in the EHGIES.

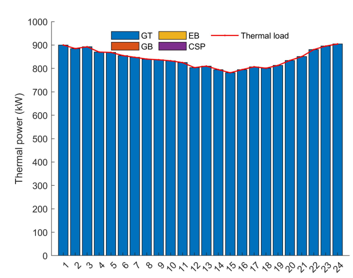

Fig. 3. The supply and consumption of thermal power in the EHGIES.

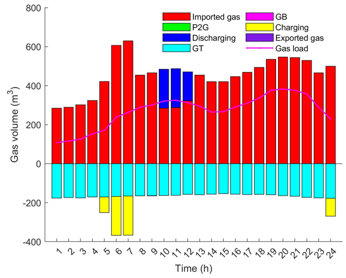

Fig. 4. The supply and consumption of gas in the EHGIES.

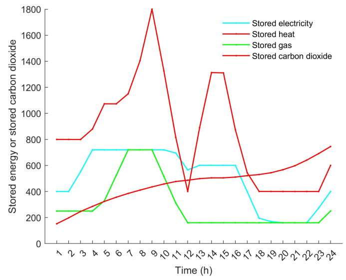

Fig. 5. Scheduling results of GES.

B. Dispatch Results Based on the RM With RA

The comparison matrix $\mathbf{H}$ of PV, wind generation, ELs, TLs, and GLs is shown as follows:

$$\mathbf{H} = \begin{array}{c} \\ \text{PV} \\ \text{WT} \\ \text{EL} \\ \text{TL} \\ \text{GL} \end{array} \begin{array}{c} \begin{array}{ccccc} \text{PV} & \text{WT} & \text{EL} & \text{TL} & \text{GL} \end{array} \\ \begin{pmatrix} 1 & 1/3 & 7 & 6 & 5 \\ 3 & 1 & 9 & 8 & 7 \\ 1/7 & 1/9 & 1 & 1/2 & 1/3 \\ 1/6 & 1/8 & 2 & 1 & 1/2 \\ 1/5 & 1/7 & 3 & 2 & 1 \end{pmatrix} \end{array}. \tag{53}$$

Based on $\mathbf{H}$, we can obtain ω_{PV}, ω_{WT}, ω_{EL}, ω_{TL}, and ω_{GL} as 0.2876, 0.5318, 0.0375, 0.0567, and 0.0864, respectively.

According to (51), the dispatch results based on the RM with RA can be obtained, as shown in Table III. As shown in Fig. 6, in the RM, total costs, CO_2 trading costs, and the comprehensive equivalent radius of the uncertainty of the EHGIES are all positively correlated with robust level factors, because the robust level factor denotes the percentage of cost increase that decision makers can accept due to uncertainties. The larger robust level factor, the larger the cost of the dispatch scheme, and the stronger the ability of the dispatch model to handle uncertainty. Conservative decision makers believe that uncertainty will lead to the development of goals in an unfavorable direction and hope to make the system bear the maximum possible uncertainty by paying more dispatch costs.

TABLE III
DISPATCH RESULTS BASED ON THE RM WITH RA

δ	α	Total cost (\$)	CO_2 trading cost (\$)
0.20	0.37083	4328.98	97.30
0.25	0.45996	4509.35	105.10
0.30	0.54888	4689.73	112.90
0.35	0.63781	4870.10	120.70

C. Dispatch Results Based on the OM With OS

As shown in Table. IV, the dispatch results based on the OM with OS can be obtained as per (52). As shown in Fig. 6, in the OM, both total costs and CO_2 trading costs are negatively correlated with opportunistic level factors. However, the comprehensive equivalent radius of the uncertainty of the EHGIES is positively correlated with the opportunistic level factor. This is because OS decision makers think that uncertainties will lead to the favorable development of the problem, and they are more inclined to accept lower dispatch costs.

TABLE IV
DISPATCH RESULTS BASED ON THE OM WITH OS

κ	α	Total cost (\$)	CO_2 trading cost (\$)
0.05	0.10722	3427.11	66.49
0.10	0.22504	3246.73	62.89
0.15	0.34695	3066.36	59.56
0.20	0.47077	2885.99	56.81

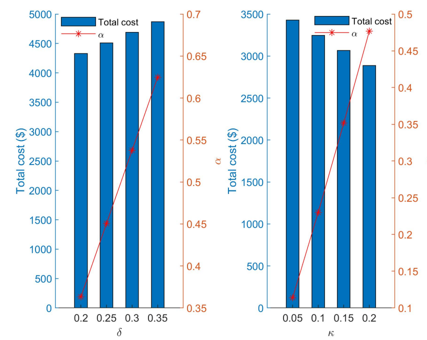

Fig. 6. Variation trends of costs and uncertainties with level factors.

VI. CONCLUSION

This paper establishes an EHGIES with the CSP and GES in order to improve the flexibility and economy of the traditional IES and formulates a deterministic dispatch model of the EHGIES. Based on info-gap theory and AHP, this paper comprehensively considers the uncertainties of PV, wind generation, ELs, TLs, and GLs, and proposes two multi-objective dispatch models with robustness and opportunity respectively according to different attitudes toward to risk. The following conclusions can be drawn through case studies.

1) The introduction of CSP and GES to the optimal operation of the EHGIES can meet the various energy needs, and realize multi-energy interconnection. However, the EHGIES has an interactive relationship with external networks, and the transaction with the external network must be maintained in real time to ensure the internal operation security of the system. The integration of CSP and GES improves the economy and flexibility of the EHGIES, and reduces the CO_2 emission of the EHGIES.
2) The CSP can act as the CHP unit and break the operation restrictions of CHP. The cooperation of the TES and the EB provides a low-cost source of heat for the TES, making the operation of the EHGIES more flexible, improving the CSP generation potential, realizing "electricity-heat-electricity" energy conversion, and effectively reducing operating costs through energy pricing mechanism.

3) GES uses their energy transfer characteristics to store energy at low prices and release energy at high prices, improving the economy and flexibility of the EHGIES.
4) Info-gap theory can better measure the uncertainty existing in the operation of the EHGIES, and the decision maker can adopt appropriate strategies as per the preference for risk. The RM model can effectively handle the negative effects of uncertainty and guarantee expected costs while realizing the robustness of the system. Nevertheless, the OS model make full use of favorable uncertainties and can obtain lower expected costs.

Due to the small geographical range of the EHSIES in this paper, the constraints of power flow and gas flow are ignored. In the follow-up research, we plan to consider power flow and gas flow, consider more uncertainties, such as market price fluctuations, policy changes, and technological advancements, and explore their impacts on IES operation. Furthermore, we intend to consider hydrogen and other new energy resources in the IES. Moreover, we will study the planning of the EHSIES.

REFERENCES

[1] D. Yu, A. G. Ebadi, K. Jermsittiparsert, N. H. Jabarullah, M. V. Vasiljeva, and S. Nojavan, "Risk-constrained stochastic optimization of a concentrating solar power plant," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 3, pp. 1464–1472, 2019.

[2] L. Yao, Y. Wang, and X. Xiao, "Concentrated solar power plant modeling for power system studies," *IEEE Transactions on Power Systems*, 2023.

[3] S. Chen, J. Liu, Q. Zhang, F. Teng, and B. C. McLellan, "A critical review on deployment planning and risk analysis of carbon capture, utilization, and storage (CCUS) toward carbon neutrality," *Renewable and Sustainable Energy Reviews*, vol. 167, p. 112537, 2022.

[4] Y. Wang, Y. Wang, Y. Huang, H. Yu, R. Du, F. Zhang, F. Zhang, and J. Zhu, "Optimal scheduling of the regional integrated energy system considering economy and environment," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 4, pp. 1939–1949, 2018.

[5] C. Qin, Q. Yan, and G. He, "Integrated energy systems planning with electricity, heat and gas using particle swarm optimization," *Energy*, vol. 188, p. 116044, 2019.

[6] Y. Xiang, H. Cai, C. Gu, and X. Shen, "Cost-benefit analysis of integrated energy system planning considering demand response," *Energy*, vol. 192, p. 116632, 2020.

[7] B. Chen, T. Liu, X. Liu, C. He, L. Nan, L. Wu, and X. Su, "Distributionally robust coordinated expansion planning for generation, transmission, and demand side resources considering the benefits of concentrating solar power plants," *IEEE Transactions on Power Systems*, vol. 38, no. 2, pp. 1205–1218, 2022.

[8] E. Du, N. Zhang, B.-M. Hodge, Q. Wang, Z. Lu, C. Kang, B. Kroposki, and Q. Xia, "Operation of a high renewable penetrated power system with CSP plants: A look-ahead stochastic unit commitment model," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 140–151, 2018.

[9] Z. Wu, M. Zhou, J. Wang, E. Du, N. Zhang, and G. Li, "Profit-sharing mechanism for aggregation of wind farms and concentrating solar power," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2606–2616, 2020.

[10] U. Pelay, L. Luo, Y. Fan, D. Stitou, and M. Rood, "Thermal energy storage systems for concentrated solar power plants," *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 82–100, 2017.

[11] Y. Cao, Y. Mu, H. Jia, X. Yu, K. Hou, and H. Wang, "A multi-objective stochastic optimization approach for planning a multi-energy microgrid considering unscheduled islanded operation," *IEEE Transactions on Sustainable Energy*, 2023.

[12] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "A stochastic multi-objective framework for optimal scheduling of energy storage systems in microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 117–127, 2016.

[13] X. Dai, Y. Li, K. Zhang, and W. Feng, "A robust offering strategy for wind producers considering uncertainties of demand response and wind power," *Applied Energy*, vol. 279, p. 115742, 2020.

[14] Y. Yang and W. Wu, "A distributionally robust optimization model for real-time power dispatch in distribution networks," *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 3743–3752, 2018.

[15] Y. Mohammadi, H. Shakouri, and A. Kazemi, "A multi-objective fuzzy optimization model for electricity generation and consumption management in a micro smart grid," *Sustainable Cities and Society*, vol. 86, p. 104119, 2022.

[16] K. G. H. Kong, J. Y. Lim, W. D. Leong, W. P. Q. Ng, S. Y. Teng, J. Sunarso, and B. S. How, "Fuzzy optimization for peer-to-peer (p2p) multi-period renewable energy trading planning," *Journal of Cleaner Production*, vol. 368, p. 133122, 2022.

[17] B. Wang, C. Zhang, and Z. Y. Dong, "Interval optimization based coordination of demand response and battery energy storage system considering SoC management in a microgrid," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2922–2931, 2020.

[18] D. Yang, C. Jiang, G. Cai, D. Yang, and X. Liu, "Interval method based optimal planning of multi-energy microgrid with uncertain renewable generation and demand," *Applied Energy*, vol. 277, p. 115491, 2020.

[19] Y. Ben-Haim, *Info-gap decision theory: decisions under severe uncertainty*. Elsevier, 2006.

[20] A. H. Shojaei, A. A. Ghadimi, M. R. Miveh, F. H. Gandoman, and A. Ahmadi, "Multiobjective reactive power planning considering the uncertainties of wind farms and loads using information gap decision theory," *Renewable Energy*, vol. 163, pp. 1427–1443, 2021.

[21] C. Murphy, A. Soroudi, and A. Keane, "Information gap decision theory-based congestion and voltage management in the presence of uncertain wind power," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 841–849, 2015.

[22] A. Rabiee, A. Soroudi, and A. Keane, "Information gap decision theory based OPF with HVDC connected wind farms," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3396–3406, 2014.

[23] A. Mehdizadeh, N. Taghizadegan, and J. Salehi, "Risk-based energy management of renewable-based microgrid using information gap decision theory in the presence of peak load management," *Applied energy*, vol. 211, pp. 617–630, 2018.

[24] A. Soroudi, A. Rabiee, and A. Keane, "Information gap decision theory approach to deal with wind power uncertainty in unit commitment," *Electric Power Systems Research*, vol. 145, pp. 137–148, 2017.

[25] Y. Zhao, Z. Lin, F. Wen, Y. Ding, J. Hou, and L. Yang, "Risk-constrained day-ahead scheduling for concentrating solar power plants with demand response using info-gap theory," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 10, pp. 5475–5488, 2019.

[26] K. Vemalaiah, D. K. Khatod, and N. P. Padhy, "Optimal day-ahead scheduling of distributed energy resources: A strategy based on information gap decision theory to address multiple uncertainties in the active distribution networks," in *2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG)*, pp. 1–6, IEEE, 2023.

[27] X. Cao, J. Wang, and B. Zeng, "A chance constrained information-gap decision model for multi-period microgrid planning," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2684–2695, 2017.

[28] Q. Yan, H. Lin, J. Li, X. Ai, M. Shi, M. Zhang, and D. Gejirifu, "Many-objective charging optimization for electric vehicles considering demand response and multi-uncertainties based on markov chain and information gap decision theory," *Sustainable Cities and Society*, vol. 78, p. 103652, 2022.

[29] L. Zuo, S. Wang, Y. Sun, S. Cui, J. Fang, X. Ai, B. Li, C. Hao, and J. Wen, "Robustness assessment of wind power generation considering rigorous security constraints for power system: A hybrid RLO-IGDT approach," *CSEE Journal of Power and Energy Systems*, 2023.

[30] M. Moradi-Dalvand, B. Mohammadi-Ivatloo, N. Amjady, H. Zareipour, and A. Mazhab-Jafari, "Self-scheduling of a wind producer based on information gap decision theory," *Energy*, vol. 81, pp. 588–600, 2015.

[31] T. L. Saaty, "Decision making—the analytic hierarchy and network processes (AHP/ANP)," *Journal of systems science and systems engineering*, vol. 13, pp. 1–35, 2004.

[32] Y. Ma, H. Wang, F. Hong, J. Yang, Z. Chen, H. Cui, and J. Feng, "Modeling and optimization of combined heat and power with power-to-gas and carbon capture system in integrated energy system," *Energy*, vol. 236, p. 121392, 2021.