

Multi-Uncertainty Capacity Planning of Integrated Energy System Considering Low-Carbon and Flexible Transformation of Coal-Fired Power Plants

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Abstract—Driven by the growing utilization of renewable energies and the pursuit of carbon neutrality goals, traditional coal-fired power plants (CFPPs) require greater flexibility in energy output dispatch and a reduction in carbon emissions. Meanwhile, in the long-term capacity planning of integrated energy systems (IESs) incorporating CFPPs, uncertainties at both the investment and operation stages cannot be ignored. Therefore, a novel low-carbon and flexible transformation structure for CFPPs is proposed in this paper, with its operation characteristics being modelled and thoroughly analyzed. Furthermore, to address multiple uncertainties, a capacity planning model for IESs based on conditional value at risk and information gap decision theory (CVaR-IGDT) is developed. The proposed model can be converted to a mixed-integer linear programming (MILP) problem to facilitate the computation. Numerical case analyses validate the effectiveness of the proposed low-carbon and flexible transformation structure for CFPPs, as well as the overall economy and reliability of the capacity planning scheme with multiple uncertainties.

Keywords—Multi-uncertainty, capacity planning, low-carbon and flexible transformation, coal-fired power plant, integrated energy system.

I. INTRODUCTION

In the face of energy crisis and other environmental challenges, there is a global shift towards low-carbon and sustainable energy consumption [1]. Nations worldwide have promoted the use of integrated energy system (IES) and renewable energy sources, such as photovoltaic (PV) and wind turbine (WT), to enhance energy efficiency and to reduce total carbon emissions [2],[3].

However, within existing IESs, traditional coal-fired power plants (CFPPs) continue to function as primary thermoelectric generation and peak-shaving units [4]. Utilizing coal as the primary fuel source, these CFPPs emit significant quantities of carbon dioxide during combustion. Moreover, with the anticipated expansion of renewable energy integration and their inherent anti-peak load output features, dispatchable traditional CFPPs must exhibit increased operational flexibility to accommodate lower energy loads and facilitate greater renewable energy consumption [5]. Traditional methods for enhancing unit flexibility include auxiliary ignition [6], adjustments to burner parameters [7], etc., yet these approaches do not easily reduce total carbon emissions. In recent years, the carbon capture and storage (CCS) devices and molten-salt energy storage (MSES) techniques have drawn much attention. In [8]-[9], the possibilities of integrating CCS devices into the energy generation process to capture and reuse carbon emissions were discussed, thereby enhancing the overall economic efficiency of the system. In [10], a MSES system incorporating multiple heat sources was proposed, which effectively reduced the

power-load ratio for flexible dispatch. Additionally, [11] presented a MSES-integrated combined heat and power (CHP) system, wherein surplus renewable energies were converted into heat via electric heaters and stored by MSES. However, the above literature primarily analyzes MSES model from a thermodynamic perspective, which can be difficult to apply to planning optimization due to its complexity and nonconvexity.

Moreover, with technological development, the costs associated with the low-carbon and flexible transformation of CFPPs may decrease during the long planning horizon. Plus, the intermittency and fluctuation of renewable energy sources can also influence the economy and reliability of optimal planning schemes. Currently, quite a few researches have been focused on the uncertain capacity planning of IES. In [12]-[13], scenario generation methods were utilized to capture the impact of short-term fluctuations of renewable energies on IES planning. In [14]-[15], box interval modeling was used to describe long-term uncertainties, including variations in multi-energy loads and market prices. Moreover, in [16], distributional robust optimization approach was adopted for expansion planning, considering both long- and short-term uncertainties of load demand and renewable energy output.

However, despite the above researches, the following problems still exist in capacity planning of current IES: 1) Few studies take both low-carbon retrofit and flexible transformation for the CFPPs at the same time. The operation characteristics together with its linearized and applicable model for system planning optimization should be further studied; 2) Existing considerations for system uncertainties emphasize more on the operation stage, both long-term investment uncertainty and short-term operation uncertainty should be considered for more reasonable planning results.

To address the above problems, a multi-uncertainty capacity planning scheme of IES with low-carbon and flexible transformation of CFPPs is proposed in this paper. The main contributions and novelty of this paper are as follows.

(1) A novel CFPP structure with low-carbon and flexible transformation is proposed. Mathematical models of the transformed CFPPs are developed and its operation characteristics are analyzed in detail

(2) A conditional value at risk (CVaR) and information gap decision theory (IGDT) based capacity planning model under both long-/short-term uncertainties is proposed. The proposed model is further linearized and solved effectively.

The rest of this paper is organized as follows. Section II develops a novel structure of low-carbon and flexible transformed CFPPs. Section III proposes a linearized CVaR-IGDT capacity planning model. Case studies are conducted in

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Section IV to verify the effectiveness of the proposed structure and model. Finally, Section V presents the conclusions.

II. LOW-CARBON AND FLEXIBLE TRANSFORMATION OF CFPP

A. Basic Structure of the Transformed CFPP

In this paper, the proposed CFPP structure considering low-carbon and flexible transformation is composed of three key components, namely the traditional CFPP, the MSES system and the CCS system (as shown in Fig.1).

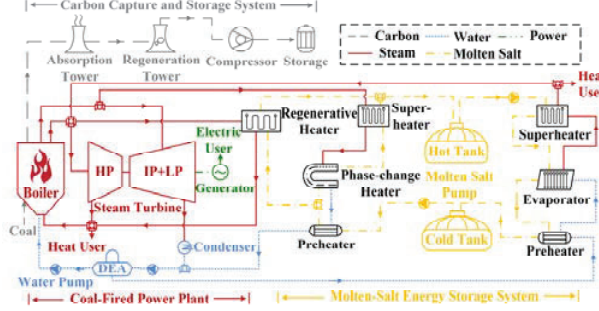


Fig. 1. Basic structure of CFPP with CCS and MSES

In the CCS system shown in Fig. 1, the exhaust gas from the boiler is directed to the absorption tower, where carbon dioxide is separated using organic amines solution. Next, the carbon-containing solution proceeds to the regeneration tower, where it will be restored into carbon dioxide, then compressed and securely sealed for secondary usage.

In the MSES integrated CFPP, during peak hours, the system operates at full load. All generated energies are directly supplied to the user side, while the MSES system remains offline. Under such circumstance, water from the condenser is conveyed to the boiler via deaerator and water pump, generating steam at different pressures and temperatures for either electric or thermal power generation. The operational characteristics at this stage are the same as traditional CFPPs.

During periods of reduced load demand or increased renewable energy output, the MSES system starts working and stores surplus energy. The low-temperature molten salt from the cold tank is conveyed to the preheater for preheating. Then, it undergoes transfer to the phase-change heater, where it exchanges heat with superheated steam and becomes high-temperature molten salt. The obtained high-temperature molten salt is then stored in the hot tank for subsequent use.

Finally, when the multi-energy load demands increase, the MSES system initiates discharging. High-temperature molten salt from the hot tank is routed from the superheater to preheater, where it facilitates the heating of condensation water into steam. The generated steam is then conveyed back to the steam turbine for energy generation or directly utilized for heat supply. After the heat exchange process, the high-temperature molten salt is cooled and stored in the cold tank.

B. Mathematical Modelling of the Transformed CFPP

As the thermodynamic models of the proposed CFPP transformation can be complex and nonconvex [17], a simplified energy flow diagram of the transformed CFPP is illustrated in Fig. 2. The proposed model is applicable for planning optimization, while retaining the essential energy coupling relationships inherent within the transformed CFPP.

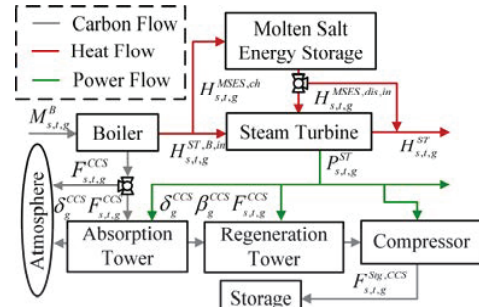


Fig. 2. Energy flow diagram of the transformed CFPP

According to Fig. 2, the mathematical model of the transformed CFPP are established as follows:

1) Boiler and Steam Turbine (ST)

The boiler model contains output power balance (1), coal-firing limits (2) and unit startup/shutdown restrictions (3)-(4).

$$H_{s,t,g}^B = \eta^B \rho^{LHV} M_{s,t,g}^B \quad (1)$$

$$u_{s,t,g}^B M_{s,t,g}^{B_{\min}} \leq M_{s,t,g}^B \leq u_{s,t,g}^B M_{s,t,g}^{B_{\max}} \quad (2)$$

$$\sum_{k=t}^{t+T_{on}^B-1} u_{s,k,g}^B \geq T_{on}^B (u_{s,k,g}^B - u_{s,k-1,g}^B) \quad (3)$$

$$\sum_{k=t}^{t+T_{off}^B-1} (1 - u_{s,k,g}^B) \geq T_{off}^B (u_{s,k-1,g}^B - u_{s,k,g}^B) \quad (4)$$

where: $H_{s,t,g}^B$ is the heat output of boiler g ; $M_{s,t,g}^B, M_{s,t,g}^{B_{\min}}, M_{s,t,g}^{B_{\max}}$ are the actual coal consumption and its limits; η^B is the efficiency factor; ρ^{LHV} is the calorific value of standard coal; $u_{s,t,g}^B$ is the 0-1 variable for boiler startup/shutdown; T_{on}^B and T_{off}^B are the continuous operating/shutdown time.

The steam turbine model contains electric power balance and its limits (5), and heat power balance and its limits (6).

$$\begin{cases} P_{s,t,g}^{ST} = (H_{s,t,g}^{ST,B,in} + H_{s,t,g}^{MSES,dis,in}) \eta_g^{ST,ele} \\ u_{s,t,g}^B P_{s,t,g}^{ST_{\min}} \leq P_{s,t,g}^{ST} \leq u_{s,t,g}^B P_{s,t,g}^{ST_{\max}} \end{cases} \quad (5)$$

$$\begin{cases} H_{s,t,g}^{ST} = (H_{s,t,g}^{ST,B,in} + H_{s,t,g}^{MSES,dis,in}) (1 - \eta_g^{ST,ele} - \eta_g^{ST,loss}) \\ u_{s,t,g}^B H_{s,t,g}^{ST_{\min}} \leq H_{s,t,g}^{ST} \leq u_{s,t,g}^B H_{s,t,g}^{ST_{\max}} \end{cases} \quad (6)$$

where: $P_{s,t,g}^{ST}, P_{s,t,g}^{ST_{\min}}, P_{s,t,g}^{ST_{\max}}$ are electric power output of ST and its limits; $H_{s,t,g}^{ST}, H_{s,t,g}^{ST_{\min}}, H_{s,t,g}^{ST_{\max}}$ are heat power output of ST and its limits; $H_{s,t,g}^{ST,B,in}$ and $H_{s,t,g}^{MSES,dis,in}$ are input heat of ST from boiler and MSES; $\eta_g^{ST,ele}$ and $\eta_g^{ST,loss}$ are efficiency factors.

2) Molten-Salt Energy Storage (MSES)

The MSES model contains energy storage balance and its limits (7), as well as charging/discharging constraints and its limits (8)-(9).

$$\begin{cases} E_{s,t,g}^{MSES} = \eta_{sif}^{MSES} E_{s,t-1,g}^{MSES} + \eta_{ch}^{MSES} H_{s,t,g}^{MSES,ch} - H_{s,t,g}^{MSES,dis} / \eta_{dis}^{MSES} \\ E_{s,t,g}^{MSES_{\min}} \leq E_{s,t,g}^{MSES} \leq E_{s,t,g}^{MSES_{\max}} \end{cases} \quad (7)$$

$$\begin{cases} 0 \leq H_{s,t,g}^{MSES,ch} \leq y_{s,t,g}^{MSES,ch} H_{s,t,g}^{MSES,ch_{\max}} \\ 0 \leq H_{s,t,g}^{MSES,dis} \leq y_{s,t,g}^{MSES,dis} H_{s,t,g}^{MSES,dis_{\max}} \\ H_{s,t,g}^{MSES,dis} \leq \zeta_{dis}^{MSES} H_{s,t,g}^B \end{cases} \quad (8)$$

$$\begin{aligned} y_{s,t,g}^{MSES,ch} + y_{s,t,g}^{MSES,dis} &\leq 1, y_{s,t,g}^{MSES,ch} \leq u_{s,t,g}^B, \\ y_{s,t,g}^{MSES,dis} &\leq u_{s,t,g}^B \end{aligned} \quad (9)$$

where: $E_{s,t,g}^{MSES}$, $E_{\min}^{MSES}$, $E_{\max}^{MSES}$ are the heat storage capacity and limits of MSES; η_{self}^{MSES} , η_{ch}^{MSES} , η_{dis}^{MSES} are the coefficients of self-loss, charging and discharging, respectively; $H_{s,t,g}^{MSES,ch}$ and $H_{s,t,g}^{MSES,dis}$ are the charging and discharging powers; ξ_{dis}^{MSES} is discharge rate limit; $y_{s,t,g}^{MSES,ch}$, $y_{s,t,g}^{MSES,dis}$ is the 0-1 status variable.

3) Carbon Capture and Storage (CCS)

The CCS model contains electric power output balance and carbon emission and storage balance (10).

$$\begin{cases} P_{s,t,g}^{Net,CFPP} = P_{s,t,g}^{ST} - (P_{s,t,g}^{Ope} + P_{s,t,g}^{Fixed}) \\ P_{s,t,g}^{Ope} = \lambda_g^{CCS} F_{s,t,g}^{CCS} \\ F_{s,t,g}^{CCS} = e_g^{CCS} H_{s,t,g}^B \\ F_{s,t,g}^{Sig,CCS} = \delta_g^{CCS} \beta_g^{CCS} F_{s,t,g}^{CCS} \end{cases} \quad (10)$$

where: $P_{s,t,g}^{Net,CFPP}$ is the net electric power output of the transformed CFPP; $P_{s,t,g}^{Ope}$, $P_{s,t,g}^{Fixed}$ are the operation and fixed electric power consumption of CCS, respectively; $F_{s,t,g}^{CCS}$ and $F_{s,t,g}^{Sig,CCS}$ are the total carbon emission of boiler and the carbon storage of CCS, respectively; e_g^{CCS} is the carbon intensity in p.u.; λ_g^{CCS} is the electric power consumption for CO₂ collection in p.u.; δ_g^{CCS} , β_g^{CCS} are the carbon capture factors.

III. MULTI-UNCERTAINTY CAPACITY PLANNING MODEL

While the current cost associated with the low-carbon and flexible transformation of CFPPs remains considerable, projections suggest a potential decrease in these costs over time [9]. This means the investment cost of CFPP transformation has long-term uncertainty. Plus, short-term uncertainty brought by renewable energy fluctuation also needs to be considered for a rational and economic planning scheme. The structure of the studied IES is shown in Fig. 3.

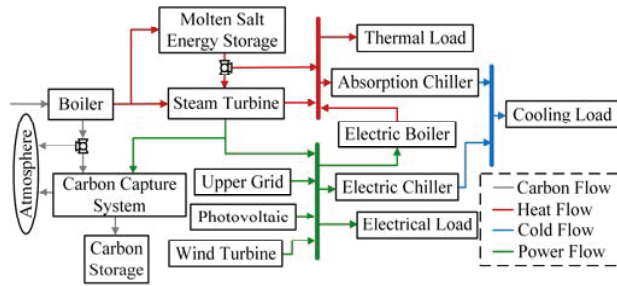


Fig. 3. Structure of the studied IES

To deal with multiple uncertainties at the same time, CVaR and IGDT are introduced for system modelling. The specific planning models are as follows. It should be noted that the investment constraints and operation constraints for multi-energy units can be found in [18]-[19], and are omitted and denoted as “I&O constraints” here due to page limit.

$$\max \alpha_{LCF} \quad (11)$$

s.t. Eqs. (1)-(10) and I&O constraints

$$g(r, y) \bar{C}^{inv,eqp} + \bar{C}^{ope} \leq (1 + \delta^{IGDT}) C_0 \quad (12)$$

$$\begin{aligned} \bar{C}^{inv,eqp} &= C^{install} + \sum_{g \in E^{CFPP}} (1 + \alpha_{LCF}) r c_g^{CFPP} P_g^{CFPP,max} \times \\ &RX_g^{CFPP} + \sum_{f \in C^{CFPP}} (1 + \alpha_{LCF}) c_f^{CFPP} P_f^{CFPP,max} X_f^{CFPP} \end{aligned} \quad (13)$$

$$\bar{C}^{ope} = \sum_{d \in D} N_d \sum_{s \in SCO} \pi(s) \bar{C}_{d,s}^{ope,eqp} + \beta^{CVaR} C^{CVaR} \quad (14)$$

$$C^{CVaR} = \delta^{VaR} + \frac{1}{1 - \alpha^{CVaR}} \sum_{d \in D} N_d \sum_{s \in SCO} \pi(s) \times [\bar{C}_{d,s}^{ope,eqp} - \delta^{VaR}]^+ \quad (15)$$

where α_{LCF} is the uncertainty boundary; $g(r, y)$ is the discount factor; $\bar{C}_n^{inv,eqp}$ is the worst-scenario total system investment; $\bar{C}^{ope}$ is the system operation cost; δ^{IGDT} is the IGDT factor; C_0 is the system planning cost under deterministic planning; $C^{install}$ is the investment cost excludes CFPPs; $r c_g^{CFPP}$ and c_f^{CFPP} are unit investment cost for transformed and newly installed CFPPs; $P^{CFPP,max}$ is the maximum capacity of CFPPs; RX^{CFPP} , X^{CFPP} are 0-1 variables for CFPP transformation and construction; N_d is the number of days in typical season d ; $\pi(s)$ is the probability for scenario s ; $\bar{C}_{d,s}^{ope,eqp}$ is the expected total operation cost; β^{CVaR} is the risk-averse factor; C^{CVaR} is the CVaR cost; δ^{VaR} is the VaR value; α^{CVaR} is confidence factor.

However, there are bilinear terms $\alpha_{LCF} r c_g^{CFPP}$ and $\alpha_{LCF} c_f^{CFPP}$, as well as absolute value term $[X]^+$ in the proposed CVaR-IGDT uncertainty planning model. Thus, McCormick method and variable substitution approach [20] are introduced for model linearization in this paper.

Using $\alpha_{LCF} r c_g^{CFPP}$ as an example for bilinear linearization:

$$\tilde{\alpha}_g = \alpha_{LCF} r c_g^{CFPP} \quad (16)$$

$$\begin{cases} 0 \leq \tilde{\alpha}_g \leq \alpha_{LCF} \\ \alpha_{LCF} + r c_g^{CFPP} - 1 \leq \tilde{\alpha}_g \leq r c_g^{CFPP} \end{cases} \quad (17)$$

For linearization of $[X]^+ = \max\{X, 0\}$, an auxiliary variable $\Psi_{d,s}^{CVaR}$ is firstly introduced, and then the absolute value term is converted into linear inequality constraints:

$$\Psi_{d,s}^{CVaR} \geq 0 \quad (18)$$

$$\bar{C}_{d,n,s}^{ope,eqp} - \delta^{VaR} \leq \Psi_{d,s}^{CVaR} \quad (19)$$

The above linearized capacity planning model with multiple uncertainties can be solved by commercial solvers such as GUROBI and CPLEX. It should be noted that despite the extra variables and constraints introduced by uncertainty modelling and problem linearization, the proposed linearized CVaR-IGDT capacity planning model is still highly scalable and can be adjusted to incorporate more multi-energy devices and renewable energy or load fluctuation scenarios. However, reasonable scenario generation and reduction methods as well as related decomposition algorithms might be in need to facilitate calculation and obtain a reliable planning results for the expanded large-scale problems within given time limits.

IV. CASE STUDIES

A. System Description

To verify the reliability and effectiveness of the proposed low-carbon and flexible transformed CFPP structure and the multi-uncertainty planning model, a real world IES with the structure as depicted in Fig. 3 in northern China is selected for analysis. Weibull and beta distributions are selected for data fitting, and Monte Carlo method is introduced for scenario generation. K-means approach is used for scenario reduction. In addition, three typical seasons are selected for planning optimization, namely summer, winter and transition season (i.e. spring and autumn). The planning horizon is 10 years with 5% investment discount rate. Uncertainty modelling parameters are $\delta^{IGDT} = 0.225$, $\beta^{CVaR} = 0.1$, $\alpha^{CVaR} = 0.9$. Other technical and economic parameters of the test IES system are detailed in [18]-[20] with reasonable adjustment under actual engineering applications.

B. Comparison Analysis of Low-Carbon and Flexible Transformation of CFPP

To investigate the effects of low-carbon and flexible transformed CFPPs on overall system planning economy and to highlight the advantages of the transformed CFPP structure with CCS and MSES, comparative analysis is performed between: 1) deterministic planning of IES without low-carbon and flexible transformation; 2) deterministic planning considering transformed and newly installed low-carbon and flexible CFPPs. Specific results are shown in Table I.

TABLE I. COMPARISON OF SYSTEM PLANNING RESULTS WITH AND WITHOUT LOW-CARBON AND FLEXIBLE TRANSFORMATION

Indices	Without Transformation	With Transformation
Transformed CFPPs (MW)	/	3200
Newly Installed CFPPs (MW)	800	500
Investment Cost (\$)	0.56×10^9	3.12×10^9
Operation Cost (\$)	18.86×10^9	12.92×10^9
Total Cost (\$)	19.42×10^9	16.05×10^9
Carbon Emission (ton)	15.55×10^4	5.46×10^4
Renewable Energy Utilization Rate (%)	84.30	89.90
Load Shedding Rate (%)	3.47	0

According to Table I, following the low-carbon and flexible transformation of 3200MW existing traditional CFPPs, 500MW of newly installed CFPPs are needed, compared to 800MW without such transformation. This is mainly because the transformation fully realizes the potential of existing units, thereby enhancing the flexibility of system operation dispatch and consequently diminishing the necessity for additional CFPPs.

Furthermore, upon incorporating the low-carbon and flexible transformation of CFPPs, the total investment cost shows an $\$2.56 \times 10^9$ increase because of the integration of CCS and MSES. By utilizing the dispatch flexibility brought by MSES, the total system operation cost witnesses a noteworthy reduction of 31.50%. Simultaneously, there is a commendable enhancement in the rate of renewable energy utilization by 5.6%, accompanied by a complete elimination of load shedding possibilities. Despite the initial increase in investment cost, the total system planning cost with CFPP transformation shows a reduction of 17.35% due to less carbon emission penalty. Besides, with the incorporation of

CCS system, the transformed CFPPs exhibit a remarkable decrease in carbon emissions by 10.09×10^4 tons, thus contributing to the realization of carbon neutrality goals.

C. Multi-Uncertainty Capacity Planning Results Analysis

For further exploration of the impact of long-term and short-term uncertainties brought by CFPP transformation investment and renewable energy sources, two cases are designed, namely deterministic planning scheme without uncertainties and multi-uncertainty planning scheme. The results for two cases are compared in Fig. 4 and Table II.

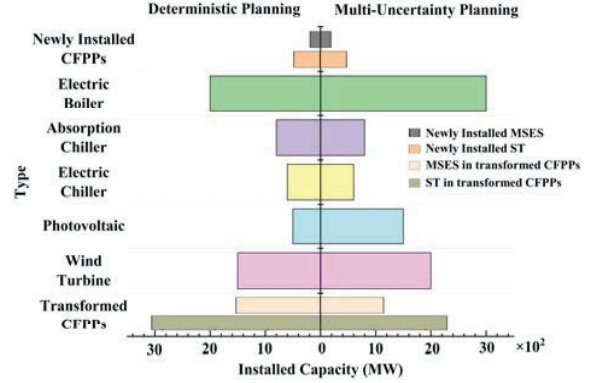


Fig. 4. Deterministic and uncertainty planning results comparison

In Fig. 4, influenced by long-term uncertainty of CFPP transformation investment cost, the transformed ST capacity in existing CFPP is reduced by 800MW and the MSES capacity is reduced by 400MW, compared to deterministic planning. To remedy these diminished CFPP outputs, additional PV and WT capacities of 1000MW and 500MW, respectively, are installed to accommodate multi-energy load demands. Moreover, a supplementary 1000MW of electric boiler is integrated to collaborate with the transformed CFPPs, thereby enhancing system dispatch flexibility under high penetration of renewable energy sources.

TABLE II. COSTS OF CAPACITY PLANNING FOR DIFFERENT CASES

Cost	Deterministic Planning	Multi-Uncertainty Planning
Investment Cost (\$)	3.12×10^9	3.29×10^9
Operation Cost (\$)	12.92×10^9	14.76×10^9
Total Cost (\$)	16.05×10^9	19.66×10^9

It can be seen from Table II, compared to deterministic planning, the total cost of multi-uncertainty planning increases by $\$3.61 \times 10^9$ due to investment fluctuation and energy redispatch. In which, approximately 5% of the increased cost is used to deal with long-term uncertainty for CFPP transformation investment cost, and the remaining 95% is used to increase operation flexibility, so as to enhance system reliability and robustness under uncertainties. Although the total system planning cost increases, the uncertainty boundary ($\alpha_{LCF} = 0.2507$) indicates that in face of a 22.5% increase in total system planning cost, the maximum variation of CFPP transformation investment that the proposed scheme can withstand is 25.07%.

D. Sensitivity Analysis of CVaR-IGDT Parameters

To validate the effectiveness of the proposed CVaR-IGDT planning model, sensitivity analysis on two key parameters is performed. The variation of uncertainty boundary with different β^{CVaR} and δ^{IGDT} is compared Fig. 5.

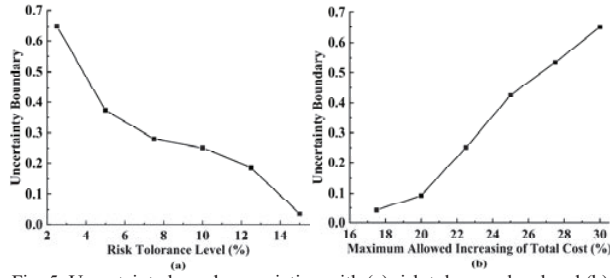


Fig. 5. Uncertainty boundary variation with (a) risk tolerance level and (b) maximum allowed increasing of total cost

It can be seen from Fig. 5 (a), with a fixed value of $\delta^{IGD} = 22.5\%$ and a growth from 0.025 to 0.15 of β^{CvaR} , the system uncertainty boundary shows a declining trade. This suggests that as the risk tolerance level increases, the decision makers tend to mitigate risks associated with short-term renewable energy fluctuations. Consequently, there is a preference for the integration of additional low-carbon and flexible transformed CFPPs, electric boilers, and power purchase from the upper grid, despite the higher costs, to meet multi-energy load demands. Fig. 5 (b) shows similar results with a reverse tendency. When β^{CvaR} is a constant at 0.1 and δ^{IGD} increases from 17.5% to 32.5% with a step of 2.5%, the uncertainty boundary grows accordingly. The results illustrate that the obtained capacity planning scheme has a strong ability to cope with the long-term uncertainty of the investment cost for CFPP transformation.

V. CONCLUSION

In this paper, a multi-uncertainty capacity planning scheme of IES is proposed, considering the low-carbon and flexible transformation of CFPPs. The main contributions and results are as follows:

(1) A novel structure for CFPPs with low-carbon and flexible transformation is designed, which can effectively enhance system flexibility and reduce carbon emissions. The mathematical model of the proposed CFPP structure is linear and applicable for system planning optimization.

(2) The developed CvaR-IGDT uncertainty capacity planning model effectively integrates both long-term investment uncertainty and short-term renewable energy output uncertainty simultaneously. And it can be further converted into a mixed integer linear programming problem to be efficiently solved by commercial solvers. Result analysis shows that the proposed model can provide reliable and economic scheme for real-world system capacity planning.

(3) According to case analysis, by considering the use of the proposed low-carbon and flexible CFPP structure, the total system planning cost can be reduced by 17.35%, while the carbon emission also being reduced by 10.09×10^4 tons. The obtained optimal capacity planning results under multiple uncertainties has the resilience to disturbance in CFPP transformation investment costs (when fluctuations lower than 25.07%) and is more reasonable for real-world IES planning.

Future work can be done, focusing on the precise linearization and convexified expression for thermodynamic analysis of the low-carbon and flexible transformed CFPPs.

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