Research on benefit evaluation method of pumped storage power station

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Abstract. The development of pumped storage power stations in China is relatively short, and there is a lack of objective evaluation of the system benefits of pumped storage power stations, which leads to the problems of inaccurate functional positioning, single investment mode, and imperfect electricity price mechanism of pumped storage power stations in China, hindering the healthy development of pumped storage power stations. In order to solve this problem, this paper establishes the benefit evaluation system of pumped storage power station, selects economic benefit, technical benefit, social benefit and environmental benefit as evaluation indexes, and constructs the benefit evaluation model based on order relation analysis and entropy weight method.

1. Introduction
Under the background of new power reform, energy revolution and energy transformation, pumped storage power station is endowed with more value and mission. Pumped storage power station will get better development with the gradual improvement of medium and long-term market and spot market. Under this background, it is urgent to put forward a comprehensive and systematic benefit evaluation method for pumped storage power station. In this paper, the environmental benefit and social benefit are added to the comprehensive benefit evaluation of pumped storage power station. This is helpful to solve the problem that the development of pumped storage power station is not balanced because it only pursues economic benefits. [1]

2. Selection of evaluation indexes for benefit evaluation system of pumped storage power station
Figure 1 lists the economic benefit index, technical benefit index, social benefit index and environmental benefit index of pumped storage power station, as follows:
Figure 1. Benefit evaluation index system of pumped storage power station.

2.1. Economic benefit index

2.1.1. Peak-valley price difference benefit. The mathematical model of the direct profit of energy storage system participating in peak shaving and valley filling of distribution network is as follows:

\[ \Delta B_T = \eta E_a \cdot P_{H} - E_a \cdot P_{L} \]  \hspace{1cm} (1)

Among them, \( P_{H} \) and \( P_{L} \) are the peak section and valley section of the electricity price, with the spot market price changes in real time, \( \eta \) is the comprehensive benefit of the pumped storage power station, \( E_a \) is the pumped storage power station during the valley period.

2.1.2. Frequency modulation benefit. In this paper, the pumped storage unit replaces the thermal power unit to provide the dynamic cost of thermal power for the system, which is called the frequency regulation benefit of pumped storage power station. [2]
2.1.3. Phase modulation benefit. In this paper, the pumped storage unit replaces the thermal power unit to provide the dynamic cost of thermal power for the system, which is called the phase adjustment benefit of pumped storage power station. The phase adjustment benefit of pumped storage power station can be expressed as:

\[
I_{13} = P_0 \cdot Q \cdot \cos \theta \cdot \sin \theta \cdot (A / P_i, i, n) + P_0 \cdot Q \cdot \cos \theta \cdot \sin \theta \cdot 2\% \tag{2}
\]

where \( I_{13} \) is the annual phase regulation benefit of pumped storage power station; \( P_0 \) represents the unit active capacity investment without considering current capacity units; \( Q \) is the reactive power capacity of the unit; \( \cos \theta \) represents rated power factor; \( i \) Represents social discount rate; \( n \) represents the design period of pumped storage power station.

2.1.4. Reserve benefit. In this paper, the dynamic cost of thermal power saved when the pumped storage unit replaces the thermal power unit to provide spinning reserve for the system is called the reserve benefit of the pumped storage power station. The calculation method is:

\[
I_{14} = C \times 30\% \times 2\eta \tag{3}
\]

where \( I_{14} \) is the accident reserve benefit, \( C \) is the total installed capacity of the power station, and \( \eta \) is the comprehensive efficiency coefficient of the pumped storage power station.

2.1.5. Black start benefit. The main costs to realize the black start function include the annual test cost (or experimental cost) of the black start function, the annual maintenance cost of the black start unit, the compensation of the minimum power cost required for the operation of the basic plant equipment, the calculation of the black start power, the compensation of the minimum power cost required for the self-starting of the unit power generation unit, the reward for the recovery of social and economic losses, and the dynamic reward. The calculation method is the summation of this part, which is expressed as a unit. [3]

2.1.6. Electricity benefit. The calculation formula of electricity benefit of pumped storage power station is:

\[
I_{16} = B' - B \tag{4}
\]

where, \( B' \) represents the daily total coal consumption when the system does not call the pumped storage power station; \( B \) Represents the total daily coal consumption of the system when the pumped storage power station participates in the auxiliary service of the system; \( I_{16} \) is the difference between the two, pumped storage power station energy efficiency.

2.1.7. Capacity benefit. The following formula for calculating capacity benefit of pumped storage power station is:

\[
I_{17} = [C_0 + I_0 (A / P_{i,n})] - [C_{ps} + I_{ps} (A / P_{i,n_{ps}})] \tag{5}
\]

In the formula, \( I_{17} \) represents the capacity benefit of pumped storage power station; \( C_0 \) represents the annual fixed operation cost of thermal power units; \( I_0 \) represents the construction investment of thermal power units; \( n \) represents the payback period of thermal power unit investment; \( I_{ps} \) represents the construction investment of the same capacity pumped storage power station; \( C_{ps} \) represents the annual fixed operation cost of pumped storage power stations with the same capacity; \( i \) represents the benchmark discount rate; \( n_{ps} \) represents the investment recovery period of pumped storage power station.
2.2. Technical benefit index

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2.2.1. Unit availability factor. Unit availability factor refers to the proportion of units in standby state during the statistical period.

\[
\text{Unit availability factor} = \frac{\text{Available hours}}{\text{Statistics period hours}} \times 100\% 
\]  

2.2.2. Success rate of start-up. The success rate of start-up refers to the probability of successful start-up of the unit in accordance with the provisions in a given time. The pumped storage unit has two working conditions of power generation and pumping. The start-up of the power generation condition mostly provides the accident reserve capacity for the power system. Therefore, the successful start-up of the former is more important.

2.2.3. Annual starting times. In this paper, the annual starting times are selected as the technical effect of pumped storage power station, which reflects the utilization of pumped storage power station. The calculation formula is as follows:

\[
\text{Average starting times of unit} = \frac{(\text{Number of power startups} + \text{Pumping start times}) + (\text{Number of phase modulation startups} - \text{Emergency frequency regulation and accident standby start times})}{\text{Number of units}} \times 100\% 
\]  

2.2.4. Annual frequency qualified rate. In this paper, the annual frequency qualified rate index of power station is used to evaluate. The calculation formula is as follows:

\[
\text{Qualified rate of daily frequency} = \frac{\text{Daily frequency qualified time (min)}}{1440} \times 100\% 
\]

\[
\text{Annual frequency qualified rate} = \sum \frac{\text{Qualified rate of daily frequency}}{\text{Days of this year}} \times 100\% 
\]

2.3. Social benefit index

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2.3.1. Employment effect. The employment effect created by building power stations is very significant. Employment effect indexes are as follows:

\[
\text{Unit investment employment} = \frac{\text{New employment (person)}}{\text{Project investment (ten thousand yuan)}} 
\]

\[
\text{Direct employment effect} = \frac{\text{Number of direct employment provided by the project (person)}}{\text{Direct investment in the project (million yuan)}} 
\]
2.3.2. **Impact on related industries.** With the development of project construction, transportation, building materials and other advanced projects will develop accordingly. The geographical location of pumped storage power station is mostly near the city and scenic area. If attention is paid to the beautification and greening of the environment during the construction period, the reservoir area will become a new tourism landscape and rest resort, which can promote the development of local tourism, business and entertainment services.

2.4. **Environmental benefit index**

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2.4.1. **Amount of pollutant discharged.** According to the design capacity of other clean energy power plants, the pumped storage power station is constructed as a "buffer" according to a certain proportion, and the emission reduction of pollutants under the supporting effect of the pumped storage power station is used as the evaluation index.

2.4.2. **Impact on soil and vegetation.** The universal soil loss equation (USLE) for the impact on soil and vegetation is a commonly used method for calculating hydraulic erosion. In this paper, USLE is selected as the evaluation index. [4]

2.4.3. **Impact on clean energy consumption.** Mainly considering the pumped storage power station connected to the local provincial or regional power grid, promote wind power, nuclear power and hydropower to increase the proportion of power generation, through the clean energy (hydropower, wind power, etc.) to calculate the pumped storage power station to promote clean energy utilization efficiency index, unit MW. [5]

3. **Benefit evaluation model based on order relation analysis and entropy weight method**

According to the characteristics of pumped storage comprehensive benefit index system, this paper calculates, analyzes and compares the advantages of subjective weighting method and objective weighting method, and puts forward the combination weighting method of order relation analysis and entropy weight method, which has the advantages of subjective and objective weighting method.

3.1. **Order relation weighting method**

Order relation analysis is an improvement of analytic hierarchy process, and this method does not need consistency test.

**Definition 1:** If the importance of evaluation index \( x_i \) relative to a certain evaluation criterion (or goal) is greater than (or not less than) \( x_j \), it is denoted as \( x_i \succ x_j \).

**Definition 2:** If the evaluation index \( x_1, x_2, \cdots, x_m \) has relation \( x_1^*, x_2^*, \cdots, x_m^* \) with respect to a certain evaluation criterion (or goal), the order relationship between the evaluation indexes is established according to "\( \succ \)". where \( \{ x_i^* \} \) represents the i-th evaluation index after the order of "\( \succ \)". \( i = 1, 2, \ldots, m \).

3.1.1. **Determine the order relationship.** For the evaluation index set \( \{ x_1, x_2, \cdots, x_m \} \), the order relationship can be established according to the following procedures:

Invites experts (or policymakers) to select, in index set \( \{ x_1, x_2, \cdots, x_m \} \), one of the most important indexes deemed to be \( x_i^* \);
Invites experts (or decision makers) to select the most important index among the remaining m-1 indexes, denoted as $x_2^*$.

Invites experts (or decision makers) to select the most important index among the remaining m-(k-1), denoted as $x_k^*$.

The remaining evaluation index selected m-1 is $x_m^*$.

In this way, the only order relation $x_1^* \succ x_2^* \succ \cdots \succ x_m^*$ is determined.

### 3.1.2. Determination of relative importance between adjacent indexes.

The ratio of importance of adjacent indexes $A$ to $B$ can be expressed as:

$$ r_k = \frac{w_k - 1}{w_k} $$

(13)

Where, $w_k$ is the weight of the $k$-th index, $k = m, m-1, \cdots, 3, 2$. According to the order relationship between indexes, the relative importance of each index is calculated. The assignment of $r_k$ can be referred to the following table. When $m$ is large, $r_{k-1}$ can be taken.

| $r_k$ Value | Implication |
|-------------|-------------|
| 1.0         | $x_{k-1}$ and $x_k$ are equally important |
| 1.2         | $x_{k-1}$ is slightly more important than $x_k$ |
| 1.4         | $x_{k-1}$ is much more important than $x_k$ |
| 1.6         | $x_{k-1}$ is greatly more important than $x_k$ |
| 1.8         | $x_{k-1}$ is extremely more important than $x_k$ |

When there is an orderly relationship between $x_1, x_2, \cdots, x_m$, then $r_{k-1}$ and $r_k$ must satisfy:

$$ r_{k-1} \geq \frac{1}{r_k}, \quad k = m, m-1, \cdots, 3, 2 $$

(14)

### 3.1.3. Calculation of index weight.

If $A$ given by experts (or decision makers) satisfies the relation (3-17), then the weight $W$ of index $m$ is:

$$ w_m = \left(1 + \sum_{k=2}^{m} \prod_{i=4}^{k} r_i \right)^{-1} $$

(15)

and $w_{k-1} = r_k w_k$, $k = m, m-1, \cdots, 3, 2$, so the weights of all evaluation indexes are obtained.

### 3.2. Entropy weight method

Entropy method is an objective weighting method. The evaluation results are mainly based on objective data, almost unaffected by subjective factors, can largely avoid the impact of human factors. The calculation steps are as follows:

#### 3.2.1. For $n$ samples, $m$ indexes, then $x_{ij}$ is the number of the $j$-th indexes for the $i$-th sample, $(i = 1, \cdots, n)(j = 1, \cdots, m)$;

#### 3.2.2. Normalization of indexes. Since the measurement units of each index are not uniform, standardization should be carried out before using them to calculate the comprehensive index, that is,
the absolute value of the index should be transformed into the relative value, so as to solve the homogenization problem of different quality index values. In addition, the positive index and negative index values represent different meanings (the higher the positive index value is, the better the negative index value is). Therefore, different algorithms are needed for data standardization of positive and negative indexes:

Positive index:

\[ x_{ij} = \frac{x_i - \min \{x_{ij_1}, \cdots, x_{ij_m}\}}{\max \{x_{ij_1}, \cdots, x_{ij_m}\} - \min \{x_{ij_1}, \cdots, x_{ij_m}\}} \]  

(16)

Negative index:

\[ x_{ij} = \frac{\max \{x_{ij_1}, \cdots, x_{ij_m}\} - x_i}{\max \{x_{ij_1}, \cdots, x_{ij_m}\} - \min \{x_{ij_1}, \cdots, x_{ij_m}\}} \]  

(17)

For convenience, the normalized data \( x'_{ij} \) is still recorded as \( x_{ij} \).

3.2.3. Calculate the proportion of the i-th sample value under the j-th index.

\[ p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_i} \quad (i = 1, \cdots, n; \ j = 1, \cdots, m) \]  

(18)

In the formula, \( x_{ij} \) is the j-th measurement of the i-th index.

3.2.4. Calculate the entropy of the j index.

\[ e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij}, \quad j = 1, \cdots, m \]  

(19)

3.2.5. Calculation of information entropy redundancy (difference).

\[ d_j = 1 - e_j, \quad j = 1, \cdots, m \]  

(20)

3.2.6. Calculate the weight of each index.

\[ \omega_j = d_j / \sum_{j=1}^{m} (1 - e_j), \quad j = 1, \cdots, m \]  

(21)

3.3. Weighting method based on order relation analysis and entropy weight method

Let \( w_j \) be the weight of the j-th index term after the combination of the order relation analysis method and the entropy weight method that combines the advantages of the subjective and objective weighting method, and \( w_j \) is expressed as the linear combination of the weight coefficient obtained by the G1 method and the weight coefficient \( w'_j \) obtained by the entropy weight method, namely:

\[ w_j = aw'_j + (1 - a)w_j \]  

(22)

In the formula, \( w_j \) is the j-th index weight after the combination of order relation analysis method and entropy weight method. \( w'_j \) is the weight coefficient obtained by G1 method; \( w'_j \) is the weight coefficient obtained by entropy weight method. \( a \) is the subjective coefficient, which is used to adjust the degree of subjective and objective factors affecting the overall weight coefficient. The value range is 0 ~ 1, and the value of \( a \) can be selected according to the need. When \( a = 0.5 \), the influence of subjective and objective factors is similar.
According to the combination weight obtained by the order relation analysis-entropy weight, the final score of each evaluation index is determined. If $s_i$ is the score of the first composite index, then

$$s_i = w_j x_{ij} \times 100$$

(23)

Where, $x_{ij}$ is the standardized data of the j-th sub index of the i-th index of $x_j$, and $s_i$ is the final score.

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