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Optimal Allocation of Community Distributed Energy and Storage Based on Regional Autonomous Balance and Sharing Mechanism

Jiangping Liu [1], Jing Wang [1], Xue Cui [2,*], Peng Liu [2], Pingzheng Tong [2] and Xuehan Dang [2]

[1] Hubei Power Exchange Center, Wuhan 430077, China; 13378770329@163.com (J.L.); wangjing200509@163.com (J.W.)
[2] School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China; liupwhu@163.com (P.L.); 2019302070317@whu.edu.cn (P.T.); 2021302191045@whu.edu.cn (X.D.)
* Correspondence: xue_cui_whu@163.com

Abstract: In the context of new power systems, the rapid development of distributed renewable energy and the drive of dual carbon targets have prompted community-level clean energy and energy storage configuration to become the key to improving energy efficiency and reducing carbon emissions. Based on the regional autonomy balance and sharing mechanism, this paper establishes a community distributed energy and energy storage optimization configuration model. With the goal of minimizing the total operating cost of the community, the established model is linearized by using the Big-M method and the McCormick method and transformed into a mixed integer linear programming model that is easy to solve. In order to comprehensively evaluate the comprehensive benefits of the established optimization scheme, this paper introduces the indicators of clean energy self-consumption rate, load self-supply rate, static investment payback period, and static CO_2 investment payback period from the aspects of energy utilization, the economy, and the environment. Finally, a calculation example analysis is conducted, and the results show that, compared with the scenario where energy storage is configured separately and distributed energy resources are not shared, the configuration strategy proposed in the article can reduce the energy storage configuration capacity by 46.6% and the distributed energy configuration capacity by 21.1%. Investment costs can be reduced by 15.6%. At the same time, 91.75% of distributed energy self-consumption and 96.80% of load self-supply are achieved, reducing grid interaction and promoting regional autonomy and balance. The static CO_2 investment payback period is also significantly shortened, and the carbon emission reduction effect is significant, providing an important reference for community energy system optimization planning and green and low-carbon development.

Keywords: distributed energy; community energy storage; optimal configuration; McCormick method; environmental benefits; regional autonomy balance; low carbon

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1. Introduction

The problem of greenhouse gas emissions caused by fossil fuel power generation is becoming more and more serious [1,2]. In order to cope with climate change, countries around the world have successively formulated policies and measures to achieve carbon neutrality [3,4]. As one of the main terminal energy consumption scenarios, strengthening its energy-saving efficiency and electrification substitution is an important countermeasure to achieve low-carbon transformation [5]. In the context of the swift advancement

of distributed renewable energy technologies [6,7], communities comprising building aggregations are anticipated to undertake a more pivotal role in initiatives aimed at carbon emission reduction within energy systems. The inherent intermittency and volatility of distributed renewable energy presents obstacles to its utilization at both the building and community scales. Furthermore, the advancement of energy storage technology facilitates the consumption of distributed renewable energy and is instrumental in enabling their effective utilization, ultimately optimizing both economic and environmental returns [8,9].

With the increasing penetration of distributed new energy, the consumption capacity of distribution networks is facing severe challenges. The direct grid-connected scheme may aggravate the instability and economic burden of power grid operation in the case of high permeability. The emergence of a sharing model has promoted the efficient use of distributed renewable energy at the community level. Considering that the reasonable dispatch of clean electricity is crucial to improving the economic efficiency of electricity use, the literature [10] has proposed a community clean electricity sharing mechanism, and a day-ahead scheduling model of community power, including energy storage systems, is established. The example shows that a power sharing mode is beneficial to improve the economy of community power consumption and the consumption rate of distributed energy, but there is no specific measure of carbon emissions in the community, nor can it reflect the community users' own clean energy consumption and load supply. In response to the problem of increasingly frequent two-way interactions between home energy networks and power grids, Reference [11] studied a joint optimization method for photovoltaic power among multiple users. The results showed that power interaction between users can effectively increase the consumption of photovoltaic power generation, but did not consider the sharing of wind power and energy storage.

The energy storage system can store the excess electric energy of distributed renewable energy and release the electric energy when the load is in demand. However, the high investment cost of energy storage limits its wide application, and the concept and related mode of shared energy storage emerge as the times require [12,13]. In view of the fact that current research on shared energy storage focuses on small and medium-sized users, Reference [14] proposed a shared energy storage mechanism on the power generation side and established a shared energy storage planning model based on cooperative game. However, it focuses on large-scale power plants and cannot be applied to distributed generation systems at the community level. Reference [15] proposed a coordinated operation mode of wind power sharing energy storage to promote wind power consumption on the power generation side, but did not consider the effect of energy storage on photovoltaic consumption.

The application of shared energy storage on the user side has been further studied. Reference [16] proposed a day-ahead optimal economic dispatch method for users based on shared energy storage power station services. The results show that the introduction of shared energy storage power station services can significantly reduce the operating costs of user groups, but it does not consider the sharing of distributed generation among users to improve the economics of the user base. Since existing energy storage configuration research mainly focuses on cost-benefit analysis, Reference [17] proposed an optimal allocation model of shared energy storage for multi-sale power companies. The example analysis shows the economy of shared energy storage, but it is limited to the sharing of energy storage at the level of electricity retailers and not applied to the community level. An energy internet with integrated energy system as the core is the key way to deal with the energy crisis and environmental pollution [18], a user collaborative optimization model of community integrated energy systems including shared energy storage is proposed. The results show that the shared energy storage mode can effectively reduce the energy

consumption cost of users, but it does not consider the problem that the community will increase the initial investment cost when equipped with energy storage and other equipment. In addition, there is no specific research on any environmental benefits, such as community carbon emissions.

Uncertainty factors, such as unpredictable energy demand and volatility of renewable energy power generation, pose significant challenges to the stability and reliability of the system. In order to deal with these challenges, existing research has conducted in-depth discussions on uncertainty from different perspectives. For example, Reference [19] proposed a deterministic optimization model that expresses the demand response problem as a mixed integer linear program, and realized energy cost management and a thermal comfort guarantee under the uncertainty of electricity market pricing through cardinality constraint uncertainty modeling and model predictive control. In addition, Reference [20] studied the optimal design of an urban community energy system under energy price uncertainty and specific carbon emission targets by constructing a two-stage stochastic programming model and revealed the dynamic adjustment law of system configuration with uncertainty and carbon emission reduction targets. Reference [21] evaluated the complementarity of wind and solar power generation in China and pointed out that most of the current target installed capacity of wind and solar power is independently planned, and these plans should be re-optimized by considering complementarity.

Based on the above research status, the research on shared energy storage focuses on economic analysis, and the consideration of environmental benefits is insufficient; the research on distributed energy and energy storage sharing at the community level is scarce.

Although current research has made some progress in exploring shared energy storage business models and optimizing scheduling, showing the potential of sharing models in improving the consumption rate of distributed energy and reducing energy costs, most studies have a single evaluation index, focusing mainly on cost analysis, that is, economic indicators, and lacking comprehensive consideration of multi-energy sharing at the community level. Especially in the current period of comprehensive green transformation of economic and social development, it is necessary to combine energy utilization, environmental benefits, etc. to establish multi-dimensional indicators to comprehensively measure the feasibility and effectiveness of the scheme, so as to provide solid theoretical support for the construction of green and low-carbon communities. In view of this, this paper proposes a community distributed energy and energy storage optimization configuration model focusing on regional autonomous balance and a sharing mechanism under the framework of the new power system. The model improves the utilization rate of resources within the community through a sharing mechanism, reduces the impact of distributed power sources on the power grid, and achieves regional autonomous balance and source-load coordination. With the goal of minimizing the total operating cost of the community, the Big-M method and the McCormick relaxation method are used to achieve linear solution. In addition, this paper innovatively introduces multiple evaluation indicators, including clean energy self-consumption rate, load self-supply rate, static investment payback period, and static CO_2 investment payback period to comprehensively evaluate the comprehensive benefits of the optimal allocation scheme from the three dimensions of energy utilization, the economy, and the environment. Furthermore, the influence of the uncertain factors of distributed generation on the optimal configuration is considered to improve the adaptability and reliability of the configuration scheme under uncertain conditions.

Finally, an example is given to verify the effectiveness and economy of the model in achieving regional autonomy balance, improving energy efficiency and reducing carbon emissions.

2. Community Distributed Energy and Energy Storage Sharing Operation Mode

The community distributed energy and energy storage sharing operation architecture is shown in Figure 1. The building itself is equipped with photovoltaic and wind power. When the building power is insufficient or surplus, it is uniformly deployed by the community energy management system, and priority is given to distributed energy sharing with other buildings.

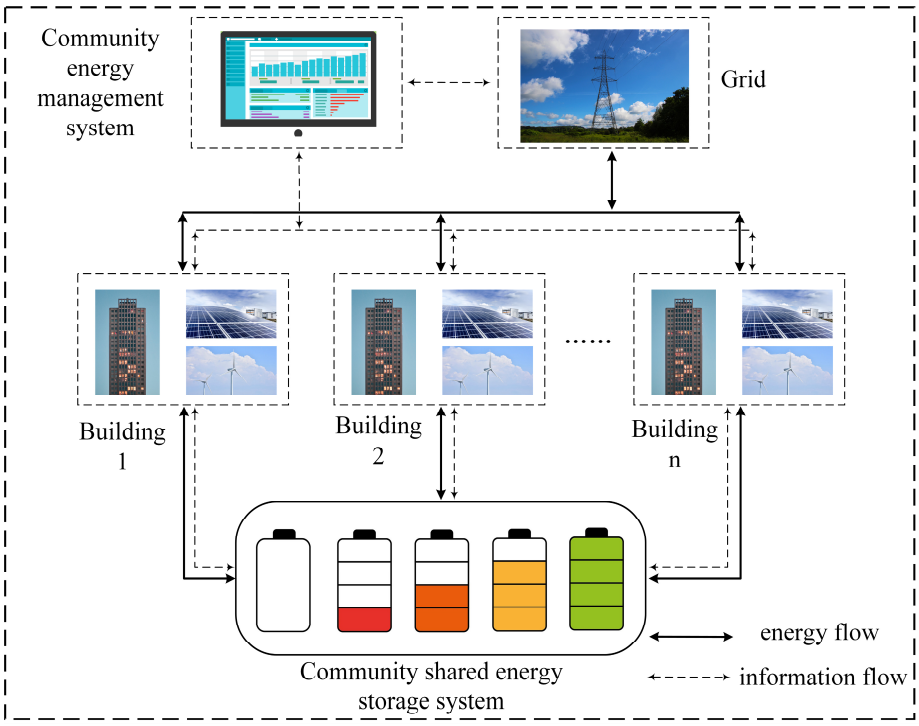


Figure 1. Community clean energy and energy storage shared operation architecture.

When the buildings in the community no longer require excess power, it is directed to charge the community energy storage system. Any remaining surplus power is then exported to the power grid.

In scenarios where the community faces a power shortage, the energy storage system is prioritized for discharging to meet the load demand. Only after utilizing the storage system is electricity purchased from the power grid to fill the gap.

The primary purpose of configuring the energy storage system is to enhance the utilization of distributed energy within the community. It also aims to minimize energy exchanges between the community and the power grid. Therefore, interactions between the community energy storage system and the power grid are not considered in this context.

The strategy for community energy management, based on distributed energy system and shared energy storage, is illustrated in Figure 2. When a building generates surplus electricity, the community energy management system first looks at whether there is a power shortage in other buildings. If such a shortage is identified, the excess electricity is redistributed to meet the demand of those buildings. If there remains surplus electricity after meeting the demands of other buildings, look at the state of charge of the energy storage system. If there is no shortage of electricity in other buildings, the system determines whether the energy storage unit has reached its maximum charge capacity. If the storage is full, the excess electricity is sold. Otherwise, the surplus energy will be used to charge the community energy storage system as a priority.

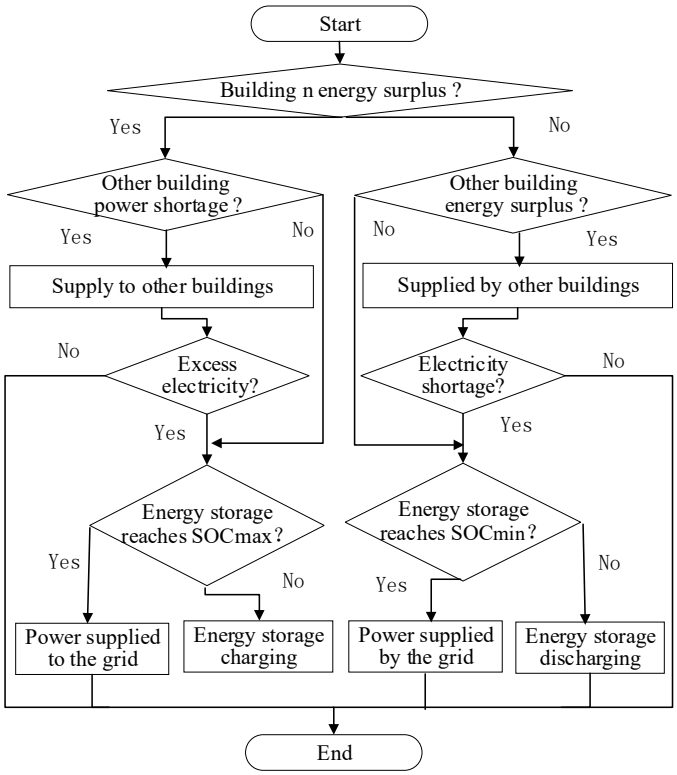


Figure 2. Community energy management strategy flowchart.

When there is insufficient electricity in the building, the community energy management system first looks at whether other buildings within the community have surplus electricity. If surplus electricity is available, it is transferred to the building in need. However, if the electricity shortage persists despite receiving surplus energy from other buildings, the state of charge of the energy storage system will be looked at. If there is no excess electricity in other buildings, the community energy storage system will reach the minimum state of charge. If the energy storage system reaches the minimum state of charge, the building will purchase electricity from the power grid to supplement the power supply. Conversely, if the energy storage system has not yet reached its minimum charge level, it is used as the primary source to address the electricity deficit.

3. Distributed Energy and Energy Storage Optimization Configuration Model

3.1. Objective Function

The shared community system for distributed energy and energy storage is designed to minimize the total operational cost. This objective function determines the optimal configuration capacity for both the energy storage system and the distributed energy sources in buildings. The total operational cost comprises several components: the initial investment cost and the operation and maintenance expenses for the energy storage system, the initial investment cost and operation and maintenance expenses for the distributed energy power station, and the net cost of electricity transactions with the power grid. The net transaction cost is calculated as the difference between the cost of electricity purchased from the grid and the revenue generated from electricity sales. The objective function is shown in Equation (1).

$$\min C_{\text{total}} = C_{BES} + C_{PV} + C_{WT} + C_{\text{buy}} + C_{\text{sell}} \quad (1)$$

In the formula, C_{total} is the total operating cost of the community, which includes the investment cost of the energy storage system C_{BES}, the investment cost of the photovoltaic system C_{PV}, the investment cost of the wind power system C_{WT}, the cost of purchasing electricity from the power grid C_{buy}, and the income of selling electricity to the power grid C_{sell}. The specific calculation formulas of each cost are as follows:

(1) Investment cost of energy storage system.

$$C_{BES} = \left[\frac{r(1+r)^{n_{BES}}}{(1+r)^{n_{BES}} - 1} \cdot C_{BES}^{init} + C_{BES}^{OM} \right] \cdot E_{BES} \tag{2}$$

In the formula, r is the discount rate, n_{BES} is the life cycle of the energy storage system, C_{BES}^{init} is the primary investment cost of the unit energy storage system, C_{BES}^{OM} is the annual operation and maintenance cost of the unit energy storage system, and E_{BES} is the configuration capacity of the energy storage system.

(2) Investment cost of photovoltaic system.

$$C_{PV} = \left[\frac{r(1+r)^{n_{PV}}}{(1+r)^{n_{PV}} - 1} \cdot C_{PV}^{\text{init}} + C_{PV}^{OM} \right] \cdot P_{PV} \tag{3}$$

In the formula, n_{PV} is the life cycle of the photovoltaic system, C_{PV}^{init} is the investment cost of the unit photovoltaic system, C_{PV}^{OM} is the annual operation and maintenance cost of the unit photovoltaic system, and P_{PV} is the size of the configuration capacity of the photovoltaic system.

(3) Investment cost of wind power system.

$$C_{WT} = \left[\frac{r(1+r)^{n_{WT}}}{(1+r)^{n_{WT}} - 1} \cdot C_{WT}^{\text{init}} + C_{WT}^{OM} \right] \cdot P_{WT} \tag{4}$$

In the formula, n_{WT} is the life cycle of the wind power system, C_{WT}^{init} is the primary investment cost of the unit wind power system, C_{WT}^{OM} is the annual operation and maintenance cost of the unit wind power system, and P_{WT} is the configuration capacity of the wind power system.

(4) The cost of purchasing electricity from the grid.

$$C_{buy} = \sum\nolimits_{\forall t} \lambda_{re}(t) \cdot P_{bxy}(t) \cdot \Delta t \tag{5}$$

In the formula, $\lambda_{re}(t)$ is the electricity price purchased by the power grid in period t, $P_{\text{buy}}(t)$ is the amount of electricity purchased by the community from the power grid in period t, and Δt is the duration of the unit scheduling period.

(5) Revenue from electricity sales to the grid.

$$C_{\text{sell}} = \sum_{\forall t} \lambda_{\text{fit}}(t) \cdot P_{\text{sell}}(t) \cdot \Delta t \tag{6}$$

In the formula, $\lambda_{\text{fit}}(t)$ is the online electricity price in period t and $P_{\text{sell}}(t)$ is the amount of electricity sold to the grid by the community in period t.

3.2. Constraint Condition

According to the community energy management strategy in Figure 2, the constraints of the community distributed energy and energy storage optimization configuration model include building power state constraints, community power state constraints [22], community purchase and sale power constraints [23], and continuity constraints of state of charge of energy storage system [24].

(1) Building power state constraints.

$$P_{BD,n}^{\text{pos}}(t) = (\eta_{PV,n}(t) \cdot P_{PV,n} + \eta_{WT,n}(t) \cdot P_{WT,n} - P_{L,n}(t)) \cdot X_{BD,n}^{pos}(t) \tag{7}$$

$$P_{BD,n}^{neg}(t) = (P_{L,n}(t) - \eta_{PV,n}(t) \cdot P_{PV,n} - \eta_{WT,n}(t) \cdot P_{WT,n}) \cdot X_{BD,n}^{neg}(t) \tag{8}$$

$$X_{BD,n}^{pos}(t) + X_{BD,n}^{neg}(t) = 1 \tag{9}$$

$$P_{BD,n}^{pos}(t) \geq 0, P_{BD,n}^{neg}(t) \geq 0 \tag{10}$$

In the formula, $P_{BD,n}^{pos}(t)$ is the remaining amount of power in building n at time t, $P_{BD,n}^{neg}(t)$ is the gap of power in building n at time t, $P_{PV,n}$ is the size of the configuration capacity of photovoltaic in building n, $P_{WT,n}$ is the size of the configuration capacity of wind power in building n, $P_{L,n}(t)$ is the load demand of building n at time t, $\eta_{PV,n}(t)$ and $\eta_{WT,n}(t)$ are the unit photovoltaic and unit wind power generation of building n at time t, respectively. $X_{BD,n}^{pos}(t)$ represents the 0–1 variable of the power surplus state in building n during the t period, and 1 is taken to indicate that there is a power surplus in building n, otherwise 0; $X_{BD,n}^{neg}(t)$ represents the 0–1 variable of the power gap state in building n during the t period. When 1 is taken, it indicates that there is insufficient power in building n, otherwise 0 is taken; the constraint in Equations (7) and (8) represent the calculation methods of excess power and gap of building n in t period, respectively. The constraint in Equation (9) indicates that the two states of excess power and insufficient power cannot appear at the same time. The constraint in Equation (10) indicates that the variables $P_{BD,n}^{pos}(t)$ and $P_{BD,n}^{neg}(t)$ are positive.

(2) Community power state constraint.

$$P_{CO}^{pos}(t) = (\sum_{n=1}^{N} P_{BD,n}^{pos}(t) - \sum_{n=1}^{N} P_{BD,n}^{neg}(t)) \cdot X_{CO}^{pos}(t) \tag{11}$$

$$P_{CO}^{neg}(t) = (\sum_{n=1}^{N} P_{BD,n}^{neg}(t) - \sum_{n=1}^{N} P_{BD,n}^{pos}(t)) \cdot X_{CO}^{neg}(t) \tag{12}$$

$$X_{CO}^{pos}(t) + X_{CO}^{neg}(t) = 1 \tag{13}$$

$$P_{CO}^{pos}(t) \geq 0, P_{CO}^{neg}(t) \geq 0 \tag{14}$$

In the formula, N is the total number of buildings in the community building group, $P_{CO}^{pos}(t)$ is the residual power of the community building group in the t-period, $P_{CO}^{neg}(t)$ is the gap of the power of the community building group in the t-period, and $X_{CO}^{pos}(t)$ is the 0–1 variable of the residual power state in the community in the t-period. When 1 is taken, it means that there is power surplus in the community building group, otherwise 0; $X_{CO}^{neg}(t)$ represents the 0–1 variable of the power gap state in the community during the t period. When 1 is taken, it indicates that there is insufficient power in the building n, otherwise 0 is taken; the constraint in Equations (11) and (12) represent the calculation method of the excess power and the gap of the community buildings in the t period, respectively. The constraint in Equation (13) indicates that the two states of excess power and insufficient power cannot appear at the same time. The constraint in Equation (14) indicates that the variables $P_{CO}^{pos}(t)$ and $P_{CO}^{neg}(t)$ are positive.

(3) Community electricity purchase and sale constraints.

$$P_{sell}(t) = (P_{CO}^{pos}(t) - P_{cha}(t)) \cdot Y_{BES}^{\max}(t) \tag{15}$$

$$P_{buy}(t) = (P_{CO}^{neg}(t) - P_{dis}(t)) \cdot Y_{BES}^{min} \tag{16}$$

$$Y_{BES}^{\max}(t) \leq 2X_{CO}^{pos} \tag{17}$$

$$Y_{BES}^{\min}(t) \leq 2X_{CO}^{neg} \tag{18}$$

In the formula, $Y_{BES}^{\max}(t)$ represents the 0–1 variable of whether the community energy storage system reaches the maximum state of charge during the t-period. When 1 is taken, it means that the energy storage system reaches the maximum state of charge, otherwise 0; $Y_{BES}^{\min}$ is a 0–1 variable that indicates whether the community energy storage system reaches the minimum state of charge in the t period. When 1 is taken, the energy storage system reaches the minimum state of charge, otherwise 0 is taken; Equations (17) and (18) represent the state of constraints of the maximum and minimum state of charge of the energy storage system, respectively. $P_{cha}(t)$ is the charging amount of the energy storage system in t period, and $P_{dis}(t)$ is the discharge amount of the energy storage system in t period. The calculation methods are as follows:

$$P_{\text{cha}}(t) = (SOC_{\max} - SOC(t-1)) \cdot \frac{E_{\text{BES}}}{\mu_{\text{cha}}\Delta t} \tag{19}$$

$$P_{dis}(t) = (SOC(t-1) - SOC_{min}) \cdot \frac{\mu_{dis}E_{BES}}{\Delta t} \tag{20}$$

In the formula, $SOC(t)$ is the state of charge of the community energy storage system at time t, $SOC_{\max}$ is the maximum state of charge of the energy storage system, $SOC_{\min}$ is the minimum state of charge of the energy storage system, μ_{cha} is the charging efficiency of the energy storage system, and μ_{dis} is the discharge efficiency of the energy storage system.

(4) Continuity constraints of state of charge for energy storage system.

$$\begin{aligned} SOC(t) = {} & SOC(t-1) \cdot (1 - Y_{BES}^{\max}(t) - Y_{BES}^{\min}(t)) \\ & + \frac{P_{CO}^{pos}(t)\mu_{cha}\Delta t}{E_{BES}}(1 - Y_{BES}^{\max}(t)) \\ & + \frac{P_{CO}^{neg}(t)\Delta t}{\mu_{dis}E_{BES}}(1 - Y_{BES}^{min}(t)) + SOC_{\max}Y_{BES}^{\max}(t) + SOC_{min}Y_{BES}^{min}(t) \end{aligned} \tag{21}$$

$$SOC(t=0) = SOC(t=last) \tag{22}$$

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \tag{23}$$

Equation (21) represents the calculation formula of the state of charge. Equation (22) represents the energy conservation of the initial and final states of the community energy storage system. Equation (23) represents that the state of charge at any time is between the maximum and minimum state of charge.

4. Comprehensive Evaluation Index

In order to quantitatively evaluate the optimization effect of the configuration model, the evaluation indexes of the distributed energy self-consumption rate, load

self-supply rate, static investment recovery period, and static CO_2 investment recovery period are provided from the perspectives of energy utilization, economic return, and environmental benefits.

(1) Self-consumption rate of distributed energy,

$$\alpha_{RE} = \frac{E_{RE} - E_{sell}^{grid}}{E_{RE}} \tag{24}$$

In the formula, α_{RE} is the self-consumption rate of distributed energy, E_{RE} is the power generated by distributed energy, and E_{sell}^{grid} is the power output from distributed energy to the power grid.

(2) Load self-supply rate.

$$\beta_L = \frac{E_L - E_{buy}^{grid}}{E_L} \tag{25}$$

In the formula, β_L is the self-supply rate of the load, E_L is the electric energy required by the load, and E_{buy}^{grid} is the electric energy purchased from the power grid to meet the load demand.

(3) Static investment payback period.

$$PBT_{\cos t} = \frac{C_{\text{total},BES} + C_{total,RE}}{C_{\text{saving}}} \tag{26}$$

In the formula, $PBT_{\cos t}$ is the static payback period, $C_{total,BES}$ is the total investment of the energy storage system, and $C_{total,RE}$ is the total investment of the distributed energy power station. The two mainly include the primary investment cost and the operation and maintenance cost in the life cycle. C_{saving} is the electricity purchase cost saved by replacing the power grid with the power generated by the distributed energy power station.

(4) Static CO_2 investment payback period.

$$PBT_{CO_2} = \frac{E_{CO_2,\text{BES}} + E_{CO_2,\text{PV}} + E_{CO_2,\text{WT}}}{E_{CO_2,\text{avd}}} \tag{27}$$

In the formula, PBT_{CO_2} is the static CO_2 investment payback period, $E_{CO_2,BES}$ is the carbon emission of the energy storage system, $E_{CO_2,PV}$ is the carbon emission of the photovoltaic system, $E_{CO_2,WT}$ is the carbon emission of the wind power system, and $E_{CO_2,avd}$ is the carbon emission avoided by using the power generation of the distributed energy power station to replace the power purchase of the power grid. Among them, the carbon emissions of energy storage systems, wind power, and photovoltaics are mainly concentrated in the manufacturing process.

5. Solution Method

In Section 3, the optimal configuration model for the distributed energy power station and energy storage system is formulated. The model uses Equation (1) as the objective function and incorporates Equations (7)–(23) as constraint conditions. Several of these constraints include nonlinear terms, specifically Equations (7), (8), (11), (12), (15), (16), (19)–(21). Consequently, the model is classified as a mixed-integer nonlinear programming problem, which cannot be directly solved using standard commercial solvers. The nonlinear terms in Equations (7), (8), (11), (12), (15), and (16) involve constant variables multiplied by binary (0–1) variables. These terms can be linearized using the Big-M method [25], where M represents a sufficiently large constant. However, the constraints in Equations (19)–(21) contain bilinear terms that cannot be addressed with the

Big-M method [26]. To manage these bilinear terms, the McCormick relaxation method is employed [27].

For the bilinear terms in Equations (19)–(21), the auxiliary variable is defined as Equation (28).

$$E(t) = SOC(t) \cdot E_{BES} \tag{28}$$

The McCormick relaxation method is applied to transform the constraint in Equation (28) into the constraint (29)–(32) as shown in Equations (29)–(32). $E_{BES}^{\max}$ is the upper limit of energy storage configuration capacity, $E_{BES}^{\min}$ is the lower limit of the energy storage configuration capacity.

$$E(t) \leq SOC_{\min} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\max} - SOC_{\min} \cdot E_{BES}^{\max} \tag{29}$$

$$E(t) \leq SOC_{\max} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\min} - SOC_{\max} \cdot E_{BES}^{\min} \tag{30}$$

$$E(t) \geq SOC_{\max} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\max} - SOC_{\max} \cdot E_{BES}^{\max} \tag{31}$$

$$E(t) \geq SOC_{\min} \cdot E_{BES} + SOC(t) \cdot E_{BES}^{\min} - SOC_{\min} \cdot E_{BES}^{\min} \tag{32}$$

After the transformation of the MINLP model into an MILP model, using the Big-M method and the McCormick relaxation method, the problem becomes solvable by commercial solvers such as CPLEX or GUROBI. In this paper, the model is resolved using CPLEX via the YALMIP toolbox on MATLAB 2018a. The computer specifications include an Intel Core i7-8750H CPU running at 2.20 GHz and 8 GB of RAM.

6. Example Analysis

6.1. Scene Setting

In order to evaluate the comprehensive benefits of distributed energy sharing and community energy storage sharing, this paper considers three scenarios based on whether to consider sharing and whether to configure the energy storage system. The definition of each scenario is as follows.

Scenario 1: The community building investor only configures the distributed energy power station, does not configure the energy storage system, and the distributed power in the community is not shared.

Scenario 2: The community building investor configures the distributed energy power station, invests separately and has an energy storage system, and the clean electricity in the community is not shared.

Scenario 3: Community building investors are equipped with distributed energy power stations, community energy operators invest in and own community energy storage systems, and clean energy and community energy storage are shared within the community.

6.2. Basic Parameters and Data

For simplicity, the typical generation curves of distributed energy and electric load profilers are used as input data for the planning example. In the example analysis, the community consists of three buildings. It is assumed that Building 1 and Building 3 are equipped with photovoltaic systems as their distributed energy sources, while Building 2 utilizes wind power as its distributed energy source. The typical daily unit generation coefficients of the distributed energy systems configured for each building are illustrated in Figure 3. The typical daily load demand for each building is presented in

Figure 4. Additionally, Figure 5 displays the electricity purchase price from the grid and the electricity sale price to the grid over a typical day. The scheduling period for the analysis is set to 1 h.

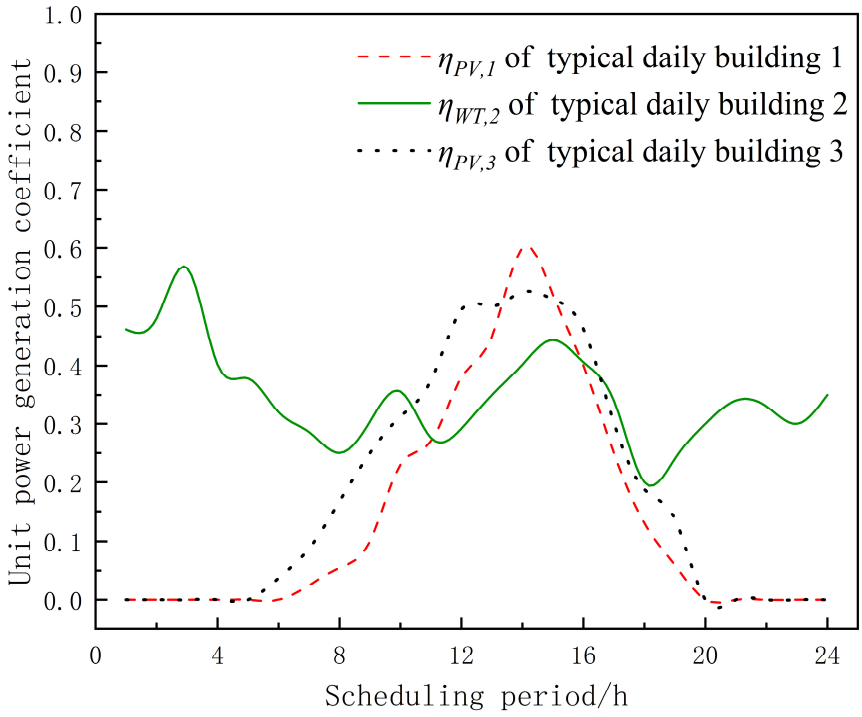


Figure 3. Coefficient of clean energy power generation per unit of typical da.

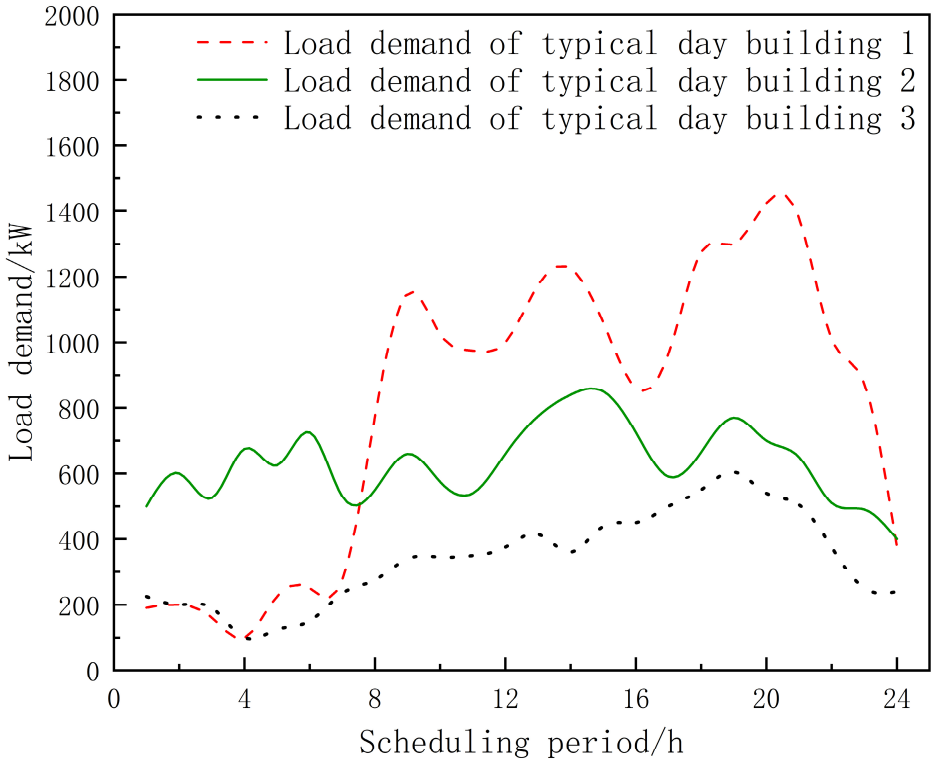


Figure 4. Typical daily load demand.

According to the actual project, it is assumed that the primary investment cost of energy storage system is 1500 yuan/kWh, the primary investment cost of photovoltaic system is 3500 yuan/kWp, and the primary investment cost of wind power system is

7500 yuan/kW. The annual operation and maintenance cost of distributed energy and energy storage projects accounts for 1–5% of the primary investment cost. According to the actual project situation, this paper assumes that the annual operation and maintenance cost is 2% of the primary investment cost. In addition, this paper assumes that the life cycle of distributed energy and energy storage projects is 20 years, and the discount rate is 5%. The charge and discharge efficiency of the energy storage system is set to 88% [28], the minimum state of charge is 0.1, the maximum state of charge is 0.9, and the capacity power ratio of the energy storage battery is assumed to be small enough to fully charge or discharge the energy storage system between two continuous scheduling intervals.

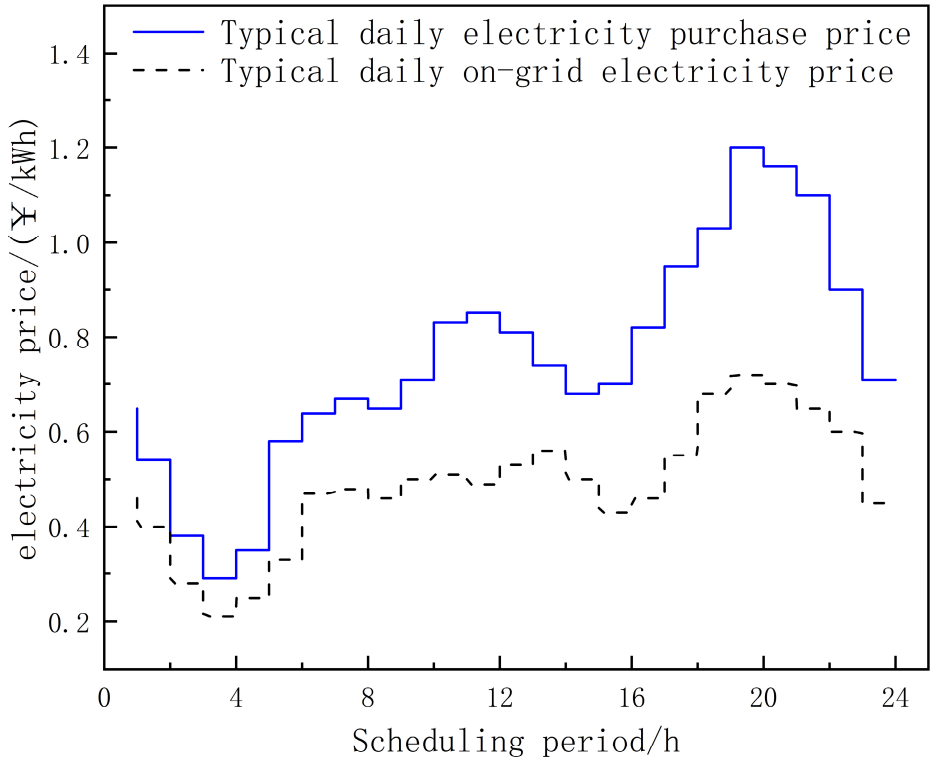


Figure 5. Typical daily electricity purchase price and on-grid electricity price.

The low carbon effect of distributed clean energy in the process of power generation is the main reason for its vigorous development. It is more important to analyze the environmental benefits of distributed energy construction under the dual carbon target. Many studies have analyzed the carbon emissions of distributed energy and energy storage systems from the perspective of life cycle [28–31]. This paper assumes that the carbon emission coefficient of the power grid is 0.673 kg/kWh [29], the life cycle CO_2 emission coefficient of the unit energy storage system is 370 kg/kWh [30], and the life cycle CO_2 emission coefficient of the unit photovoltaic system is 1650 kg/kW [31]. The life cycle CO_2 emission coefficient of the unit wind power system is 1100 kg/kW [32].

6.3. Analysis of Optimal Configuration Results of Distributed Energy and Energy Storage System

The configuration results of distributed energy and energy storage systems in the three scenarios are shown in Table 1. The configuration size of the energy storage system in Scenario 3 is 1500 kWh. The total energy storage system configuration size of the community in Scenario 2 is 2811 kWh. It can be seen that, in the scenario of shared energy storage system, the energy storage configuration capacity of the community is saved by 46.6%. The total configuration capacity of distributed energy in Scenario 2 is 1870 kW, and the total configuration capacity of distributed energy in Scenario 3 is 1475 kW. It can be

seen that, in Scenario 3 where distributed energy and energy storage are shared, compared with Scenario 2, the community's distributed energy configuration is saved by 21.1%.

Table 1. Clean energy and energy storage system configuration results.

Scene	Architecture	Energy Storage Configuration/kWh	Photovoltaic Configuration/kWp	Wind Power Configuration/kW
1	BD1	/	522	/
	BD2		/	357
	BD3		187	/
2	BD1	1874	1100	/
	BD2	240	/	394
	BD3	697	376	/
3	BD1	1500	525	/
	BD2		/	750
	BD3		200	/

6.4. Analysis of Distributed Energy Self-Consumption Rate and Load Self-Supply Rate

The results of the distributed energy self-consumption rate and the load self-supply rate in three scenarios are shown in Table 2. The distributed energy self-consumption rate in each scenario is relatively high, which minimizes the interaction between distributed energy and the power grid and avoids the waste of distributed energy. It shows that the proposed optimal configuration model can effectively solve the configuration capacity of distributed energy power stations required by buildings and communities. In Scenario 1, only distributed energy is configured, and the load self-supply rates of Building 1 and Building 3, with only photovoltaics, are 42.79% and 46.13%, respectively. This is because photovoltaics do not generate electricity at night, so Building 1 needs to purchase electricity from the grid to meet its own load demand.

Table 2. Clean energy self-consumption rate and load self-supply rate.

Scene	Architecture	Self-Consumption Rate of Distributed Energy		Load Self-Supply Rate
1	BD1	/	90.91%	42.79%
	BD2		89.38%	88.33%
	BD3		92.44%	46.13%
2	BD1	/	88.63%	87.87%
	BD2		91.76%	100%
	BD3		87.37%	87.84%
3	BD1	90.78%	90.65%	42.90%
	BD2		48.18%	100%
	BD3		88.97%	47.57%

At the same time, it can be seen from Table 1 that the total configuration capacity of distributed energy in Scenario 1 is 1066 kW. Without energy storage, it cannot maximize the supply of distributed energy, so the total configuration capacity of distributed energy in Scenario 1 is also the lowest. With energy storage in Scenario 2, the load self-supply rate of each building is effectively improved. Among them, Building 2 achieves 100% load self-supply and does not need to obtain electric energy from the power grid. In Scenario 3, the self-consumption rate of distributed energy in Building 2 is only 48.18%, while the load self-supply rates of Building 1 and Building 3 are only 42.90% and 47.57%, respectively. This shows that the main supply of Building 1 and Building 3 at night, without photovoltaic

power generation, is wind power from Building 2. Using the complementary characteristics of distributed energy, the self-consumption rate and load self-supply rate of distributed energy in community interest reached 90.78% and 95.79%, respectively, which basically realized the self-sufficiency of community energy.

6.5. Analysis of Economic and Environmental Benefits

The primary investment cost, static payback period and static CO_2 payback period in the three scenarios are shown in Table 3. The one-time investment cost in Scenario 1 is the lowest, which is 8.446 million yuan. The static investment payback period and static CO_2 investment payback period of each building are also shorter. However, from Table 2, it can be seen that the self-supply rate of buildings is relatively low without energy storage, and the community cannot achieve effective self-sufficiency. The primary investment cost in Scenario 2 is the highest, which is 20.195 million yuan, and its energy utilization efficiency and self-sufficiency ability are also strong. However, each building invests in the construction of energy storage systems and does not share distributed energy, resulting in a significant extension of its static investment payback period and static CO_2 investment payback period. In Scenario 3, the sharing of distributed energy and the energy storage system is considered. It can be seen from Table 2 that the community achieves a higher self-consumption rate of distributed energy and self-supply rate of load under Scenario 3. At the same time, the investment cost is between Scenario 1 and Scenario 2, which is 16.743 million yuan. Compared with Scenario 2, it saves 17.1% of the investment cost and shortens the static investment payback period. In Scenario 3, the sharing of community distributed energy can effectively realize the self-sufficiency of the community as a whole, with little interaction with the power grid, thus avoiding a large amount of carbon emissions and having significant environmental benefits. Therefore, the static CO_2 investment payback period is only 1.2 years, which shows that the sharing of community distributed energy and the energy storage system can effectively reduce the overall carbon emissions of the community.

Table 3. Static payback period and static CO_2 payback period.

Scene	Architecture	Primary Investment Cost/Ten Thousand Yuan	Static Investment Payback Period/Year	Static CO_2 Investment Payback Period/Year
1	BD1	299.2	6.0	1.9
	BD2	438.5	5.8	0.5
	BD3	106.9	4.8	1.5
2	BD1	1090.3	9.9	3.0
	BD2	542.6	6.5	0.7
	BD3	386.6	8.3	2.4
3	BD1 BD2 BD3	1674.3	6.8	1.2

From the above comparative analysis, it can be seen that the investment cost of only configuring distributed energy is relatively low. However, due to its spatial and temporal characteristics, especially that photovoltaic does not generate electricity at night, the self-supply rate of load is not high, and communities and buildings still have a lot of power interaction with the power grid, and the environmental benefits are not significant. The use of distributed energy with energy storage can effectively improve the load self-supply rate of community buildings and avoid the interaction between community buildings and power grids. However, the disadvantage is that the investment cost is high, the investment

recovery period is long, and the allocation of energy storage may lead to the waste of energy storage resources. Under the operation strategy of a community distributed energy and an energy storage sharing system proposed in this paper, the community, as a community of interests, carries out the unified optimal configuration of distributed energy and the community energy storage system. Using the complementary characteristics of distributed energy, while maximizing the self-consumption rate and load self-supply rate of distributed energy, the configuration capacity of distributed energy and the energy storage system is saved, and the economic investment cost is saved. The static investment recovery period is short and has considerable profit space. Community distributed energy and energy storage system sharing can also effectively reduce the overall carbon emissions of the community, and the static CO_2 investment recovery period is only 1.2 years, which has significant environmental benefits and contributes to the achievement of the dual carbon target.

6.6. Analysis of the Uncertainty of Distributed Energy Wind and Solar Output in the Community

Considering the randomness of wind power and photovoltaic power generation, this randomness and correlation should be taken into account in the planning of community distributed energy resources. As shown in Figure 6, in view of this, we analyze the sample space of the annual wind and solar output in a certain area, and finally use the K-means clustering method to cluster the 365 sets of sampling results into four typical daily scenarios. According to the probability distribution of the typical scenarios, the daily unit distributed energy generation coefficient map shown in Figure 7 is finally calculated.

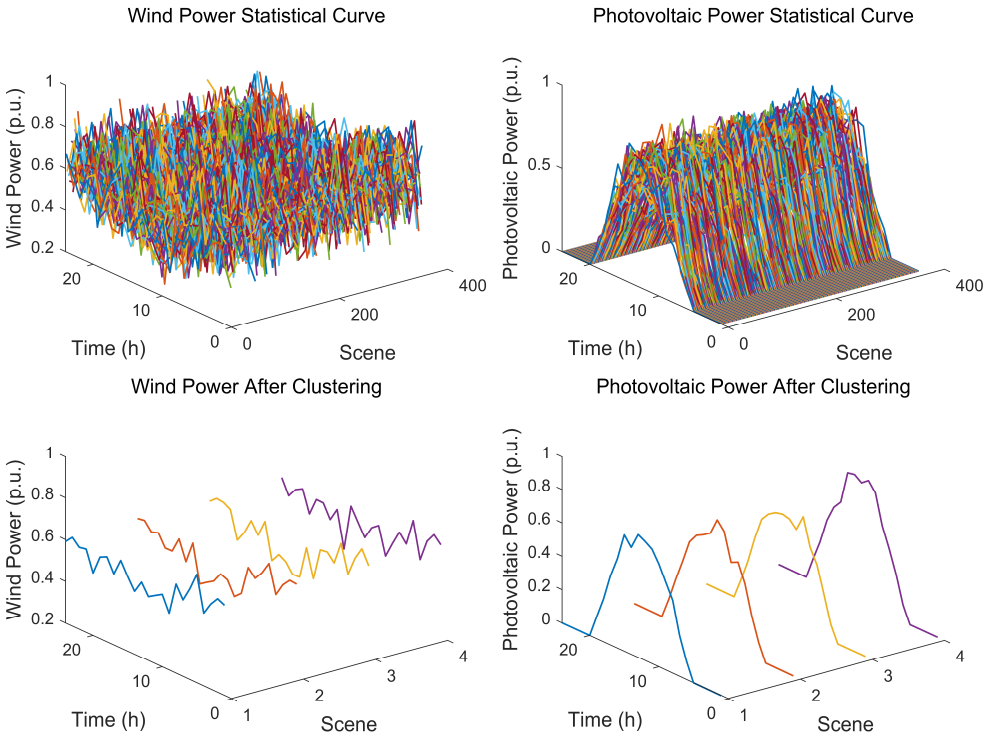


Figure 6. Power diagram considering uncertainty of wind and light.

Since the superiority of Scenario 3, community energy autonomous sharing has been highlighted in the previous example of deterministic analysis using typical days, this section further considers the uncertainty of distributed energy output, and gives the operation results shown in Table 4, so as to compare with the above deterministic analysis results. On the premise of meeting the balance between community autonomy and energy supply demand, this study sets up two configuration schemes for the uncertainty of distributed

energy output, namely, optical storage complementary consumption (A scenario) and wind-solar complementary output (B scenario).

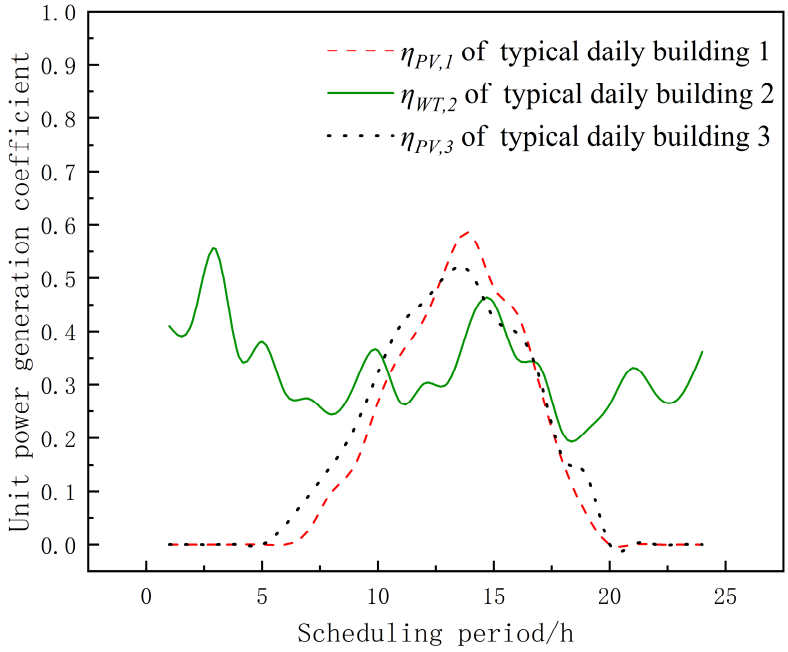


Figure 7. The daily power generation coefficient diagram of distributed energy considering power uncertainty.

Table 4. Self-balancing shared community planning results considering output uncertainty.

Scenario	Configuration Change Mode	Architecture	Energy Storage Configuration /kWh	Photovoltaic Configuration /kWp	Wind Power Configuration /kW	Primary Investment Cost/Ten Thousand Yuan	Static CO_2 Investment Payback Period/Year
A	Energy storage and photovoltaic	BD1 BD2 BD3	1563	598 / 200	/ 750 /	1762	1.2788
B	Wind and photovoltaics	BD1 BD2 BD3	1500	488 / 200	/ 800 /	1744	1.2124

In the A scenario, the photovoltaic configuration and energy storage configuration increase synchronously. The total photovoltaic capacity configuration is 598 kWp, and the energy storage configuration is 1563 kWh, forming an effective complementarity between photovoltaic and energy storage, which can smooth the fluctuation of photovoltaic output and improve the absorptive capacity of resources. By contrast, in scenario B, by increasing the wind power capacity (800 kW) and moderately reducing the photovoltaic configuration, the complementarity of wind energy and light energy in time distribution is utilized to reduce the instability of energy supply. Although the capacity allocation strategies of the two scenarios are different, the investment cost of the system is increased compared with the results obtained in Section 6.5. By comparing the data under different scenarios, we found that, in order to cope with uncertainty, the system may need to increase specific energy capacity and configure energy storage to balance supply and demand to ensure stable operation. Although the cost has increased, the system stability has been improved.

7. Conclusions

In the context of the new power system, this paper innovatively explores the optimal allocation of community distributed energy and energy storage based on regional autonomous balance and a sharing mechanism. By constructing a community distributed

energy and energy storage sharing operation mode, this paper proposes a corresponding community energy unified management strategy and establishes an optimal configuration model accordingly. Aiming at the nonlinear constraints in the model, this paper uses the Big-M method and the McCormick relaxation method to solve the linearization.

In terms of comprehensive evaluation, this paper innovatively introduces key indicators, such as distributed energy self-consumption rate, load self-supply rate, static investment recovery period, and static CO_2 investment recovery period, to comprehensively evaluate the economic, technical, and environmental benefits of the optimal allocation scheme.

Through the calculation and analysis of the configuration results and evaluation indicators in three different scenarios, this paper draws the following conclusions:

(1) Under the background of the new power system, the optimal allocation model of community distributed energy and energy storage based on regional autonomy balance and the sharing mechanism proposed in this paper is not only suitable for the optimal planning of community distributed energy and energy storage capacity, but the established evaluation index system can fully reflect the economic, technical, and environmental benefits of community planning. The model realizes the effective matching of distributed resources and load through the sharing mechanism, improves the energy utilization efficiency, and reduces the system operation cost.

(2) The community distributed energy sharing and energy storage sharing model proposed in this paper promotes the realization of regional autonomy balance, improves the resource utilization rate of the community, and reduces the investment cost by optimizing the allocation of resources. Specifically, compared with the scenario where energy storage is configured alone and distributed energy is not shared, this model can save about 46.6% of the energy storage configuration capacity and 21.1% of the distributed energy configuration capacity, reduce the primary investment cost by about 15.6%, and shorten the static investment recovery period to 6.9 years, which has significant economic benefits.

(3) Under the community energy management strategy of distributed energy and energy storage sharing, this paper uses the complementary characteristics of distributed energy, combined with energy storage sharing services, to achieve a higher self-consumption rate and load self-supply rate of distributed energy. Specifically, under the sharing mode of distributed energy and energy storage, the self-consumption rate and load self-supply rate of distributed energy reach 91.75% and 96.80%, respectively, which effectively reduces the power interaction with the power grid and further promotes the regional autonomy balance and source-load coordination.

(4) The community distributed energy and energy storage sharing model proposed in this paper performs well for environmental benefits. Specifically, the payback period of static CO_2 investment under this model is only 1.2 years, and the community as a whole reduces the purchase of electricity from the power grid, thus avoiding a large amount of carbon emissions. This achievement is not only conducive to the achievement of the dual-carbon goal, but has made a positive contribution to promoting green and low-carbon development and realizing the balance and sharing of regional autonomy.

(5) This paper discusses the impact of distributed energy output uncertainty on the operation of community energy system. The research shows that uncertainty increases the capacity allocation cost of the system, but through the wind–solar complementary and energy storage adjustment strategy, the energy consumption capacity can be effectively improved, and the system autonomy balance can be guaranteed.

8. Future Work

The current research only considers the uncertainty of wind and solar output, and future work can be further extended to the self-balanced community planning and operation strategy with multiple uncertainties, such as electricity price fluctuation and energy demand. By comprehensively considering these factors, it is expected to improve the overall stability and economic benefits of the energy system and provide a more comprehensive solution for community energy management.

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