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Low-carbon scheduling of independent microgrid considering uncertainty of source and load sides

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***Abstract*—In this paper, the uncertainty of load and renewable energy is considered, and a low-carbon economic scheduling model based on fuzzy opportunity constraints is proposed. The carbon trading costs based on step-price carbon trading framework is introduced into the objective function to improve the system environmental protection. The fuzzy opportunity constraint is introduced to represent the uncertain factors of the system, and the triangular fuzzy parameters are used to clear the constraint conditions, the model is solved by CPLEX. The case analysis shows that in uncertain environments, the higher the carbon trading price, the lower the carbon emissions, on the contrary, the system operation cost and carbon emission cost are higher.**

Keywords-renewable energy, source-load uncertainty, fuzzy opportunity constraint, clear equivalent forms, low-carbon scheduling

I. NOMENCLATURE

$\mathrm{Pos}\{.\}$	Probability of event occurrence
$\boldsymbol{x}$	Decision vector
ξ	Fuzzy parameter vector
$f(\boldsymbol{x},\xi)$	Objective function
$g(\boldsymbol{x},\xi)$	Equation constraint
$h(\boldsymbol{x},\xi)$	Inequality constraint
E_q	Total emission quota of the system, (t)
E_d	Actual carbon emission, (t)
ΔE	Carbon over-emissions, (t)
ε	Emission quota per unit of electricity, (t/MW)
δ_i	Emission intensity of thermal power unit *i*, (t/MW)
P_t	Output of all generating units at moment *t*, (MW)
$P_{i,t}$	Output of thermal power unit *i*, (MW)
$P_{w,t}$	Output of wind turbine, (MW)
$P_{p,t}$	Output of photovoltaic system, (MW)
$P_{h,t}$	Output of hydroelectric unit, (MW)
$P_{bess,t}$	Output of battery energy storage system, (MW)
d, l	Carbon emission interval length, (t)
ϖ	Carbon trading price, (¥/t)
s	Growth rate of carbon trading price
f	Total system operating cost, (¥)
C_1	Carbon trading cost, (¥)
C_2	Thermal power unit generation cost, (¥)
C_3	Wind unit generation cost, (¥)
C_4	Photovoltaic cost, (¥)
C_5	Hydroelectric cost, (¥)
C_6	Battery energy storage system cost, (¥)
a_i, b_i, c_i	Cost factor of thermal power unit *i*, (¥/MW)
e_i	Thermal power unit *i* start-up costs, (¥)
$u_{i,t}$	Start/stop status of thermal power unit *i*
γ_h	Cost factors of hydropower units, (¥/MW)
γ_w	Cost factors of wind turbine, (¥/MW)
γ_p	Cost factors of photovoltaic system, (¥/MW)
γ_{bess}	Cost factor of energy storage system, (¥/MW)
$\tilde{P}_{w,t}$, $\tilde{P}_{p,t}$	Expected output of renewable energy, (MW)
e_w, e_p	Penalty factors of wind and photovoltaic, (¥/MW)
ΔP_i	Climbing rate of thermal unit *i*, (MW)
$T_{i,on}$, $T_{i,off}$	Minimum start/stop time of thermal unit *i*, (h)
η	Charging and discharging efficiency
E	Battery energy storage system capacity, (MWh)
$P^f_{L,t}$	Load forecasts, (MW)
$P^f_{w,t}$	Wind generation forecasts, (MW)
$P^f_{p,t}$	Photovoltaic generation forecasts, (MW)
$\varphi_{L,t}$	Prediction error of load, (MW)
$\varphi_{w,t}$	Prediction error of wind generation, (MW)
$\varphi_{p,t}$	Prediction error of photovoltaic generation, (MW)
$P_{L1,t}$	Load membership parameters
$P_{w1,t}$	Wind generation membership parameters
$P_{p1,t}$	Photovoltaic generation membership parameters

II. INTRODUCTION

Development of renewable energy sources such as wind and solar is an effective means to meet the complex electricity demand and protect environment. However, the uncertainty of the new energy and the diverse user demands bring security risks to the stable operation of the system [1,2]. Therefore, scheduling decision makers must consider the uncertainty factors of source and load. How to balance the

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reliability, economy and environmental protection of the power grid has become an important issue.

For power systems, a dispatching strategy that considers carbon emissions is more economical. In [3], carbon trading cost is introduced into the power system, which effectively reduces the output of thermal power units and reduces the system carbon emission. In [4], an energy system optimal dispatching method considering seasonal carbon trading mechanism is proposed, which effectively reduces carbon emissions and system operation costs. In [5], a low-carbon economic optimal dispatching strategy for energy systems considering electric and thermal flexible loads and carbon trading is proposed to improve the utilization of renewable energy and control carbon emissions, and the case analysis verified the effectiveness of the proposed model. It is worth mentioning that the carbon trading models in [3-5] all adopt a ladder-type tariff framework. Based on the above studies, a new step-type carbon trading framework is proposed.

For practical dispatch, it is necessary to consider the uncertainty on both sides of the source and load [6]. In [7], a new method for estimating the uncertainty set of wind generation is proposed by fully considering the uncertainty of wind generation and weighing some conflicting objectives. In [8], a robust optimization model for transmission congestion management is proposed to characterize the uncertainty of wind and solar power generation. [9] establish a function-based joint wind-solar distribution function to generate power output scenarios and propose an improved scenario generation and scenario reduction method for uncertainty modeling of wind and solar power generation. [10] propose a new method for optimal dispatching of microgrid systems consisting of generating units and demand response resources considering the load uncertainty. In [11], uncertainty modeling in the optimal scheduling of the energy hub (OSEH) has been addressed in a fuzzy-based optimization framework. The impacts of uncertainties caused by energy demands, wind power generation and electricity price on the OSEH problem are analyzed. In [3], fuzzy opportunity constraints are considered to represent the uncertainty of load and source. [12] is based on a power system containing a high proportion of renewable energy and reveals the power balance principle, proposing a probability model for flexibility margin. [13] simulate the predicted error values of load and wind speed using segmented Gaussian distribution, and then find the most economical unit output method. [14] relaxes the power balance equation in the constraint conditions into an inequality equation in uncertain environments for scheduling models containing large-scale renewable energy, and introduces it into the objective programming model. [15] introduces the concept of net load and combines Monte Carlo simulation with analytical methods to address the uncertainty of wind, solar, and load.

This paper uses a fuzzy opportunity constrained programming model to characterize the uncertainty of both sources and loads, introduces a new stepped carbon trading framework into the economic dispatch model, and finally discusses the dispatch results under different confidence levels to verify the relationship between economic dispatch and environmental protection in power systems.

The rest of this study is organized as follows. Section III describes the fuzzy opportunity constrained model. Section IV gives the design process of the carbon trading model. Section V shows the scheduling model considering fuzzy opportunity constrained programming. Section VI shows the case analysis. Section VII gives the conclusion.

III. Fuzzy Opportunity Constrained Model

The principle of fuzzy chance programming is that decisions are allowed to be made without satisfying constraints to a certain extent to simulate the results of the system in an unfavorable environment, but the probability that the decisions made satisfy the constraints must not be less than a certain confidence level α. The model with fuzzy parameters is shown as equation (1)

$$\begin{cases} \min f(\boldsymbol{x},\boldsymbol{\xi}) \\ s.t. \quad \mathrm{Pos}\{g(\boldsymbol{x},\boldsymbol{\xi})=0\} \geq \alpha \\ \quad\quad \mathrm{Pos}\{h(\boldsymbol{x},\boldsymbol{\xi})\leq 0\} \geq \alpha \end{cases} \tag{1}$$

Transforming the (1) into a corresponding clear equivalence form is viewed as an efficient method for solving chance constrained programming with fuzzy parameters. Here, the clear equivalence form derivation procedure is briefly described: assuming that both the constraints $g(x,\xi)$ and $h(x,\xi)$ are linear functions of ξ, the constraints can be expressed as:

$$g(\boldsymbol{x},\boldsymbol{\xi}) = h_1(x)\xi_1 + h_2(x)\xi_2 + ... + h_t(x)\xi_t + h_0(x) \tag{2}$$

where, assume that ξ_k are trapezoidal fuzzy numbers:

$$\xi_k = (r_{k1}, r_{k2}, r_{k3}, r_{k4}), \quad k=1,2,3,...,\mathrm{t} \tag{3}$$

Define $h_k^+(\boldsymbol{x})$ and $h_k^-(\boldsymbol{x})$ are non-negative functions and satisfies $h_k(x) = h_k^+(x) - h_k^-(x)$,(2) can be transformed into:

$$g(\boldsymbol{x},\boldsymbol{\xi}) = \sum_{k=1}^{t}\left[h_k^+(\boldsymbol{x})\xi_k + h_k^-(\boldsymbol{x})\xi_k^{'}\right] + h_0(\boldsymbol{x}) \tag{4}$$

where, $h_0(\boldsymbol{x})$ is the rest of the constraint. $\xi_k^{'}$ is also the trapezoidal fuzzy parameters:

$$\xi_k^{'} = (-r_{k4}, -r_{k3}, -r_{k2}, -r_{k1}), \quad k=1,2,3,...,\mathrm{t} \tag{5}$$

In summary, the clear equivalence form is expressed as:

$$\begin{aligned} &(1-\alpha)\sum_{k=1}^{t}\left[r_{k1}h_k^+(\boldsymbol{x}) - r_{k4}h_k^-(\boldsymbol{x})\right] + \\ &\alpha\sum_{k=1}^{t}\left[r_{k2}h_k^+(\boldsymbol{x}) - r_{k3}h_k^-(\boldsymbol{x})\right] + h_0(\boldsymbol{x}) \leq 0 \end{aligned} \tag{6}$$

IV. Carbon Trading Model

The source side units in this paper contains: thermal power units, hydro power units, renewable energy and energy storage system. Therefore, carbon emissions mainly come from thermal units, and carbon emission allowances are shown in equations (7) and (8):

$$E_q = \sum_{t=1}^{T} \varepsilon P_t \tag{7}$$

$$P_t=\sum_{i=1}^{M}P_{i,t}+P_{w,t}+P_{p,t}+P_{h,t}+\left|P_{bess,t}\right| \tag{8}$$

The carbon emission is shown as equation (9):

$$E_d=\sum_{t=1}^{T}\sum_{i=1}^{M}\delta_i P_{i,t} \tag{9}$$

The carbon trading model in this paper adopts a stepped framework, which divides carbon emissions into four intervals. The framework is shown in Fig. 1.

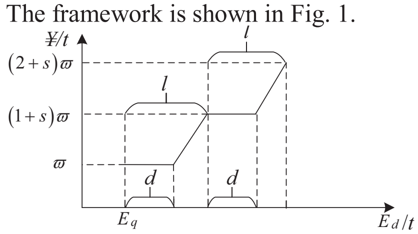

Fig. 1 The price of carbon trading.

The carbon trading cost is modeled as a segmented function, as shown in equation (11).

$$\Delta E=E_d-E_q \tag{10}$$

$$C_1=\begin{cases}\varpi(\Delta E),E_q<E_d\le E_q+d\\ \left[\dfrac{s\varpi}{l-d}(\Delta E-d)+\varpi\right](\Delta E-d)+d\varpi,\\ \qquad E_q+d<E_d\le E_q+l\\ (1+s)\varpi(\Delta E-d)+d\varpi,\\ \qquad E_q+l<E_d\le E_q+l+d\\ \left[\dfrac{\varpi}{l-d}(\Delta E-2l)+(2+s)\varpi\right](\Delta E-l-d)\\ \quad +(1+s)\varpi l+d\varpi,\\ \qquad E_q+l+d<E_d\le E_q+2l\end{cases} \tag{11}$$

$$0<s\le 1,\qquad 0<d\le l \tag{12}$$

V. Low-Carbon Scheduling Model Considering Fuzzy Opportunity Constrained Programming

A. Objective function

In this paper, we consider the generation costs of thermal power units, renewable energy, battery energy storage systems and carbon trading costs. The objective function is shown in equation (13)

$$\min f=C_1(E_d)+C_2(P_{i,t})+C_3(P_{w,t})+C_4(P_{p,t})+C_5(P_{h,t})+C_6(P_{bess,t}) \tag{13}$$

The thermal power generation cost only considers the fuel cost:

$$C_2=\sum_{t=1}^{T}\sum_{i=1}^{M}\left[\left(a_iP_{i,t}^2+b_iP_{i,t}+c_i\right)+u_{i,t}\left(1-u_{i,t-1}\right)e_i\right] \tag{14}$$

Wind and solar power and hydro units do not consume fuel, so only unit operation and maintenance costs and undesired output penalties are considered:

$$C_3=\sum_{t=1}^{T}\gamma_w P_{w,t}+e_w\left|\tilde{P}_{w,t}-P_{w,t}\right| \tag{15}$$

$$C_4=\sum_{t=1}^{T}\gamma_p P_{p,t}+e_p\left|\tilde{P}_{p,t}-P_{p,t}\right| \tag{16}$$

$$C_5=\sum_{t=1}^{T}\gamma_h P_{h,t} \tag{17}$$

$$C_6=\sum_{t=1}^{T}\gamma_{bess}\left|P_{bess,t}\right| \tag{18}$$

B. Constraint condition

Thermal power unit constraints are shown as (19)-(21).

Output constraint:

$$P_i^{\min}\le P_{i,t}\le P_i^{\max} \tag{19}$$

Climbing rate constraint:

$$\left|P_{i,t}-P_{i,t-1}\right|\le \Delta P_i \tag{20}$$

Minimum start/stop time constraint:

$$\begin{cases}\left(u_{i,t-1}-u_{i,t}\right)\left(T_{i,t-1}-T_{i,on}\right)\ge 0\\ \left(u_{i,t}-u_{i,t-1}\right)\left(-T_{i,t-1}-T_{i,off}\right)\ge 0\end{cases} \tag{21}$$

Due to the special characteristics of solar and hydro power generation, only output constraints are considered:

$$P_w^{\min}\le P_{w,t}\le P_w^{\max} \tag{22}$$

$$P_p^{\min}\le P_{p,t}\le P_p^{\max} \tag{23}$$

$$P_h^{\min}\le P_{h,t}\le P_h^{\max} \tag{24}$$

Energy storage system constraints are shown as (25)-(27).

Charging and discharging power constraints:

$$\left|P_{bess,t}\right|\le P_{bess}^{\max} \tag{25}$$

To maintain the battery health of the energy storage system, the State of charge (SOC) needs to satisfy the following constraints:

$$SOC_{\min}\le SOC_t\le SOC_{\max} \tag{26}$$

$$SOC_t=SOC_{t-1}+\frac{\eta P_{bess,t}}{E}\Delta t \tag{27}$$

Supply and demand power balance constraint:

$$P_{L,t}^f+\varphi_{L,t}-\left(P_{w,t}^f+\varphi_{w,t}+P_{p,t}^f+\varphi_{p,t}\right)-\sum_{i=1}^{M}u_{i,t}P_{i,t}-P_{h,t}-P_{bess,t}=0 \tag{28}$$

Spinning reserve capacity constraint:

$$P_{L,t}^f+\varphi_{L,t}-\left(P_{w,t}^f+\varphi_{w,t}+P_{p,t}^f+\varphi_{p,t}\right)-\sum_{i=1}^{M}u_{i,t}P_i^{\max}-P_h^{\max}-P_{bess}^{\max}\le 0 \tag{29}$$

C. Model solving

Power system operation must ensure safety, α must be maintained at a certain level [3], when $\alpha\ge 0.5$, (6) can be transformed into:

$$(2-2\alpha)\sum_{k=1}^{t}\left[r_{k3}h_k^{+}(\boldsymbol{x})-r_{k2}h_k^{-}(\boldsymbol{x})\right]+(2\alpha-1)\sum_{k=1}^{t}\left[r_{k4}h_k^{+}(\boldsymbol{x})-r_{k1}(\boldsymbol{x})\right]+h_0(\boldsymbol{x})\le 0 \tag{30}$$

We use clear equivalence forms under the triangular fuzzy parameters, (28) and (29) can be transformed into:

$$(2-2\alpha)\left[P_{L2,t}-P_{w2,t}-P_{p2,t}\right]+(2\alpha-1)\left[P_{L3,t}-P_{w1,t}-P_{p1,t}\right]+ P_{bess,t}-P_{h,t}-\sum_{i=1}^{M}u_{i,t}P_{i,t}=0 \tag{31}$$

$$(2-2\alpha)\left[P_{L2,t}-P_{w2,t}-P_{p2,t}\right]+(2\alpha-1)\left[P_{L3,t}-P_{w1,t}-P_{p1,t}\right]+ P_{bess,t}-P_{h,t}-\sum_{i=1}^{M}u_{i,t}P_{i,t}^{\max}\leq 0 \tag{32}$$

Suppose $\xi_k=(r_{k1},r_{k2},r_{k3})$ is triangular fuzzy parameters, then the expectation satisfies (33):

$$E(\xi_k)=\frac{(1-\alpha)r_{k1}+r_{k2}+\alpha r_{k3}}{2} \tag{33}$$

Therefore, the expected values of solar and wind output and load demand are shown as:

$$E\left(\tilde{P}_{w,t}\right)=\frac{1-\alpha}{2}P_{w1,t}+\frac{1}{2}P_{w2,t}+\frac{\alpha}{2}P_{w3,t} \tag{34}$$

$$E\left(\tilde{P}_{p,t}\right)=\frac{1-\alpha}{2}P_{p1,t}+\frac{1}{2}P_{p2,t}+\frac{\alpha}{2}P_{p3,t} \tag{35}$$

$$E\left(\tilde{P}_{L,t}\right)=\frac{1-\alpha}{2}P_{L1,t}+\frac{1}{2}P_{L2,t}+\frac{\alpha}{2}P_{L3,t} \tag{36}$$

VI. CASE ANALYSIS

A. Basic parameters

The data of one day is selected for the study, the forecasted values of new energy output and load demand during this dispatch day are shown in Fig. 2.

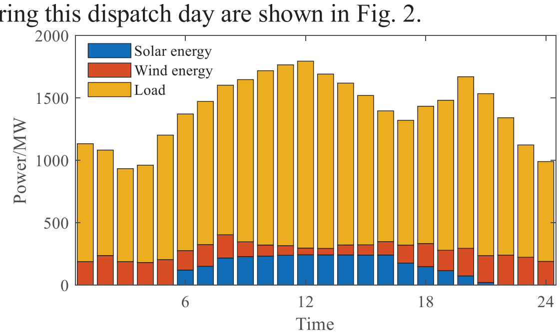

Fig. 2 Predicted values of new energy output and load demand.

The triangular fuzzy membership parameters of wind and solar output, and load demand are shown in Table II in the Appendix. In carbon trading model, $s=0.25$, $d=40(\mathrm{t})$, $l=70(\mathrm{t})$, and other parameters are shown in Table III in the Appendix. In the scheduling model, $SOC_{\min}=0.2$, $SOC_{\max}=0.9$, $\eta=0.95$, $E=400(\mathrm{MWh})$, $P_h^{\min}=0$, $P_h^{\max}=280(\mathrm{MW})$. The parameters of thermal power units are shown in Table IV in the Appendix.

B. Simulation result

When $\alpha=0.95$, $\varpi=120(¥/\mathrm{t})$. The output of each unit is shown in Fig. 3, and the actual output and predicted output of wind and solar power are shown in Fig. 4.

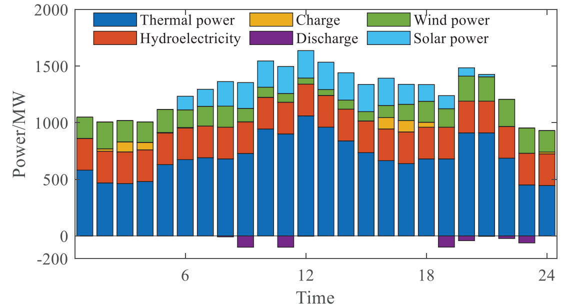

Fig. 3 Output of each power generation unit.

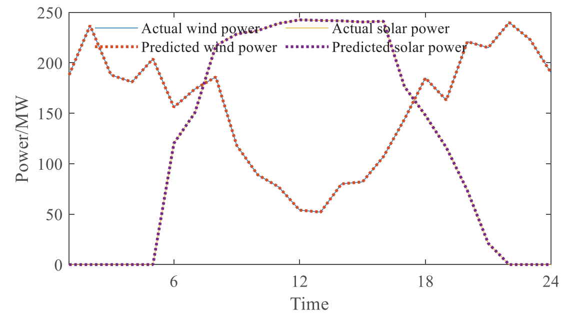

Fig. 4 Comparison of renewable energy output.

As can be seen from the above figures, as the main power generation units, the output of thermal power units is significantly greater than that of other power generation units. Due to the economy of renewable energy, hydropower units are at their maximum output at all scheduling times, and wind power and photovoltaic power are completely absorbed.

The wasted wind and solar volume, and system reserve capacity at different confidence levels can reflect the impact of source load uncertainty on the power system. The specific data are shown in Table I.

TABLE I. SCHEDULING RESULTS UNDER CONFIDENCE LEVELS

α	**Rotating reserve capacity /MW**	**Wasted wind volume /MW**	**Wasted solar volume /MW**
0.60	198.46	0	0
0.65	633.59	0	0
0.70	1070.74	0	0
0.75	1509.93	0	0
0.80	1951.15	0	0
0.85	2394.40	0	0
0.90	2839.69	0	0
0.95	3287.01	0	0

In order to maintain economic operation, the power system has fully absorbed the new energy output. The reserve capacity is an additional capacity set to prevent adverse effects on the system due to load growth and wind and solar abandonment. The reserve capacity in this paper is the difference between the actual output and the expected output of the units. It is worth noting that as the α increases, the system becomes more stable, and the rotating reserve capacity continues to increase.

To explore the relationship between low-carbon operation and economy of the system, the scheduling cost and carbon trading cost under different confidence levels are shown in Fig. 5 and Fig. 6, the total emissions are shown in Fig. 7.

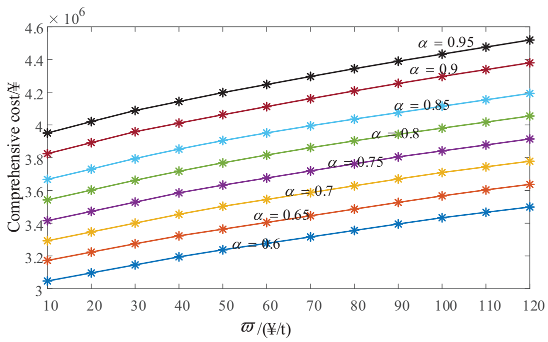

Fig. 5 Comprehensive cost under different confidence levels.

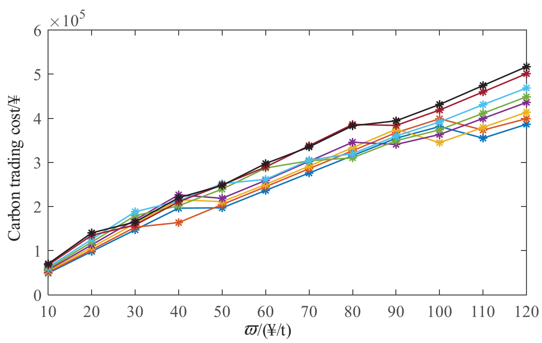

Fig. 6 Carbon trading cost under different confidence levels.

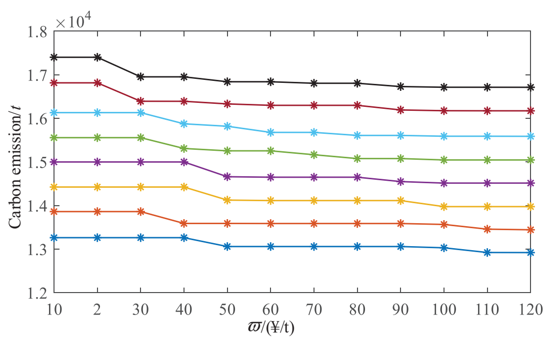

Fig. 7 Carbon emission under different confidence levels.

The reserve capacity is closely related to the confidence level. As it increases, the capacity and safety of the system increase, and the economy decreases. During the scheduling process, it is necessary to comprehensively consider the safety and economy of the system, and select an appropriate confidence level based on the actual needs of the system.

At any confidence level, as the carbon trading price increases, the overall operating costs of the system increase significantly, and carbon emissions decrease considerably. This is because the power grid will choose to reduce carbon emissions in order to avoid dynamically increasing carbon trading prices. However, due to the non-linear relationship between carbon trading costs and carbon emissions, even if carbon emissions are reduced, the carbon trading costs still show an increasing trend.

VII. CONCLUSION

For the low-carbon scheduling of wind and solar grid connected power systems, this paper considers the uncertainties on both sides of the source and load, the impact of power generation costs, carbon transaction costs, and proposes a low-carbon scheduling model containing renewable energy based on fuzzy opportunity constraints. The conclusions are as follows:

1) By setting different confidence levels to control the risk level of the system, it can be seen that the more stable the scheduling environment, the less economical the system operation, and the lower the environmental protection.

2) The lower the carbon trading price, the more economical the power system scheduling will be. However, low prices make electric power systems less sensitive to carbon emissions, and they increasingly prefer thermal power generation to meet scheduling needs, further increasing the cost of carbon trading.

It is worth noting that the objective function of this paper does not consider improving the absorption of wind and solar energy. For low-carbon scheduling, improving the grid connection rate of wind and solar power and promoting its consumption can also reduce carbon emissions. Related research work will also be carried out in the future.

VIII. APPENDIX

The tables in Appendix show parameters not given above.

TABLE II. FUZZY PARAMETER SETTING

Object	r_{k1}	r_{k2}	r_{k3}
Wind power	0.6	0.9	1.1
Solar power	0.7	0.91	1.08
Load demand	0.9	0.95	1.05

TABLE III. CARBON TRADING FRAMEWORK PARAMETERS

Thermal power units	δ_i **(t/MW)**
Unit 1	0.97
Unit 2	1.11
Unit 3	1.06
Unit 4	0.98
Unit 5	1.03

TABLE IV. THERMAL POWER UNITS PARAMETERS

Thermal power units	Parameters	Values
Unit 1	$P_1^{\max} / P_1^{\min}$	460/230
	$T_{1,on} / T_{1,off}$	8/8
	ΔP_1	240
	$a_1 / b_1 / c_1 / e_1$	0.004/250/400/25.6
Unit 2	$P_2^{\max} / P_2^{\min}$	400/200
	$T_{2,on} / T_{2,off}$	6/6
	ΔP_2	210
	$a_2 / b_2 / c_2 / e_2$	0.003/240/195/22.3
Unit 3	$P_2^{\max} / P_2^{\min}$	350/150
	$T_{3,on} / T_{3,off}$	5/5
	ΔP_3	150
	$a_3 / b_3 / c_3 / e_3$	0.002/230/300/16.2
Unit 4	$P_4^{\max} / P_4^{\min}$	300/120
	$T_{4,on} / T_{4,off}$	4/4
	ΔP_4	120
	$a_4 / b_4 / c_4 / e_4$	0.0015/200/250/12.3
Unit 5	$P_5^{\max} / P_5^{\min}$	150/70
	$T_{5,on} / T_{5,off}$	3/3
	ΔP_5	70
	$a_5 / b_5 / c_5 / e_5$	0.0009/1800/200/4.6

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