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Does it reasonable to include grid-side energy storage costs in transmission and distribution tariffs? Benefit evaluation based on economic externality

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ABSTRACT

Grid-side energy storage has become a crucial part of contemporary power systems as a result of the rapid expansion of renewable energy sources and the rising demand for grid stability. This study aims to investigate the rationality of incorporating grid-side energy storage costs into transmission and distribution (T&D) tariffs, evaluating this approach using economic externality theory. We first develop a comprehensive benefit evaluation framework based on economic externality theory considering system stability, renewable energy integration, end-user, and environmental impacts. Then, using the CPLEX solver, an operating model of grid-side energy storage is constructed with the goal of reducing substation load variations. Through a case study, it is found that grid-side energy storage has significant positive externality benefits, validating the rationale for including grid-side energy storage costs in T&D tariffs. Sensitivity analysis suggests that with cost reduction and market development, the proportion of grid-side energy storage included in the T&D tariff should gradually recede. As a result, this study offers important information about whether it is reasonable to include grid-side energy storage costs in T&D tariffs in China.

1. Introduction

To address climate change and achieve sustainable development, China is constructing a power system centered on renewable energy [1]. The uncertain characteristics of renewable energy generation pose significant challenges for the safe operation of power systems [2]. Grid-side energy storage plays a key role in solving these challenges due to its flexible site selection and rapid response [3, 4].

In recent years, grid-side energy storage has been extensively deployed on a large scale and supported by government policies in China [5]. By the end of 2022, the total grid-side energy storage in China reached approximately 5.44 GWh, representing a 165.87 % increase compared to the same period last year [6]. However, due to the high investment cost and the absence of corresponding market mechanisms, energy storage projects are not commercially viable in China's electricity market [7]. To enhance energy storage investment, the National Development and Reform Commission and the National Energy Administration jointly issued "The Guidance on Accelerating the Development of New Energy Storage", which plans to incorporate the cost benefits of grid-side energy storage into the

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T&D tariff for recovery [8]. This guidance contradicts the cost formulation method for transmission and distribution services and has generated considerable debate among market investors and users [9].

It is generally acknowledged that energy storage should not be allowed to earn revenue from both market and regulatory sources since the dual system could result in disputes over how to determine regulatory rates and who owns energy storage operations [10,11]. The UK prohibits direct investment in energy storage resource operation by electrical system operators [12]. The European Union forbids transmission and distribution operators from owning and operating energy storage systems and instead encourages them to hire third parties to provide these services [13]. In principle, the Federal Energy Regulatory Commission (FERC) does not allow independent system operators to own energy storage assets, and New York State and Texas regulators prohibit utilities from owning energy storage assets [14,15]. However, the ISOs in California, Pennsylvania-New Jersey-Maryland, and the midcontinent are engaging in the practice of including energy storage as a transmission and distribution asset [16–18]. In recent years, a growing number of scholars have investigated energy storage as a transmission and distribution asset. Compared to traditional transmission and distribution facilities, energy storage is easier to install, and energy storage plays an important role in the reliable supply of electricity and the safe operation of power systems [19,20]. Some researchers suggest that grid-side energy storage projects may be economical when using surplus power to stack with other functions [21,22]. Hu et al. (2012) show the potential of installing an energy storage system to reduce the cost of grid investments [23]. Lawder et al. (2014) illustrated that the use of battery storage systems in the grid can reduce installed capacity redundancy and improve grid efficiency because there is a disconnect between the amount of energy consumers require and the energy generated [24]. Current studies generally agree that there are two models of energy storage as a transmission asset: one is energy storage as a single transmission asset that no longer provides market services; the other is energy storage as a hybrid asset that provides both transmission services and market services [25]. Arteaga et al. (2021) examine the use of energy storage for transmission congestion mitigation services as a transmission alternative, and simulation results provide the financial benefits and risks associated with allowing SATA to share its excess capacity for additional revenue [26]. Moreover, the optimal placement, type, and size of grid-side energy storage remain issues that need to be considered when designing transmission and distribution networks [27,28]. Aguado et al. (2017) targeted the problem of planning the expansion of battery energy storage systems in the transmission network, proposing a model for transmission network expansion considering energy storage systems in a market environment and verifying the validity in a modified Garver system and an IEEE 24 bus system [29]. To summarize, previous studies have demonstrated that grid-side battery storage helps to improve the stability and reliability of the electricity grid and reduces the need for costly upgrades to T&D infrastructure [30,31]. However, there is a lack of rational explanation for the inclusion of grid-side energy storage in T&D prices.

We are not aware of any strategy to conduct a formal analysis of the reasonableness of energy storage to be included in transmission and distribution tariffs at present. In particular, China's electricity market is a typically regulated market with tariffs regulated by the government, making it difficult to obtain the true marginal value and assess the value of grid-side energy storage [32,33]. Under such a background, it is necessary to objectively evaluate and maximize the value of grid-side energy storage applications and to scientifically design policy mechanisms accordingly to promote the sustainable development of grid-side energy storage [34]. Economic externalities can be an effective tool to evaluate energy storage in terms of its economic benefits to the community [35,36]. Consequently, we focus on the comprehensive application value of grid-side energy storage and establish a model for evaluating the value of grid-side energy storage considering multiple beneficiary entities based on externality theory, which analyses the rationale for accounting for the cost of grid-side energy storage in the recovery of T&D tariffs in China. Compared with previous studies, the contributions of this paper are as follows: (1) Based on the theory of economic externality, the full benefits of grid-side energy storage are evaluated, including the impact on the grid, generators, end-customer and the environment. (2) Proposes a rational approach and related policy recommendations on the inclusion of grid-side energy storage in T&D tariffs. It should be noted that this paper only considers the application of battery energy storage on the grid side and does not include some other energy storage technologies, such as pumped

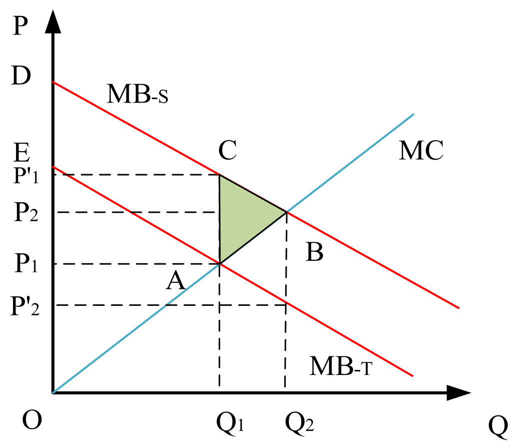

Fig. 1. The supply and demand curves for energy storage under positive externality.

storage and compressed air storage. Due to data limitations, we were only able to make a preliminary estimate of the value of energy storage based on a typical load at a provincial substation. However, we still believe that the results may be useful for policy makers and stakeholders.

The remainder of the paper is organized as follows: Section 2 introduces the theoretical foundation of this article. Section 3 constructs the model. Section 4 carries out a case study. The main conclusions and policy implications are drawn in Section 5.

2. Application of the economic externality theory in grid-side energy storage

Externality theory is an essential theoretical foundation for the study of economics, which means that the actions of one economic agent have a negative or positive impact on other economic agents without receiving a corresponding penalty or incentive [37]. A negative impact means a negative externality, and a positive impact means a positive externality. Externality theory suggests that there is a difference between quantifiable revenue and the actual economic value, which leads to a loss of social welfare. By quantifying the externality value of energy storage, multiple revenue streams can be created if market rules can be traded to compensate for each service provided by the new energy storage [38]. When energy storage investors can access the revenue streams generated by the value of this storage, energy storage projects are more likely to be invested in. Fig. 1 below shows the supply and demand for energy storage under a positive externality.

In Fig. 1, MC represents the supply curve of energy storage investors, MB-S represents the social demand curve of energy storage, and MB-T represents the market demand curve of energy storage. Point A represents the equilibrium point of market demand for energy storage, the market equilibrium price is P_1 and market demand is Q_1 at this time; Point B represents the equilibrium point of social demand for energy storage, the social equilibrium price is P_1 and social demand is Q_1 at this time; Point C represents that at Q_1. The economic significance represented by line CA is the value of the positive externality of energy storage that is not compensated by the market. When the market fails to compensate for the externality, the consumer surplus is $S_{\triangle}EP_1A$, the producer surplus is $S_{\triangle}OP_1A$, and the total economic welfare is $S_{\triangle}EOA$; when the market fully reflects the externality benefits of energy storage, the consumer surplus is $S_{\triangle}DP_2B$, the producer surplus is $S_{\triangle}OP_2B$, and the total economic welfare is $S_{\triangle}DOB$. However, because in the current electricity market environment, there is no subsidy for the energy storage positive externality value, the actual consumer surplus generated is $S_{\triangle}DP_1AC$, the producer surplus remains the same as $S_{\triangle}OP_2B$, and the actual total economic welfare is $S_{\triangle}DOAC$. Therefore, the portion of the actual total economic welfare that is less than the theoretical total economic welfare, $S_{\triangle}DOB—S_{\triangle}DOAC$, which is $S_{\triangle}CAB$, is called the net welfare loss or needless loss. The needless loss distorts the relationship between costs and benefits for market players and can lead to market inefficiencies or even failures. If externalities are not curbed, the environment on which economic development depends will continue to deteriorate and eventually the economy will lose its conditions for development.

Taking grid-side energy storage investors and social demand as an example, the externalities of grid-side energy storage are the positive or negative impacts on other economic agents arising from the production and consumption of battery energy storage systems that are not reflected in market prices [39]. More specifically, in the existing electricity market, only arbitrage and some ancillary services are available for GBES to obtain revenue [40]. Other invisible services cannot be quantified, so the energy storage cannot be compensated in a proportional way. When grid-side energy storage is operated in the power system, it generates externalities for other entities in the power system, including the grid, generators, consumers and the environment [21,41]. A schematic of grid-side energy storage electricity and externality transmission is shown in Fig. 2.

We summarize that the externalities of grid-side energy storage are mainly manifested in the following ways:

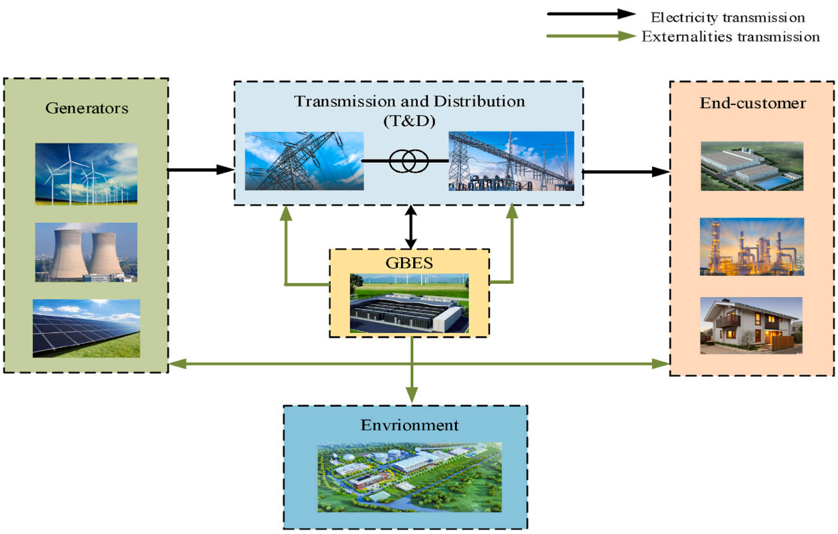

Fig. 2. Schematic of grid-side energy storage electricity and externality transmission.

(1) Delaying the investment of T&D. The most significant externality value of grid-side energy storage is deferring investment in T&D equipment, which is the most crucial reason for governments to include grid-side energy storage in T&D tariff recovery. The capacity of T&D equipment is usually planned according to the maximum load; when T&D lines become overloaded, the grid requires investment in expansion. Grid-side energy storage can charge at low loads and discharge at peak loads, which delays T&D investment.
(2) Reducing the line losses of the network. Grid-side energy storage can reduce the electric current flowing through the network lines during peak periods, which has the effect of reducing line losses and improving energy efficiency.
(3) Reducing renewable energy abandonment. Grid-side energy storage can help store renewable energy during low times and release it during peak periods, effectively balancing fluctuations in wind and solar energy and reducing renewable energy that cannot be absorbed.
(4) Saving backup generation capacity. Grid-side energy storage can provide power during peak demand periods, equivalent to a generator, and acts as a backup unit capacity for the system, which can save backup generation capacity and reduce costs.
(5) Enhancing customers' power reliability. For the customer, grid-side energy storage improves the reliability of the system power supply and ensures power quality, reducing possible electricity shortage losses.
(6) Reducing the cost of pollutant emissions. Grid-side energy storage helps reduce reliance on fossil fuel power generation and lower emissions of greenhouse gases and other pollutants, mainly SO2, NO2, CO, fly ash, slag, suspended particulate matter, etc.
(7) Decarbonization value. Grid-side energy storage supports the large-scale application of renewable energy and helps to achieve a low-carbon transformation of the energy structure. Therefore, the benefits of reducing carbon emissions from grid-side energy storage are called decarbonization value. However, some studies have shown that energy storage may lead to increased emissions from the power system, that is, negative externalities [42,43].

Point 1 and Point 2 are the externality values for the grid, Point 3 and Point 4 are the externality values for the generators, Point 5 is the externality value for the end-customer, and Point 6 and Point 7 are the externality values for the environment. The total value of grid-side energy storage is the stacking of all externality values. Combined with the analysis in Fig. 1, the value loss of externality from grid-side battery storage is shown in Fig. 3.

3. Model

In this section, we will introduce the benefit evaluation model of grid-side energy storage, including the deterministic formula of market revenue, externality value, cost, and the optimal output model of grid-side energy storage.

3.1. Externality value model

The model of the externality value is shown in Eq. (1):

$$V = V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 \tag{1}$$

where V is the total externality value, V_1 is the externality value of T&D investment deferral, V_2 is the value of reducing line losses, V_3 is the value of reducing renewable energy abandonment, V_4 is the value of saving backup generation capacity, V_5 is the value of enhancing customers' power reliability, V_6 is the value of environmental benefits, and V_7 is the value of decarbonization.

3.1.1. Externality value for the grid

The T&D investment deferral value is shown in Eq. (2):

$$V_1 = C_{sd} P_{dis} \tag{2}$$

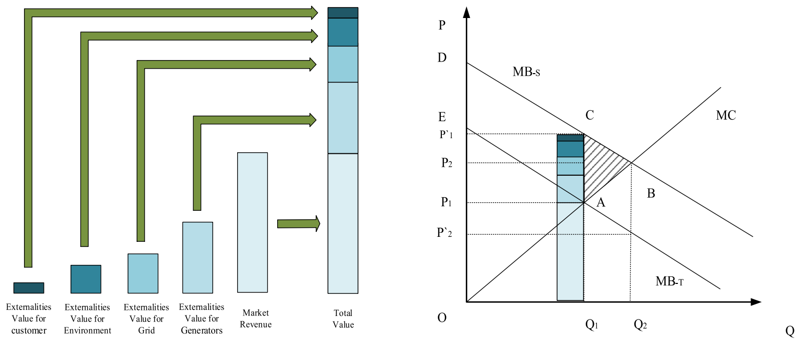

Fig. 3. The value loss of externality from grid-side battery storage.

where C_{sd} is the capacity cost of T&D equipment and P_{dis} is the load cut by the grid-side energy storage plants.

The line loss reduction value is shown in Eq. (3):

$$V_2 = \eta T Q_{char} l_s p^+(t) \tag{3}$$

where η is the round-trip efficiency, T is the number of running days, Q_{char} is the daily charge electricity of the grid-side energy storage plant, l_s is the line loss rate, and p^+(t) is the charge electricity price at moment *t*.

3.1.2. Externality value for the generators

Reducing renewable energy abandonment value is shown in Eq. (4):

$$V_3 = \eta T p_w Q_{char} \tag{4}$$

where p_w is the feed-in tariff for renewable energy. We make an assumption that all the charging power of the grid-side energy storage plant comes from renewable energy sources.

The savings backup generation capacity value is shown in Eq. (5):

$$V_4 = \eta C_{fd} P_{rate} \tag{5}$$

where C_{fd} is the capacity cost of the generation equipment and P_{rate} is the rated power of the grid-side energy storage plant.

3.1.3. Externality value for the customer

Enhancing customers' power reliability value is shown in Eq. (6):

$$V_5 = \eta S V_{DL} P_{rate} \tag{6}$$

where *S* is the number of system outages and V_{DL} is the electricity benefits for customers, measured in kWh GDP.

3.1.4. Externality value for the environmental benefits

The environmental benefits value is shown in Eq. (7):

$$V_6 = T C_{ei} Q_{dis} \tag{7}$$

where C_{ei} is the cost of pollutant treatment.

The decarbonization value is shown in Eq. (8):

$$V_7 = T p_{co^2} E_{co^2} Q_{dis} \tag{8}$$

where p_{co2} is the average market price for the carbon tax, E_{co2} is the carbon emission intensity of all forms of generation, and Q_{dis} is the daily discharge electricity of the grid-side energy storage plant.

3.2. Market revenue model

According to the existing Chinese electricity market rules, the revenue of the grid-side energy storage comes from arbitrage of electricity time-shifting, providing ancillary services and policy subsidies, etc. Therefore, the market revenue is calculated using Eq. (9).

$$R = R_1 + R_2 + R_3 \tag{9}$$

where *R* is the total revenue of the grid-side energy storage, R_1 is the electricity time-shifting revenue, R_2 is the ancillary services revenue, and R_3 is the policy subsidies revenue.

3.2.1. Electricity time-shifting revenue

The electricity time-shifting revenue obtained by the grid-side energy storage through charging at low tariffs and discharging at high tariffs is calculated using Eq. (10).

$$R_1 = \eta T \sum_{t=1}^{24} [p^-(t)P^-(t) - p^+(t)P^+(t)] \tag{10}$$

where p^-(t) is the discharge electricity price at moment t, P^-(t) is the discharge power at moment t, and P^+(t) is the charge power at moment t.

3.2.2. Ancillary services revenue

Ancillary service revenue of grid-side energy storage includes the provision of peak modulation, frequency modulation, voltage support regulation, black start, etc. The revenue of ancillary services is calculated according to "two rules" in China. The two rules are to compensate grid-connected power plants that provide paid auxiliary services in accordance with the principle of compensating costs and reasonable returns, with the shortfall to be shared by the grid-connected power plants on the basis of a uniform standard. The ancillary service revenue is calculated using Eq. (11).

$$R_2 = R_{\text{tf}} + R_{\text{tp}} + R_{\text{black}} + R_{\text{else}} \tag{11}$$

where R_{tf} is the peak modulation revenue of the grid-side energy storage, R_{tp} is the frequency modulation revenue, R_{black} is the black start revenue, and R_{else} is the other ancillary services revenue.

3.2.3. Policy subsidies

To encourage the construction of energy storage plants, government and local institutions will give investment subsidies or electricity subsidies to energy storage plants to cover the cost of energy storage. Policy subsidies obtained by grid-side energy storage are shown in Eq. (12):

$$R_3 = Tp_{\text{sub}} Q_{dis} \tag{12}$$

where p_{sub} is the subsidy price for the grid-side energy storage plant.

3.3. Cost model

3.3.1. Construction cost

The initial investment cost is mainly composed of the battery body (BP), the power conversion system (PCS), and the battery storage management system (BMS), including control devices, protection devices, installation materials, labor costs for the initial installation, etc. The initial investment cost is shown in Eq. (13):

$$C_{\text{ini}} = C_{\text{PCS}} + C_{\text{BP}} + C_{\text{BMS}} \tag{13}$$

where C_{ini} is the initial investment cost, C_{BP} is the cost of BP, C_{PCS} is the cost of PCS, and C_{BMS} is the cost of BMS.

Therefore, the cost of the annual average initial investment is shown in Eq. (14):

$$C_1 = C_{\text{ini}} \frac{r(1+r)^N}{(1+r)^N - 1} \tag{14}$$

where C_1 is the cost of the annual average initial investment, r is the interest rate, and N is the battery life.

3.3.2. Operation and maintenance costs

Operation and maintenance (O&M) costs mainly include daily maintenance, repair costs, labor wages, etc., which are related to the rated power of the energy storage. The operation and maintenance costs are shown in Eq. (15):

$$C_2 = C_{\text{om}} P_{\text{rate}} \tag{15}$$

where C_2 is the cost of O&M, and C_{om} is the unit O&M costs.

3.4. Benefit evaluation model

Considering the time value of money, three economic evaluation indicators, net present value (NPV), payback period (PP), and internal rate of return (IRR), are used to evaluate the economics of grid-side energy storage projects. Benefit valuation models without externality value are described by Eqs. 16–18:

$$NPV_1 = \sum_{\text{n}}^{N} \frac{R - C}{(1+r)^N} - C_{\text{ini}} \tag{16}$$

$$PP_1 = k - 1 + \frac{\left|NPV_1{}^{k-1}\right|}{NPV_1{}^{k} - NPV_1{}^{k-1}} \tag{17}$$

$$\sum_{\text{n}}^{N} \frac{R - C}{(1+IRR_1)^N} - C_{\text{ini}} = 0 \tag{18}$$

Therefore, the benefit evaluation models based on the externality value are described by Eqs. 19–21:

$$NPV_2 = \sum_{\text{n}}^{N} \frac{R + V - C}{(1+r)^N} - C_{\text{ini}} \tag{19}$$

$$PP_2 = k - 1 + \frac{|NPV_2{}^{k-1}|}{NPV_2{}^{k} - NPV_2{}^{k-1}} \tag{20}$$

$$\sum_{n}^{N} \frac{R + V - C}{(1 + IRR_2)^N} - C_{ini} = 0 \tag{21}$$

3.5. Optimized operating model

3.5.1. Objective model

After the construction of the grid-side energy storage plant, the load of the substation at moment t is shown in Eq. (22):

$$D_1(t) = D(t) - P^+(t) + P^-(t) \tag{22}$$

where $D_1(t)$ is the load of the substation after the construction of the grid-side energy storage plan at moment t and $D(t)$ is the load of the substation before the construction of the grid-side energy storage plan at moment t.

The objective model is to minimize the variance of the system load:

$$f = \min \sigma^2(D_1(t)) \tag{23}$$

It is important to note that, due to the application in grid-side scenarios, the actual operation of grid-side energy storage considers the load curve of the grid and operates to minimize the load fluctuations of the grid side. It does not operate to maximize the market revenue, so the market revenue on energy storage may not always be optimized.

3.5.2. Restrictions

Power constraint: As shown in Eqs. 24 and 25, the power constraint means that the charge and discharge power must not exceed the rated power. And the battery cannot be charged and discharged at the same time during cycling, as shown in Eqs. 26 and 27.

$$0 \le P^-(t) \le b^-(t) P_{\text{rate}} \tag{24}$$

$$0 \le P^+(t) \le b^+(t) P_{\text{rate}} \tag{25}$$

$$b^-(t) + b^+(t) \le 1 \tag{26}$$

$$b^-(t), b^+(t) \in \{0, 1\} \tag{27}$$

where b^-(t) is the boolean variable of discharge electricity price at moment t, b^+(t) is the boolean variable of discharge power at moment t.

The state of charge (SOC) constraint is shown in Eqs. 28–30.

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \tag{28}$$

$$SOC(t) = SOC(t-1) + \frac{\eta[P^+(t) - P^-(t)]}{E_{\text{rate}}} \tag{29}$$

$$SOC(1) = SOC(24) \tag{30}$$

where $SOC(t)$ is the state of charge for the battery at moment t, $SOC_{\min}$ is the minimum state of charge for the battery, and $SOC_{\max}$ is the maximum state of charge for the battery. E_{rate} is the rated capacity of the grid-side energy storage plant.

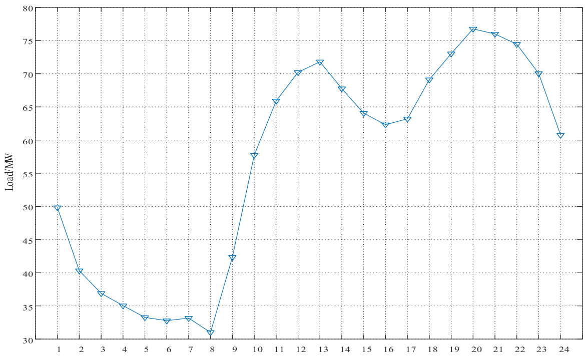

Fig. 4. The typical daily load data of a 95MWA substation in Hunan Province.

3.5.3. Solving algorithm

The objective model is a linear problem, so we use the YALMIP toolkit invoking the CPLEX solver to solve the optimization model of energy storage output in Eq. (23). The CPLEX solver has the advantages of fast convergence and good robustness to linear problems, which is suitable for solving the optimized model.

4. Case study

4.1. Basic settings

A 95MWA substation in Hunan Province of central China is taken as an example for simulation. The typical daily load data curve is shown in Fig. 4. Its load peak is 76.76 MW at 19:00, the subpeak is present at 12:00, the average load is 56.58 MW, and the daily load rate reaches 59.60 %. The substation is already operating under a heavy load. To relieve the pressure on the electricity supply, one grid-side energy storage unit is expected to be invested in a 10 MW/20 MWh energy storage plant. The energy storage plant is an AC-side grid-side energy storage plant, and the battery material is a lithium iron phosphate battery. The cost parameters required in this paper are shown in Table 1. According to Hunan Province's time-of-use tariff policy, the electricity tariff was divided into peak, flat and low periods, with peak periods being (7:00–11:00, 14:00–18:00), flat periods being (11:00–14:00, 18:00–23:00) and low periods being (23:00–7:00 the following day). The time-of-use tariff of Hunan Province is shown in Fig. 5. The auxiliary service revenue of this energy storage plant is mainly derived from peak and frequency regulation. According to the two rules, the auxiliary service revenue of grid-side energy storage is CNY 647,700. The local subsidy for energy storage plants is CNY 0.1/kWh. The other required parameters are shown in Table 2. This study was conducted with informed consent from all participants.

4.2. Optimized operation results

According to the algorithm in MATLAB 2018a, the results of the optimized power output for grid-side energy storage in the typical daily load data are shown in Fig. 6, and the comparison of the substation load curves before and after the installation of the grid-side energy storage is shown in Fig. 7.

As shown in Figs. 6 and 7, when the substation is at peak load, the grid-side energy storage will discharge electricity; when the system load is reduced, the grid-side energy storage will charge electricity, and the load cut by the grid-side energy storage is 4.26 MW (Pdis = 4.26 MW). The daily discharge electricity of the grid-side energy storage is 32.44 MWh. Unlike traditional energy storage plants, this grid-side energy storage plant does not operate in a peak-to-valley arbitrage mode; it is fully charged at low electricity prices and fully discharged at high electricity prices but regulates its own output to support the operation of the grid as the load of the substation fluctuates.

4.3. Benefit evaluation results

Analysis of the combined value of installing grid-side energy storage is simulated below in Table 3 and Table 4.

From the perspective of an investor without accounting for externalities, the NPV of the investment for the investor in the grid-side energy storage is negative, the ultimate loss of the investor would be −31719847.54 CNY, PP is 34.89 years, and the IRR for grid-side energy storage is −18.00 %. From the results of the above index calculations, it is clear that the energy storage project is not economical without accounting for externality.

From an overall perspective that considers externalities to other entities of interest, the energy storage in this example will eventually produce a benefit of 21272094.74 CNY, and the initial investment will be fully recovered after 4.81 years. The internal rate of return on the investment in grid-side energy storage is 16.12 %, which is greater than the benchmark discount rate of 6 % chosen in this paper, so grid-side energy storage is economically sound from a social perspective that takes into account externalities. The results verify the effectiveness of the phased price mechanism and economic accounting model designed in this paper and illustrate the rationality of including grid-side energy storage in transmission and distribution tariffs to a certain extent.

Based on the results of Table 4, the proportion of each externality of grid-side energy storage is calculated and shown in Fig. 8. The proportions of externalities generated by grid-side energy storage for the grid side, the generation side, the user side, and the environment are 12.86 %, 64.23 %, 4.81 %, and 18.10 %, respectively, showing that the largest beneficiaries of grid-side energy storage are generators, especially renewable energy generators. Among them, reducing the renewable energy abandonment value is 59 %, which is the largest of all externality benefits.

Based on the above analysis results, the externalities of grid-side energy storage are significant, including reducing the curtailment of renewable energy, improving grid stability, and reducing dependence on fossil fuels, so it can be preliminarily concluded that it is

Table 1
Parameters of the characteristics and cost of the grid-side energy storage.

Parameter	Numerical value	Parameter	Numerical value	Parameter	Numerical value
Prate(MW)	10	T	365	CPCS(CNY/MWh)	2,020,000
Erate(MWh)	20	N	10	CBMS(CNY/MWh)	1,000,000
η	80 %	r	5 %	Com(CNY/MWh)	1,000,000

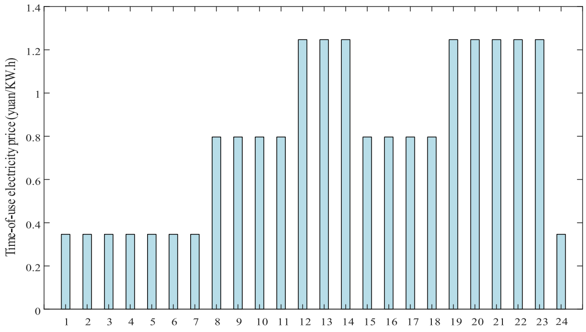

Fig. 5. Time-of-use electricity price (CNY/kWh).

Table 2
Other values of grid-side energy storage.

Parameter	Numerical value	Parameter	Numerical value	Parameter	Numerical value
C_{sd}(CNY) [44]	4,177,000	C_{fd}(CNY) [44]	3,539,000	C_{ei}(CNY/kWh) [45]	0.11
l_s(CNY)	2 %	S	2	p_{co2}(CNY/t) [45]	60
p_w(CNY/kWh) [44]	0.41	V_{DL}(CNY/kWh)	21.66	E_{co2}(kg/kWh)	2.7

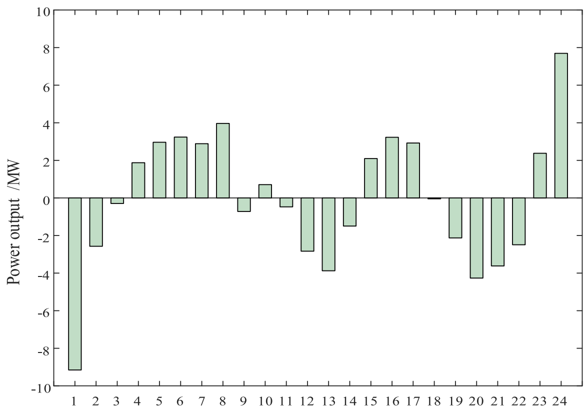

Fig. 6. Power output of the grid-side energy storage in the typical daily load data.

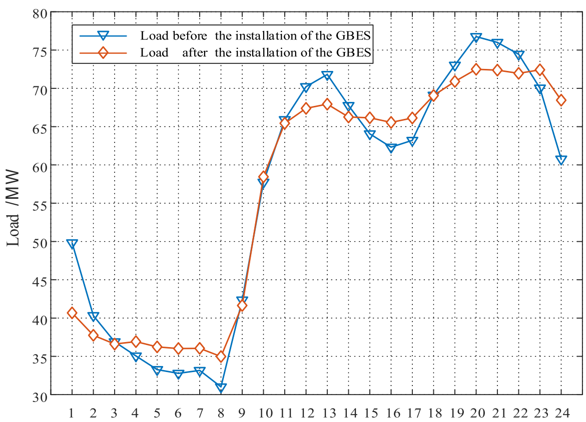

Fig. 7. Substation load curves before and after the installation of the grid-side energy storage.

Table 3
Grid-side energy storage economics assessment results (without considering externality).

		VALUE
Cash outflows	C1	5461891.92
	C2	1200000
Cash inflow	R1	520384.507
	R2	647700
	R3	1184096.5
Value evaluation indicators	NPV	−31719847.54
	PP	34.89
	IRR	−18.00 %

Table 4
Grid-side energy storage economics assessment results (considering externalities).

		VALUE
Cash outflows	C1	5461891.92
	C2	1200000
Cash inflow	R1	520384.507
	R2	647700
	R3	1184096.5
	V1	711760.8
	V2	214084.64
	V3	4262747.4
	V4	361827.36
	V5	346560
	V6	1302506.15
	V7	420.5910768
Value evaluation indicators	NPV	21272094.74
	PP	4.81
	IRR	16.12 %

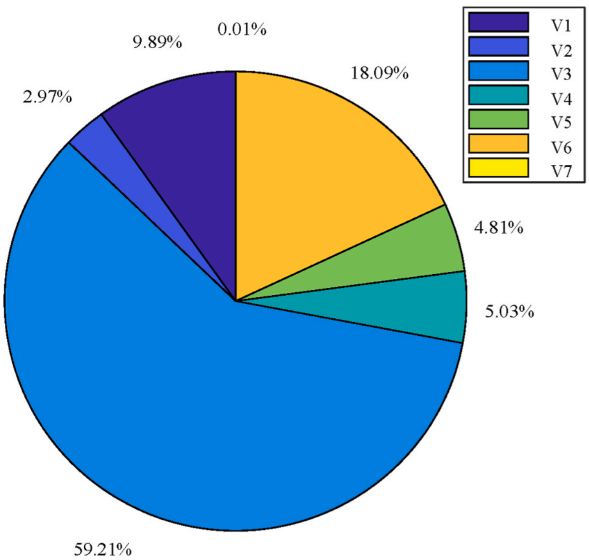

Fig. 8. Percentage of each externality for grid-side energy storage in total externality.

reasonable to consider the grid-side battery energy storage cost in the transmission and distribution price. By incorporating grid-side battery storage costs into transmission and distribution pricing, utilities can better reflect the true cost of providing reliable and safe power to customers. This could also spur the deployment of grid-side battery storage and other energy storage technologies for a more efficient and cost-effective grid. In terms of promoting the development of renewable energy, the mechanism can promote more efficient resource allocation and more sustainable development of renewable energy in China.

4.4. Sensitivity analysis

4.4.1. The impact of cost changes in economic value evaluation

Considering the development of energy storage technology, the value evaluation index of grid-side energy storage under the gradual decrease in investment cost is calculated in Table 5. Table 5 reflects that the economics of energy storage show a trend of year-on-year improvement as the cost of energy storage decreases, and when the initial cost of grid-side energy storage decreases by 60 % from the existing base, the investment in grid-side energy storage projects is only economical when externality is not being considered. However, the NPV at this point is still less than zero since the discount rate chosen for this simulation is 6 %.

4.4.2. The impact of market revenue changes on economic value evaluation

As shown in Table 6, the economics of grid-side energy storage investments gradually emerge with increasing market returns. Considering the future development of the electricity market, the widening of the peak-to-valley price difference and the increasing variety of auxiliary services, the externality of grid-side energy storage can be compensated accordingly. When the market revenue is 2.5 times the existing revenue, the grid-side energy storage project can ensure that the investment in the energy storage project does not suffer a loss without considering external factors, although the rate of return is only 1.87 %, and the net present value is still less than zero at this point.

Through sensitivity analysis, it can be seen that the economy of the grid-side energy storage system is affected by factors such as energy storage cost and market revenue. In terms of the investment cost of grid-side energy storage, the investment cost will decrease with continuous improvement of battery technology and the continuous increase of production scale; on the other hand, China's electricity market is gradually widening the peak-valley price difference, promoting energy storage to participate in the electricity market as an independent entity to obtain more benefits. At this stage, the incentive and subsidy policies to include the cost of grid-side energy storage in the transmission and distribution price can help the grid-side energy storage tide over the current investment dilemma, improve the economic benefits of the energy storage system, and promote the large-scale use of energy storage technology in the power grid. In the future, the amount of grid-side energy storage costs included in transmission and distribution prices can be gradually reduced until grid-side energy storage can compensate for the externality when it can obtain sufficient benefits in the market.

5. Conclusion and policy implications

In this study, we establish a value assessment and optimal operation model of grid-side energy storage to explore the rationality of incorporating grid-side energy storage costs into the transmission and distribution tariff mechanism based on economic externality theory. The main findings of this study are as follows. First, grid-side energy storage has significant positive externality benefits. Among them, grid-side energy storage has the largest externality benefits for generators, especially renewable energy units, emphasizing the importance of supporting the deployment of grid-side energy storage as part of an integrated strategy to promote renewable energy in China. Second, incorporating grid-side battery storage costs into transmission and distribution pricing mechanisms is a key aspect of ensuring the financial viability and sustainability of grid-side energy storage. The results of the sensitivity analysis revealed that the cost of energy storage and market revenue are the two main factors affecting the large-scale development of grid-side energy storage.

These findings verify the rationality of including the cost of grid-side energy storage stations in transmission and distribution tariffs, which has important implications for decision-makers and stakeholders in the energy system. Based on the research results, this paper puts forward the following policy recommendations to support the sustainable development of China's grid-side energy storage: (1) Encouraging investment in grid-side energy storage. From the perspective of the all-society benefit economic evaluation, grid-side energy storage has a good externality. For a specific grid-side energy storage project, a comprehensive benefit assessment model can be set to carry out a financial analysis oriented to the benefit of the power system, which can provide guidance for grid-side energy storage investment, construction, and sustainable development paths. (2) Developing a sharing mechanism that considers the costs and benefits of grid-side energy storage. Policymakers should work with stakeholders to design and implement pricing mechanisms that consider the costs and benefits of grid-side battery storage systems while addressing potential challenges and drawbacks. (3) Improving data collection and analysis. Accurately estimating the costs and benefits of grid-side battery energy storage systems is critical to designing effective pricing mechanisms. Policymakers should conduct data collection and analysis efforts to better understand the impact of battery storage integration on the grid and to inform the development of pricing structures. (4) Establishing a clear incentive and assessment system. The inclusion of grid-side energy storage in transmission and distribution tariffs may trigger

Table 5
Evaluation indicator values in cost reduction without considering externalities.

	NPV	PP	IRR
Initial cost	−40200000	34.89035122	−18.01 %
Initial cost reduction of 10 %	−36180000	28.43934928	−15.56 %
Initial cost reduction of 20 %	−32160000	23.10044444	−12.90 %
Initial cost reduction of 30 %	−28140000	18.60888337	−9.95 %
Initial cost reduction of 40 %	−24120000	14.77777274	−6.54 %
Initial cost reduction of 50 %	−20100000	11.47141758	−2.42 %
Initial cost reduction of 60 %	−16080000	8.588913112	2.87 %

Table 6
Evaluation indicator values in market returns increasing without considering externalities.

	NPV	PP	IRR
Initial market revenue	−31719832.57	34.89	−18.01 %
Initial market revenue increased by 30 %	−26526146.34	21.64	−12.03 %
Initial market revenue increased by 60 %	−21332460.11	15.68	−7.44 %
Initial market revenue increased by 90 %	−16138773.88	12.30	−3.59 %
Initial market revenue increased by 120 %	−12676316.4	10.75	−1.29 %
Initial market revenue increased by 150 %	−7482630.169	9.04	1.87 %
Initial market revenue increased by 180 %	−2288943.94	7.80	4.78 %

problems with a large amount of grid-side energy storage invested but the efficiency of its use. In considering the design of pricing mechanisms for grid-side energy storage, these challenges need to be carefully considered and addressed by establishing an incentive mechanism for grid-side capacity tariffs.

In this paper, we discuss the rationality of including grid-side energy storage costs in transmission and distribution tariffs from the perspective of economic externalities, but we believe that this study still has some limitations. First, in evaluating the economic value of the externality of grid-side energy storage, the externality value measured in this study may have some bias because some of the externality values cannot yet be quantified. Second, this paper does not explore the potential impact of grid-side energy storage costs incorporated into transmission and distribution on various stakeholders (including energy generators, consumers, and grid operators). These limitations will be further developed in subsequent studies.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Shanshan Huang: Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Ze Ye:** Writing – review & editing, Supervision, Resources. **Yunxiang Huang:** Software, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] F. Zhao, F. Bai, X. Liu, Z. Liu, A review on renewable energy transition under China's carbon neutrality target, Sustainability 14 (22) (2022), https://doi.org/10.3390/su142215006. Article 22.
[2] X. Deng, T. Lv, J. Xu, X. Hou, F. Liu, Assessing the integration effect of inter-regional transmission on variable power generation under renewable energy consumption policy in China, Energy Pol. 170 (2022), 113219, https://doi.org/10.1016/j.enpol.2022.113219.
[3] S. Bellocchi, M. Manno, M. Noussan, M. Vellini, Impact of grid-scale electricity storage and electric vehicles on renewable energy penetration: a case study for Italy, Energies 12 (7) (2019), https://doi.org/10.3390/en12071303. Article 7.
[4] R.H. Byrne, T.A. Nguyen, D.A. Copp, B.R. Chalamala, I. Gyuk, Energy management and optimization methods for grid energy storage systems, IEEE Access 6 (2018) 13231–13260, https://doi.org/10.1109/ACCESS.2017.2741578.
[5] The State Council Information Office, Responding to climate change: China's policies and actions. http://english.scio.gov.cn/m/whitepapers/2021-10/27/content_77836502.htm, 2021. (Accessed 27 October 2021).
[6] Energy Storage China Network, Industry Statistics of Electrochemical Energy Storage Power Stations in 2022. April 4, 2023. http://cesa.escn.com.cn/news/show-1571462.html.
[7] Y. He, Y. Liu, M. Li, Y. Zhang, Benefit evaluation and mechanism design of pumped storage plants under the background of power market reform—a case study of China, Renew. Energy 191 (2022) 796–806, https://doi.org/10.1016/j.renene.2022.03.070.
[8] National Development and Reform Commission, National Energy Administration, Guidance on Accelerating the Development of New Energy Storage, 2021. http://www.gov.cn/zhengce/zhengceku/2021-07/24/content_5627088.htm.
[9] National Energy Agency, Cost Formulation Method for Transmission and Distribution Services, 2019. http://www.gov.cn/xinwen/.
[10] R. Sioshansi, P. Denholm, T. Jenkin, Market and policy barriers to deployment of energy storage, Econ. Energy Environ. Pol. 1 (2) (2012) 47–64. https://www.jstor.org/stable/26189491.
[11] Z.Y. Shi, C.X. Wang, J. Hu, A price formation mechanism and cost diversion optimization method for designing an independently new energy-storing power station, Energy Storage Sci. Technol.. 2022 11 (12) (2022) 4067–4076, https://doi.org/10.19799/j.cnki.2095-4239.2022.0367.
[12] Ofgem, Upgrading Our Energy System-Smart Systems and Flexibility Plan, 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633442/upgrading-our-energy-system-july-2017.pdf.
[13] Council of Eurpean Energy Regulators, Implementation of TSO and DSO Unbundling Provisions–Update and Clean Energy Package Outlook.C18-LAC-02-08 14 June 2019, 2019. https://www.ceer.eu/documents/104400/-/-/f69775aa-613c-78a5-4d96-8fd57e6b77d4.

[14] M. Brooks, RTOs/ISOs file FERC order 841 compliance plans, in: RTO Insider, 2018. https://rtoinsider.com/ferc-order-841-energy-storage-compliance-107534.
[15] J. Chang, J. Pfeifenberger, K. Spees, M. Davis, The Value of Distributed Electricity Storage in Texas. Prepared for ONCOR, The Brattle Group, 2015. https://www.brattle.com/wp-content/uploads/2017/10/7589_the_value_of_distributed_electricity_storage_in_texas.pdf.
[16] California ISO (CAISO), Storage as a transmission asset. Issue paper. March 20. http://www.caiso.com/Documents/IssuePaper-StorageasaTransmissionAsset.pdf, 2018.
[17] PJM, Storage as a transmission asset. , 2020 https://www.pjm.com/committees-and-groups/issue-tracking/issue-trackingdetails.aspx?Issue={B435C39B-D4BB-4C3CADA9-8EFBC0E52246}.
[18] Midcontinent Independent System Operator, Compliance Filing for Storage as a Transmission Only Asset Docket No. ER20-588, 2021. https://cdn.misoenergy.org/2020-09-23_Docket%20No.%20ER20-588-002477500.pdf.
[19] Sandia, Energy storage for the electricity grid: benefits and market potential assessment guide, in: A Study for the DOE Energy Systems Program, 2010. Sandia National Laboratories, https://www.smartgrid.gov/files/energy_storage.pdf.
[20] D.S. Mallapragada, N.A. Sepulveda, J.D. Jenkins, Long-run system value of battery energy storage in future grids with increasing wind and solar generation, Appl. Energy 275 (2020), 115390, https://doi.org/10.1016/j.apenergy.2020.115390.
[21] P.J. Balducci, M.J.E. Alam, T.D. Hardy, D. Wu, Assigning value to energy storage systems at multiple points in an electrical grid, Energy Environ. Sci. 11 (8) (2018), https://doi.org/10.1039/C8EE00569A.
[22] T. John, I. Sarantakos, T.T. Teo, Stacking different services of an energy storage system in a grid-connected microgrid, Renew. Energy 195 (2022) 357–365, https://doi.org/10.1016/j.renene.2022.06.035.
[23] Z. Hu, F. Zhang, B. Li, Transmission expansion planning considering the deployment of energy storage systems, in: 2012 IEEE Power and Energy Society General Meeting, 1–6, 2012, https://doi.org/10.1109/PESGM.2012.6344575.
[24] M.T. Lawder, B. Suthar, P.W.C. Northrop, S. De, C.M. Hoff, O. Leitermann, M.L. Crow, S. Santhanagopalan, V.R. Subramanian, Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications, Proc. IEEE 102 (6) (2014) 1014–1030, https://doi.org/10.1109/JPROC.2014.2317451.
[25] D.P. Brown, D.E.M. Sappington, Motivating the optimal procurement and deployment of electric storage as a transmission asset, Energy Pol. 138 (2020), 111202, https://doi.org/10.1016/j.enpol.2019.111202.
[26] J. Arteaga, H. Zareipour, N. Amjady, Energy storage as a service: optimal sizing for transmission congestion relief, Appl. Energy 298 (2021), 117095, https://doi.org/10.1016/j.apenergy.2021.117095.
[27] M. Perčić, L. Frković, T. Pukšec, B. Ćosić, O.L. Li, N. Vladimir, Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation, Energy 251 (2022), 123895, https://doi.org/10.1016/j.energy.2022.123895.
[28] G.A. Di, A. Giuseppi, F. Liberali, A. Ornatelli, A. Rabezzano, L.R. Celsi, On the Optimization of Energy Storage System Placement for Protecting Power Transmission Grids against Dynamic Load Altering Attacks. 2017 25th Mediterranean Conference on Control and Automation (MED). 986–992, 2017, https://doi.org/10.1109/MED.2017.7984247.
[29] J.A. Aguado, S. de la Torre, A. Triviño, Battery energy storage systems in transmission network expansion planning, Elec. Power Syst. Res. 145 (2017) 63–72, https://doi.org/10.1016/j.epsr.2016.11.012.
[30] H. Othman, Energy Storage Applications in Transmission and Distribution Grids. Elements in Grid Energy Storage, 2022, https://doi.org/10.1017/9781009029223.
[31] W. Jeon, J.Y. Mo, The true economic value of supply-side energy storage in the smart grid environment – the case of Korea, Energy Pol. 121 (2018) 101–111, https://doi.org/10.1016/j.enpol.2018.05.071.
[32] W. Wu, B. Lin, Application value of energy storage in power grid: a special case of China electricity market, Energy 165 (2018) 1191–1199, https://doi.org/10.1016/j.energy.2018.09.202.
[33] Z. Wang, X. Wang, Y. Mao, Commercial Mechanism Analysis and Benefit Evaluation of Energy Storage. E3S Web of Conferences, 2021, https://doi.org/10.1051/e3sconf/202127101002.
[34] D. Parra, R. Mauger, A new dawn for energy storage: an interdisciplinary legal and techno-economic analysis of the new EU legal framework, Energy Pol. 171 (2022), 113262, https://doi.org/10.1016/j.enpol.2022.113262.
[35] Y. Liu, Z. Abdul Karim, N. Khalid, F.F. Said, Benefit modeling and analysis of wind power generation under social energy economy and public health, J. Environ. Publ. Health 2022 (2022), 5635853, https://doi.org/10.1155/2022/5635853.
[36] X. Wang, H. Zhao, Q. Su, Z. Siqin, Y. Zhao, J. Wang, Value quantification of multiple energy storage to low-carbon combined heat and power system, Environ. Sci. Pollut. Res. Int. 29 (48) (2022) 73577–73598, https://doi.org/10.1007/s11356-022-21036-w.
[37] K. Arrow, Political and Economic Evaluation of Social Effects and Externalities, Front. Quant. National Bureau of Economic Research, 1971. http://www.nber.org/chapters/c3349.
[38] R. Sioshansi, P. Denholm, T. Jenkin, J. Weiss, Estimating the value of electricity storage in PJM: arbitrage and some welfare effects, Energy Econ. 31 (2) (2009) 269–277, https://doi.org/10.1016/j.eneco.2008.10.005.
[39] N.S. Wade, P.C. Taylor, P.D. Lang, P.R. Jones, Evaluating the benefits of an electrical energy storage system in a future smart grid, Energy Pol. 38 (11) (2010) 7180–7188, https://doi.org/10.1016/j.enpol.2010.07.045.
[40] Y. Xie, L. Yu, X. Chang, X. Yin, H. Zheng, Research on the transaction mode and mechanism of grid-side shared energy storage market based on blockchain, Energy Rep. 8 (2022) 224–229, https://doi.org/10.1016/j.egyr.2021.11.044.
[41] J.M. Eyer, G.P. Corey, Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide : a Study for the DOE Energy Storage Systems Program. (SAND2010-0815). Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States), 2010, https://doi.org/10.2172/1031895.
[42] E.S. Hittinger, I.M.L. Azevedo, Bulk energy storage increases United States electricity system emissions, Environ. Sci. Technol. 49 (2015) 3203–3210, https://doi.org/10.1021/es505027p.
[43] Y. Lin, J.X. Johnson, J.L. Mathieu, Emissions impacts of using energy storage for power system reserves, Appl. Energy 168 (2016) 444–456, https://doi.org/10.1016/j.apenergy.2016.01.061.
[44] China Electricity Council, China Power Industry Annual Development Report, China Building Materials Press, 2021. https://cec.org.cn/detail/index.html?3-298424.
[45] H. Zhao, H. Lu, S. Zhang, Y. Wang, Value measurement and economic evaluation of energy storage system considering externality, J. Tech. Econ. 39 (10) (2020) 19–26+53.