Economic Evaluation of BESS on the Generation Side for Frequency and Peak Regulation Considering the Benefits of Unit Loss Reduction

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[[1]](#footnote-1)

*Abstract*—The indirect benefits of battery energy storage system (BESS) on the generation side participating in auxiliary service are hardly quantified in prior works. Nevertheless, the configuration of BESS could be affected by its indirect benefits. In this paper, we purpose a quantitative economic evaluation method of BESS considering the indirect benefits from the reduction in unit loss and the delay in investment. First, we complete further the cost model of BESS for frequency and peak regulation based on the whole life cycle theory. Second, we quantify the indirect benefits of BESS in thermal power plants based on the theory of rotor fatigue life loss and establish a benefits model that considers the unit loss reduction during frequency regulation and the delay in investment during peak regulation. Finally, we propose a set of indexes for economic evaluation of the thermal power plant with BESS. The simulation results show that the total benefits of BESS can be improved effectively by considering the indirect benefits from unit loss reduction and the delay in investment, proving the effectiveness of the proposed approach which can be meaningful for the future investment in BESS on the generation side.

*Index Terms*—Generation-side battery energy storage, frequency and peak regulation, fatigue wear, economic benefit evaluation.

# NOMENCLATURE

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| **Nomenclature**  In this section, all symbols used in this paper are classified into acronyms and parameters.  *Acronyms*  BESS  Battery Energy Storage System  LCC Life Cycle Cost  FM Frequency Modulation  *Parameters*  *P*ratedThe rated configuration power of BESS  *S*rated The BESS capacity  *C*inv The investment cost  *C*p The unit power cost of BESS  *C*s The unit capacity cost of BESS  *C*om The operation and maintenance cost  *C*pom The operation and maintenance cost of unit power  *C*som The operation and maintenance cost of unit capacity  *C*d The cost of decommissioning disposal  *C*pd The decommissioning disposal cost of unit power  *C*sd  The decommissioning disposal cost of unit capacity  *C*F The cost of fault loss  *C*lcc  The whole life cycle cost of energy storage  *C*fuel  The price of unit fuel  *C*NOX The expense on pollution emission of nitrogen oxides for each unit of power generation  *C*SO2  The expense on pollution emission of sulfur dioxide for each unit of power generation  *C*CO2  The expense on pollution emission of carbon dioxide for each unit of power generation  *C*I The cash inflow  *C*O The cash outflow  *R*f1 The compensation income of FM mileage  *R*f2 The indirect benefit of the reduction in unit loss  *R*thermal The annual average operating profits of thermal power units  *R*f3 The indirect benefit of the reduction in fuel cost for system power generation  *R*f4 The indirect benefit of the reduction in pollution emission cost from system power generation  *R*f The total benefit of BESS participating in auxiliary frequency regulation service of thermal power units  *R*p1 The benefits of the price compensation of BESS for peak regulation in the whole year  *R*p2 The indirect benefits of the delay in the installation cost of thermal power units  *R*p3 The indirect benefit of the reduction in maintenance cost of thermal power units  *R*p4 The indirect benefits of the reduction in the fuel cost of system power generation  *R*p5 The indirect benefits of the reduction in the cost of pollution emissions from system power generation  *R*p The total benefit of BESS participating in auxiliary peaking regulation of thermal power units  *R*recyle The recycling benefit of BESS  *R*metali The price of metal *i*  *R*inv The rate of return on investment  *Ri* The total income of BESS in thermal power plants at *ith* year  *R* The total benefits of BESS deployed in thermal power plants for frequency and peak regulation  *N*y  The whole life cycle  *N*life The equivalent cycle life of energy storage  N The annual average number of failures of energy storage equipment  *N*f The number of operation days of energy storage for FM in one year  *N*p  The operation days of BESS for peak regulation in one year  *N*B The annual average net income during the whole life cycle of system  *N*t The fracturing cycles  *A*1 The year that the unit has been in operation  *ΔA* The operating life of the units extended by the deployment of energy storage  *A* The remaining operational life of the thermal power unit  *Dt* The actual regulation depth of FM unit on the execution day  *D*f The low cycle fatigue loss  *T*off The annual average outage time of the energy storage equipment  *T*P The dynamic investment payback period  *T* The annual operation time of thermal power plants  *Wt* The annual charge and discharge capacity of energy storage at year *t*  *W*fuel The fuel quantity required for the unit power generation  *E* The elastic modulus  *Et*  The discharge capacity of energy storage for frequency regulation at day *t*  *Ei*  The discharge capacity of BESS during peak regulation at day *i*  *P*thermal The installation cost of unit capacity  *K*Ap The comprehensive FM performance index of FM unit on the execution day  *M* The operation life of thermal power units  *K* The total investment in the project  *V* The net present value  *q* The ratio of basic peak regulation capacity to maximum output of thermal power units  *e* The contract price of power plant  *c* The fatigue ductility index  *b* The fatigue strength index  *r* The discount rate  *ε*  The total strain amplitude  *ε*f The fatigue ductility coefficient  *δ*f The fatigue strength coefficient  *c*F The average failure handling cost  *et* The annual average electricity price in auxiliary service market at year *t*  *ρ*metali The content of metal i in the unit weight of energy storage battery  *δ*energu\_i The energy-to-weight ratio of the energy storage system  *λ*1 The mileage settlement price  *λ*2 The coefficient |

# Introduction

With the increasingly prominent problem of energy crisis and environmental pollution, renewable energy generation such as wind power and PV are developing rapidly, and their uncertainties have adverse effects on the operation of the power grid. Among them, the problem of frequency and peak regulation is particularly outstanding [1-2]. To make the power generation more flexible, the state has been taking measures: building peaking power sources such as gas power plants and hydropower plants, undertaking the renovation of coal-fired units, and building energy storage systems [3-6]. Because of the rapid development of large-capacity energy storage technology and its excellent regulation performance, utilizing energy storage systems for frequency and peak regulation becomes a popular research topic [7-8]. However, because of the imperfect market mechanism and the high price, the investors’ interests cannot be guaranteed, which hinders the further promotion of energy storage [9-10]. How to scientifically calculate the direct and indirect benefits of energy storage systems participating in frequency and peak regulation services is conducive to the improvement of future market mechanisms. Also, it is essential to promote the application of energy storage technology.

Some scholars have made lots of research findings on the economic benefit evaluation of BESS for frequency and peak regulation. Most of them are about how to configure energy storage in the new energy power plants or thermal power plants to realize joint regulation.

The energy storage in new energy power plants could effectively improve the renewable energy penetration and the economic benefits by providing high-quality auxiliary services including frequency and peak regulation [11]. Ma et al. established a comprehensive economic benefit model of BESS for wind power auxiliary services and evaluated the benefits by calculating the return rate on investment and payback period [12]. Lu et al. aimed at how the economy of the PV system with energy storage was influenced by the cost of energy storage, electricity price and load characteristics [13]. Further, references [14-15] stated that preliminarily optimizing the capacity and operation of BESS could improve its benefits and effectively mitigate the abandon rate of wind and solar power. Therefore, there have been a few demonstration applications of wind-PV-storage hybrid systems in China. However, large-scale renewable energy access on power grids results in the problem of renewable energy accommodation, causing the function of conventional thermal power units transforming from power generation to frequency and peak regulation. Hence, for conventional thermal power units, the provision of auxiliary services has become an important way to make profits [16].

Energy storage configured in thermal power plants is mainly used to participate in peak and frequency regulation, which can not only make profits, but also alleviate the excessive coal consumption and serious equipment wear in power generation process [17-18]. Chen et al. evaluated the benefits of AGC for frequency regulation with the assist of energy storage considering the life loss cost of BESS. Although the participation of lithium-ion battery energy storage and generators in joint frequency regulation could bring economic benefits, the subsequent recycling cost of energy storage was not involved [19]. Huang et al. improved BESS cost model by considering scrap processing, power shortage punishment and power abandonment loss based on life cycle theory, a capacity configuration method is proposed considering BESS participating in the primary frequency regulation, which showed that reasonable capacity configuration of BESS could balance the effect and economy of primary frequency regulation [20]. Li et al. mainly evaluated the economy of BESS on the thermal power side for auxiliary peak regulation and verified that BESS could effectively reduce the peak regulation cost of units, besides, BESS could achieve its own economic balance during the life cycle [21]. In [22], based on the current situation that the large-scale applications of energy storage were hindered by the cost, the benefits of the delay in upgrading and reconstruction of thermal power units resulting from energy storage for auxiliary peak regulation were analyzed quantitatively. Compared with [19-22], Oudalov A et al. evaluated the economic benefits from the joint participation of BESS in auxiliary frequency and peak regulation, which broadened further the profit space of BESS. Besides, by comparing the economy of lead-acid, vanadium flow and sodium-sulfur BESS for frequency and peak regulation, it is expected that BESS has a bright application prospect in frequency and peak regulation in the next three to five years [23].

To summarize, the BESS in thermal power plants provides high-quality frequency and peak regulation auxiliary services and alleviates many problems, such as excessive coal consumption and serious wear of generating units. Moreover, it can delay the investment in upgrading and reconstruction of units. However, there are no previous works that have quantified the above benefits. In addition, most cost models of BESS based on LCC ignore the failure loss cost and the decommissioning disposal cost, while most benefit models of BESS ignore the recycling benefits. These shortcomings affect the authenticity of investment accounting and are not conducive to the further promotion of energy storage applications.

Therefore, this paper proposes a modeling and evaluation method for the economic benefits of BESS on the generation side considering the unit loss reduction during frequency regulation and the delay in investment in peak regulation. Based on the life cycle theory, a cost model including investment, replacement, operation and maintenance, failure and decommissioning disposal of BESS is established. Furthermore, this paper proposes a quantitative calculation method of measuring the indirect benefits of reduction in unit losses and the delay in investment on upgrading and reconstruction of units. By increasing the indirect benefits in the cost and benefit model of BESS, the actual profitability of BESS can be evaluated more scientifically, which serves as guidance for the formulation of auxiliary service market mechanism.

# Life Cycle Cost Model of BESS for Frequency and Peak Regulation

According to the definition in IEC603003-3, LCC refers to all direct and, indirect costs that occur over the entire life cycle of a system. In this work, the LCC model of BESS includes investment cost, operation and maintenance cost, failure loss cost, and decommissioning disposal cost.

## The Cost of Investment

The cost of investment in BESS usually includes the initial cost and the replacement cost, and the former refers to the one-time fixed investment at the initial stage of the BESS construction, while the latter refers to the capital spent to replace the battery energy storage equipment during the operation. The investment cost *C*inv of BESS over its whole life cycle is given by (1)



where *n* is the total amount of replacement. *n*+1 is the times of BESS put into service in total. *n*=*N*y/*N*life, and *N*life is calculated equivalently by rain flow counting method.

## Operation and Maintenance Cost

The operation and maintenance cost are the dynamic investment to ensure the normal operation of energy storage in its service life, which usually includes a fixed part determined by the power conversion system and a variable part determined by the charge and discharge capacity of energy storage.



## Failure Loss Cost

The failure loss cost includes the fault handling cost and the power outage loss cost. The fault handling cost incurs when the owner departments repair and eliminate the fault according to the maintenance procedures, which is equal to the product of the annual average number of faults and the average faults handling cost. The outage loss cost is caused by the downtime of BESS, which is equal to the product of the annual average charge and discharge capacity of BESS, the annual average power outage duration, and the average electricity price in auxiliary service market, where the annual average power outage duration is equal to the product of the average repair time and annual average number of failures. The annual average number of faults, average failure handling cost and average repair times refer to [24].



## Decommissioning Disposal Cost

The decommissioning disposal cost is occurred to dispose and recycle battery energy storage equipment harmlessly at the end of its entire life cycle. The lithium iron phosphate battery used in this paper does not contain heavy metal elements such as Pb, Cd, and Hg, which harm the environment, so the corresponding environmentally harmless disposal costs are slightly low. The specific model is shown below.



Based on the above analysis, the LCC model of energy storage *C*lcc can be shown as follows:



# The Benefit Model of BESS for Frequency and Peak Regulation

## The Benefit Model of BESS for FM Considering Unit Loss Reduction

The benefits of BESS participating in auxiliary frequency modulation include direct and indirect benefits.

### Direct benefits of FM mileage compensation

The direct benefits of FM market compensation are divided into the income of FM mileage compensation and the income of AGC capacity compensation. All generation units providing qualified AGC services can obtain corresponding AGC capacity compensation income. However, the deployed BESS is expected to have little impact on the AGC capacity compensation income. The increase of FM income mainly results from FM mileage compensation income. Hence, the benefits model of BESS only considers FM mileage compensation income, which is affected by FM mileage, FM performance indicators and mileage settlement price. The calculation model is:



where *K*Ap is equal to the product of regulation rate, regulation accuracy and response time [16].

### Indirect benefits of unit loss cost reduction

The participation of BESS in thermal power plants in frequency regulation can reduce the fatigue loss of turbine rotors and other core components caused by the continuous variable load operation, and extend the service life of the units [25]. In this paper, we assume that the benefits from the units in their extended service life are the indirect benefits of BESS.

Since the calculation of the turbine rotor life is complicated, there is no recognized calculation formula in the current research. In this work, in the light of the Δ*ε*-*N* low cycle fatigue characteristic relationship of rotor material, we firstly calculate the low cycle fatigue life loss, and then obtain the extended operating life of the unit resulting from the configuration of energy storage. Lastly, we quantify the benefit from the power plant in its extended service life, which is the indirect benefits of the reduction in unit loss.

The Manson-coffin formula describes the relation between the total strain amplitude and the number of rotors fracturing cycles, and their functional relationship is:



where parameters refer to [26].

We use the finite element calculation software ANSYS to calculate the rotor thermal stress and the centrifugal tangential stress at the time when the unit is generating, to calculate the total strain amplitude of the rotor [27]. And the fracturing cycles can be computed by Manson coffin formula.

The relationship between the low cycle fatigue life loss and the number of rotors fracturing cycles is:



According to the calculated cumulative fatigue life loss [28], the prediction of the remaining operational life *A* of the thermal power unit is given by (9):



where *A*1 is the time that the unit has been in operation.

The difference between the remaining operational life of units before and after the deployment of BESS is Δ*A*, which is the extended operating life of units resulting from BESS.

Then the indirect benefit of BESS from the reduction in unit loss can be calculated as follows:



The complete calculation process is shown in Fig. 1.

### Indirect benefits of fuel cost reduction

The participation of BESS in frequency regulation can reduce the output of thermal power units. The corresponding reduced fuel cost is the benefit of BESS for frequency regulation, which is calculated:



### Indirect benefits of pollution emission cost reduction

The participation of BESS in frequency regulation can reduce the output of thermal power units, thereby reducing greenhouse gas emissions. The corresponding reduced pollution emission cost is the benefit of BESS for frequency regulation, which is calculated as follows:



Fig.1 The calculation process of indirect benefit calculation process of the unit loss reduction



In summary, the total benefit of BESS participating in auxiliary frequency regulation service is:



## BESS Peak Regulation Benefit Model

The benefits of BESS participating in peak regulation service include direct and indirect benefits.

### Direct benefits of peak regulation compensation

When BESS assists thermal power units with peak regulation or participates in peak regulation auxiliary service market as an independent entity, its discharge capacity should be settled according to the relevant contract price of the conventional power plant. Thus, the compensation benefits are calculated:



### Indirect benefits of the delay of thermal power plant investment

BESS participating in peak regulation can reduce the output of thermal power units, which means the installation capacities of units are equivalently reduced. Considering the time value of funds, the corresponding delayed installation capacities investments are the benefits of BESS, which are calculated:



### Indirect benefits of the maintenance cost reduction of thermal power units

Because of the reduction in the installation capacity of units, the corresponding reduced maintenance cost is the benefit of BESS for peak regulation, which is calculated:



where *R*p3 is the indirect benefit of the reduction in maintenance cost of thermal power units. *λ*2 is the coefficient.

### Indirect benefits of fuel cost reduction

Because of the reduction in the output of units, the corresponding reduced fuel cost is the benefit of BESS for peak regulation, which is calculated:



### Indirect benefits of pollution emissions reduction

Because of the reduction in the output of units, the greenhouse gas emissions can be reduced, and the corresponding reduced pollution emission cost is the benefit of BESS for peak regulation, which is calculated:



Hence, the total benefit of BESS participating in auxiliary peaking regulation of thermal power units are:



## Recycling benefits of BESS

Recycling benefits can be obtained when useful materials are extracted from the waste and processed into reusable products. For the lithium iron phosphate battery energy storage, after the end of its operating life, there can be cobalt, lithium and other metal compounds separated from the waste batterie at a high recovery rate and processed into reuse. Hence, the recycling benefit model of BESS is established:



where specific parameter settings refer to [10].

In summary, the total benefit of BESS in thermal power plants is:



# Economic Benefit Evaluation Indexes of BESS in Thermal Power Plants

In view of the time value of funds, we select typical economic indexes such as dynamic investment payback period, return rate on investment and net present value to evaluate the economic benefits of thermal power plants with energy storage scientifically and effectively.

## Return Rate on investment

The return rate on investment is an important indicator to reflect the profitability of a project. A higher rate of return on investment means better profitability of the project. The rate of return on investment can be calculated by the ratio of the annual average net return to the total investment during the whole life cycle of the system. The calculation formula is as follows:





where *Ri* can be calculated by formula (21).

## Net present value

The net present value refers to the difference between the present value of the total income of a project and the present value of its total expenditure. It reflects the profitability of a project considering the time value of funds. A positive net present value of BESS indicates it worth building. On the contrary, the negative net present value indicates it not worth investing. When we evaluate different projects for investment, the one with the largest net present value is the best. The calculation formula is:





where *C*I is the annual profit of thermal power plants with energy storage. *C*O is calculated according to formula (25). (*C*I-*C*O)*t* is the net cash flow at year *t*.

## Dynamic investment payback period

The investment payback period can be calculated according to the investment cash flow statement. The investment payback period of a project is the point at which the cumulative net investment cash flows rise from negative to zero, which is calculated:

 (25)

# Case Study

## Parameter Setting

In this paper, we use a 300MW thermal power plant with a 100MW/100MWh BESS participating in frequency and peak regulation in the auxiliary service market as the test case. The case is based on the historical operation data of that power plant, and the capacity ratio and dispatching strategy of BESS participating in frequency and peak regulation are set according to references [13,18]. The connection mode of the BESS is shown in Fig. 2.

According to the LCC and benefit model constructed in this paper, the case studies are divided into two scenarios. In Scenario 1, we do not consider the indirect benefits of reduction in unit loss and the delay of power plant investment; while in scenario 2, we consider the above indirect benefits. In this paper, a lithium iron phosphate BESS is adopted as an example for economic benefit analysis. The parameters of BESS and conventional units refer to Table A1 in the appendix.



Fig.2 The connection mode of the BESS in power plant side

## Calculation of the cost and benefit indexes

As we change the ratio of the BESS capacity for frequency regulation to the capacity for peak regulation, the costs and benefits can be calculated in scenario 1 and scenario 2, respectively, and the changes of them are presented in Fig. 3.

It can be seen from Fig. 3 that the costs of BESS in the two scenarios are the same. As the capacity ratio of BESS for frequency regulation increases, its LCC increases in the beginning, then reaching a maximum of 489.72 million Yuan when the ratio reaches 80%. Whereafter, the LCC decreases gradually. The reason is that as the ratio of increases from 0 to 80%, charge and discharge capacity provided by BESS increases, increasing the operation cost and failure loss cost during frequency regulation, and besides its growth rate is higher than the descending rate of peak regulation cost. Therefore, LCC shows an upward trend as the ratio increases. But after that, the power output for peak regulation of BESS decreases with the increase of the capacity ratio of BESS for frequency regulation. As a result, the operation and maintenance cost and failure losses cost during peak regulation decreases, so LCC shows a downward trend. The changes of each kind of cost are shown in Fig. 4.



Fig.3 Changes in costs and benefits in scenarios 1 and 2



Fig.4 Changes in four types of costs

It can be seen from Fig. 3 that the total benefit of BESS in the two scenarios has the same trend. As the capacity proportion of BESS for frequency regulation increases, the total benefit increases at first and reaches the maximum value at 60%, where it reaches 476.32 million Yuan in scenario 1 and 608.54 million Yuan in scenario 2, and then falls gradually. Generally, the frequency regulation demand is relatively larger than the peak regulation demand in a power plant. When BESS only participates in auxiliary peak regulation at the beginning, the annual average charge and discharge capacity is 7.47×103MWh. With the ratio increasing from 0% to 60%, the annual average charge and discharge capacity increases to 1.41×104 MWh because of BESS participating in both frequency and peak regulation, which is 1.88 times of the original. Hence, the direct and indirect benefits of BESS participating in auxiliary frequency services increase significantly, resulting in a significant rise in total incomes. When the ratio increases from 60% to 100%, the output power of BESS for peak regulation gradually decreases to zero. Currently, because of the income only coming from frequency regulation, the annual average charge and discharge power is only 50.05% of the optimal value, so the total income of BESS for frequency regulation and peak regulation decreases rapidly with the decrease in its output power.

To summarize, the cost of BESS is maximum when the ratio is 80% and the income of BESS is maximum when the ratio is 60%. In addition, the income of scenario 2 is higher than the corresponding cost when the ratio is ranging from 50% to 60%, which means profitable.

## Economic benefit evaluation and analysis

Table A2 and Table A3 in the appendix list the calculation results of each economic evaluation index in each scenario. The changing trends of the three types of indexes are drawn in Figs. 5-7 for analyses.

It can be observed from Fig. 5 that *R*inv firstly increases and then decreases with the change of the capacity ratio of BESS for frequency regulation. When the ratio is 60%, *R*inv is the largest, and the value of *R*inv in scenario 2 is greater than that in scenario 1, so there are more economic benefits in scenario 2. When the ratio increases from 0 to 60%, the income growth is significantly greater than the cost growth. From Eq. (23), the higher *R*inv means better profitability. Conversely, when the ratio exceeds 60%, the growth of cost is higher than that of income, so *R*inv and profitability both decreases. Since the income in scenario 2 is higher than that in scenario 1, *R*inv in scenario 2 is higher than that in scenario 1.



Fig.5 Changes of *R*inv in scenarios 1 and 2



Fig.6 Changes of *V* in scenarios 1 and 2

It can be seen from Fig. 6 that *V* firstly increases and then decreases with the change of the capacity ratio of BESS for frequency regulation. When the ratio is 60%, *V* is maximum v, and its value in scenario 2 is larger than that in scenario 1. When the ratio ranging from 50% to 60%, *V* is positive, which indicates that BESS is worth investing. When the ratio increases from 0 to 60%, the income gradually increases, and its growth rate is higher than the growth rate of cost, so *V* increases. However, in scenario 1, because each income is lower than the corresponding cost, *V* is always negative. By contrast, in scenario 2, the income is higher than the cost in when the ratio is 50%-60%, making *V* positive, which means profitable. When the ratio exceeds 60%, the increase in cost is higher than that in income, so *V* and profitability both decreases.



Fig.7 Changes of *T*p in scenarios 1 and 2

It can be seen from Fig. 7 that *T*p first decreases and then increases with the change of the capacity ratio of BESS for frequency regulation. When the ratio is 60%, *T*p is the smallest, and *T*p in scenario 2 is smaller than that in scenario 1, which means the profitability in scenario 2 is better. When the ratio increases from 0 to 60%, the income growth is greater than the cost growth, so the investment payback period on BESS is shortened. Lower *T*p indicates shorter investment payback period. Conversely, when the ratio exceeds 60%, the cost growth is greater than the income growth resulting in higher *T*p and longer investment payback period. In Scenario 2, when the ratio reaches 50% or 60%, its *T*p is close to the industry benchmark, which is 12 years, so the project is profitable within the life cycle of BESS.

Above all, when the of BESS is 60%, the three types of indicators reach optimal. Compared with the industry benchmark of each indicator, most BESS projects are unprofitable. However, if we optimize the operation strategy of BESS according to the market mechanism, it can make profits, even approaching the benchmark. With the advancement of energy storage technology, the profitability of the project will gradually increase.

## Analysis of the impact of energy storage capacity on economic benefits

To analyze the impact of BESS capacity on its economic benefits, this section sets the capacity to 90%, 150%, and 200% of the original capacity, setting the capacity ratio for frequency regulation as 60%, and calculates the economic indicators. The results are shown in Table 1.

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| --- | --- | --- | --- | --- |
| TabLE.I  Impact of different capacity on BESS cost and indicators | | | | |
| The Capacity of BESS /MW•h | Total Cost *C*lcc/billion Yuan | Economic Evaluation Indexes | | |
| *T*p/yeat | *R*inv*/*% | *V/*104 Yuan |
| 90 | 4.6590 | 17.8 | 5.7678 | 1034.3 |
| 100 | 4.8501 | 12.9 | 6.3061 | 4063.5 |
| 150 | 6.8651 | >20 | 4.8256 | -5982.8 |
| 200 | 11.490 | >20 | 2.8833 | -35754 |

It is observed from Table I that when the capacity of BESS increases to 150% and 200% of the original, the total cost rises faster than its income, and *T*P is greater than the whole life cycle of BESS. Moreover, *R*inv decreases, and *V* appears negative. The above three indicators all indicate that the project is unprofitable. Also, the BESS capacity has a huge impact on its cost, and the sharp increase in cost leads to the rapid deterioration of each indicator. When the capacity reduces to 90%, the reduction of income is greater than its cost, resulting in the worse results of various economic indicators. In summary, when the capacity increases to 150% and 200%, or reduced to 90%, the three indicators all deteriorate. On the one hand, it proved that the BESS capacity set in this paper is reasonable. On the other hand, to make profits by deploying BESS, its capacity needs to be set properly in accordance with the specific power plants.

# CONCLUSION

This paper proposes a modelling and evaluation method to quantify the indirect benefits of BESS on the thermal power plant side for frequency and peak regulation considering the reduction in unit losses and the delay in investment. We use a thermal power plant configured with BESS as the actual example to verify the rationality of the model and evaluation method. The results of the case studies show that:

* From the perspective of cost and benefit, when the capacity ratio of BESS for frequency regulation is 80%, the cost is the largest, and when the ratio is down to 60%, the benefit is the largest. Meanwhile, when we consider the reduction in unit losses and the delay in investment, the benefit of BESS is higher than the cost when the ratio is 50%-60%, which means the deployment of BESS has profitability.
* From the analysis of indexes such as *T*p, *R*inv and *V*, when the capacity ratio of BESS for frequency regulation is 60%, the three types of indicators and economic benefits are optimal.
* Under the given capacity of thermal power units and frequency regulation demand, the capacity configuration of BESS has the optimal value.

References

1. J. Suh, D. Yoon, Y. Cho, and G. Jang, "Flexible Frequency Operation Strategy of Power System With High Renewable Penetration," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 1, pp. 192-199, Jan. 2017.
2. Y. Yoo, S. Jung and G. Jang, “Dynamic Inertia Response Support by Energy Storage System with Renewable Energy Integration Substation,” *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 2, pp. 260-266, March 2020.
3. Y. J. Gu, J. Xu, D. C Chen, Z. Wang, and Q. Q. Li, “Overall review of peak shaving for coal-fired power units in China,” *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 723-731, Nov, 2015.
4. R. Barzin, J. J. Chen, B. R. Young, M. M. Farid, “Peak load shifting with energy storage and price-based control system,” *Energy*, vol 92, no. 3, pp. 505-514, Dec, 2015.
5. D. M. OJEDA-ESTEYBAR, R. G. RUBIO-BARROS, A. VARGAS, “Integrated operational planning of hydrothermal power and natural gas systems with large scale storages,” *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 3, pp. 299–313, May, 2017.
6. C. T. Cheng, C. G. Su, P. L. Wang, and J. J. Shen et. al. “An MILP-based model for short-term peak shaving operation of pumped-storage hydropower plants serving multiple power grids”, *Energy*, vol. 163, pp. 722-733, Aug, 2018.
7. M-R. Jon, Z. Ekaitz, D. Argandona, and F-G. Unai, et al. “Multi-objective optimization of production scheduling using particle swarm optimization algorithm for hybrid renewable power plants with battery energy storage system,” *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 2, pp. 285–294, Sep, 2021.
8. P. Thais, B. G. L. Teixeira, “Operation strategies for coordinating battery energy storage with wind power generation and their effects on system reliability,” *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 1, pp. 190–198, July, 2021.
9. B. Zakeri, S. Syri, “Electrical energy storage systems: A comparative life cycle cost analysis,” *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 569-596, Feb, 2015.
10. X. Li, S. Wang, “A review on energy management, operation control and application methods for grid battery energy storage systems,” *CSEE Journal of Power and Energy Systems*, doi: 10.17775/CSEEJPES.2019.00160.
11. S. Wang, G. Geng, J. Ma, Q. Jiang, H. Huang and B. Lou, “Operational Bottleneck Identification Based Energy Storage Investment Requirement Analysis for Renewable Energy Integration,” I*EEE Transactions on Sustainable Energy*, vol. 12, no. 1, pp. 92-102, Jan, 2021.
12. M. T. Ma, T. J. Yuan, G. Y. Chen, et al. “Analysis of comprehensive economic benefits of energy storage participating in wind power auxiliary services,” *Power System Technology*, vol. 40, no. 11, pp. 3362-3367, Oct, 2016.
13. S. H. Lv, S. X. Cai, S. X. Wang, “Economic evaluation and development suggestions for distributed photovoltaic-energy storage systems,” *Electric Power*, vol. 48, no. 02, pp. 139-144, Feb, 2015.
14. L. Liang, J. L. Li, D. Hui, “Optimal allocation of energy storage device capacity for large-scale wind farms,” *High Voltage Technology*, vol. 37, no. 04, pp. 930-936, 2011.
15. H. M. Liu, D. Lu, B. Yang Bo, et al. “Dispatching strategy of energy storage power station capable of suppressing high-permeability distributed photovoltaic power generation fluctuations,” *High Voltage Technology*, vol. 41, no. 10, pp. 3213-3223, April, 2015.
16. Y. Q. Liu, P. Zou, Z. S. Yan, et al. “Design and operation practice of Shanxi electric power frequency modulation market mechanism,” *Electric Power System Automation*, vol. 43, no. 16, pp. 175-182, July, 2019.
17. H. Chen, Y. B. Jia, J, Zheng, et al, “Research on Market Mechanism and Dispatch Strategy of FS Auxiliary Service for Large-scale Energy Storage,” *Power System Technology*, vol. 43, no. 10, pp. 3606-3617, June, 2019.
18. Y. Cheng, M. Tabrizi, M. Sahni, et al. “Dynamic Available AGC Based Approach for Enhancing Utility Scale Energy Storage Performance,” *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 1070-1078, March, 2014.
19. D. Y. Chen, L. Z. Zhang, L. G. Wang. “Research on Control Strategy and Investment Return Evaluation of Energy Storage Frequency Modulation System,” *Modern Electric Power*, vol. 33, no. 01, pp. 80-86, Feb, 2016.
20. J. Y. Huang, X. R. Li, M. Chang, et al. “Capacity allocation method considering the energy storage battery participating in the primary frequency modulation technology economic model,” *Transactions of China Electrotechnical society*, vol 32, no. 21, pp. 112-121, July, 2017.
21. J. H. Li, J. H. Zhang, G. Mu, et al. “Hierarchical Optimal Scheduling of Energy Storage Assisted Fossil Power Units,” *Power System Technology*, 2019, vol 43, no. 11, pp. 3961-3970, Oct, 2019.
22. J. H. Li, S. Wang Sai. “Optimization of combined energy storage-assisted peak regulation scheme with both technical and economic benefits,” *Automation of Electric Power Systems*, vol 41, no. 09, pp. 44-50, May, 2017.
23. A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer, “Value Analysis of Battery Energy Storage Applications in Power Systems,” *2006 IEEE PES Power Systems Conference and Exposition*, Oct, 2006, pp. 2206-2211.
24. Y. Xu, S. H. Qiaolin, “Optimal capacity allocation of optical storage power station based on full life cycle theory,” *Journal of North China Electric Power University (Natural Science Edition)*, vol.25, no. 03, pp.16-23, March, 2018.
25. R. X. Wang, F. S. Li, Y. F. Zhang, et al. “Research on the influence of supercritical unit participating in one frequency regulation on steam turbine life,” *Journal of Engineering for Thermal Energy and Power*, vol. 29, no. 04, pp. 367-373, July, 2014.
26. W. Zhang, Y. F. Hu, “Research on low cycle fatigue loss of steam turbine rotor based on finite element analysis,” *Journal of Engineering for Thermal Energy and Power*, vol. 33, no. 09, pp. 31-38, Sep, 2018.
27. L. Lin, L. Q. Zou, P, Zhou, et al. “Multi-angle economic analysis of deep peak regulation of thermal power units under the condition of large-scale wind power grid connection,” *Automation of Electric Power Systems*, vol. 41, no. 07, pp. 21-27, April, 2017.
28. D. Zhou, F, Blaabjerg, T, Franke, et al. “Comparison of Wind Power Converter Reliability With Low-Speed and Medium-Speed Permanent-Magnet Synchronous Generators,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 10, pp. 6575-6584, Oct, 2015.

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