Electricity Market Trading Mechanism and Business Model Under Coordination of Distribution and Storage

Shengyong Ye[1], Chuan Long[1], Xuna Liu[1], Ting Li[1], Jun Wei[1], Xinting Yang[1], Da Li[1], Liyang Liu[1], and Yixin Yao[2](✉)

[1] State Grid Sichuan, Economic Research Institute, Chengdu, Sichuan, China
[2] College of Electrical Engineering, Sichuan University, Chengdu, Sichuan, China
13219115818@163.com

Abstract. Combined with the current electricity price structure and market trading rules, this paper analyzes electricity market trading mechanism and business model under coordination of distribution and storage. Electricity market trading mechanism includes direct transactions, Locational Marginal Pricing (LMP) of distribution and storage and distributed iterative clearing mechanism; business model includes the leasing model of shared energy storage. Based on LMP, is designed for ES; a double auction-based mechanism is proposed to study the behavior in an energy sharing market composed of distributed PV producers and consumers, thus summarizing the distributed iterative clearing mechanism. The calculation example gives the nodal electricity price and market clearing under the coordination of distribution and storage and the dynamic capacity leasing model of shared energy storage is analyzed to verify the feasibility and effectiveness of the proposed model.

Keywords: Distribution · Storage · Market Development · New Power System

1 Introduction

In response to climate change, many countries in the world have put forward carbon neutrality programs. China has also announced the goal of 'carbon peak in 2030 and carbon neutrality in 2060'. As a major carbon emitter, the power industry needs to build a new power system with new energy as the main body, and vigorously develop renewable energy such as wind power and photovoltaic to accelerate the decarbonization process. Energy storage can well solve the challenge of renewable energy introduction [1–5], so it plays an important role in the new power system. On the one hand, it can solve the problem of mismatch between the peak of wind and solar output and the peak of load. Through peak clipping and valley filling, valley load is increased to promote the consumption of renewable energy, and peak load is reduced to delay the demand for

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capacity investment. On the other hand, it can solve the frequency stability problem caused by the randomness and volatility of wind and solar output, especially the new energy storage with fast response speed such as electrochemistry, which can provide frequency modulation service to improve the reliability of power grid.

With the advancement of electricity market reform in major developed countries, the future development and operation of energy storage will be mainly realized under the background of marketization.

Some scholars have studied the market development potential of the allocation and storage coordination. Including direct trading mechanism within the distribution network, distributed clearing, distribution network side node price, cooperative game mechanism. In References [6, 7], under the framework of tradeable energy, the design mechanism helps the direct transaction interaction of energy storage on the distribution network side to form a decentralized flat transaction system. Reference [8] adopted a distributed iterative clearing method and an adaptive pricing method for transactions. Reference [9] designed a node price mechanism on the distribution network side to reflect the role of energy storage in alleviating congestion. References [9, 10] designed a cooperative game system for energy storage sharing in microgrid to help market players save energy storage investment costs and reduce peak load costs.

In view of this, this paper combined with the current electricity price structure and market trading rules, analyzing electricity market trading mechanism and business model under coordination of distribution and storage. Based on LMP, is designed for ES; a double auction-based mechanism is proposed to study the behavior in an energy sharing market composed of distributed PV producers and consumers. Taking into account the operability, proposing a market development business model of the coordination of distribution and energy storage in the new power system, establishing a dynamic capacity leasing model for shared energy storage. The dynamic capacity leasing model of shared energy storage is analyzed to verify the feasibility and effectiveness of the proposed model.

2 Current Electricity Price Structure and Market Rules

2.1 Current Electricity Price Structure

Since the reform and opening up, in line with the reform of the electricity system and the electricity market, the electricity price system has experienced the reform of building an independent grid price, transmission and distribution price and improving the sales price from a single sales price, and basically formed a relatively perfect electricity price system.

So far, China's electricity price reform can be divided into three stages. The first stage is from 1985 to 2002, in the future, to encourage fund-raising and attract investment in electricity, China has implemented the policy of repaying the cost and paying interest, and then improved to the operating period price, initially formed an independent electricity price, and accordingly formed a variety of sales prices, which effectively accelerated China's power construction.

The second stage is during the implementation of the first round of power system reform in 2002–2015, the electricity price system added the electricity price for generating electricity, the electricity price for trans-provincial transmission, the electricity price for direct purchase of electricity by large users in some provinces and the compensation standard for ancillary services on the basis of the simple sales price structure.

The third stage is since the beginning of a new round of power system reform in 2015, the electricity price reform focuses on two aspects: the implementation of independent transmission and distribution price supervision, completed the first regulatory cycle of provincial power grid, regional power grid and special transmission project independent transmission and distribution price supervision completely covered; through various forms of electricity trading, the provinces have realized the marketization of partial power generation price and large industrial electricity price.

2.2 Market Rules

Bilateral transaction prices are implemented in accordance with the contract between the parties. Centralized trading price mechanism is determined by regional market rules. Among them, centralized bidding transactions can adopt marginal clearing or high-low matching price formation mechanism; rolling matching transaction can adopt rolling quotation and price formation mechanism of matching transaction; the listing transaction adopts the price formation mechanism of one party listing and delisting.

3 Electricity Market Trading Mechanism of Distribution and Storage

In the environment of increasingly fierce market competition, distribution to enhance the core competitiveness, to promote the positive development of the power industry, it is necessary to apply more advanced technology in the construction of distribution. Energy storage technology has a broad application prospect in distribution, which can solve a series of problems existing in current distribution work.

3.1 Direct Transactions in the Distribution-Storage Market

The tradeable energy system oriented to distributed subjects forms a flat, even decentralized trading architecture in the distribution network side, which is beneficial to improve the convenience of market members' transactions. The trading mechanism characterized by direct trading and quotation payment also provides the possibility for distributed generation, energy storage, users to participate in the market and profit from the changing price. The mechanism design of the tradeable energy system is essentially to extend the response to both sides of demand and supply. Through the design of reasonable and effective incentive mechanism, the incentive compatibility of individual income and system benefit can be achieved.

From the perspective of transaction time scale, spot transactions and medium- and long-term transactions coexist in the tradeable energy system. For example, the purchaser and the seller reach a transaction at medium- and long-term menu price, and they can also purchase electricity in real time from the production consumers.

From the operational level of transactions, the execution of transactions in the negotiable energy system is mostly automated, and the decision-making and confirmation process of transactions is also as automated as possible. This can not only sensitively respond to value signals and reduce labor costs, but also ensure that transaction execution is real and effective, and improve the real-time balance ability of the system (Fig. 1).

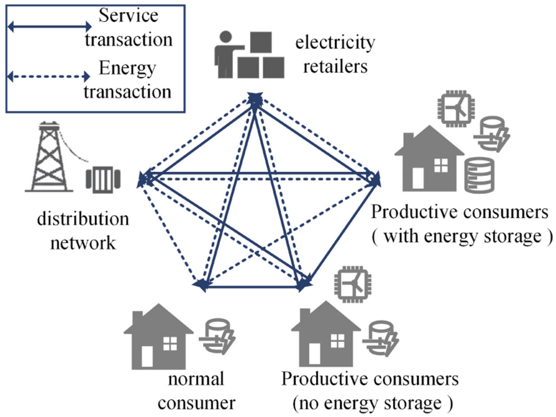

Fig. 1. Transaction structure of transactive energy system

3.2 LMP of Distribution and Storage

In order to promote the development of photovoltaic power generation, this paper proposes a new energy storage pricing scheme and charging and discharging strategy. To solve the problem of third-party energy storage system and system blocking, a new charging and discharging strategy scheme needs to be specified. The specific operation is as follows: the purpose of discharge is to reduce the blockage caused by load, and the purpose of charging is to reduce the blockage caused by photovoltaic power generation. The binary search method is used to control the energy storage system to minimize the blocking cost. Finally, according to the relevant concepts of LMP, considering the impact of energy storage on system operation cost, a new energy storage pricing method for distribution network is proposed.

The purpose of this method is to observe the charging and discharging effect of energy storage on power flow. According to the running status of the energy storage system, the energy transfer status and the change of its position are reflected to price, and the price changes of charging and discharging action at different times are displayed. In general, LMP includes three parts, namely energy, loss and blocking, which are related to generation cost and branch heating.

LMP at the bus i (λ_i) is composed of these parts: 1) λ_r is energy storage price based on generation cost, Energy System is regarded as load when charging; 2) λ_i^L is the marginal loss component of node price; 3) λ_i^{con} is the nodal price. They can be represented by the following formula:

$$LMP_i = \lambda_r + \lambda_i^L + \lambda_i^L \tag{1}$$

$$\lambda_r = \frac{dC_{ES}(P_{ES})}{dES_k} \tag{2}$$

$$\lambda_i^L = -\lambda_r \times LF_k = -\lambda_r \times \frac{\partial L_t}{\partial PF_i} \tag{3}$$

$$\lambda_i^{con} = -\sum_{l=1}^{n} (\alpha_{l,i} \times TL_l) \tag{4}$$

$\alpha_{l,i}$ is the distribution factor; TL_l is line l constraint; LF_k is the factor of loss at bus k; C_{ES} (P_{ES}) is the important cost for Energy system. ES_k is the current of charge of Energy System at k and L_t is the loss of system.

The factor of loss LF_k can be represented by loss L_t caused by Energy System. The power change and the branch impedance in (5). The Energy System output or input in (6). Distribution factor can be represented by the impedance of the system in (7).

$$L_t = \sum_{l=1}^{n} F_l^2 Z_l \tag{5}$$

$$F_l = \sum_{i=1}^{N} \alpha_{l,k} ES_{tk} \tag{6}$$

$$\alpha_{l,k} = (\frac{Z_{ik} - Z_{jk}}{Z_l}) \tag{7}$$

where F_l is the power flow of line l caused by the Energy System, ES_{tk} is Energy System output/input at time t; Z_l is the impedance of line l, Z_{ik} and Z_{jk} are the send and receive bus of l. Combining (5–6), factor of loss can be represented as:

$$LF_k = \frac{\partial(\alpha_{l,i} ES_{tk})^2 Z_l}{\partial ES_{tk}} \tag{8}$$

TL_l equals total cost change divided by power flow change.

The LMP for Energy System can be represented as:

$$LMP_{St} = \lambda_r \times (1 - \frac{\partial L_t}{\partial ES_{tk}}) - \sum_{l=1}^{n} (\alpha_{l,i} \times TL_l) \tag{9}$$

The LMP for load is (10):

$$LMP_{tk} = \lambda_r \times (1 - \frac{\partial L_t}{\partial D_{tk}}) - \sum_{l=1}^{n} (\alpha_{l,i} \times TL_l) \tag{10}$$

3.3 Distributed Iterative Clearing Mechanism

Through the establishment of community energy markets and incentives to promote the sharing of distributed photovoltaic energy storage. Community energy markets not only provide financial support for single households, but also provide storage incentives for large consumers. All agents can determine the price and quantity they bid in the market, thus forming a dynamic market mechanism.

The key of distributed clearing mechanism is to establish a two-stage decision to improve the economic benefits of community energy market. The objective of the first stage is to reduce the total cost of electricity in decision making by analyzing the supply and demand relationship and estimating the electricity price. The purpose of the second stage is to solve the final spot price of the non-cooperative game through the algorithm, and use the reward and punishment rules to solve the undetermined supply and demand in the real-time market clearing process.

When bidding, a dynamic adaptive strategy considering both historical data and forecast data is adopted. In the absence of an open market, agents can only predict market trends with limited information. However, in the community energy market, the final bidding price can be determined by drawing on the experience of successful bidding history and the forecast data of future professionals (Fig. 2).

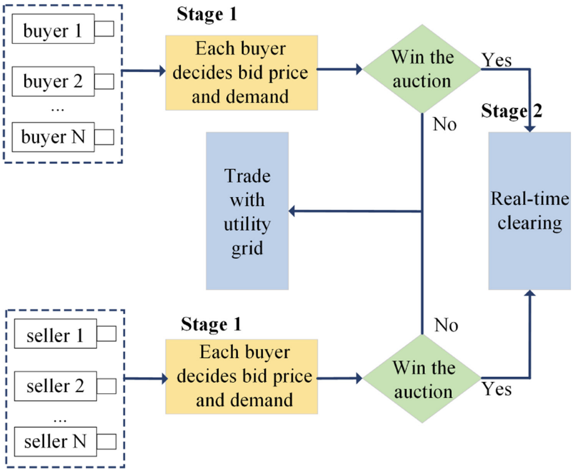

Fig. 2. Two-stage decision making process diagram

It is assumed that the agent has full knowledge of the amount of energy produced and demand in the previous hour. At the end of each trading phase t − 1 [11], the agents will give their expected bids for the next round t, and then the operator will execute the one-hour ahead auction, announce the spot price, and inform all auctioners to buy or sell the goods they need to trade. At the end of T, the transaction amount is calculated based on the final supply/demand and spot price. However, due to the increased flexibility of energy storage due to the involvement of agents, the error between prediction and reality always exists. In practice, non-open auctions are more susceptible to non-strategic bidding [12].

The market added two clearing rules to prevent errors. First, the market allows for non-iterative bidding, where operators charge only one bidding price per round, which prevents bidders from bidding more than once for the same project. Second, the market proposes a reward and punishment rule based on the value of contribution, with the aim of encouraging energy trading in the market, maintaining an orderly and fair environment, and preventing agents from fraudulent bidding.

4 The Dynamic Capacity Leasing Model of Shared Energy Storage

At present, China has not yet formed a relatively mature business model on energy storage. According to the relevant policies of ES, the current electricity price mechanism, and the market trading rules, the distribution-storage collaborative business model can be divided into two categories, namely, the transmission and distribution cost supervision model and the competitive business model. Transmission and distribution cost supervision mode includes leasing mode, competitive business mode includes auxiliary service market mode, spot trading market mode, etc. This section will consider the flexibility and operability, explore leasing mode, shared energy storage, virtual power plant three new business models of distribution-storage coordination, mining the market development potential of distribution-storage coordination.

4.1 Leasing Mode

With the deepening of electricity reform, more and more social capital will appear in the form of market players of electricity sales companies. Become the representative of social capital participating in the electricity market. As an intermediary between power grid enterprises and power users, power sales companies can further act as energy storage providers or operation service providers, integrate all kinds of energy storage resources in society, and lease equipment to users through leasing, financing leasing and other modes.

The operation process of energy storage equipment is dominated by users, and power sales companies guide the participation in sharing energy storage. In the process of energy trading, power companies accurately analyze the load characteristics of various users through big data platforms, improve the accuracy of load forecasting, and reasonably design the charging and discharging strategy of energy storage system to provide low-cost electricity for users. For users, the use of leasing in the early stage has less investment capital, low barriers to entry and small risks, which is conducive to promoting the active participation of all parties in the investment of energy storage projects and promoting the development of large-scale energy storage.

4.2 Shared Energy Storage Rental Model

The operational objective of shared energy storage providers is to meet the maximum charging and discharging requirements and operational benefits of energy storage to stabilize power fluctuations. The centralized construction of shared energy storage power station provides energy storage lease service for distribution network, and also provides total energy storage lease demand. After obtaining the total demand for net energy storage charging and discharging, the charging and discharging strategy of shared energy storage is formulated to meet the demand. Multiple energy storage capacity is involved in the peak shaving scheduling of distribution network, and it is profitable through low energy storage and high power amplifier.

This section proposes a dynamic capacity leasing model of shared ES from the perspective of leasing capacity, revealing the essence of shared ES to improve efficiency. From the aspects of whether the microgrid side participates in the shared energy storage service and whether the microgrid side responds to the demand, the simulation comparison in Sect. 4 is conducted, which provides a reference scheme for solving the capacity allocation and allocation of shared energy storage.

The framework includes multiple integrated energy microgrids, shared energy storage system (SESS) and distribution network (Fig. 3).

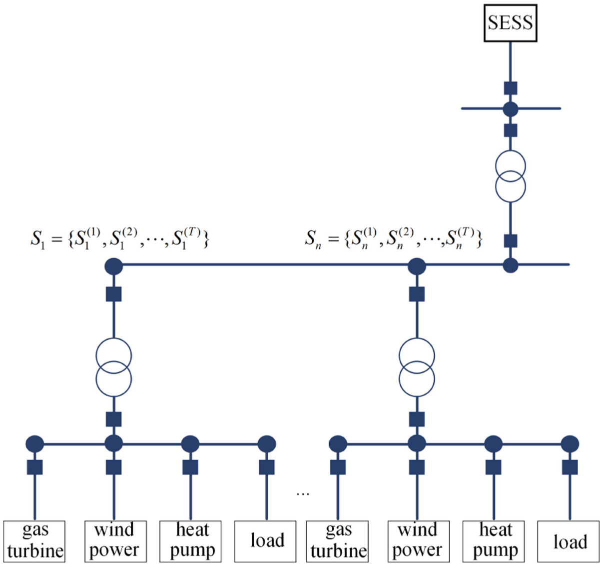

Fig. 3. Schematic diagram of dynamic capacity lease mechanism of shared energy storage

Where, $S_1^{(t)}$ is the rated energy storage capacity of the first microgrid in period t of the day; S_n is the set of energy storage rated capacity strategies allocated in each period of the last microgrid in a day; T is the research period.

T = 24, the income of sharing energy storage side in one day is expressed as:

$$F_{SESS} = \lambda_{SESS} \sum_{t=1}^{T} \sum_{i=1}^{n} (P_{i,SESS,c}^{(t)} + P_{i,SESS,d}^{(t)}) \Delta t$$

$$-\frac{\lambda_P P_{SESS}^{\max} + \lambda_E E_{SESS}^{\max}}{T_s} - M_{SESS} \tag{11}$$

where, Δt is the study period, the unit is h; λ_{SESS} is the capacity of microgrid using shared ES service; n is the number of microgrids in the studied scenario; $P_{i,SESS,c}^{(t)}$, $P_{i,SESS,d}^{(t)}$ are the power of microgrid i using shared energy storage at time t; λ_P and λ_E are the power cost and capacity cost of shared energy storage; $P_{SESS}^{\max}$ and $E_{SESS}^{\max}$ are the power limit and rated capacity of shared ES; T_s and M_{SESS} are the service life and daily maintenance cost of shared ES. Let the rated capacity of shared ES be linear with the power limit, as follows:

$$P_{SESS}^{\max} = \beta E_{SESS}^{\max} \tag{12}$$

where β is the ratio of shared ES of rated capacity.

5 Case Studies

5.1 LMP for ES

The node electricity price model under the coordination of distribution and storage will be calculated in the actual grid supply point in Fig. 4 [13]. Compared with the traditional GSP, this paper adds energy storage at 1006 and 1007. The energy storage capacity is set to 25MWH and the life span is 35 years [14].

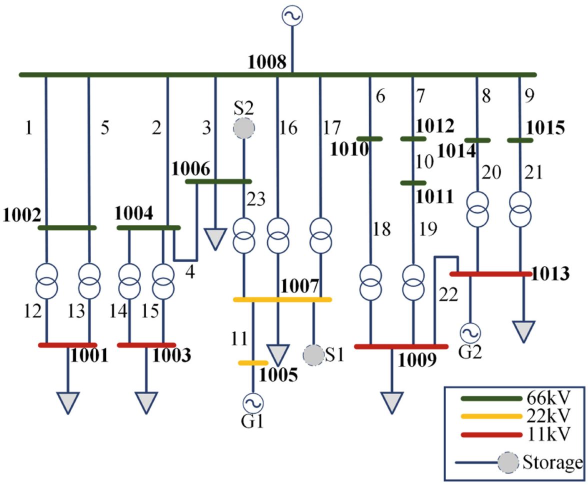

Fig. 4. A GSP area test system

The power station is at 1005 in order to support the photovoltaic power station. G2 is located at bus 1013 and the rest system is regarded as 1008.

The node electricity price of distribution and storage coordination at bus 1006 and 1007 are shown in Fig. 5. And Fig. 6. If the node electricity price is less than 0, energy storage should be rewarded due to the increase in power flow. For energy storage on the 1006, while there is a reward for load reduction, there is also a penalty for price increase. Although the blockage on the branch is solved by energy storage, it will make the blockage on other branches worse. Therefore, energy storage will be penalized between 10:00 and 15:00 and will be rewarded between 17:00 and 21:00.

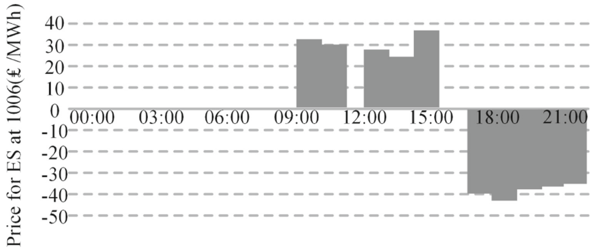

Fig. 5. Price for Energy System at 1006 in one day

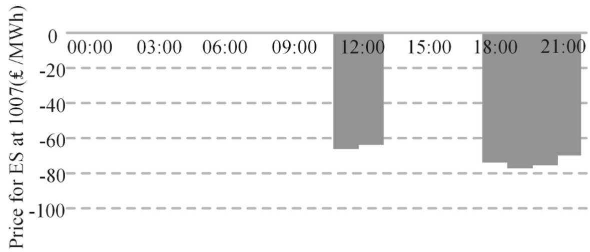

Fig. 6. Price for Energy System at 1006 in one day

5.2 Market Clearing Mechanism

Figure 7 shows the spot price change and the total grid load change in the week before and after the community market energy sharing. On clear days, energy sharing takes place between 10 am and 4 pm. During the break, all agents need to rely on other grids to meet supplying and demanding. The market spot price is always between the public electricity price and the buyback price, indicating that all agents are willing to participate in community market energy sharing.

Figure 8 shows the energy transactions with other grids during the day in two different situations: without and with rewards and punishments. A positive value indicates that energy needs to be purchased from another grid, while a negative value indicates that energy is sold. The difference will be split between consumers or sellers. It can be seen that the penalty and reward charging method can better balance the community market energy trading.

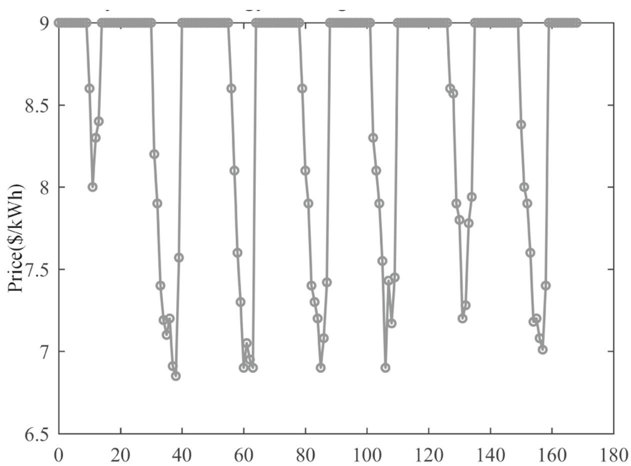

Fig. 7. Market spot price

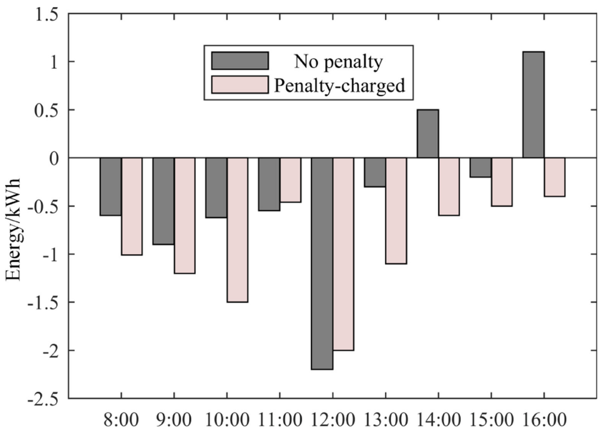

Fig. 8. Before and after penalty regulation change of energy.

5.3 Shared Energy Storage Rental Model

The initial energy storage capacity of each microgrid is half of its lease capacity from the shared energy storage at the initial time [15]. The ratio of the rated capacity to the power limit is 0.2. The unit charge and discharge service cost is 0.35 CNY/(kW·h). The capacity cost and power cost are 1150 CNY/kW and 1100 CNY/kW, respectively. The annual maintenance cost is 74 CNY and the service life is 9 years. The power interaction limit between all microgrids and distribution network is 160 kW, the upper limit of load shedding is 300 kW, and the unit load transfer cost is 0.6 CNY/kW.

The above examples are burst simulated on MATLAB platform, and burst modeling and solving are conducted by using Yalmip, CPLEX and IPOPT solvers.

Set Mode1 for all microgrids without energy storage equipment, independent operation; Mode2 configures energy storage equipment for all microgrids and operates independently; Mode3 is the cooperative operation of multi-microgrids using shared ES services regardless of demand response; Mode4 is coordinated operation of multi-microgrid using shared ES service considering demand.

The benefits of shared ES operators and the total operating costs of microgrid groups under the four modes are shown in Table1. The rated capacity and power limit configuration results of energy storage equipment in Mode2 to Mode4 are shown in Table 2.

Table 1. Sess Operator Profitability and Total Operation Costs of Microgrid Group in Four Modes

Mode	SESS Operator Profit /CNY	Microgrid Group /CNY
Mode1		23454.65
Mode2		19436.34
Mode3	238.56	19335.92
Mode4	193.59	18343.45

Table 2. Configuration Results of Rated Capacity and Power Limit of Energy Storage Equipment in Modes 2 to 4

Mode	Object	Capacity /(kW·h)	Power/kW
Mode2	Microgrid1	834.45	164.32
	Microgrid2	1543.32	267.24
	Microgrid3	0	0
Mode3	SESS	2343.57	467.21
Mode4	SESS	2485.24	476.37

It should be pointed out that the capacity allocation results of Mode4 are 141.67 kW·h more than that of Mode3, which is due to the introduction of electric and thermal comprehensive demand response at the microgrid side of Mode4, which makes the power interaction between the microgrid group and the shared energy storage in each period of the day more uneven. The shared energy storage operators need to earn as much income as possible, resulting in large capacity invested in construction.

6 Conclusion

This paper combined with the current electricity price structure and market trading rules, analyzed the market development potential of the coordination of distribution and storage

[16]. It can help grid operators reward or penalize Energy System based on grid impact and energy production. This result includes that although there is no reduction in energy costs, the proposed emission process can reduce losses and congestion.

In order to minimize energy costs for consumers, a two-step decision strategy was developed, the first step involved the use of the utility network [8] and the second step involved real-time exit from the market. There is also a repetition algorithm for non-cooperative games that can be eliminated in real time on the market.

The proposed shared ES dynamic capacity leasing model promote the optimal capacity for microgrid, overcome the user power interaction introduced by the traditional modeling method, and reveal the essence of shared energy storage to improve efficiency.

In the future work, it is necessary to build a software platform for the allocation and storage collaborative capacity configuration, economy and business model research results, and give full play to the versatility and practicability of the theoretical research.

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References

1. Sun, W., Pei, L., Xiang, W., et al.: Evaluation method of system value for energy storage in power system. Autom. Electr. Power Syst. **43**(8), 47–55 (2019)
2. Li, J., Tian, L., Lai, X.: Outlook of electrical energy storage technologies under energy Internet background. Autom. Electr. Power Syst. **39**(23), 15–25 (2015)
3. Ziegler, M.S., Mueller, J.M., Pereira, G.D., et al.: Storage requirements and costs of shaping renewable energy toward grid decarbonization. Joule **3**(9), 2134–2153 (2019)
4. Dowling, J.A., Rinaldi, K.Z., Ruggles, T.H., et al.: Role of long-duration energy storage in variable renewable electricity systems. Joule **4**(9), 1907–1928 (2020)
5. Sepulveda, N.A., Jenkins, J.D., Edington, A., et al.: The design space for long-duration energy storage in decarbonized power systems. Nat. Energy **6**, 506–516 (2021)
6. Chen, Q., Wang, K., Chen, S., et al.: Transactive energy system for distributed agents: architecture, mechanism design and key technologies. Autom. Electr. Power Syst. **42**(3), 1–7 (2018)
7. Nunna, H.K., Anudeep, S., Kumar, R.A., et al.: Multiagent-based energy trading platform for energy storage systems in distribution systems with interconnected microgrids. IEEE Trans. Ind. Appl. **56**(3), 3207–3217 (2020)
8. He, L., Zhang, J.: A community sharing market with PV and energy storage: an adaptive bidding-based double-side auction mechanism. IEEE Trans. Smart Grid **12**(3), 2450–2461 (2021)
9. Bayram, I.S., Abdallah, M., Tajer, A., et al.: A stochastic sizing approach for sharing-based energy storage applications. IEEE Trans. Smart Grid **8**(3), 1075–1084 (2017)
10. Wang, J., Zhong, H., Wu, C., et al.: Incentivizing distributed energy resource aggregation in energy and capacity markets: an energy sharing scheme and mechanism design. Appl. Energy **252** (2019)
11. Alabdullatif, A.M., Gerding, E.H., Perez-Diaz, A.: Market design and trading strategies for community energy markets with storage and renewable supply. Energies **13**(4), 972 (2020)
12. Wang, Y., Saad, W., Han, Z., Poor, H.V., Başar, T.: A game-theoretic approach to energy trading in the smart grid. IEEE Trans. Smart Grid **5**(3), 1439–1450 (2014)

13. Gu, C., Li, F., He, Y.: Enhanced long-run incremental cost pricing considering the impact of network contingencies. IEEE Trans. Power Syst. **27**, 344–352 (2012)
14. Li, F., Tolley, D.L.: Long-run incremental cost pricing based on unused capacity. IEEE Trans. Power Syst. **22**, 1683–1689 (2007)
15. Shuai, X., Wang, X., Wu, X., et al.: Shared energy storage capacity allocation and dynamic lease model considering electricity-heat demand response. Autom. Electr. Power Syst. **45**(19), 24–32 (2021)
16. Yan, X., Gu, C., Li, F., et al.: LMP-based pricing for energy storage in local market to facilitate PV penetration. IEEE Trans. Power Syst. **33**(3), 3373–3382 (2018)