Cost–Benefit Analysis of Energy Storage in Distribution Networks

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Abstract: Due to the challenges posed to power systems because of the variability and uncertainty in clean energy, the integration of energy storage devices (ESD) has provided a rigorous approach to improve network stability in recent years. Moreover, with the rapid development of the electricity market, an ESD operation strategy, which can maximize the benefits of ESD owners as well as the contribution to the electricity network stability, plays an important role in the marketization of ESDs. Although the benefits for ESD owners are discussed in many studies, the economic impact of ESD operation on distribution networks has not been commendably taken into account. Therefore, a cost–benefit analysis method of ESD which quantifies the economic impact of ESD operation on distribution networks is proposed in this paper. Considering the time-of-use (TOU) price and load demand, the arbitrage of ESD is realized through a strategy with low price charging and high price discharging. Then, the auxiliary service of ESD is realized by its capability of peak shaving and valley filling. In this paper, the long-run incremental cost (LRIC) method is adopted to calculate the network price based on the congestion cost. Based on the dynamic cost–benefit analysis method, the cost–benefit marginal analysis model in the ESD life cycle is proposed through the calculation of the present value of benefit. Subsequently, the optimal ESD capacity and charge/discharge rate is obtained to get the shortest payback period by analyzing different operation parameters. Finally, a case study is undertaken, where the ESD operation model mentioned above is simulated on a two-bus system and a 33-bus system, and the ESD cost–benefit analysis and the analysis of corresponding influence factors are carried out adequately.

Keywords: energy storage device (ESD); cost–benefit analysis; long-run incremental cost method; payback period

1. Introduction

With the intensification of global issues, such as environmental pollution, global warming, and energy shortages, the permeability of clean energy in power systems rises rapidly, while the technology of clean energy consumption is still immature. As a result, it is important to develop an energy storage technology. In practice, energy storage devices (ESD) can be deployed for different applications, such as peak shaving and valley filling, power quality improvement, and grid stabilization [1]. On this basis, the ESD will exert an economical influence on the system operation, because of congestion mitigation and investment deferral. An appropriate ESD pricing method can reasonably describe the system economic impact caused by ESD, so that ESD owners can profit under specific charging and discharging modes. At the same time, there will also be more investors attracted to expanding ESD markets. Furthermore, both the system stability and consumption of clean energy will be improved.
significantly. Hence, it is important to put forward an appropriate cost–benefit method of ESDs in distribution networks.

Moreover, the electricity market reform has been carried out gradually around the world, and the pilot work of an incremental distribution network is on its way [2]. The incremental distribution network encourages multiple subjects, such as grid companies or individual users, to invest jointly, thus, there is no longer a single form of monopoly for system planning and construction. The permeability of clean energy, such as solar energy, wind energy, tidal energy, nuclear energy, and geothermal energy is increasing rapidly, and the number of ESD users in local power networks is also increasing year by year. Under the background described above, the power supply, network, and load construction are presented as a new mode of investment opening. Therefore, it is more practical to discuss the investment benefits of ESDs in the network under the mode.

The motivation and incitement of this paper were discussed above. To keep abreast of current information and development in the field of ESDs, the literature reviews are introduced as follows.

There are several relevant studies on the charge and discharge rate of the ESD and its coordinated operation between ESD and generator. In [3], a control strategy for an ESD and wind power generation was proposed to eliminate the output clearance. Then, the charging and discharging rate of the ESD and its output limitation was analyzed. In [4], a two-layer equilibrium model was proposed, which combined wind turbines with traditional generators to achieve output coordination between power generation and the ESD. However, the above studies mostly focused on the performance and benefits of the ESD itself. They did not consider the impact of the ESD on network operation stability and economy. Therefore, the research on ESD operation mode is still insufficient.

The ESD operation mode varies with its types and optimization goals. Based on the genetic algorithm, the fast charging problem of a lithium battery and its optimized temperature rise strategy were studied to achieve a balance between the life cycle and charge/discharge rate of an energy storage battery [5]. The research considered the effect of the charge/discharge rate on the life cycle of energy storage and did further research for their collaborative optimization, which provides reference value for this paper. [6] studied the charging and discharging modes of multi-tank thermal ESD, based on the thermal behavior of multi-tank thermal ESD in the transient system (TRNSYS). A charging and discharging method of a coupled system containing photovoltaics and ESD, based on time-of-use price, was proposed in [7]. Furthermore, the economic benefits of ESDs in the new type of distributed photovoltaic network were also evaluated in [7]. The above literature discussed the charging and discharging methods of different ESD technologies, which varied with ESD type. At present, charge/discharge methods related to lithium battery ESDs have some reference value for the high energy conversion efficiency, relatively low cost, and high popularity of the lithium battery.

The ESD operation model and investment scheme also have a significant impact on its planning method. The ESD locating and sizing problem were discussed mainly from a cost reducing perspective. Based on the energy storage system in the transmission network, reference [8] discussed the economic benefits of the ESD’s participation in the electricity market from the aspects of direct and indirect benefit, and considered the impact of charge and discharge on the life cycle of energy storage. Then, a multi-objective double layer model considering the comprehensive planning and optimized allocation of ESDs was proposed, which can help us with ESD locating and sizing under an electric market. In [9], it was concluded that the capacity of an energy storage system affected by the charging strategy can be less than 200 MW/h. Reference [10] determined the optimal capacity of an energy storage system using dynamic programming, which showed that the optimal capacity of the ESD varied with daily load and seasonal load. Considering investment cost, [11] determined the optimized location and capacity of ESD using Benders decomposition, which reduced daily operation costs significantly. In [12], a charging and discharging predictive control method for battery ESDs was proposed. On this basis, it presented that the ESD capacity required for reducing hourly wind power fluctuation and minimizing operation cost should be about 75% of the nameplate capacity of the wind farm. In practice, ESDs in different types and capacities are deployed in different application scenarios, such as energy
management, backup power, load balancing, frequency regulation, voltage stability, and grid stability. However, considering different operation modes and investment planning, energy storage locating and sizing results will also be affected by investment decisions, due to the different benefits of users.

Many studies have quantified the economic benefits of ESDs. In [13], an ESD economic benefit model based on policy subsidies and time-of-use price, which promoted wind energy consumption, was proposed. Reference [14] discussed the ESD in order to promote photovoltaic consumption, and maximized the economic benefits of the coordinated operation of ESDs and photovoltaics through optimization algorithms. In [15], it was concluded that the cost of a hybrid energy storage system is greatly affected by ramp-rate and dependence between the power of wind farms and photovoltaic stations. In [16], both the economic benefits of pumped storage and compressed-air ESDs were analyzed, and the advantages and potentials of ESD arbitrage were evaluated. Reference [17] analyzed the economic benefits of ESD arbitrage through demand response, but there were some insufficiencies, including investment costs exceeding profit capping in certain regions. The ESD benefits mainly came from the investment deferral and system ancillary service. Reference [18] discussed how individual investors made profits with ESDs through random frameworks in the day-ahead electricity market. In [19], the optimization model for maximal revenue of the photovoltaic-battery energy storage system in typical scenarios, considering power generation revenue, assessing rewards or penalties, and peak shaving and valley filling, revenue of the battery energy storage system (BESS) was established. In [20], a profit model of energy storage based on a strategy in which the ESD charged when prices were low, and otherwise the ESD discharged, was proposed.

However, these studies mainly focused on the benefits mode and actual possible benefits of ESDs, but the economic impact of ESD operation on distribution networks were not considered. On this basis, an ESD control strategy based on dual-response mechanism is proposed in this paper. Furthermore, the network price of ESDs, which quantifies the economic impact of ESDs on congestion mitigation and investment deferral in distribution networks, is analyzed in this paper.

The main contributions of this paper are as follows:

1. An ESD control strategy is proposed, which responds to time-of-use (TOU) price for the user benefits in the first place, and then responds to load demand for the network benefits. More specifically, the candidate period for ESD charging and discharging is determined in accordance with the variation of price, and then the charge/discharge scheme is determined on the basis of the actual load profile. As a result, the operation of ESDs can make the power flow flatter, and an arbitrage mode with low price charging and high price discharging is achieved;

2. A pricing model based on the congestion cost is proposed to calculate ESD value potentiality using long-run incremental cost method, which quantifies the benefits of users from ESD operation;

3. A calculation model based on the pricing model is proposed to conduct cost–benefit marginal analysis. By analyzing the cost and profits of ESD users, the impact of different ESD capacities and charge/discharge rates on payback period is determined. As a result, the optimal ESD capacity and charge/discharge rate can be determined, which has an important reference value for ESD planning in the future.

The rest of this paper is organized as follows. In Section 2, the models, including ESD operation strategy and benefits calculation, as well as quantitative analysis parameters, are established. Section 3 presents an overview of evaluating ESD operation benefits. In Section 4, numerical case studies verify the effectiveness of the proposed models. The conclusions are given in Section 5.

2. Cost–Benefit Analysis Model

The benefits of ESD operation are mainly reflected in the strategy with low price charging and high price discharging and in the network investment deferral. The appropriate investment strategy can help ESD users to explore the value potential of ESDs further. By selecting optimal battery capacity and operation parameters, ESD users can maximize their profits, and thus, more potential investors are
attracted to join the ESD market, which pushes the marketization of ESD. Therefore, after confirming specific indexes for evaluating investment projects, the actual parameters of the ESD, and the constraint conditions of the local distribution network, the benefit modes, based on different investment methods, are presented for ESD investors, and the optimal investment method is subsequently determined.

2.1. Cost–Benefit Analysis Indexes

The cost–benefit analysis method, which analyzes the advantages and disadvantages according to the economic and social benefits of the target investment project, can help make corresponding judgments and conclusions on the specific attributes of the investment project. In the process of evaluating the economic benefits of the investment project, due to the consideration of the present value of income and expenses during the project, the cost–benefit analysis is divided into the dynamic cost–benefit analysis method and static cost–benefit analysis method, according to the time span of the investment project. Since the network pricing method proposed in this paper is determined by the difference in the benefit from investment deferral before and after the ESD integration, the dynamic cost–benefit analysis method is adopted in this paper. In order to quantify the economic impact on users and network operators because of the operation of ESD, the net present value, the payback period and the internal rate of return are utilized in this paper as the cost–benefit analyses indexes, where the payback period and the internal rate of return are calculated based on the net present value.

Among the various dynamic analysis methods, the net present value method is widely used because of its simple calculation and intuitive results. The amount of income and expenses during the ESD life cycle are converted into the algebraic sum of the initial values of the project, which can be expressed as [21]:

\[
\text{Profit} = \text{Benefit}_{\text{now}} - \text{Cost}_{\text{now}}, \tag{1}
\]

\[
\text{Benefit}_{\text{now}} = \sum \frac{\text{Benefit}}{(1 + dr)^{\text{year}}}, \tag{2}
\]

where Profit is the net present value of the investment project; Benefit\text{now} is the profit present value of the investment project; Cost\text{now} is the cost present value of the investment project; Benefit is the annual profit of the investment project; dr is the discount rate.

The discount rate is the ratio of the expected income in the future to the present value, which represents the rate of return under certain conditions. When the objective can be divided into economic benefit and social benefit, the value of the market interest rate can be the discount rate. For energy users, on the one hand, they maximize their own profits. On the other hand, they also undertake social responsibility as they improve the network stability through the ability of peak shaving and valley filling. As a result, when choosing the value of the discount rate, the market interest rate is adopted in this paper.

Through the calculation of the net present value, it is easy to estimate all the income and expenses during the project period. If the net present value of a project is a positive number, the project is profitable. Otherwise, the project will generate losses and should be rejected. It should be explained that a net present value of zero means no losses and no profits in the investment project. That is, the benefit is equal to the investment, which means the payback period is achieved. In the follow-up analysis, the investment scheme which has the shortest payback period can be found according to the different values of ESD capacity and charge/discharge rate.

In the net present value calculation mentioned above, the discount rate is considered as a specific value. However, the actual discount rate varies with time and region. So, the internal rate of return is adopted as the auxiliary qualitative analysis. The internal rate of return is an expected return rate of a certain project, and it can be used to confirm whether the project is profitable, which means the larger the value is, the bigger the profit is. One problem is that it cannot reflect the exact investment benefit, nor the comparison between investment projects. However, combined with the net present value analyzing cost benefits, the cost–benefit analysis in the life cycle of ESD can be done.
The investment horizon and the net present value of investment benefits are used to calculate the internal rate of return, and the calculation of the net present value needs the economic benefits brought from the operation of ESD, the investment cost, and the duration of ESD life cycle. Based on the cost–benefit analysis indexes, the economic parameters of ESD are obtained to conduct economic analysis in regard to ESD.

2.2. Operation Model of ESD

The client of the ESD must be clear before designing the charge/discharge strategy of the ESD. For power grid operators, the optimization objective is grid stability, i.e., the objectives are aimed at minimizing the variation range of the power flow and flattening the load profile. When the client comes to the ESD owner, the optimization objective should be maximizing the benefits to the users. In this paper, in order to attract more potential ESD investors, the ESD users are considered as the research subject and the charge/discharge strategy is designed based on the TOU price and load demand [22].

The designing of the charge/discharge strategy is dependent on the client of the ESD, and should aim to maximize the users’ benefits. The ESD arbitrage is achieved through the charge/discharge strategy which responds to the TOU price. That is, the state of the ESD is established based on the strategy with low price charging and high price discharging. Then, the charge/discharge period can be determined combined with the load demand. The objective is presented as:

$$PR_{opt} = \text{Max} \sum_{t=1}^{24} \left( Dr_t \times Tou_t \times \frac{pf_t \times I_{impact}}{pf_{AVE}} - Cr_t \times Tou_t \times \frac{pf_t \times I_{impact}}{pf_{AVE}} \right), \quad (3)$$

where $Dr_t$ and $Cr_t$ represents the charge/discharge rate of the ESD, respectively, at time $t$; $PR_{opt}$ is the benefit obtained from the strategy based on the low price charging and high price discharging; $Tou_t$ is the price under the time-of-use price mode; $pf_t$ represents the real-time load at the bus where the ESD locates at time $t$, which represents the power flow at the bus in the subsequent calculation as well; $pf_{AVE}$ represents the average value of the real-time load in a day; $I_{impact}$ is the impact factor of the load profile, which is set as a small value in order not to affect the main response factor of $Tou_t$.

The constraints contain the upper limit of line capacity, the power balance constraint and related parameters constrains of ESD. The formulations are shown as follows:

$$\text{Power}_{l} \leq \text{Capacity}_{l}; \quad (4)$$

$$p^G_k - p^L_k = \sum_{i=1}^{N} V_i V_k [G_{ki} \cos(\theta_k - \theta_i) + B_{ki} \sin(\theta_k - \theta_i)]; \quad (5)$$

$$Q^G_k - Q^L_k = \sum_{i=1}^{N} V_i V_k [G_{ki} \sin(\theta_k - \theta_i) + B_{ki} \cos(\theta_k - \theta_i)]; \quad (6)$$

$$\sum_{t=1}^{24} Dr_t = \sum_{t=1}^{24} Cr_t; \quad (7)$$

$$Dr_t \leq D\text{rate}; \quad (8)$$

$$Cr_t \leq C\text{rate}; \quad (9)$$

$$S\text{OC}_{\text{Min}} \leq \text{SOC} \leq S\text{OC}_{\text{Max}}; \quad (10)$$

where $\text{Power}_{l}$ represents the power flow of line $l$; $\text{Capacity}_{l}$ represents the upper capacity limit of line $l$; $p^G_k$, $p^L_k$, $Q^G_k$ and $Q^L_k$ represent the active power and reactive power of the generator and load at bus $k$, respectively, $i, k \in N$ ($N$ is the bus number); $V$ is the bus voltage with the angle $\theta$; $C\text{rate}$ is the maximum
charge rate per hour; \( D_{rate} \) is the maximum discharge rate per hour; \( SOC_{Min} \) and \( SOC_{Max} \) are the state constraints of ESD.

2.3. Profits Model of ESD

In the above ESD operation scheme, the daily benefits through ESD operation can be calculated as:

\[
PR = \sum_{t=1}^{24} (D_t \times Tou_t - C_t \times Tou_t).
\]  

(11)

In the operation process of ESD, in addition to the profits from the strategy with low price charging and high price discharging, the economic impact of peak shaving and valley filling by the ESD on the network can also be a part of the user’s income. In order to quantify the economic impact of ESD on users and the network accurately, the long-run incremental cost method is introduced to calculate the present value of annual congestion cost and annual investment cost, for which the comparison determines the investment triggering time. Then, through power injection, the network price can be obtained by comparing the moment of change. The total annual congestion cost is presented as [23]:

\[
Cc = \sum_{t=1}^{8760} \sum_{i=1}^{N_G} Ca_i^{G_i} \times c_i^{G_i} \times \left( \frac{l f_i^{G_i} - l f_i^{G_i}}{T} \right),
\]  

(12)

\[
l f_i^{G_i} = \frac{\sum_{t=1}^{T} P_i^{G_i}}{Ca^{G_i} \times DT},
\]  

(13)

where \( Cc \) is the total congestion cost of all generators in the system within one year; \( c_i^{G_i} \) is the cost of generator \( G_i \) at time \( t \); \( Ca_i^{G_i} \) is the installed capacity of \( G_i \) at time \( t \); \( l f_i^{G_i} \) is the load factor of \( G_i \) without line capacity constraints; \( l f_i^{G_i'} \) is the load factor of \( G_i \), considering line capacity constraints; \( P_i^{G_i} \) is the output power of \( G_i \) at time \( t \); \( Ca^{G_i} \) is the capacity of \( G_i \); \( DT \) is the duration of time \( T \); \( N_G \) is the number of the generator in the distribution network.

The power transfer distribution factor (PTDF) matrix can quantify the impact of nodal power variation on the branch power flow. Assuming the power flow change of node \( m \) is \( \Delta P_m \), and the power flow change of line \( l \) by which node \( m \) and node \( n \) are connected is \( \Delta P_l \), then PTDF can be expressed as [24]:

\[
PTDF = \frac{\Delta P_l}{\Delta P_m}
\]  

(14)

The change in line power flow is highly correlated with the change in the nodal power injection. The change in generator cost in a specific node can be converted into the congestion cost of the line, which connects to the node though the PTDF method. The PTDF allocation method of converting the node to the line is presented as:

\[
Cc_{lm} = PTDF_l \times Cc_m,
\]  

(15)

where \( Cc_m \) is the total annual congestion cost of generator in node \( m \); \( Cc_{lm} \) is the congestion cost of line \( l \) connected to the node \( m \). \( Cc_m \) is calculated as:

\[
Cc_m = \sum_{i=1}^{8760} Ca_i^{G_i} \times c_i^{G_i} \times (l f_i^{G_i} - l f_i^{G_i'}).
\]  

(16)

For line \( l \), the total annual congestion cost is presented as:

\[
Cc_l = \sum_{m=1}^{N_G} (PTDF_l \times Cc_m).
\]  

(17)
It is convenient to calculate the cost using PTDF, which converts the congestion cost of the generator into the line’s congestion cost. The long-run incremental cost (LRIC) method used in this paper is based on the change in long-term cost caused by micro-increments. For node \( m \), the benefit from investment deferral before and after power injection is different. The change in the annual investment cost after the power injection is considered \( \Delta IC \). Then, the long-run incremental cost can be calculated through the ratio of \( \Delta IC \) to the nodal power injection. The formula is written as:

\[
    L = \frac{\Delta IC_l}{\Delta P_{im}}
\]  

where \( L \) is the long-run incremental cost; \( \Delta IC_l \) is the change of annual investment cost after the power injection; \( \Delta P_{im} \) is the nodal power injection (the micro-increment).

The LRIC method is calculated based on the investment time variation when the power injection happens. For node \( m \), the power injection is \( \Delta P_{im} \), and the power flow variation of line \( l \) caused by \( \Delta P_{im} \) is \( \Delta P_l \). As a result, the congestion cost and investment time are changed accordingly. The new investment time after the power injection is:

\[
    y_I = y_C + y_{CM} \quad \text{when} \quad CC^y_l > IC^y_l,
\]

where \( y_I \) is the investment horizon after the power injection; \( CC^y_l \) and \( IC^y_l \) are the annual congestion present value and the annual investment present value after power injection, respectively; \( y_C \) is the time when line congestion occurs; \( y_{CM} \) is the time deferral because of congestion management. The calculation formulas are as follows:

\[
    IC^y_l = \frac{A_l \times AF}{(1 + dr)^{y_I}},
\]

\[
    CC^y_l = \frac{CC^y_l}{(1 + dr)^{y_I}},
\]

where \( A_l \) is the initial investment cost of branch \( l \); \( AF \) is the annuity factor; \( CC^y_l \) is the congestion cost of branch \( l \) at time \( y_I \).

Combined with the method presented in Equation (18), the network price considering congestion management is presented as [25]:

\[
    L_l = \frac{IC^y_l - IC^{y_I}_l}{\Delta P_{im}},
\]

where \( IC^y_l \) is the annual investment present value without power injection.

The integration of energy storage is not considered in the above network pricing method. When energy storage is integrated into the network, the power flow changes and the new investment time is generated. The network price after the ESD integration is determined as:

\[
    L_{ls} = \frac{IC^{y_{ls}}_l - IC^{y_{ls}}_{ls}}{\Delta P_{im}},
\]

where \( IC^{y_{ls}}_l \) is the annual investment present value after power injection, when the ESD is integrated into the network; \( IC^{y_{ls}}_{ls} \) is the annual investment present value without power injection after ESD integration.

Through the difference in the network price with and without ESD operation, the economic impact of ESD on the network can be quantified:

\[
    L_s = L_{ls} - L_l.
\]
If the result is positive, it means that the owner of the ESD needs to pay the network operator for harming network operation. If the result is negative, it means that the ESD owner should get the reward from network operator for the auxiliary service. That is, the network investment is deferred due to the ability of peak shaving and valley filling by the ESD, which improves the network stability further. Finally, the net present value of ESD is determined as:

$$\text{Benefit}_{\text{now}} = PR_{\text{Is}} - L_is, \quad (25)$$

where $PR_{\text{Is}}$ is the daily arbitrage present value, and it is calculated as:

$$PR_{\text{day}} = \frac{\sum_{t=1}^{24} (Dr_t \times Tou_t - Cr_t \times Tou_t)}{(1 + dr)^{n_{\text{day}}}}, \quad (26)$$

where $n_{\text{day}}$ is the number of ESD operation days.

### 3. Framework of Cost–Benefit Analysis

Figure 1 shows an overview of the steps employed in the proposed strategy and models. The charge/discharge strategy for the ESD, network price calculation, and investment analysis are shown in Figure 1, which can be divided into two parts: the operation optimization model and network price calculation model. The internal connections among them are that the benefits calculation model is obtained from the operation optimization model. Then, the cost–benefit analysis is based on the operation optimization model and the benefits calculation model.

The left half of the figure represents the operation optimization model of ESD. The threshold price of charging and discharging, which mainly depends on the average level of the daily load or the daily price defined subjectively, is set first. Since the value of the threshold price is at the middle level, it can be described as the balanced price as well. In this paper, the average value is adopted as the threshold price. Comparing the electricity price per unit time with the threshold price, if the electricity price is higher than the threshold price, the ESD owner could get the benefit from ESD discharging, thus, this time will be listed as a candidate for discharge, which conforms to the principle of high price discharging. In contrast, if the electricity price is lower than the threshold price, the ESD owner could reduce the cost by charging, so this time will be appropriate for the ESD to charge, which is also consistent with the ESD operation strategy of low price charging. After the charge/discharge time of candidate is obtained, the charge and discharge period and the capacity of ESD could finally be determined, combining with the load demand based on the principle of peak shaving and valley filling. At last, the capacity constraint and the charge/discharge power balance constraint are checked and then the charge/discharge strategy could be finally determined. As a result, based on the ESD operation scheme mentioned above, the ESD operators can make profits through the arbitrage from the strategy with low price charging and high price discharging, according to the different TOU price in a day and benefits from the effect of stability enhancement in distribution networks because of the peak shaving and valley filling of ESD.

The right half of the figure represents the network price calculation model of ESD. The load level of each node at each period is determined first, then the power flow is calculated without considering line parameters and line capacity limits of the system. Then, if there is no line congestion, the next period is entered and the power flow calculation is made again until congestion occurs. When line congestion occurs, the power flow is calculated, considering line capacity limits, and the congestion cost of the node should be calculated before entering the cycle of next period. If there is no congestion happening all the time, the investment trigger time is delayed. Since the load selected is the average annual load, the present value of annual congestion cost could be calculated on the basis of this. Then, comparing the present value of congestion cost with the present value of investment cost, the investment trigger
time with congestion management and ESD integration could be determined. If the present value of congestion cost is lower than the investment cost, the grid operator can choose to undertake the congestion cost to defer network investment. When the congestion cost is higher than the investment cost, it is not sensible to make congestion management again, thus, the investment trigger time can be obtained. When ESD is integrated, the time of network investment will be deferred further.

**Figure 1.** General procedure for cost–benefit analysis.

Subsequently, based on the LRIC method, the network price with or without ESD could be calculated, combining with the ESD operation plan mentioned above. Specifically, when a unit of power is integrated to the network, the new investment trigger time is generated, because of the micro-increment injection, whether there is ESD in the network or not. So, according to the LRIC method, when there is no ESD in the network, the long-run incremental cost can be calculated by comparing different investment cost after micro-increment. When ESD is integrated in the network, do the similar calculation again and a new long-run incremental cost is obtained. Then, the network price can be obtained by comparing the two cost. Simultaneously, the benefit from the ESD operation strategy with low price charging and high price discharging could be calculated based on the ESD
operation plan and the investment trigger time. Then, based on the calculation mentioned above, the present value of total benefits from ESD operation could finally be obtained.

Therefore, the cost–benefit analysis is conducted based on the ESD operation optimization model and the network price calculation model mentioned above. The parameters, including the return on investment in life cycle, the net present value of investment in life cycle, the payback period, the internal rate of return, the daily profit excluding discount rate, and the daily load variance with and without ESD, are calculated to conduct analysis quantitatively. The effects of different charge/discharge strategies, charge/discharge rates, and capacities of ESD on network operators and ESD owners are analyzed respectively. The marginal analysis, considering the correlation between payback period and ESD charge/discharge rates and the correlation between payback period and ESD capacities, is conducted to help ESD owners make right investment decisions further. Details of the cost–benefit analysis process are provided in Section 4.

4. Case Study

The basic principle of the ESD operation model has been described in detail in the previous sections. In this section, the proposed model is applied to a simple two-bus system, which shows the specific simulation process of the model through a two-bus system shown in Figure 2.

![Figure 2. Single line diagram for the two-bus network.](image)

The parameters and related assumptions are as follows:

1. Generator: Both G1 and G2 are thermal power generators with stable power output, and the generation cost does not fluctuate during the simulation time;
2. Transmission Line: The capacity upper limit of the line connecting bus 1 and bus 2 is 45 MW. Since the two generators are connected by a single line, the PTDF is 1;
3. Load: The typical daily load data is shown in Table 1, and the annual growth rate is 2%;
4. Energy storage: The daily storage period is 1. The energy storage resource is composed of the lithium battery, whose life cycle is seven years and capacity is 15 MWh, and the maximum output power per hour is 5 MW. To simplify the calculation, it is assumed that the battery has no energy loss;
5. Economic parameters: The TOU price and load data within one day are shown in Table 1. The modern equivalent asset value of the line is £3,193,400, and the modern equivalent asset value of the ESD is £80,000/MWh. The annuity factor is 0.0831, and the discount rate is 5.6%.

The calculation models of the generation costs are as follows:

\[
G_1 = 0.02P_1^2 + 20P_1 (0 \leq P_1 \leq 50 \text{ MW}),
\]

\[
G_2 = 0.02P_2^2 + 30P_2 (0 \leq P_2 \leq 50 \text{ MW}),
\]

When the actual power required by the system is less than 100 MW, the generation cost of G1 is less than G2. Therefore, G1 generates electricity when congestion does not occur. Once the line congestion occurs, physical law takes precedence over economic law, so that G2 starts working.
4.1. Decision-Making Process of the Charge and Discharge Model

Assuming that the electricity price of each period in a day under the TOU price is constant, the value of the TOU price in a day is shown in Table 1:

| T   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| TOU (£/MWh) | 77  | 77  | 77  | 77  | 77  | 77  | 77  | 77  | 77  | 77  | 77  | 100 |
| LOAD (MW)     | 38  | 35  | 33  | 32  | 31  | 32  | 32  | 34  | 38  | 42  | 44  | 45  |

| T   | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 24  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| TOU (£/MWh) | 100 | 100 | 77  | 77  | 130 | 130 | 130 | 130 | 130 | 77  | 77  | 77  |
| LOAD (MW)     | 44  | 43  | 43  | 42  | 43  | 46  | 48  | 47  | 46  | 45  | 43  | 40  |

Plugging the TOU price into the proposed charging and discharging model, the comparison between the new load profile and the original load profile is shown in Figure 3. It is not difficult to find the peak–valley difference due to the operation of the ESD. By calculating the variance of the load data with and without ESD, the variances are 16.98 and 30.46, respectively, which means the load profile becomes more flat.

![Figure 3. Operation mode of the ESD.](image)

The ESD control strategy in this paper is to select the candidate charge/discharge period by responding to the TOU price and determine the charge/discharge period by responding to the load demand. The objective of the control strategy is to make the energy storage user have the highest profits from TOU arbitrage. There are different operation strategies in other works. In [26], the control mechanism was to charge during the off-peak period and to discharge it during the peak period, and made energy arbitrage on this basis, which was opposite with the operation strategy in this paper. In this case, energy operators may not make enough benefits under TOU price compared with the dual-response mechanism proposed in this paper.

There are two points that need special instructions:

1. Determination of the objective function: Since the charge and discharge model is based on the strategy in which the candidate charging and discharging period is determined by responding to the TOU price, and then the charging and discharging period is determined at last according to the load demand, the TOU price factor is introduced to correct the final result;

2. Simplification of constraint conditions: Since the load curtailment is used to calculate the congestion cost, the power flow constraint of the network can be met. As a result, the power flow constraint of the network is not involved in the program. Besides, the number of charge and discharge cycles can be reflected after running the program, and the state constraint is satisfied because the amount of charge and discharge in one day are both less than the ESD capacity, so the state constraint is not given as well.
4.2. Investment Benefit Evaluation Based on ESD Operation Model in Life Cycle

After determining the charge and discharge scheme of ESD, this section evaluates the investment benefits based on the ESD operation mode throughout the life cycle.

The evaluation of investment benefits is to analyze the advantages and disadvantages of the economic and social benefits of the target investment project. Furthermore, on this basis, the corresponding estimation judgments and comparison conclusions are made according to the specific properties of the investment project. As mentioned above, the dynamic cost–benefit analysis method is adopted in this paper and the net present value method is proposed to know whether the investment project makes a profit. The present value of investment benefit \( W \) and the net present value \( Q \) can be expressed as:

\[
W = L_s \times \text{Capacity}_s + \sum_{\text{Day}=1}^{N_s \times 365} PR_{\text{Day}},
\]

\[
Q = W - \frac{8 \times 10^4 \times \text{Capacity}_s}{(1 + dr)^{365}},
\]

where \( \text{Capacity}_s \) is the capacity of the ESD.

The results of the calculated net present value are shown in Figure 4. It is not difficult to find that the net present value of the investment becomes positive in the fifth year, which means the investment scheme is profitable in the fifth year.

![Return on investment curve under dynamic analysis.](image)

**Figure 4.** Net present value of the ESD in its life cycle.

The return on investment \( P \) under the dynamic analysis is obtained according to the present value of the investment benefit. Then, the growth curve reflecting the economic benefit from the investment is made in proportion, considering the net present value of income and expenses. The specific formula is:

\[
P = \frac{W}{Q} \times 100\%,
\]

where \( W \) is the present value of profits; \( Q \) is the present value of investment.

The return on investment curve is shown in Figure 5.

According to Figure 5, as the time increases, the net present value of the investment continues to increase until it reaches the initial investment present value on the 1708th day, i.e., 4.6795 years, which is the payback period. In other words, the owner of the ESD will begin to make profits on September of the fourth year. By the end of the seventh year, which is the end of the life cycle of the ESD, the total profit was £1,689,100, which is 1.4076 times the original investment.
While users try to maximize their own profits, the network operator has also gained network stability and investment deferral opportunities, and the integration of clean energy has also been promoted at the same time.

The discount rate is assumed to be 5.6% in the above calculation. However, the actual discount rate varies with time and region, so it is necessary to introduce the internal rate of return to increase the accuracy. The net present value is calculated in the model, hence, the investment value can be determined further through the supplementary analysis of the internal rate of return (IRR) to help potential ESD investors to make investment predictions.

The value of the internal rate of return is the value of the discount rate when the payback period is exactly reached. The calculation formula is as follows:

\[ IRR = \frac{dr}{(1+\text{Profit})} \]

There is an IRR function in the function package of EXCEL software. Inputting the economic data of the model, IRR can be calculated as 53% (the base discount rate is 5.6%). Combined with the daily income of users calculated with the charge/discharge strategy, the economic parameters, operating parameters, and investment parameters of the investment model are shown in Table 2.

![Figure 5. Return on investment curve under dynamic analysis.](image)

**Table 2. Annual cost present value after power injection.**

| Parameter Category                  | Parameter Meaning                                                                 | Beneficiary             | Parameter Value   |
|------------------------------------|-----------------------------------------------------------------------------------|-------------------------|-------------------|
| Return on Investment in Life Cycle | Proportion of final profits in life cycle; quantitative analysis                  | ESD owners              | 140.77%           |
| Net Present Value of Investment in Life Cycle | Final profits in life cycle; quantitative analysis                          | ESD owners              | £489,185.67       |
| Payback Period                     | The duration of the payback period; efficiency analysis                           | ESD owners              | 4.68 Years        |
| Internal Rate of Return            | Estimate whether investment is profitable; qualitative analysis                  | ESD owners              | 53% (the base discount rate is 5.6%) |
| Daily Profit Excluding Discount Rate | Profits of ESD owners in one day                                                  | ESD owners              | £795.00           |
| Daily Load Variance with and without ESD | The ability of peak shaving and valley filling of ESD | Network operators Without ESD: 30.46 With ESD: 16.11 |

It can be found from the data in Table 2 that investing ESD under the model is certainly profitable for the ESD owner, who is the service subject of the pricing model. There are corresponding estimated values of the daily income, the payback period, and the final profits for users as a measure of investment. While users try to maximize their own profits, the network operator has also gained network stability and investment deferral opportunities, and the integration of clean energy has also been promoted at the same time.
4.3. Impact of Different Charge/Discharge Strategies

Different charge/discharge strategies have a direct impact on the results. To explore the influence of different charge/discharge strategies, a charge/discharge strategy opposite to the original scheme is proposed. That is, in the opposite strategy, which we can call Scheme 4.3, when the TOU price is low, the ESD discharges, and when the TOU price is high, the ESD charges. The explanations of Scheme used in this paper are shown in Table A1 in the appendix. The load profile compared with the original scheme is shown in Figure 6.

![Figure 6. Comparison of load profile in Scheme 4.3 with the original scheme.](image)

Figure 6 shows that charging during the peak load period and discharging during the valley load period lead to more serious fluctuations in the power flow curve of the grid, causing the peak load to be higher and the valley load to be lower, which is unfavorable for power system security and safety, and simultaneously works against the network congestion mitigation.

It should be noted that the internal rate of return can only be used to evaluate the economic benefits of an individual project, so the internal rates of return of multiple investment projects cannot be directly compared or analyzed. Therefore, in this and the following sections, the internal rate of return is no longer analyzed comparatively. The calculation and comparison are mainly carried out in the context of the ESD owner’s daily profit, dynamic investment payback period, life cycle net present value, life cycle return on investment, and load variance. The specific characteristics of the proposed scheme are further explored. The comparison of the parameters with the original scheme is shown in Table 3.

| Parameter Category                        | Parameter Value of the Original Scheme | Parameter Value of Scheme 4.3 |
|-------------------------------------------|---------------------------------------|--------------------------------|
| Return on Investment in Life Cycle        | 140.77%                               | -140.82%                       |
| Net Present Value of Investment in Life Cycle Payback Period | £489,185.67                           | -£2,889,851.24                 |
| Daily Profit Excluding Discount Rate      | 4.68 Years                             | None                           |
| Daily Load Variance with and without ES  | Without ESD: 30.46                     | Without ESD: 30.46             |
|                                           | With ESD: 16.11                        | With ESD: 56.98                |

As can be seen from Table 3, the integration of ESD brings about more dramatic fluctuations to the line power flow, which effectively proves the analysis above. The variance is significantly larger than the original result, even exceeding the variance value with no ESD integration. Therefore, the operation of ESD with Scheme 4.3 increases the line congestion, which results in a positive economic signal for the network price—that is, the network operator needs to charge the user an additional fee.
At the same time, because the ESD discharges when the price is low, and otherwise the ESD charges, the daily profit is negative, which means a loss. In addition, the remaining possible profits are not included in the investment model, which leads to the life cycle return on investment and the net present value all being negative. The payback period is also unlikely to be achieved in a continuous loss mode.

Therefore, compared with Scheme 4.3, the original pricing model can result in more benefits to the user and a shorter payback period. The original model may also improve the power system security and safety and renewable energy consumption may be promoted by peak load shifting. However, this does not mean that the larger capacity is better. If the capacity is too large, which leads to an excessive growth in investment cost, there will be a decrease in profit or a longer payback period, due to the limit of the arbitrage ability of the TOU price.

4.4. Impact of Different Charge/Discharge Rates

Different charge/discharge rates will directly affect the operation scheme of ESD. When the charge/discharge rate is faster, the peak load shifting has a significant effect on the peak shaving. However, the lower rate can make the overall load profile more flat. To further explore the effect of different charge/discharge rate on the results, compared the rate of 5 MW/h in the original scheme with a reduced rate of 3 MW/h, which we call Scheme 4.41. The unit of charge/discharge rate in this paper is MW/h. The power flow curve is shown in Figure 7.

![Figure 7. Comparison of load profile in Scheme 4.41 with the original scheme.](image)

It can be seen that with the reduction of the charge/discharge rate, the minimum value of the power flow curve increases and the maximum value remains constant, thus the overall curve smoothing is realized. Without considering the profits of ESD users, this solution is more conducive for network operators to maintain stable operation of network.

The ESD network pricing, the ESD owner’s daily profit, the dynamic investment payback period, the life cycle net present value, and the life cycle return on investment obtained by this scheme are consistent with the original ones. The only change is the daily load variance with and without ESD. When the ESD capacity and the charge/discharge strategy remain unchanged, the proper reduction of the charge/discharge rate may have little effect on the revenue of the ESD users, but it can further improve the power flow distribution and the stability of network. However, if the charging rate is reduced too much, there may be a different situation.

When the charge/discharge rate is reduced to 2 MW/h, which we call Scheme 4.42, the results are different, as can be seen in Figure 8.
Table 4. It is not difficult to find that the investment benefits of the model, whose charge/discharge rate is reduced to 2 MW/h, fall. Also, in Scheme 4.42, the ESD owner’s daily profit, life cycle net present value, and life cycle return on investment all decline, while the variance, which decreases in Scheme 4.41, increases. In other words, when the charge/discharge rate of the ESD is reduced to a certain value, there are no advantages for either the users or the network. In addition, when the parameters of the model are already given, the investment strategy can create a reciprocal game situation, in which both the users and the network are profitable through a specific charge/discharge rate. For example, Scheme 4.41 can be used as the optimization scheme of the original one. In this situation, the user’s benefits are not damaged, and more benefits will be created for the network operators, which is in line with the Pareto equilibrium principle.

Table 4. Comparison of parameters of Scheme 4.42 with the original scheme.

| Parameter Category                        | Parameter Value of the Original Scheme | Parameter Value of Scheme 4.42 |
|-------------------------------------------|----------------------------------------|--------------------------------|
| Return on Investment in Life Cycle        | 140.77%                                | 124.84%                        |
| Net Present Value of Investment in Life Cycle | £489,185.67                            | £298,021.44                    |
| Payback Period                           | 4.68 Years                             | 5.37 Years                     |
| Daily Profit Excluding Discount Rate      | £795.00                                | £705.00                        |
| Daily Load Variance with and without ESD | Without ESD: 30.46                      | Without ESD: 30.46             |
|                                           | With ESD: 16.11                         | With ESD: 16.63                |

Different from the correlation between the battery capacity and the payback period, the payback period will not be affected when the charge/discharge rate increases to a certain extent. As shown in Figure 9, when the charge/discharge rate is low, the efficiency of low price charging and high price discharging is low, so the payback period is longer and the profits decline. When the charge/discharge rate exceeds a certain value, the charge/discharge period will not change any more. As a result, the payback period remains constant and the profits are not affected either. However, if the charge/discharge rate is too high, a sudden change in power flow will affect the network stability. The correlation between the variance of load profile and charge/discharge rate is shown in Figure 10. Comparing the centralized optimization method to calculate the optimal charge/discharge rate, the simulation time is shorter and the result can be obtained efficiently and accurately using the method used in this paper.

As we can see from Figure 10, when the charge/discharge rate is too low, the effect of peak shaving and valley filling is not obvious. However, if the rate is too fast, the variance of load profile is also big due to the saltation of the power flow. As a result, the charge/discharge rate of the ESD, which leads in short payback period as well as flat load profile, ranges from 3 MW/h to 5 MW/h.
Values of Scheme 4.5 and the original one by calculation are shown in Table 5. The corresponding payback period will not be affected when the charge/discharge rate increases to a certain extent. As shown in Figure 9, the correlation between payback period and charge/discharge rate of the ESD.

4.5. Impact of Different ESD Capacities

Figure 11 shows the impact on the load profile of Scheme 4.5, when the charge/discharge rate remains constant and the capacity of the ESD changes from 15 MWh to 25 MWh. The corresponding values of Scheme 4.5 and the original one by calculation are shown in Table 5.

Table 5. Comparison of Scheme 4.5 with the original scheme.

| Parameter Category                              | Parameter Value of the Original Scheme | Parameter Value of Scheme 4.5 |
|------------------------------------------------|----------------------------------------|-----------------------------|
| Return on Investment in Life Cycle              | 140.77%                                | 172.06%                     |
| Net Present Value of Investment in Life Cycle   | £489,185.67                             | £1,441,231.72               |
| Payback Period                                  | 4.68 Years                              | 4.68 Years                  |
| Daily Profit Excluding Discount Rate            | £795.00                                | £1325.00                    |
| Daily Load Variance with and without ESD       | Without ESD: 30.46                      | Without ESD: 30.46          |
|                                                | With ESD: 16.11                         | With ESD: 10.02             |

Figure 10. The correlation between load profile variance and charge/discharge rate of ESD.

Figure 11. Comparison of load profile of Scheme 4.5 with the original scheme.
According to Table 5, it is easy to find that with the increase of ESD capacity, the cost increases accordingly (a certain amount per MWh is used in the cost calculation), so the investment payback period changes slightly. However, in the practical production, in addition to the purchasing cost of the battery, the cost of operation and maintenance is also involved in the investment, thus the proportion of investment determined by the battery capacity is reduced. Compared with the original scheme, Scheme 4.5 makes the investment payback period shorter.

In addition, the final net present value, return on investment, and the network pricing profit have been greatly improved, and the daily profit has also increased greatly with the increase in the disposable capacity. For the ESD owner, the profit increases when the opportunity cost is not considered, and the investment is more valuable. At the same time, the network stability has been further improved, which is conducive to consuming more renewable energy under a long-term stable operation.

The change of the payback period due to the increasing capacity is depicted in Figure 12.

![Figure 12](image-url)

**Figure 12.** The correlation between payback period and ESD capacity.

It can be clearly seen that when ESD capacity is no more than 20 MWh, the payback period decreases as the capacity increases, but when it exceeds 20 MWh, the payback period increases with the capacity. That is, a slight increase of the energy storage battery capacity can actually make payback period shorter, but an excessive increase has a negative effect, which makes the payback period longer.

When the battery price is increased, the cost of ESD is increased as well. The correlation between the capacity and the payback period will be different, which is shown in Figure 13.

![Figure 13](image-url)

**Figure 13.** Impact of cost increasing on the correlation between payback period and ESD capacity.

As we can see above, when the cost of ESD is increased, the average payback period is larger than the original one. However, when the capacity is smaller than 15 MWh, the payback period of the one with larger cost is shorter than the original one. Therefore, when the life cycle of energy storage is limited, it may be better to choose the one with smaller capacity.
4.6. Enrichment in Complex System

To verify the feasibility of the strategy and network price method proposed in this paper, the formulation is applied on the IEEE 33-bus system, which is shown in Figure 14.

![Single line diagram for the IEEE 33-bus system.](image)

Compared with the two-bus system, due to the improved node scale, the grid structure must be considered, thus the power flow should be calculated in the IEEE 33-bus system, which leads to the process of analysis being more complexed. As the complexity of the distribution network increases, the detailed calculation process is no longer listed.

The economic parameters and assumptions are the same as the two-bus system. It must be assumed that the ESD, which is configured as a cluster, is integrated in bus 29, and the cost models of the two generators G1, which is located in bus 29, and G2, located in bus 3, are:

\[
G_1 = 0.014P_1^2 + 20P_1 + 100 \quad (P_1 > 0 \text{ MW}),
\]

\[
G_2 = 0.003P_2^2 + 60P_2 + 700 \quad (0 < P_2 < 1.162 \text{ MW}),
\]

The cost of G1 is relatively low compared to G2. Similar to the two-bus system, when there is no line congestion, the distribution network is supplied by G1, and when the line power exceeds the upper capacity limit, G1 and G2 jointly generate electricity. This also happens in actual distribution networks. Since G2 is a distributed renewable energy, the cost of generating electricity far exceeds that of conventional thermal power or hydropower. G2’s capacity is small, even if line congestion occurs, G1 still supplies most of the output power.

The data of the load in bus 29 and the TOU price in a day is shown in Table 6:

| T             | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---------------|---|---|---|---|---|---|---|---|---|----|----|----|
| TOU(£/MWh)   | 80| 66| 66| 66| 80| 80| 80| 80| 80| 110| 110| 110|
| LOAD(MW)      | 16.32| 15.03| 14.17| 13.74| 13.31| 13.74| 13.74| 14.6| 16.32| 18.04| 18.9| 19.33|

| T             | 13| 14| 15| 16| 17| 18| 19| 20| 21| 22| 23| 24 |
|---------------|---|---|---|---|---|---|---|---|---|---|---|----|
| TOU(£/MWh)   | 80| 80| 80| 80| 80| 120| 120| 80| 80| 80| 80 | 80 |
| LOAD(MW)      | 18.9| 18.47| 18.47| 18.04| 18.47| 19.76| 20.61| 20.19| 19.76| 19.33| 18.47| 17.18 |

Based on the TOU price and load profile, the operation scheme could be obtained. That is, the ESD would charge in times 2, 3, 4, 5, and 7, with a charge rate of 2 MW/h, and would discharge in times 11, 12, 18, 19, and 20, with a discharge rate of 2 MW/h. When the ESD is integrated in bus 29, the load profile becomes more flat, due to the ability of peak shaving and valley filling of the ESD, which is shown in Figure 15. The corresponding parameters are calculated, which are shown in Table 7.
value and internal rate of return through the dynamic cost–benefit analysis method. In the process of numerically results and investment benefit analysis, the conclusions obtained are as follows:

The proposed model is applied to a simple two-bus system. The charge/discharge periods, ESD capacity, and the charge/discharge rates are analyzed in the two-bus system. In addition, the economic benefits of the investment scheme are evaluated, which include the calculation of the net present value and internal rate of return through the strategy with low price charging and high price discharging.

In this paper, a modeling analysis and numerical results of the ESD charge/discharge strategy are carried out. Furthermore, economic benefits analyses of specific investment projects are conducted in the case study.

The main process of the modeling analysis includes: designing the charge/discharge strategy of the ESD, quantifying the economic benefits of the ESD owner and the network, then promoting the development of the ESD market. The ESD charge/discharge model maximizes the profits of ESD users through the strategy with low price charging and high price discharging.

The proposed model is applied to a simple two-bus system. The charge/discharge periods, ESD capacity, and the charge/discharge rates are analyzed in the two-bus system. In addition, the economic benefits of the investment scheme are evaluated, which include the calculation of the net present value and internal rate of return through the dynamic cost–benefit analysis method. In the process of numerical results and investment benefit analysis, the conclusions obtained are as follows:

- The proposed operation scheme of ESD can commendably realize the peak shaving and valley filling, which is conducive to the network stability and the arbitrage of ESD users, based on the strategy with low price charging and high price discharging;
- Different operation parameters of ESDs will bring about different pricing results and investment benefits. A slight increase in energy storage battery capacity can indeed make the investment payback period shorter, but an excessive capacity increase will have a negative effect, leading to a longer payback period. The capacity for 20 MWh may be the optimal result that leads to the

| Parameter Category                      | Beneficiary      | Parameter Value |
|----------------------------------------|------------------|-----------------|
| Return on Investment in Life Cycle     | ESD owners       | 115.4473%       |
| Net Present Value of Investment in Life Cycle | ESD owners       | £154,473.1049    |
| Payback Period                         | ESD owners       | 7.5014 Years    |
| Network Price of ESD                   | ESD owners and   | –£1,706.6086    |
|                                        | Network operators|                 |
| Daily Profit Excluding Discount Rate    | ESD owners       | £444.00         |
| Daily Load Variance with and without ESD | Network operators| Without ESD: 5.63 |
|                                        |                  | With ESD: 2.39  |

From Table 7, it can be found that for ESD users, ESD investment under the cost–benefit analysis model is profitable. Users can use ESD daily profit, payback period, and network price as the reference data to make investment decisions. At the same time, while users strive to maximize their own benefits, network stability is improved, and the investment horizon is also deferred, which improves the benefits to network operators as well.

5. Conclusions

In this paper, a modeling analysis and numerical results of the ESD charge/discharge strategy are carried out. Furthermore, economic benefits analyses of specific investment projects are conducted in the case study.

The main process of the modeling analysis includes: designing the charge/discharge strategy of the ESD, quantifying the economic benefits of the ESD owner and the network, then promoting the development of the ESD market. The ESD charge/discharge model maximizes the profits of ESD users through the strategy with low price charging and high price discharging.

The proposed model is applied to a simple two-bus system. The charge/discharge periods, ESD capacity, and the charge/discharge rates are analyzed in the two-bus system. In addition, the economic benefits of the investment scheme are evaluated, which include the calculation of the net present value and internal rate of return through the dynamic cost–benefit analysis method. In the process of numerical results and investment benefit analysis, the conclusions obtained are as follows:

- The proposed operation scheme of ESD can commendably realize the peak shaving and valley filling, which is conducive to the network stability and the arbitrage of ESD users, based on the strategy with low price charging and high price discharging;
- Different operation parameters of ESDs will bring about different pricing results and investment benefits. A slight increase in energy storage battery capacity can indeed make the investment payback period shorter, but an excessive capacity increase will have a negative effect, leading to a longer payback period. The capacity for 20 MWh may be the optimal result that leads to the

Figure 15. Influence of ESD operation on load demand in a complex system.
shortest payback period. However, when the cost of ESD is increased, it may be better to choose the one with a smaller capacity if a life cycle limitation exists;

- Different from the correlation between the battery capacity and the payback period, the payback period will not be affected when the storage charge/discharge rate increases to a certain extent. However, if the charge/discharge rate is too high, a sudden change of the power flow will affect the network stability. So, it is better to use a charge/discharge rate which ranges from 3 MW/h to 5 MW/h;

- Under the given cost–benefit analysis model, the investment strategy can create a reciprocal game situation, in which both users and network operators make profits through a specific charge and discharge rate. In the case that users’ benefits do not decline, more benefits will be created for the network operators, which is in accordance with the Pareto equilibrium principle.

The benefits of energy storage users can be maximized through the charge/discharge strategy proposed in this paper. Except for the arbitrage, the users can also gain benefits from congestion alleviation due to ESD operation, which is also conducive to improving network stability, especially in the current distribution network situation, with a high penetration of clean energy. Besides this, a cost–benefit marginal analysis is also introduced in this paper, which can help users to select the optimal ESD capacity and charge/discharge rate.

The specific costs in the process of installing energy storage device, such as the cost for a converter and battery management system, are not considered in this paper. To make the method more practical, these costs can be considered in next research process.

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**Abbreviations**

- $dr$ discount rate
- $PR_{opt}$ energy arbitrage
- $Cr_t$ charge rate at time $t$
- $Dr_t$ discharge rate at time $t$
- $Tou_t$ price under time-of-use price mode
- $pf_t$ real-time load at time $t$
- $pf_{AVE}$ average value of real-time load in a day
- $I_{impact}$ impact factor of load profile
- $Power_l$ power flow of line $l$
- $Capacity_l$ upper capacity limit of line $l$
- $P^G_k$ active power of generator at bus $k$
- $Q^G_k$ reactive power of generator at bus $k$
- $P^L_k$ active power of load at bus $k$
- $Q^L_k$ reactive power of load at bus $k$
- $N$ bus number
- $C_{rate}$ maximum charge rate per hour
- $D_{rate}$ maximum discharge rate per hour
- $SOC_{Min}$ minimum state of charge level
- $SOC_{Max}$ maximum state of charge level
- $Cc$ annual total congestion cost of all generators
- $G_i$ the generator
 Appendix A. Nomenclature

Table A1. Explanation of Scheme used in this paper.

| Name of Scheme | Explanation |
|----------------|-------------|
| the Original Scheme | The strategy is low price charging and high price discharging, and the capacity and charge/discharge rates are 15 MWh and 5 MW/h, respectively. |
| Scheme 4.3 | The strategy is low price discharging and high price charging. |
| Scheme 4.41 | The charge/discharge rate is reduced to 3 MW/h. |
| Scheme 4.42 | The charge/discharge rate is reduced to 2 MW/h. |
| Scheme 4.5 | The capacity of ESD is changed to 25 MWh. |

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