IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 15 October 2023, accepted 12 November 2023, date of publication 16 November 2023, date of current version 22 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3334008

RESEARCH ARTICLE

Optimized Configuration of Distributed Power Generation Based on Multi-Stakeholder and Energy Storage Synergy

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This work was supported in part by the National Key Research and Development Program of China under Grant 2021YFB1506902, in part by the National Natural Science Foundation of China under Grant 52267005, and in part by the Major Science and Technology Projects in Xinjiang under Grant 2022A01001-4.

ABSTRACT Traditional distributed generation (DG) planning often only considers a single stakeholder and does not take into account demand response, which fails to take into account the interests of various stakeholders in the market and ignores the regulation capabilities of load and energy storage. Aiming at the above problems, this article proposes an optimal distributed power allocation model that takes into account the interests of distributed power operators, distribution companies and power users, as well as the demand response. Carbon trading mechanism and green certificate trading mechanism are introduced to take into account the carbon emissions during power generation and transmission and the flexibility resources on the energy storage side to establish a multi-principal allocation model that considers the environmental cost of carbon emissions and demand response; the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) comprehensive evaluation idea to maximise the benefits of each subject, and adopt the second-order cone relaxation technique for planning solution. The case analysis results show that the proposed optimal allocation model can effectively balance and improve the income of each subject. Compared with the traditional model, which does not consider energy storage and only maximizes the benefits of DG operators, the comprehensive benefits are improved by 43.7 %, and the consumption capacity of distributed generation is improved. It promotes carbon emission reduction and reduces carbon emissions by 1,243.05 t, which verifies the effectiveness of the proposed model.

INDEX TERMS Distributed power generation, renewable energy source, stakeholders, demand response.

NOMENCLATURE

$C_{\mathrm{AE}}^{\mathrm{in}}$	Annual investment cost of energy storage.
$C_{\mathrm{AE}}^{\mathrm{op}}$	Annual operating cost of energy storage.
$C_{\mathrm{DG}}^{\mathrm{buy}}$	Cost of purchasing electricity from DG operators.
$C_{\mathrm{DG}}^{\mathrm{en}}$	Annual carbon emission cost.
$C_{\mathrm{DG}}^{\mathrm{fg}}$	Annual fuel cost.
$C_{\mathrm{DG}}^{\mathrm{in}}$	DG annual investment cost.
$C_{\mathrm{DG}}^{\mathrm{op}}$	Annual operation and maintenance cost.
$C_{\mathrm{NET}}^{\mathrm{buy}}$	Distribution company to the upper power grid purchase costs.
$C_{\mathrm{NET}}^{\mathrm{en}}$	Annual carbon emission cost during the energy transmission process.
$C_{\mathrm{NET}}^{\mathrm{loss}}$	Annual active power loss cost of the distribution company.
$C_{\mathrm{NET}}^{\mathrm{sub}}$	Annual subsidy cost of interruptible loads.
$E_{\mathrm{DG}}^{\mathrm{sell}}$	Annual power generation enterprise sales revenue.
$E_{\mathrm{DG}}^{\mathrm{sub}}$	Renewable energy generation subsidies.
$E_{\mathrm{NET}}^{\mathrm{sell}}$	Annual sales revenue of the distribution company to power users.

The associate editor coordinating the review of this manuscript and approving it for publication was Hao Wang.

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$E^{\mathrm{sa}}_{\mathrm{USER}}$	Cost of electricity saved year-round by electricity users responding to demand.
$E^{\mathrm{sub}}_{\mathrm{USER}}$	Incentive subsidy for year-round interruptible loads.
$P^{\mathrm{sell}}_{\mathrm{DG},s,t}$	Power sold by DG in t period under s scenario.
$P^{\mathrm{buy}}_{\mathrm{NET},s,t}$	Amount of electricity purchased from the upper power grid during t period in the s scenario.
$P^{e0}_{\mathrm{SL},i}$	Initial load at time t.
$D_{\mathrm{a,t}}$	Obtained carbon emission quota in the t period.
$D_{\mathrm{G,t}}$	Actual carbon emission in the t period.
D_s	Number of days corresponding to scenario s.
E_{CT}	Carbon emissions revenue.
E_{g}	Green certificate transaction revenue.
E_{NET}	Income of distribution company.
E_{USER}	Annual revenue of electricity users.
N_s	Number of scenarios.
N_t	Total number of time intervals for typical days.
$P_{\mathrm{cut},s,t}$	Interruptible load of t period in s scenario.
P_{IL}	Total load that takes part in the excitation demand response in one day.
$P_{\mathrm{in},s,t}$	Load that can be transferred in of t period in s scenario.
$P_{\mathrm{load},s,t}$	Total load.
$P_{\mathrm{loss},s,t}$	Active power loss of t period in s scenario.
$P_{\mathrm{MT},s,t}$	The power output of the micro gas unit in t period under s scenario.
P_{MT}	Output power of the micro-gas-turbine.
$P_{\mathrm{out},s,t}$	Load that can be transferred out of t period in s scenario.
$P_{\mathrm{PV},s,t}$	Photovoltaic power output in t period under s scenario.
$P_{\mathrm{re,t,s}}$	Renewable energy sales in t period under s scenario.
$P_{\mathrm{WG},s,t}$	Wind power output in t period under s scenario.
$P_{s,t}$	Active output of all distributed power sources at time t in scenario s.
CO_2	Carbon dioxide.
DG	Distributed generation.
MT	Micro-gas-turbine.
PV	Photovoltaic.
SOC	State of charge.
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution.
WG	Wind generator.
WT	Wind turbine.

I. INTRODUCTION

With the depletion of resources, environmental protection, low carbon and how to achieve sustainable development have become the common goals of the world [1]. General Secretary Xi Jinping of China proposed the development goal of "carbon peak" and "carbon neutrality" in 2020. It is critical to realize the energy transformation, and the development of distributed generation is a critical step toward achieving carbon emission reduction and energy transformation [2]. On the one hand, the large number of distributed generation connections in the distribution system has led to the inability to plan DG configuration based on the benefits of a single entity, but rather to shift to joint decision-making among multiple stakeholders [3]. Joint planning among multiple stakeholders is beneficial for synergistically increasing the benefits of multiple entities and increasing the level of renewable energy consumption. On the other hand, once the renewable energy generation subsidies are reduced or even cancelled, the development space of distributed renewable energy will be limited, and DG operators will gradually reduce the new installed capacity. In order to avoid the effects of the reduction or cancellation of subsidies for renewable energy generation, it is necessary to introduce market incentive mechanisms. Moreover, in addition to considering flexibility resources on both the source and load sides, it is also necessary to further explore additional flexibility resources to expand potential for renewable energy consumption and the benefits for multiple stakeholders.

Wind power generation and photovoltaic power generation have strong intermittency and volatility, poor adjustment ability, and there are some differences in the timing characteristics of their output, which bring certain risks to the distribution network [4]. It is necessary to fully tap the flexible resources of multiple links in the system. Therefore, more attention should be paid to the allocation of flexible resources in the distribution network when optimising the configuration of DG in the distribution network. In [5], considering the spatial and temporal distribution characteristics of distributed photovoltaic output, a multi-objective chance constrained programming model is established to minimise the total cost of photovoltaic, power grid operation cost and active management cost. In [6], the DG configuration of the ring distribution network is carried out to improve the voltage stability and reduce the loss under the premise of considering the load growth. In [7], considering the total operating cost, the economic loss of voltage sag and the inhibitory effect of energy storage on the fluctuation of wind-solar output, an optimal configuration model of distributed wind-solar system is proposed. The above literature has optimized the configuration of DG from different angles. However, most of the articles only consider the WG and PV with uncertain output in the planning, and do not consider the joint planning of the gas turbine with flexible output and the above two types of DG.

With the development of active distribution networks, demand response on the user side and flexibility resources on the storage side have great potential for adaptation. On the grid side, batteries are used to smooth the intermittency of renewables. On the consumer side, effective energy storage and load scheduling contribute to energy management to minimise energy costs [8]. In [9], the DG planning model considering demand response and network reconfiguration was constructed and transformed into a three-layer planning model through decomposition and coordination. In [10], a multi-objective stochastic planning method for active distribution networks considering active management and demand response was proposed and solved using Monte Carlo simulation. In [11], a novel energy optimization model for smart microgrid integrating probabilistic modelling of renewable energy, a hybrid demand response programs and inclined block tariff approach, and multi-objective optimization algorithms. In [12], a multi-objective day-ahead scheduling model was developed based on wind turbines, diesel engines, energy storage and corresponding user demand side, which was less costly and less polluting than the conventional system. In [13], a collaborative planning strategy for an active distribution network that considered multiple DGs and incentivised demand response was presented. In [14], energy storage was used to compensate for the predicted variability of renewable energy and the optimal energy storage configuration capacity was determined with the aim of minimising the energy storage configuration cost. In [15] and [16], an optimised configuration model including energy storage and DG was established with the aim of maximising the total revenue. In [16], by using energy storage to support the optimal operation of wind and solar, the benefits of energy storage in delaying transmission grid upgrades are considered, and multi-objective source-storage-load planning is performed to maximise the overall benefits of the distribution grid.

With the rapid development of the electricity market, in order to protect the interests of multi-agent, the optimisation of DG allocation is turning to multi-agent planning. In [17], considering the uncertainty of wind power, the planning model was established with the aim of minimising the total cost of both source and grid side. In [18], demand response was incorporated into the planning to achieve the two-sided coordinated planning of source and load to achieve the lowest cost of each agent. In [19], a model for optimal expansion planning of distribution networks and distributed generation was proposed to maximise the benefits of distribution companies and DG operators. As the rapid development of renewable energy sources has led to a shortage of renewable energy subsidy funds, the subsidy level has been repeatedly revised to alleviate this phenomenon, which is not a continuous solution to promote the sustainable growth of the electricity industry, there is an urgent need for market incentives to alleviate the shortage of funds for renewable energy generation subsidies. In [20], the carbon trading mechanism was incorporated into the operation of power system dispatching, and a multi-objective dispatching model was developed that takes into account investment costs, carbon trading revenues and penalty costs. In [21] and [22], the environmental cost was included in the total cost planning, and the DG planning model considering the carbon trading mechanism was constructed. Although many studies had proposed market strategies to promote the transition to green and low-carbon energy, they mainly focused on the main grid, and only some studies had considered the carbon trading mechanism in the distribution grid separately. Therefore, more research is needed on how to effectively balance the overall interests of multiple parties, consider a variety of market mechanisms to promote carbon emission reduction, and enhance the consumption capacity of the DG.

The purpose of this article is to propose a distributed power optimal configuration model based on multi-stakeholder and energy storage cooperation, which can optimise the configuration according to the demand difference of different stakeholders, on the basis of considering both source and load-side flexibility resources, the energy storage-side flexibility resources and market incentive mechanism can be further integrated into the planning. The main contributions are twofold:

(1)Considering the demand difference of "source-network-load" multi-stakeholder, the cooperative relationship among distributed power operators, distribution companies and power users is analyzed. On this basis, considering the renewable energy consumption and multi-link environmental costs, a distributed power optimization configuration model considering source-load interaction and multi-stakeholders is established.

(2)On the basis of considering the flexible resources of the source-load side and multi-stakeholders, the adjustment ability of the flexible resources of the energy storage side is further explored, and the market incentive mechanism is introduced. An optimal configuration model of distributed generation considering source-load-storage coordination and market incentive mechanism is established. It can further improve the comprehensive income and renewable energy consumption capacity, and effectively alleviate the problem of shortage of subsidy funds for clean power generation.

The rest of this article is structured as follows: The features of flexible resources on the source load side and the energy storage side are analyzed and modeled in the second part. The third part analyzes the trading systems for green certificates and carbon emissions. In the fourth part, the second-order cone relaxation method and the optimal configuration method based on TOPSIS theory are proposed. The efficiency of the optimized setup strategy suggested in this article is validated in the fifth part.

II. RESOURCE ANALYSIS OF SOURCE-CHARGE-STORAGE FLEXIBILITY

A. POWER SIDE FLEXIBILITY RESOURCE

On the power side, micro gas turbines can alleviate fluctuations in the power grid and are often used as flexible resources for characteristic analysis. The output power of the micro gas turbine is as follows:

$$P_{\mathrm{MT}} = \frac{V_{\mathrm{f}}\eta_{\mathrm{MT}}\mathrm{LHV}}{\Delta t} \tag{1}$$

where, V_{f} is the amount of natural gas consumption in the electricity generation process; η_{MT} is the efficiency of power generation; Δt is the time of generating electricity. *LHV* is low calorific value of natural gas, take 8342.4 $kcal/m^3$ [23];

B. LOAD SIDE FLEXIBILITY RESOURCE

This article examines interruptible load-based demand response and price-based demand response are investigated and related optimal allocation models are created.

1) PRICE BASED DEMAND RESPONSE BASED ON TIME OF USE ELECTRICITY PRICE

This article uses the elastic price matrix [23] to describe the price based demand response characteristics of time of use electricity prices, as follows:

$$e_{i,j} = \frac{\Delta P^{e}_{\mathrm{SL},i}/P^{e0}_{\mathrm{SL},i}}{\Delta\rho_j/\rho^0_j} \tag{2}$$

$$E_{\mathrm{SL}} = \begin{bmatrix} e_{pp}\ e_{pf}\ e_{pv} \\ e_{fp}\ e_{ff}\ e_{fv} \\ e_{vp}\ e_{vf}\ e_{vv} \end{bmatrix} \tag{3}$$

$$\Delta P^{e}_{\mathrm{SL},i} = P^{e0}_{\mathrm{SL},i}[\sum_{j=1}^{24} E_{\mathrm{SL}}(i,j)\frac{\Delta\rho_j}{\rho^0_j}] \tag{4}$$

where, $e_{i,j}$ is the elasticity of the load change at time i in the elasticity matrix for the price change at time j, i = j is the self-elasticity coefficient, i ≠j is the cross-elasticity coefficient; $\Delta P^{e}_{\mathrm{SL},i}$ is the relative change of load after demand response at time t; $P^{e0}_{\mathrm{SL},i}$ is the initial load at time t; $\Delta\rho_j$ is the relative change of price after demand response at time j; ρ^0_j is the initial price at time j; E_{SL} the elastic price matrix, f, p and v represent the peak, flat and valley hours of the tariff.

2) DEMAND RESPONSE BASED ON INTERRUPTIBLE LOAD

The interruptible load protocol states that each period's interruptible load shall be limited as follows:

$$\begin{cases} P_{\mathrm{IL}} = \sum_{t=h_a}^{h_b} P_{\mathrm{load},t}\beta_{\mathrm{IL}} \\ \beta_{\min} \le \beta_{\mathrm{IL}} \le \beta_{\max} \end{cases} \tag{5}$$

where, $P_{\mathrm{load},t}$ is the load at t-moment; h_a and h_b are the upper and lower limits of the pre-signed interruptible load period; β_{IL} is the proportion coefficient of interruptible load; $\beta_{\max}$ and $\beta_{\min}$ are the upper and lower limits of the interruptible load ratio coefficient.

C. ENERGY STORAGE SIDE FLEXIBILITY RESOURCES

Energy storage allows for the smoothing of distributed renewable energy output power as well as the capacity to change DG output power in response to actual load demand, enhancing DG flexibility. Energy storage can meet cross-time demand for power while lowering grid operating costs and DG operating costs by storing surplus DG power, preventing waste of excess DG power at low load times, and releasing the stored power at peak load times. To reduce the consumption of coal and other traditional energy sources, renewable energy and distributed generation can be better utilized through the arrangement of energy storage.

In the energy storage system, due to the internal resistance of the battery itself, the stored electrical energy cannot be fully released, so it is necessary to discharge the depth of the battery in real time, that is, SOC.

The state of charge of the energy storage at time t can be expressed as:

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) + \eta_{ch}\frac{P_{ch}(t-1)\Delta t}{W} - \frac{P_{dc}(t-1)\Delta t}{\eta_{dc}W} \tag{6}$$

where, P_{ch} and P_{dc} are the charging and discharging power of the energy storage system at time t-1; η_{ch} and η_{dc} are the charging and discharging efficiency of the energy storage system; W is the rated capacity of the battery in the energy storage system.

III. GREEN CERTIFICATE TRADING MECHANISM AND CARBON TRADING MECHANISM

A. GREEN CERTIFICATE TRADING MECHANISM

The quota target of the green certificate trading system is generally a certain percentage of renewable energy sales in total electricity sales [24]. When the proportion of renewable energy online exceeds the specified proportion, the excess green certificate can be sold to obtain benefits; if the proportion does not exceed the specified proportion, the green certificate shall be purchased. The green certificate trading revenue model is as follows:

$$E_{\mathrm{g}} = \sum_{s=1}^{N_s} D_s \begin{cases} \sum_{t=1}^{N_t} e_{\mathrm{lv}}\left(P_{\mathrm{re,t,s}} - \alpha P_{\mathrm{DG,t,s}}\right), u \ge \alpha \\ -\sum_{t=1}^{N_t} e_{\mathrm{lv}}\left(\alpha P_{\mathrm{DG,t,s}} - P_{\mathrm{re,t,s}}\right), u < \alpha \end{cases} \tag{7}$$

where, α is the quota ratio of renewable energy electricity sales to total electricity sales; u is the ratio of actual renewable energy sales to total electricity sales; $e_{\mathrm{lv}}$is the trading price of green certificates. According to the relevant policy [25], because China's green certificate trading is still in the voluntary subscription stage, so the unit price of green certificates is small, this article sets the trading price of green certificates is 0.25 $yuan/KWh$.

B. CARBON TRADING

In this article, the carbon quota is determined by the CO_2 intensity emitted by the electricity supply of the enterprise unit, and the relevant units distribute free carbon quotas to DG operators, encouraging DG operators to use renewable energy for electricity generation and to sell excess carbon quotas to increase revenues. The carbon trading revenue model is as follows:

$$D_{\mathrm{G,t}} = \lambda P_{s,t} \tag{8}$$

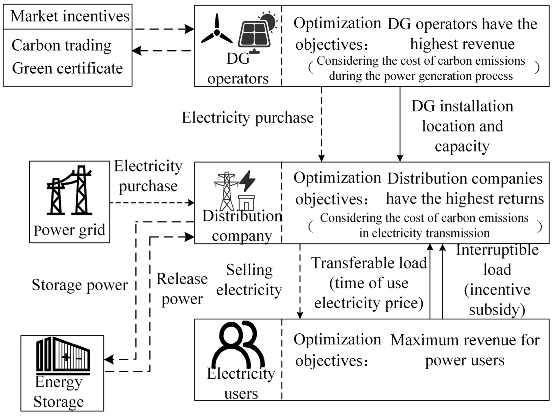

FIGURE 1. Multi-stakeholder partnership diagram.

$$E_{\mathrm{CT}}=\sum_{s=1}^{N_s}D_s\begin{cases}-\sum_{t=1}^{N_t}(D_{\mathrm{G,t}}-D_{\mathrm{a,t}})e_{\mathrm{co_2}},\, D_{\mathrm{a,t}}\leq D_{\mathrm{G,t}}\\ \sum_{t=1}^{N_t}(D_{\mathrm{a,t}}-D_{\mathrm{G,t}})e_{\mathrm{co_2}},\, D_{\mathrm{a,t}}>D_{\mathrm{G,t}}\end{cases} \tag{9}$$

where, $e_{\mathrm{co_2}}$ is the carbon allowance transaction price. λ is the average unit power supply CO_2 emission intensity of the power generation enterprise, which is taken as 0.550 [26].

IV. THE OPTIMAL ALLOCATION MODEL OF EACH MARKET MAIN BODY

In this article, the cooperative relationship among DG operators, distribution companies and power users is considered, and flexible resources when both the supply and load side are taken into consideration, furthermore, the flexible resource of energy storage side is incorporated into the optimal allocation model. Taking into account the future development of the reduction or elimination of subsidies for renewable energy generation, to guarantee the benefits of multi-stakeholder entities and encourage the integration of renewable energy, considering two market trading mechanisms. The multi-stakeholder relationship is shown in Fig. 1.

A. DG OPERATOR PLANNING MODEL

The DG operator model applies the address and capacity of the DG installation as decision variables, introduces a variety of market incentives, and takes into consideration source load timing characteristics and the cost of carbon emissions during the power generation process, DG operator to maximize revenue planning objectives.

1) OBJECTIVE FUNCTION

The objective function of the optimal allocation model is considered from the benefit and cost of DG generation enterprise. The objective function of the optimization configuration model is considered from both the benefits and costs of DG power generation enterprises, where $E_{\mathrm{DG}}^{\mathrm{sell}}$, $E_{\mathrm{DG}}^{\mathrm{sub}}$,E_{CT} and E_{g} represents the annual electricity sales revenue of power generation enterprises, subsidies for renewable energy generation, carbon emissions revenue, and green certificate revenue. $C_{\mathrm{DG}}^{\mathrm{in}}$, $C_{\mathrm{DG}}^{\mathrm{op}}$,$C_{\mathrm{DG}}^{\mathrm{fg}}$ and $C_{\mathrm{DG}}^{\mathrm{en}}$ are the annual investment cost, annual operation and maintenance cost, annual fuel cost, and annual carbon emission cost for power generation. The objective function of the optimal configuration model of DG operator as follows:

$$\max E_{\mathrm{DG}}=\max(E_{\mathrm{DG}}^{\mathrm{sell}}+E_{\mathrm{DG}}^{\mathrm{sub}}+E_{\mathrm{CT}}+ E_g-C_{\mathrm{DG}}^{\mathrm{in}}-C_{\mathrm{DG}}^{\mathrm{op}}-C_{\mathrm{DG}}^{\mathrm{fg}}-C_{\mathrm{DG}}^{\mathrm{en}}) \tag{10}$$

Among them:

$$E_{\mathrm{DG}}^{\mathrm{sell}}=\sum_{s=1}^{N_s}D_s(\sum_{t=1}^{N_t}e_{\mathrm{DG}}^{\mathrm{sell}}P_{\mathrm{DG},s,t}^{\mathrm{sell}}) \tag{11}$$

$$E_{\mathrm{DG}}^{\mathrm{sub}}=\sum_{s=1}^{N_s}D_s[\sum_{t=1}^{N_t}e_{\mathrm{DG}}^{\mathrm{sub}}(P_{\mathrm{WG},s,t}+P_{\mathrm{PV},s,t})] \tag{12}$$

$$E_{\mathrm{CT}}=\sum_{s=1}^{N_s}D_s[\sum_{t=1}^{N_t}e_{\mathrm{CO_2}}(\lambda P_{\mathrm{DG},s,t}-K_{\mathrm{CO_2}}P_{\mathrm{WT},s,t})] \tag{13}$$

$$E_{\mathrm{g}}=\sum_{s=1}^{N_s}D_s[\sum_{t=1}^{N_t}e_{\mathrm{lv}}(P_{\mathrm{WG},s,t}+P_{\mathrm{PV},s,t}-\alpha P_{\mathrm{DG},s,t})] \tag{14}$$

$$C_{\mathrm{DG}}^{\mathrm{in}}=\frac{r(1+r)^{n_s}}{(1+r)^{n_s}-1}(\sum_{i=1}^{N_i}x_i z_i c_{\mathrm{DG}}^{\mathrm{in}}P_{\mathrm{DG}}^{\mathrm{rated}}) \tag{15}$$

$$C_{\mathrm{DG}}^{\mathrm{op}}=\sum_{s=1}^{N_s}D_s(\sum_{t=1}^{N_t}c_{\mathrm{DG}}^{\mathrm{op}}P_{\mathrm{DG},s,t}) \tag{16}$$

$$C_{\mathrm{DG}}^{\mathrm{fg}}=\sum_{s=1}^{N_s}D_s(\sum_{t=1}^{N_t}c_{\mathrm{fg}}P_{\mathrm{MT},s,t}) \tag{17}$$

$$C_{\mathrm{DG}}^{\mathrm{en}}=\sum_{s=1}^{N_s}D_s[\sum_{t=1}^{N_t}K_{\mathrm{co_2}}P_{\mathrm{MT},s,t}(V_{\mathrm{co_2}}+R_{\mathrm{co_2}})] \tag{18}$$

where, n_s is the DG life; r is the discount rate; N_i is the total number of nodes; x_i is a 0-1 variable; x_i representing 1 and 0 means that the node has and does not have DG access, respectively; z_i is the number of i nodes accessing DG stations; $e_{\mathrm{DG}}^{\mathrm{sell}}$ is the DG unit electricity sale price; $e_{\mathrm{DG}}^{\mathrm{sub}}$ is a unit of renewable energy subsidies; $c_{\mathrm{DG}}^{\mathrm{in}}$ is the cost per unit of capacity of DG; $P_{\mathrm{DG}}^{\mathrm{rated}}$ is a single DG rated capacity; c_{fg} is DG unit power generation operation and maintenance costs; $c_{\mathrm{DG}}^{\mathrm{op}}$ is the operation and maintenance cost of DG unit power generation. $K_{\mathrm{co_2}}$ is the CO_2 emission intensity of the micro-gas-fired unit, which is 0.6101 kg/KWh [26]; $V_{\mathrm{co_2}}$ and $R_{\mathrm{co_2}}$ are the environmental cost coefficient and the additional penalty cost per 1kg of CO_2 emitted.

2) CONSTRAINTS

(1) Node Access DG Number Constraint:

$$0\leq Z_i\leq Z_i^{\max} \tag{19}$$

where, $Z_i^{\max}$ is the maximum number of i nodes that can access DG.

(2) DG Access Permeability Constraint:

$$\sum P_{\mathrm{DG}}^{\mathrm{rated}} \leq \eta P_{\mathrm{load}}^{\mathrm{total}} \tag{20}$$

where, η is the DG access permeability; $P_{\mathrm{load}}^{\mathrm{total}}$ is the total load of the distribution network.

(3) Active Power Output Constraint and Climbing Constraint:

$$Z_{\mathrm{MT},i}P_{\mathrm{MT}}^{\min} < P_{\mathrm{MT},i,s,t} < Z_{\mathrm{MT},i}P_{\mathrm{MT}}^{\max} \tag{21}$$

$$-Z_{\mathrm{MT},i}P_{\mathrm{MT}}^{\mathrm{down}} \leq P_{\mathrm{MT},s,t,i} - P_{\mathrm{MT},s,t-1,i} \leq Z_{\mathrm{MT},i}P_{\mathrm{MT}}^{\mathrm{up}} \tag{22}$$

where, $P_{\mathrm{MT},i,s,t}$ is the active output of the micro gas turbine at the node i in time period t under the s-scenario; $Z_{\mathrm{MT},i}$ is the number of micro gas turbine installations at node i; $P_{\mathrm{MT}}^{\min}$ and $P_{\mathrm{MT}}^{\max}$ are the minimum and maximum active power output of a single micro gas turbine; $P_{\mathrm{MT}}^{\mathrm{down}}$ and $P_{\mathrm{MT}}^{\mathrm{up}}$ are a single micro gas turbine down, up the maximum climbing speed.

B. DISTRIBUTION COMPANY PLANNING MODEL

Distribution companies plan to take into account the cost of carbon emissions in the transmission of electricity, and include energy storage as a flexible resource, with storage installation location and capacity as decision variables. The model is built with the aim of maximising the profit of the distribution company.

1) OBJECTIVE FUNCTION

Similar to the objective function of DG operator, the objective function of the optimal configuration model of distribution company. Considering from two aspects of income and cost, where $E_{\mathrm{NET}}^{\mathrm{sell}}$ is the annual electricity sales income of the distribution company to the power users; $C_{\mathrm{NET}}^{\mathrm{loss}}$, $C_{\mathrm{NET}}^{\mathrm{sub}}$, $C_{\mathrm{NET}}^{\mathrm{en}}$, $C_{\mathrm{AE}}^{\mathrm{in}}$ and $C_{\mathrm{AE}}^{\mathrm{op}}$ are the annual active power loss cost of the distribution company, the annual subsidy cost of the interruptible load, the annual carbon emission cost during the power transmission process, the annual investment cost of the energy storage, and the annual operating cost of the energy storage. The following is the optimization configuration model's objective function for distribution companies:

$$\max E_{\mathrm{NET}} = \max(E_{\mathrm{NET}}^{\mathrm{sell}} - C_{\mathrm{DG}}^{\mathrm{buy}} - C_{\mathrm{NET}}^{\mathrm{buy}} - C_{\mathrm{NET}}^{\mathrm{loss}} - C_{\mathrm{NET}}^{\mathrm{sub}} - C_{\mathrm{NET}}^{\mathrm{en}} - C_{\mathrm{AE}}^{\mathrm{in}} - C_{\mathrm{AE}}^{\mathrm{op}}) \tag{23}$$

Among them:

$$E_{\mathrm{NET}}^{\mathrm{sell}} = \sum_{s=1}^{N_s} D_s\left(\sum_{t=1}^{N_t} e_{\mathrm{NET},t}^{\mathrm{sell}}\left(P_{\mathrm{load},s,t} + P_{\mathrm{in},s,t} - P_{\mathrm{out},s,t} - P_{\mathrm{cut},s,t}\right)\right) \tag{24}$$

$$C_{\mathrm{DG}}^{\mathrm{buy}} = E_{\mathrm{DG}}^{\mathrm{sell}} = \sum_{s=1}^{N_s} D_s\left(\sum_{t=1}^{N_t} e_{\mathrm{DG}}^{\mathrm{sell}} P_{\mathrm{DG},s,t}^{\mathrm{sell}}\right) \tag{25}$$

$$C_{\mathrm{NET}}^{\mathrm{buy}} = \sum_{s=1}^{N_s} D_s\left(\sum_{t=1}^{N_t} c_{\mathrm{NET},t}^{\mathrm{buy}} P_{\mathrm{NET},s,t}^{\mathrm{buy}}\right) \tag{26}$$

$$C_{\mathrm{NET}}^{\mathrm{loss}} = \sum_{s=1}^{N_s} D_s\left(\sum_{t=1}^{N_t} c_{\mathrm{NET}}^{\mathrm{loss}} P_{\mathrm{loss},s,t}\right) \tag{27}$$

$$C_{\mathrm{NET}}^{\mathrm{sub}} = \sum_{s=1}^{N_s} D_s\left(\sum_{t=1}^{N_t} c_{\mathrm{NET}}^{\mathrm{sub}} P_{\mathrm{cut},s,t}\right) \tag{28}$$

$$C_{\mathrm{NET}}^{\mathrm{en}} = \sum_{s=1}^{N_s} D_s\left(\sum_{t=1}^{N_t} M_{\mathrm{co_2}} P_{\mathrm{loss},s,t}\left(V_{\mathrm{co_2}} + R_{\mathrm{co_2}}\right)\right) \tag{29}$$

$$C_{\mathrm{AE}}^{\mathrm{in}} = \frac{r(1+r)^{n_a}}{(1+r)^{n_a}-1}\left(\sum_{i=1}^{N_i} x_i m_i c_{\mathrm{AE}}^{\mathrm{in}} P_{\mathrm{AE}}^{\mathrm{rated}}\right) \tag{30}$$

$$C_{\mathrm{AE}}^{\mathrm{op}} = \sum_{s=1}^{N_s} D_s\left[\sum_{t=1}^{N_t} c_{\mathrm{AE}}^{\mathrm{op}}(P_{\mathrm{rec},s,t} + P_{\mathrm{dis},s,t})\right] \tag{31}$$

where, $e_{\mathrm{NET},t}^{\mathrm{sell}}$ is the distribution network t-time electricity price; $c_{\mathrm{NET},t}^{\mathrm{buy}}$ is the price of selling electricity in t period of the superior power grid; $c_{\mathrm{NET}}^{\mathrm{loss}}$ is the distribution network active power loss unit electricity cost; $M_{\mathrm{co_2}}$ is the CO_2 emission coefficient of power transmission in the line, $M_{\mathrm{co_2}} = 0.5271 kg/KWh$ [27]. $c_{\mathrm{NET}}^{\mathrm{sub}}$ is the unit of interruptible load subsidy costs; n_a is the life of energy storage; m_i is the number of i node access energy storage; $c_{\mathrm{AE}}^{\mathrm{in}}$ is the investment cost of energy storage unit capacity; $P_{\mathrm{AE}}^{\mathrm{rated}}$ is the rated capacity of a single energy storage unit; $c_{\mathrm{AE}}^{\mathrm{op}}$ is the operating cost per unit of charge and discharge for energy storage; $P_{\mathrm{rec},s,t}$ and $P_{\mathrm{dis},s,t}$ are the active power of t-period energy storage charge and discharge in s scenario.

2) CONSTRAINTS

(1) Power Flow Balance Constraints:

$$\begin{cases} P_{ij,s,t} - I_{ij,s,t}^2 R_{ij} - P_{jk,s,t} + P_{\mathrm{DG},j,s,t} \\ -P_{\mathrm{rec},j,s,t} + P_{\mathrm{dis},j,s,t} = P_{\mathrm{load},j,s,t} \\ Q_{ij,s,t} - I_{ij,s,t}^2 X_{ij} - Q_{jk,s,t} + Q_{\mathrm{DG},j,s,t} = Q_{\mathrm{load},j,s,t} \end{cases} \tag{32}$$

$$U_{j,s,t}^2 = U_{i,s,t}^2 - 2R_{ij}P_{ij,s,t} - 2X_{ij}Q_{ij,s,t} + (R_{ij}^2 + X_{ij}^2)I_{ij,s,t}^2 \tag{33}$$

$$U_{i,s,t}^2 \cdot I_{ij,s,t}^2 = P_{ij,s,t}^2 + Q_{ij,s,t}^2 \tag{34}$$

where, $P_{ij,s,t}$, $P_{jk,s,t}$, $Q_{ij,s,t}$ and $Q_{jk,s,t}$ are the active power and reactive power of t-segment node i, j and nodes j, k respectively; $P_{\mathrm{rec},j,s,t}$ and $P_{\mathrm{dis},j,s,t}$ are the energy storage charging active power and discharge active power of t node in s scenario. This article does not consider the reactive power in the process of energy storage charging and discharge; $I_{ij,s,t}$ is the line current between node i and j in t period under s scenario; $P_{\mathrm{DG},j,s,t}$ and $Q_{\mathrm{DG},j,s,t}$ are the active power and reactive power of DG on t-segment node in s scenario; R_{ij} and X_{ij} are the line resistance and reactance between nodes i and j respectively; $P_{\mathrm{load},j,s,t}$ and $Q_{\mathrm{load},j,s,t}$ are the active and reactive load of node j in t period under s scenario; $U_{i,s,t}$ and

$U_{j,s,t}$ are the node voltage of node i and j in t period under s scenario.

(2) Node Voltage Constraint:

$$U_{\min} \leq U_{i,s,t} \leq U_{\max} \tag{35}$$

where, $U_{\min}$ and $U_{\max}$ are the upper and lower limits of the node voltage.

(3) Line Power Constraint:

$$P_{ij,s,t} \leq P_{\max} \tag{36}$$

where, $P_{\max}$ is the upper limit of the transmission power of the line.

(4) The Constraint of Purchasing Power from The Superior Grid:

$$P_{\mathrm{NET},s,t}^{\mathrm{buy}} \leq P_{\max}^{\mathrm{buy}} \tag{37}$$

where, $P_{\max}^{\mathrm{buy}}$ is the distribution company to the upper power grid purchase ceiling.

(5) Energy Storage Installation Capacity Constraint:

$$\sum P_{\mathrm{AE}}^{\mathrm{rated}} \leq P_{\mathrm{AE}}^{\max} \tag{38}$$

where, $P_{\mathrm{AE}}^{\max}$ is the maximum installed capacity of energy storage.

(6) Energy Storage Charge and Discharge Constraints:

$$\begin{cases} 0 \leq P_{\mathrm{rec},i,s,t} \leq P_{\mathrm{rec}}^{\max}(1 - m_{\mathrm{sign},i,s,t}) \\ 0 \leq P_{\mathrm{dis},i,s,t} \leq P_{\mathrm{dis}}^{\max} m_{\mathrm{sign},i,s,t} \end{cases} \tag{39}$$

$$P_{\mathrm{rec},i,s,t} P_{\mathrm{dis},i,s,t} = 0 \tag{40}$$

where, $P_{\mathrm{rec},i,s,t}$ and $P_{\mathrm{dis},i,s,t}$ are the t-time node i energy storage charge and discharge active power in the s scenario; $m_{\mathrm{sign},i,s,t}$ is the state of energy storage, charge and discharge of node i in t period under s scenario.

(7) State of Charge Constraints for Energy Storage:

$$E_{\mathrm{AE},i,s,t+1} = E_{\mathrm{AE},i,s,t} - \eta_{\mathrm{rec}} P_{\mathrm{rec},i,s,t} + \frac{P_{\mathrm{dis},i,s,t}}{\eta_{\mathrm{dis}}} \tag{41}$$

$$SOC_{\min} \leq \frac{E_{\mathrm{AE},i,s,t}}{E_r} \leq SOC_{\max} \tag{42}$$

where, $E_{\mathrm{AE},i,s,t}$ is the t-time node i single energy storage under the s scenario. η_{rec}, η_{dis} are the charging and discharging efficiency of the energy storage system; $SOC_{\max}$ and $SOC_{\min}$ are the upper and lower limits of the charged state of energy storage, respectively.

C. POWER USER PLANNING MODEL

1) OBJECTIVE FUNCTION

The power user optimisation configuration model's objective function is as follows:

$$\max E_{\mathrm{USER}} = \max(E_{\mathrm{USER}}^{\mathrm{sa}} + E_{\mathrm{USER}}^{\mathrm{sub}}) \tag{43}$$

$$E_{\mathrm{USER}}^{\mathrm{sa}} = \sum_{s=1}^{N_s} D_s \left(\sum_{t=1}^{N_t} e_{\mathrm{NET},t}^{\mathrm{sell}} \left(P_{\mathrm{out},s,t} + P_{\mathrm{cut},s,t} - P_{\mathrm{in},s,t} \right) \right) \tag{44}$$

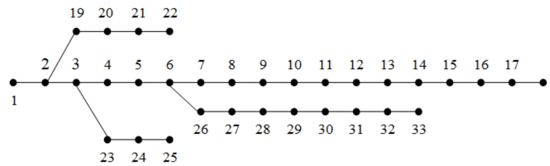

FIGURE 2. IEEE33 node distribution network.

$$E_{\mathrm{USER}}^{\mathrm{sub}} = C_{\mathrm{NET}}^{\mathrm{sub}} = \sum_{s=1}^{N_s} D_s \left(\sum_{t=1}^{N_t} c_{\mathrm{NET}}^{\mathrm{sub}} P_{\mathrm{cut},s,t} \right) \tag{45}$$

2) CONSTRAINTS

(1) Transferable Load Constraints:

$$\begin{cases} 0 \leq P_{\mathrm{in},i,s,t} \leq P_{\mathrm{load},i,s,t} \alpha_{\max} \\ 0 \leq P_{\mathrm{out},i,s,t} \leq P_{\mathrm{load},i,s,t} \alpha_{\max} \end{cases} \tag{46}$$

$$\sum_{s=1}^{N_s} D_s \left(\sum_{t=1}^{N_t} P_{\mathrm{in},s,t} \right) = \sum_{s=1}^{N_s} D_s \left(\sum_{t=1}^{N_t} P_{\mathrm{out},s,t} \right) \tag{47}$$

where, $P_{\mathrm{in},i,s,t}$, $P_{\mathrm{out},i,s,t}$ and $P_{\mathrm{load},i,s,t}$ are load that can be transferred in, load that can be transferred out and total load of node i of t period in s scenario; $\alpha_{\max}$ is the upper limit of the transferable load coefficient.

(2) Interruptible Load Constraint:

$$P_{\mathrm{load},i,s,t} \beta_{\min} \leq P_{\mathrm{cut},i,s,t} \leq P_{\mathrm{load},i,s,t} \beta_{\max} \tag{48}$$

where, $P_{\mathrm{load},i,s,t}$ is the interruptible load of node i in t-time under the s scenario; $\beta_{\max}$ and $\beta_{\min}$ are the upper and lower limit of the interruptible load factor.

V. COMPREHENSIVE OPTIMIZATION CONFIGURATION MODEL AND SOLUTION METHOD

Based on the Topsis comprehensive evaluation theory, the article combines the three subjects of DG operators, distribution companies and power users, and considers the benefits of the three, and constructs the model as follows:

$$\max f = \max\left(\frac{E_{\mathrm{DG}}}{\max E_{\mathrm{DG}}} + \frac{E_{\mathrm{NET}}}{\max E_{\mathrm{NET}}} + \frac{E_{\mathrm{USER}}}{\max E_{\mathrm{USER}}}\right) \tag{49}$$

where, $\max E_{\mathrm{DG}}$, $\max E_{\mathrm{NET}}$ and $\max E_{\mathrm{USER}}$ represents the maximum revenue generated when planning for a single stakeholder.

The second order cone relaxation technique is used to relax the model into a second order cone constraint, and then the model is transformed into a second-order cone programming problem for solution.

$$\begin{cases} P_{ij,s,t} - \varphi_{ij,s,t} R_{ij} - P_{jk,s,t} + P_{\mathrm{DG},j,s,t}^{\mathrm{sell}} - P_{\mathrm{rec},j,s,t} \\ + P_{\mathrm{dis},j,s,t} = P_{\mathrm{load},j,s,t} \\ Q_{ij,s,t} - \varphi_{ij,s,t} X_{ij} - Q_{jk,s,t} + Q_{\mathrm{DG},j,s,t}^{\mathrm{sell}} = Q_{\mathrm{load},j,s,t} \end{cases} \tag{50}$$

$$U_{j,s,t}^2 = U_{i,s,t}^2 - 2R_{ij} P_{ij,s,t} - 2X_{ij} Q_{ij,s,t} + (R_{ij}^2 + X_{ij}^2) I_{ij,s,t}^2 \tag{51}$$

$$\left\| \begin{matrix} 2P_{ij,s,t} \\ 2Q_{ij,s,t} \\ \varphi_{ij,s,t} - \gamma_{i,s,t} \end{matrix} \right\|_2 \leq \varphi_{ij,s,t} + \gamma_{i,s,t} \tag{52}$$

where, $\varphi_{ij,s,t} = I_{ij,s,t}^2$, $\gamma_{j,s,t} = U_{j,s,t}^2$, $\gamma_{i,s,t} = U_{i,s,t}^2$.

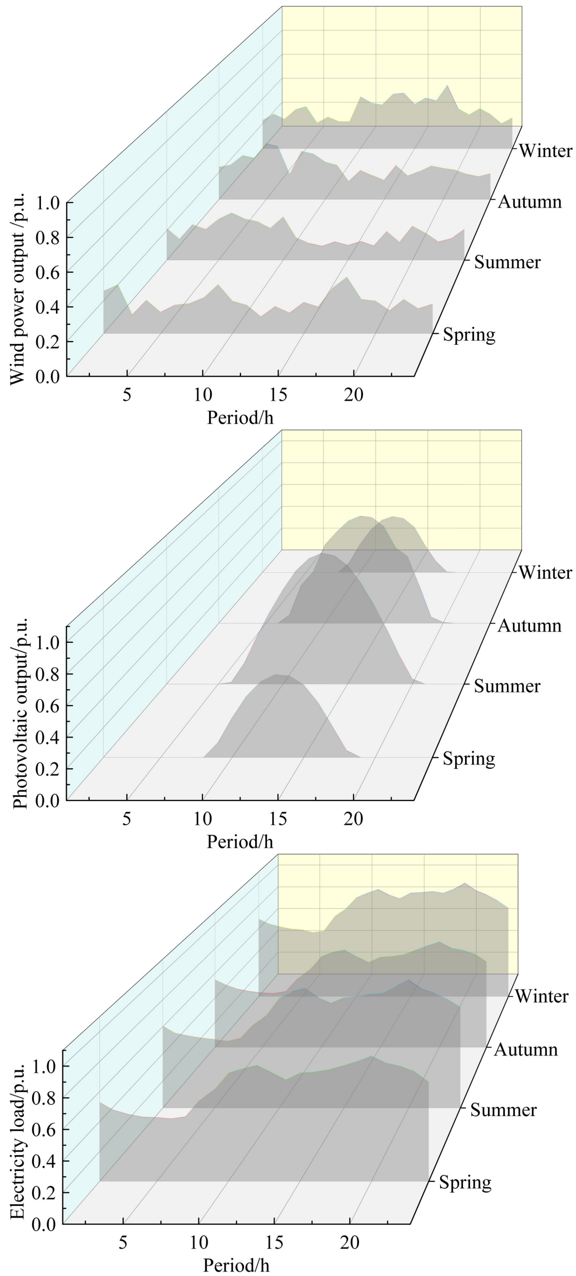

FIGURE 3. Wind power output, photovoltaic output and load curve diagram.

VI. SIMULATIONS AND DISCUSSION

A. BASIC DATA

In this article, the CPLEX solver is used to solve the configuration model in the MATLAB simulation platform, and the IEEE33-node distribution network is analyzed as an example [28], as shown in Fig. 2. The total active and reactive loads of the distribution network are set to 3715 kW and 2300 kVar. The DG includes three types of wind power, photovoltaic and micro gas turbine. The specific parameters are shown in Table 1 [27]. Set the rated capacity of DG unit to 30 kW, each node can access up to 10 units, all nodes can access DG. DG has a service life of 20 years, a DG power factor of 0.9.

TABLE 1. DG related parameters.

Parameters	Set
Investment cost per unit capacity of wind power/(yuan/kW)	6400
PV unit capacity investment cost/(yuan/kW)	8500
Investment cost per unit capacity of gas/(yuan/kW)	4800
Operating and maintenance costs of wind power and PV/(yuan/kWh)	0.2
Gas operation and maintenance cost/(yuan/kWh)	0.3
Wind power subsidies/(yuan/kWh)	0.2
Solar subsidies/(yuan/kWh)	0.36
Environmental value of carbon emissions/(yuan/t)	23
Carbon cost/(yuan/t)	10
Price of electricity sold for Clean Energy/(yuan/kWh)	0.5
Gas-fired electricity price/(yuan/kWh)	0.65

TABLE 2. Distribution network and user related parameters.

Parameters	Set
Upper limit of node voltage/(p.u.)	1.05
Lower limit of node voltage/(p.u.)	0.95
Upper limit of branch power/(MW)	9.9
Distribution companies purchase electricity prices from power grids/(yuan/kWh)	peak:0.70 normal:0.50 valley:0.30
Distribution company selling electricity price/(yuan/kWh)	peak:0.90 normal:0.70 valley:0.30
Interruptible load subsidy/(yuan/kWh)	0.4
Network loss expenses/(yuan/kWh)	0.6

The K-means clustering algorithm is used to reduce the wind, light output and load data of a certain area to obtain the typical daily wind power, photovoltaic output and load data curve of the four seasons, as shown in Fig. 3.

Time-sharing tariffs are implemented by dividing the time periods according to the demand for electricity, with the peak periods being 11:00-13:00 and 18:00-21:00; the normal time periods being: 8:00-10:00, 14:00-17:00 and 22:00-24:00; the valley period being 1:00-7:00; and the interruptible load time period being 11:00-21:00. Table 2 shows distribution network and user related parameters [29], [30]. Table 3 shows the main parameters of energy storage equipment [27].

B. ONLY CONSIDER MULTI-STAKEHOLDER

1) CONSIDER THE INFLUENCE OF MULTI-STAKEHOLDER ON DG CONFIGURATION

When constructing the optimal configuration model, taking the interests of different subjects as the goal will have different effects on the configuration of DG. The following four scenarios were compared to compare DG configurations for different targets to analyze the impact of considering the combined interests of multiple stakeholders on DG configurations, as shown in Table 4. In a DG configuration, the number in parentheses represents the location of the access node, and the number out parentheses represents the number of DG installations.

Scenario 1: Optimizing DG configuration only to maximize the revenue of DG operators;

Scenario 2: Optimizing DG configuration only to maximize distribution company revenue;

Scenario 3: Optimizing DG configuration only to maximize the revenue of power users;

TABLE 3. Relevant parameters of energy storage equipment.

Parameters	Set
Discount rate of annual expenses	8%
Service life/(year)	15
Energy storage unit rated capacity/(yuan/kWh)	30
Energy storage charge and discharge rated power/(kW)	15
Investment cost per unit of energy storage capacity/(yuan/kWh)	2000

TABLE 4. Consider the allocation plan of multiple stakeholders.

Scenarios	Wind power	Photovoltaics	Gas turbine
Scenario 1	17(5) 18(9) 30(7)	13(1) 14(1) 15(1) 18(1) 33(2)	14(1) 16(2) 31(1) 32(6)
Scenario 2	18(4)	14(3) 15(2) 16(1) 18(1)30(3) 31(5) 32(2) 33(1)	16(2) 17(2)18(1) 31(1) 32(7) 33(2)
Scenario 3	—	2(2)	16(2) 17(2) 18(2) 31(2) 32(6) 33(2)
Scenario 4	13(1) 14(2) 16(4) 17(5) 31(4) 32(6) 33(7)	—	18(3) 31(1) 32(4)

Scenario 4: Optimizing DG configuration with the goal of maximizing the comprehensive benefits of multi-stakeholder;

As demonstrated in Table 4, when maximizing the revenue of DG operators is the goal, there are more wind and solar installations and fewer gas installations; when maximizing the revenue of distribution companies is the goal, the largest number of photovoltaic installations; the least number of DG installations when the objective is to maximize the revenue of electricity users; and the largest overall revenue of multi-stakeholder targets when the photovoltaic output is concentrated during the day, choose more wind power building on the premise of ensuring the balance of electric power, giving the multi-stakeholder interest main body to earn greater profits.

2) CONSIDER THE INFLUENCE OF MULTI-STAKEHOLDER ON THE REVENUE AND RENEWABLE ENERGY CONSUMPTION

Considering multiple stakeholders in a complete manner will have a greater effect on each stakeholder's revenue and the amount of renewable energy consumption than considering merely "source", "network", and "load" as the aim. The same four scenarios will be compared, and the income and renewable energy consumption figures for each subject are displayed in Fig. 4 and Fig. 5.

As demonstrated in Fig. 4, the revenue of DG operators is increased by 1.78% compared with scenario 4, while the revenue of distribution companies and power users is decreased by 30.57% and 47.56% respectively, the net loss cost increased by 414,900 yuan, and the comprehensive income decreased by 29.13%. The small increase of the income of a single subject reduced the income of other subjects to a certain extent, which was not conducive to the improvement of the overall economy. In contrast to Scenario 4, the revenue of distribution companies increased by 135,700 yuan, with the lowest loss cost, while the revenue of DG operators and power users decreased by 66.33% and 24.95% respectively, it can be concluded that this configuration scheme is not conducive to promoting the activity of electricity market transactions. Scenario 3: revenue of electricity users increased slightly, but the revenue of DG operators and distribution companies decreased by 69.45% and 42.58% respectively. DG operators suffered serious revenue loss and network loss cost increased significantly, the comprehensive income was reduced by 1.573 million yuan, which is not conducive to the sustainable development of DG.

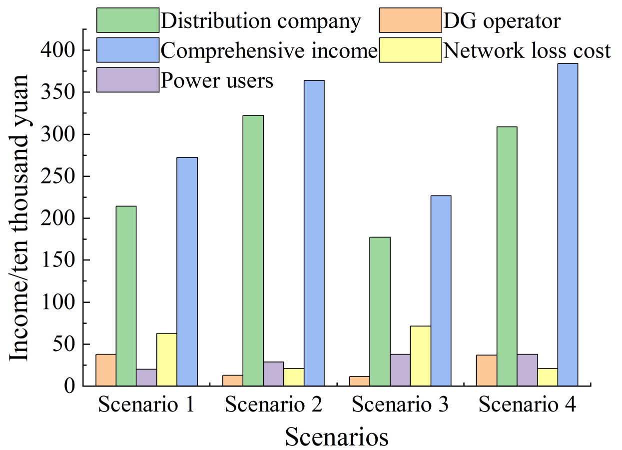

FIGURE 4. Benefit outcomes of multiple stakeholders.

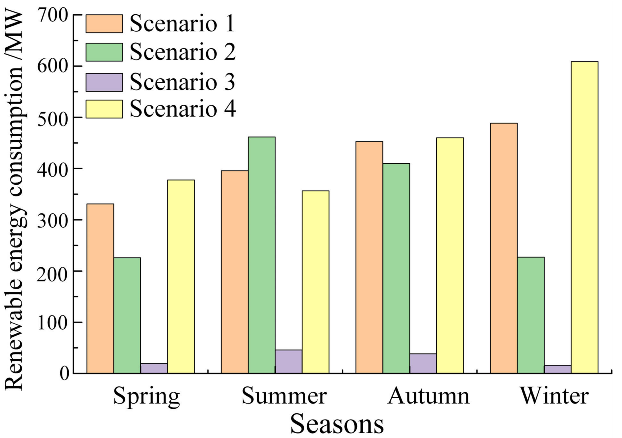

FIGURE 5. Consumption of renewable energy in different scenarios.

As shown in Fig. 5, Scenario 1 chooses to invest more in wind power. Due to seasonal factors, the output of wind power is relatively high in winter, resulting in more renewable energy consumption in winter. Scenario 2: in order to ensure that the distribution company generates more revenue from the construction of photovoltaics, the output of photovoltaics is relatively high in summer, so the renewable energy consumption capacity is stronger in summer. Scenario 3: The annual renewable energy consumption has dramatically decreased as a consequence of a decrease in wind and photovoltaic construction units. Scenario 4 has the largest number of distributed renewable energy installations, resulting in the largest amount of renewable energy consumption. It can be seen clearly that when targeting the benefits of multiple stakeholders, the benefits of each entity should be further enhanced based on the improvement of their renewable energy consumption capacity to ensure the overall economic efficiency.

TABLE 5. Configuration plan considering environmental costs.

Scenarios	Wind power	Photovoltaics	Gas turbine
Scenario 5	—	13(2) 14(5) 30(10) 32(4)	15(1) 16(2) 17(1) 18(2) 30(4) 32(4) 33(2)
Scenario 6	15(3) 16(3) 17(2) 18(4) 31(7) 32(6) 33(4)	—	16(1) 17(1) 18(1) 32(4) 33(1)
Scenario 7	—	13(2) 14(4) 17(1) 18(1) 30(9) 31(3) 33(1)	15(2) 16(1) 17(1) 18(2) 31(2) 32(7) 33(1)
Scenario 4	13(1) 14(2) 16(4) 17(5) 31(4) 32(6) 33(7)	—	18(3) 31(1) 32(4)

C. CONSIDER THE IMPACT OF ENVIRONMENTAL COSTS

1) CONSIDER THE IMPACT OF ENVIRONMENT COST ON DG CONFIGURATION

The following 4 scenarios are compared and analyzed. The following scenarios are all aimed at the comprehensive benefits of multi-stakeholder subject. The DG configuration schemes obtained from each scenario are shown in Table 5.

Scenario 4: Considering the environmental cost of power generation and power transmission to optimize the DG configuration;

Scenario 5: Optimizing DG configuration without considering environmental costs;

Scenario 6: Optimal DG configuration considering only the environmental cost of electricity generation;

Scenario 7: Optimal DG configuration considering only the environmental cost of power transmission.

Table 5 demonstrates that Scenario 5 is different from Scenario 4 in that it does not include the cost of carbon emissions. As a result, the cost of electricity by source of micro-gas turbines decreases and revenue from electricity sales per unit of power increases, leading in an increase in the number of micro-gas turbines constructed. On the basis of flexible electricity demand satisfaction, as the clean subsidies for photovoltaic power generation are more abundant and the output is concentrated during peak electricity consumption periods, more photovoltaic construction is chosen to increase the profits of DG operators and distribution companies. Comparing Scenario 6 and Scenario 7, it can be seen clearly that considering the environmental cost during the power generation process has a much greater impact on the optimization of DG configuration than considering the environmental cost during the power transmission process. This encourages the construction of distributed renewable energy more, because the amount of electricity lost in the grid during power transmission is much smaller than the annual power generation of micro-gas turbines.

2) CONSIDERING THE IMPACT OF ENVIRONMENTAL COSTS ON THE RETURNS OF MULTI-STAKEHOLDER ENTITIES

The environmental costs generated by carbon emissions have a significant impact on the economy, and an increase in environmental costs will affect the profitability of the entity. Comparative analysis considers various economic indicators after considering environmental costs, as shown in Fig. 6.

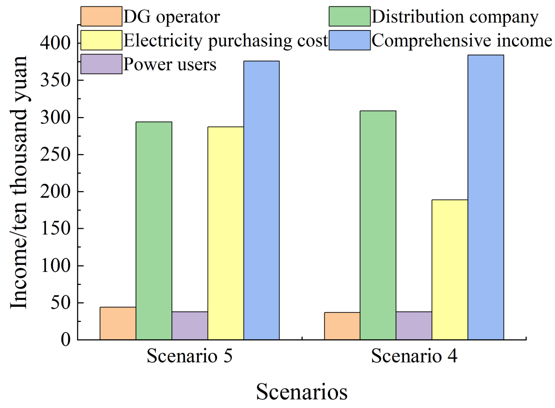

FIGURE 6. Profit results under different scenarios.

As shown in Fig. 6, since Scenario 5 does not consider the environmental cost in the configuration, the gas turbine output is flexible and adjustable, and the investment cost is low, the increase in electricity sales led to a 19.32% increase in revenue for the DG operator compared to the DG operator in Scenario 4. The power purchase cost of the DG operator increased by 985,100 yuan because the gas price was higher than the normal and trough power price paid to the upper grid, the revenue of the distribution company decreased by 150,200 yuan and the comprehensive income decreased by 2.05%, which shows that considering the environmental cost can promote the sustainable development of the economy.

3) CONSIDERING THE IMPACT OF ENVIRONMENTAL COST ON ENVIRONMENTAL PROTECTION

This article compares four scenarios, all of which aim at the comprehensive benefits of the multi-stakeholder without considering environmental costs (Scenario 5), only considering carbon emissions in the power generation process (Scenario 6), only considering carbon emissions in the power transmission process (Scenario 7), and considering carbon emissions in both the power generation and power transmission processes (Scenario 4), the environmental indicators are shown in Fig. 7.

Fig. 7 demonstrates that the amount of carbon emission and environmental cost in Scenario 5 have increased significantly without considering the environmental cost, while unlike Scenario 5, Scenario 6 considers the carbon emission during power generation, due to the reduction of the number of micro gas turbines installed, the carbon emission is reduced by 1147.71 t, and the environmental cost is reduced by 50.67%. Scenario 7 considers carbon emissions in power transmission. This process mainly depends on the active network loss of the line. The network loss is less than the gas power generation, so the carbon emissions are only slightly lower than Scenario 5, indicating that the effect of considering the environmental cost of power generation on carbon emission reduction is stronger than that of considering the environmental cost of power transmission. Scenario 4 takes into account the carbon emissions of power generation and transmission. Compared to Scenario 6, Scenario 4 further

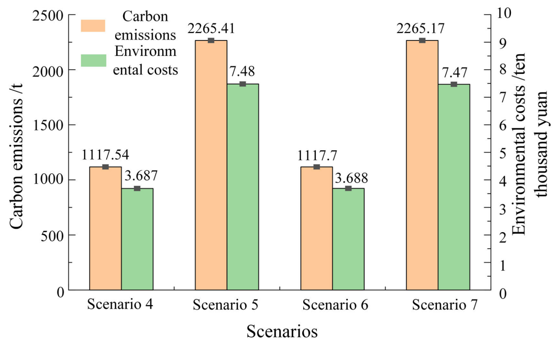

FIGURE 7. Environmental protection index maps under different scenarios.

TABLE 6. Configuration plan considering demand response.

Scenarios	Wind power	Photovoltaic	Gas turbine
Scenario 8	17(5) 18(3) 30(1) 32(5) 33(2)	30(1)	14(2) 15(2) 16(2) 18(2) 30(1) 31(5) 32(5) 33(1)
Scenario 4	13(1) 14(2) 16(4) 17(5) 31(4) 32(6) 33(7)	—	18(3) 31(1) 32(4)

TABLE 7. Consider the benefits and cost results of demand response (in Ten thousand yuan).

Scenarios	DG operator	Distribution Company	Power users	Electricity purchase cost	Electricity sales revenue
Scenario 8	29.60	284.01	0	300.99	1587.72
Scenario 4	37.06	308.99	38.08	189.04	1559.50

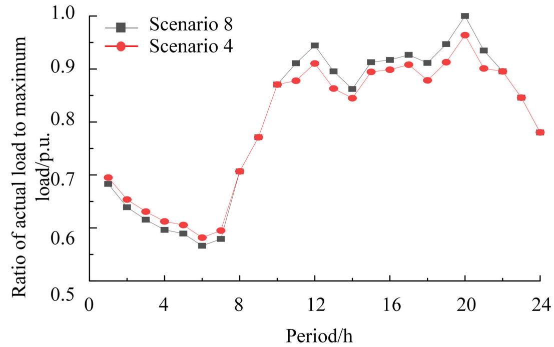

FIGURE 8. Daily load curve comparison chart.

reduces environmental costs and facilitates the achievement of carbon emission reduction targets.

D. CONSIDERING THE IMPACT OF DEMAND RESPONSE

1) CONSIDERING THE IMPACT OF DEMAND RESPONSE ON DG CONFIGURATION

The following two scenarios are compared. Both scenarios aim at the comprehensive income of multi-stakeholder. The DG configuration scheme is shown in Table 6.

Scenario 4: DG optimal configuration considering demand response;

Scenario 8: DG optimal configuration without considering demand response.

It can be seen from Table 6 that compared with Scenario 4, after Scenario 8 does not consider the demand response, the number of distributed renewable energy installations decreases, and the number of installations of micro gas turbines increases. The reason is that the peak-valley difference of load is larger than that of demand response, and it is necessary to build more micro gas turbines that can flexibly adjust output to maintain the balance of supply and demand.

2) CONSIDERING THE IMPACT OF DEMAND RESPONSE ON THE BENEFITS OF MULTI-STAKEHOLDER

Demand response can provide a more flexible power consumption plan, adjust the power consumption behavior of power users, and affect the income of each subject without considering the lack of active participation of power users after demand response, as shown in Table 7.

As shown in Table 7, without considering the demand response, the increase in micro-gas units has led to an increase in DG electricity sales revenue of 1.1195 million yuan. However, due to the reduction of cleaning subsidies and the increase in fuel, operation and maintenance costs, the final DG operator 's revenue is less than Scenario 4. Compared with scenario 4, the electricity sales revenue of distribution companies in scenario 8 increased by 282,200 yuan, but the cost of purchasing electricity from DG operators increased by 59.22 %, resulting in a decrease of 249,800 yuan in the revenue of distribution companies. Considering the demand response, the income of each subject has increased, especially for power users, which is conducive to improving the overall economy and promoting the development of distributed renewable energy.

3) CONSIDERING THE IMPACT OF DEMAND RESPONSE ON THE OPTIMAL LOAD CURVE

The load curve is shown in Fig. 8. Compared with the load peak-valley distribution in Scenario 8, considering the demand response, part of the load is transferred from the high electricity price period to the low electricity price period, and the user is encouraged to interrupt part of the load during the specified period through incentive subsidies, so as to optimize the power load curve and realize peak load shifting.

E. CONSIDER ENERGY STORAGE AND MULTI-STAKEHOLDER

Compare the following three scenarios, the results of DG Planning, economic indicators and renewable energy consumption are shown in Table 8, Fig. 9, Fig. 10 and Fig. 11.

Scenario 1: Optimizing configuration with the goal of maximizing revenue for DG operators;

Scenario 2: Optimizing allocation with the goal of maximizing profits for distribution companies;

Scenario 3: Optimize configuration with the goal of maximizing the comprehensive income of multiple stakeholders.

Table 8 shows that the number of wind installations increases when energy storage is considered, while the number of gas and PV installations decreases when the DG

TABLE 8. Considering the configuration scheme of energy storage and multi-stakeholders.

Scenarios	Wind power	Photovoltaic	Gas turbine	Energy storage
Scenario 1	18(7) 31(10) 32(9) 33(10)	—	32(1)	15(3) 16(3) 17(3) 18(1)
Scenario 2	18(1)	14(5) 15(2) 17(2) 18(1) 30(4) 31(6) 32(3) 33(1)	16(2) 18(3) 32(6) 33(2)	9(1) 11(1) 29(1) 30(2)
Scenario 3	16(4) 17(1) 18(5) 31(3) 32(10) 33(10)	17(2)	15(1) 18(1)	14(1) 15(1) 16(1) 18(1) 31(2) 32(4)

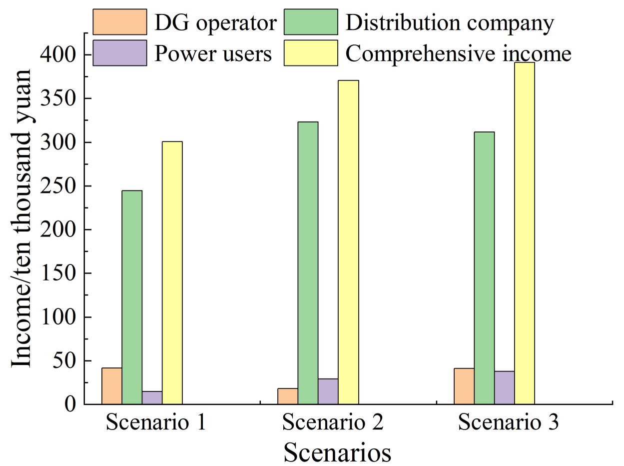

FIGURE 9. The results of multi-stakeholder income considering energy storage.

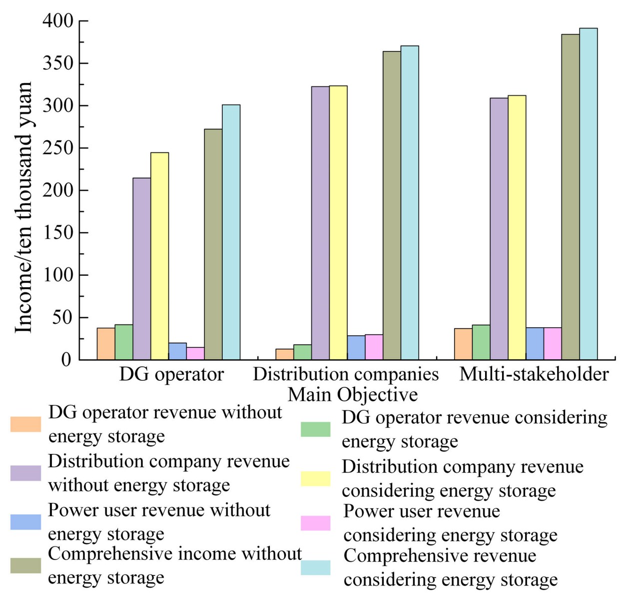

FIGURE 10. Considering the impact of energy storage on the income of multi-stakeholder.

operator's revenue maximization is considered; when the distribution company's revenue maximization is taken as the allocation goal, the number of PV installations increases; when the multi-stakeholder's overall revenue maximization is taken as the goal, the total number of distributed renewable energy installations increases and the number of gas turbine installations decreases.

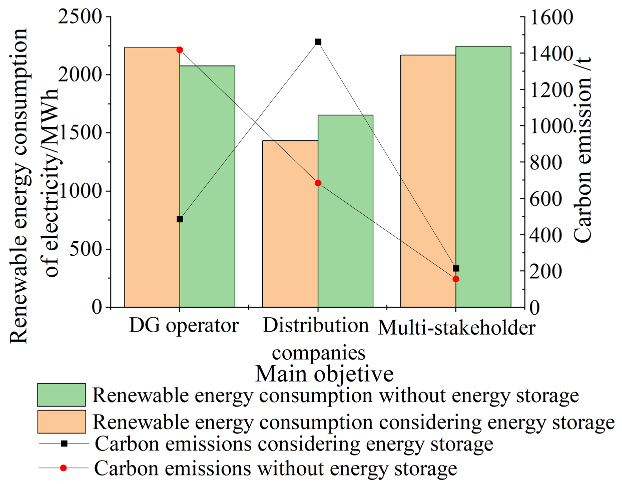

FIGURE 11. Renewable energy consumption and carbon emissions results.

As can be seen from Fig. 9 and Fig. 10, the revenue of DG operators increased by 10.31% and the revenue of distribution companies increased by 300,300 yuan, when the optimal allocation was aimed at maximizing the revenue of DG operators, the combined revenue increased by 10.56%, and the optimal allocation of energy storage and DG has slightly increased the maximum revenue of distribution companies, when the revenue of distribution companies is the largest target, the revenue of DG operators and power users increased by 51,800 yuan and 5100 yuan, respectively, and their combined revenue increased by 1.78%. When the revenue of multi-stakeholder entities is the largest target, compared to when energy storage is not included in the planning, the revenue for DG operators and distribution companies increased by 42,300 yuan and 30,200 yuan, respectively, and their combined revenue increased by 1.85%. The optimal allocation model considering energy storage and multi-stakeholder income maximization is 43.7 % higher than the comprehensive income of the traditional model without considering energy storage and only aiming at maximizing the income of DG operators. It can be seen that incorporating energy storage into the optimal allocation can not only increase the income of a single subject, but also increase the income of multiple subjects, which has a positive effect on the optimal allocation of DG.

Fig. 11 demonstrates that renewable energy consumption increases on the original basis after taking into account energy storage when the target is the income of a single subject or multi-stakeholder. The increase in renewable energy generation reduced carbon emissions by 1,243.05 tons when the income of DG operators was taken into account, and by 11.04% when the distribution companies were the main target. The carbon emissions were reduced by 673.02 tons when the income of multi-stakeholder was taken as the target, which indicates that the introduction of energy storage could reduce the carbon emissions of DG, lessen the influence on the environment, and improve the absorptive capacity of renewable energy.

TABLE 9. Consider the configuration scheme of subsidies for renewable energy generation.

Scenarios	Wind power	Photovoltaic	Gas turbine	Energy storage
Scenario 3	—	—	10(1) 11(1) 12(1) 13(1) 14(3) 15(1) 16(1)17(1) 18(2)29(1) 30(10)31(4) 32(5) 33(2)	—
Scenario 4	16(4) 17(1) 18(5)31(3) 32(10) 33(10)	17(2)	15(1) 18(1)	14(1) 15(1) 16(1) 18(1) 31(2) 32(4)

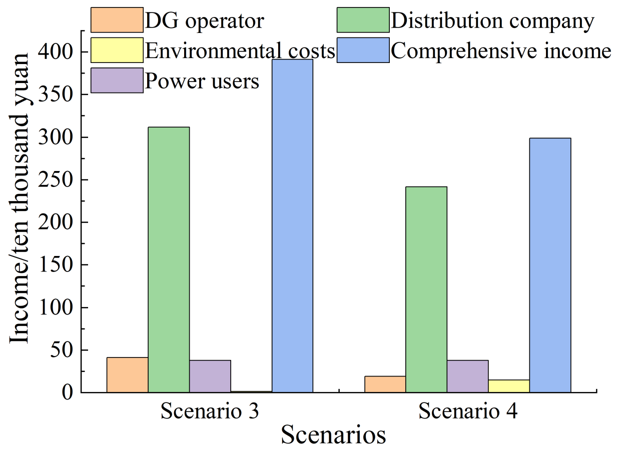

FIGURE 12. Considering the income results of renewable energy generation subsidies.

F. CONSIDER RENEWABLE ENERGY GENERATION SUBSIDIES AND MARKET INCENTIVES

1) CONSIDER THE IMPACT OF RENEWABLE ENERGY GENERATION SUBSIDIES

Compare the following two scenarios, both of which aim at the comprehensive benefits of multi-stakeholder agents. The scenario DG configuration and the benefits of each agent are shown in Table 9 and Fig. 12.

Scenario 3: Optimized allocation considering renewable energy generation subsidies;

Scenario 4: Optimization without considering renewable energy generation subsidies;

As can be seen from Table 9 and Fig. 12, due to the high investment costs of wind and solar power and the high volatility of output, once the subsidies for renewable energy generation are removed, the profit of sales of electricity per unit of generation of distributed renewable energy will decrease, will be detrimental to the long-term development of renewable energy. In order to protect the interests of DG operators, choose to build more gas-fired units, resulting in a sharp drop in the income of the distribution company, the comprehensive income fell by 23.67%. Through economic means, renewable energy subsidies encourage and support the development of renewable energy, reduce its cost and effectively improve its market competitiveness. At the same time, renewable energy subsidies can also reduce carbon emissions, reduce environmental pollution and damage, and promote sustainable energy development.

TABLE 10. Consider the allocation plan of market incentive mechanism.

Scenarios	Wind power	Photovoltaic	Gas turbine	Energy storage
Scenario 4	—	—	10(1)11(1) 12(1)13(1) 14(3) 15(1) 16(1)17(1) 18(2)29(1) 30(10)31(4) 32(5) 33(2)	—
Scenario 5	15(2) 16(2) 17(6) 18(4) 31(7) 32(7) 33(3)	—	15(1) 18(1) 32(3) 33(1)	17(1) 32(1) 33(1)
Scenario 6	16(2) 17(5) 18(8)31(4) 32(6)33(10)	—	2(1) 32(1)	15(2) 18(1) 30(2)32(1) 33(3)
Scenario 7	15(3) 16(2) 17(3)18(6) 30(2) 31(2) 32(7) 33(8)	—	17(1) 32(1)	10(1)14(2) 15(3)17(1) 32(2)

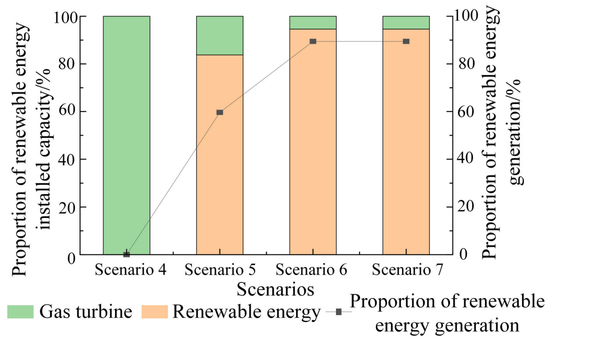

FIGURE 13. Considering the comprehensive income and carbon emission results of market incentive mechanism.

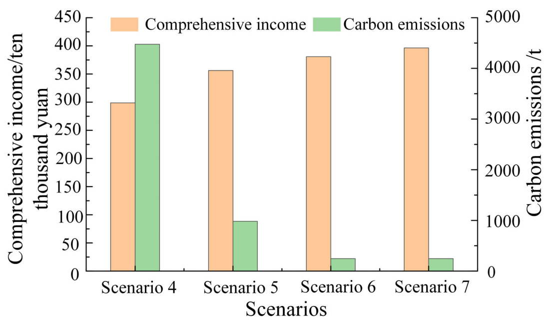

FIGURE 14. The proportion of renewable energy installation and power generation considering market incentive mechanisms.

2) CONSIDER THE IMPACT OF MARKET INCENTIVES

Four scenarios are compared and the impact of introducing a market incentive mechanism without considering subsidies for renewable energy generation is analysed.

Scenario 4: Optimisation without considering subsidies for renewable energy generation;

Scenario 5: Introduction of an emissions trading mechanism to optimise allocation;

Scenario 6: Introduction of a green certificate trading mechanism to optimise configuration;

Scenario 7: Optimize the allocation under full consideration of the two market mechanisms.

As can be seen from Table 10, Fig. 13, and Fig. 14, the number of distributed renewable energy installations increased significantly after the introduction of market incentives, compared with Scenario 4, due to the limitation of photovoltaic power generation output time limit, in order to obtain more market trading income, choose to invest more in wind power. In contrast with Scenarios 5 and 6, following the adoption of the green certificate trading system, both the quantity of wind power installations and the percentage of renewable energy generation increased, demonstrating that the green certificate trading mechanism had a stronger incentive effect than the carbon trading mechanism. In terms of comprehensive income, renewable energy installation and the share of renewable energy in power generation, the combination of the two market mechanisms is better than the single mechanism, and carbon emissions have also declined. In order to promote more DG construction and local energy consumption, distribution companies will set an upper limit on the purchase of electricity from the higher power grid. Therefore, in terms of the proportion of renewable energy power generation, the comprehensive consideration of the two mechanisms is less than only considering the green certificate trading mechanism. However, after considering the two market incentive mechanisms, the income of multi-stakeholder can reach the income when considering clean energy power generation subsidies. It shows that after the shortage or cancellation of renewable energy power generation subsidies, the market incentive mechanism can play a certain incentive role to maintain the development of distributed renewable energy and enhance the income of multi-stakeholder.

VII. CONCLUSION

This article comprehensively analyses the cooperative relationship among DG operators, distribution companies and power users, and establishes a power supply optimisation configuration model that considers multi-stakeholder benefits, multiple links carbon emission costs, demand response and multiple flexible resources. The carbon trading mechanism and the green certificate trading mechanism are introduced. Finally, based on the TOPSIS idea and the second-order cone programming method, the optimisation solution of the model is realised. The analysis of the results of the example shows that:

1) The multi-stakeholder planning model not only improves the level of DG consumption, but also balances the benefits of each stakeholder, reduces the network active power loss, and can provide a reference for the optimal allocation of the actual power supply.
2) Taking into account the cost of carbon emissions in power generation and transmission, it not only reduces the environmental cost but also increases the allocation capacity of distributed renewable energy in the distribution network; taking into account demand response, it rationally adjusts the electricity consumption behaviour of electricity users, shifting part of the peak load to the trough and interrupting part of the load, smoothing the load curve and improving the overall revenue.
3) Considering that energy storage can further enhance the consumption of renewable energy and the comprehensive income of multi-stakeholder, the introduction of market incentive mechanism can avoid the adverse impact of the decline or cancellation of renewable energy generation subsidies on the development of distributed renewable energy, which is both economical and environmentally friendly.

In the future work, the following applications can be considered for the optimal configuration of distributed generation:

- More network-side flexibility resources can be introduced to establish a DG optimal configuration model considering source-grid-load-storage coordination.
- Based on the net load curve of the difference between the distributed renewable energy output and the load, the price-based demand response considering the dynamic time-of-use price can be established.

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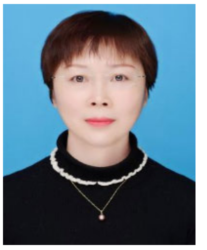

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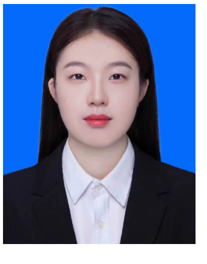

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