Study on generation expansion planning evaluation method based on envelope optimization model

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Abstract. Participants involved in power generation construction were incomplete information and decision-making with bounded rational. Their motivations and behaviours may deviate from environment-friendly and social-welfare generation expansion planning. This paper proposes an envelope optimization model, which aims to meet the goals of minimizing the amount of abandoned water and maximizing the proportion of non-fossil power generation. And it presents a method for evaluating a certain generation expansion planning scheme quantitatively by using this model to calculate non-fossil power sources proportion and abandoned water electricity indicators. Finally, this evaluation method is proved by a regional power system's generation expansion planning scheme example. The generation expansion planning evaluation method presented in this paper is flexible and practical, which is conducive to guiding and evaluating short-term and long-term regional power development schemes.

1. Introduction

Increasing the proportion of non-fossil energy sources is a global common goal to develop generation. However, maximizing non-fossil energy sources proportion causes power output characteristics intermitted and irrepressible, which can’t satisfy load demand well. Participants such as investors, grid enterprises, government and local residents are "bounded rational" on decision-making in generation expansion planning with economic view. It is difficult for them to get complete information and make rational decisions and meet generation expansion planning goal. Generally, typical generation expansion planning optimization models used the minimum present value of total cost as objective function [1]. Apart from power source developers’ economic benefits, the existing power supply structure, load characteristics, social benefits reduction, wasteful investment and other influences were not considered. Some improved models were proposed to solve incomplete information problem by increasing variables and constraints. But objective function complexity could bring curse of dimensionalities [2] [3] [4]. The results of generation expansion planning optimizations were often not practical and adaptable.

This paper puts forward a method for evaluating generation expansion planning by sorting power output characteristic indicators, modelling envelope optimization method, and calculating evaluation indicators. This evaluation model is benefit for generation expansion planning scheme to adapt to changes in external boundary conditions, and estimates its deviation from eco-friendly and social-benefit power development targets.
2. Envelope optimization model

2.1. Indicators calculating and power sources sequencing
Calculate power balance to meet load demand in the given year with the status quo power sources, and get annual power shortage $Q_a$ and dry-season power shortage $Q_d$. Collect planning power sources data of annual power generation $P_a$ and dry-season power generation $P_d$. Define and calculate dry-season power shortage ratio $Q_r$ and dry-season power generation ratio $P_r$:

$$Q_r = \frac{Q_a}{Q_d}$$ (1)

$$P_r = \frac{P_a}{P_d}$$ (2)

Define and calculate power output characteristic indicator $M_o$ of a certain planning power source:

$$M_o = |P_r - Q_r|$$ (3)

According to formula (3), calculate several classes (total in J classes) of planning power sources output characteristic indicator $M_{o1}$, $M_{o2}$, ..., $M_{oj}$ in a regional power system. Particularly, generators with fossil fuel can be regulated flexibly, and its output characteristic indicator can be considered as zero. Sort $M_{o1}$, $M_{o2}$, ..., $M_{oj}$ from small to large, and a planning power source with higher ranking is considered to meet system load demand characteristics with higher matching degree in the nth year.

2.2. Lower envelope optimization model
Establish lower envelope optimization model for eco-friendly generation expansion planning: optimization goal in this model is minimization of abandoned water electricity, and constraint condition is that generation expansion planning scheme meets annual load demand in the given year.

- **Step 1:** Form a set of planning power sources: $G = \{G_1, G_2, \cdots, G_n\}$ with load demand characteristics matching degree is obtained from high to low based on indicator calculation, $G_i$ is the planned power supply in the ranking $i$, $i = 1, 2, \cdots, n$.
- **Step 2:** Select a planning power source $G_i$ from the set $G$ in turn, and add it to the status quo power source set $J$ in this grid, then get the power source set $J + G_i$, which is mixed the planning with the existing ones.
- **Step 3:** Calculate power balance with the given year load and power sources in the power collection $J + G_i$. If annual demand is met, then go to the next step; if not, add the next power source $G_i$ in the set $G$ to the set $J$, and go back to Step 2.
- **Step 4:** According to balance calculation result, determine the relationship between the amount of abandoned water electricity $A_i$ and the newly added electricity $A_{j}$. If $A_i <= A_{j}$, then add the planning power sources $G_i$ to lower envelope generation expansion planning scheme $J + G_{lower}(i)$ set, and calculation ends; if $A_i > A_{j}$, don’t put it in the set,
and go back to Step 2. \( J + G_{lower}(t) \) is a set of optimal planning power supply for social benefits.

2.3. Upper envelope optimization model
Establish upper envelope optimization model for eco-friendly power development: optimization goal in this model is maximization of non-fossil power generation, and constraint condition is the same as lower envelope model.

- Step 1 and Step 2: These two steps uses the same method to form power sources sets \( G \) and \( J + G \), as the lower envelope optimization model in Step 1.
- Step 3: If a planning power source \( G \) is non-fossil power source, add this power source to the status quo power source set \( J \), and skip to Step 5; if not, decide and select the next power source in order until all non-fossil power sources are chosen.
- Step 4: If there are no other non-fossil power sources in the set \( G \), select the fossil power sources with higher ranking from the set \( G \) and add them to the status quo power source set \( J \).
- Step 5: Calculate power balance with the given year load and power sources in the power collection \( J + G \). If annual demand is met, then go to the next step of calculation; if not, add the next power source \( J + G \) to the set \( J \), and go back to Step 3.
- Step 6: According to the balance calculation result, determine the relationship between the amount of abandoned water electricity \( A_i \) and maximum level of abandoned water electricity \( A_3 \). If \( A_i \leq A_3 \), add the planning power sources \( G \) to upper envelope generation expansion planning scheme set \( J + G_{upper}(t) \), and calculation ends; if \( A_i > A_3 \), don’t put it in the set, and go back to Step 2. \( J + G_{upper}(t) \) is a set of eco-friendly planning power supply.

3. Generation expansion planning evaluation method
Two sets of generation expansion planning schemes based on lower and upper envelope optimization model in different given year is as follows.

\[
J + G_{lower}(t) = \{J + G_{lower}(1), J + G_{lower}(2), \cdots, J + G_{lower}(n)\} \\
J + G_{upper}(t) = \{J + G_{upper}(1), J + G_{upper}(2), \cdots, J + G_{upper}(n)\}
\]

In formula (4): \( t \) is one of the given years, both of two sets \( J + G_{lower}(t) \) and \( J + G_{upper}(t) \) are meet annual load demand of the 1st to nth year.

Calculate indicators such as non-fossil power sources proportion \( R(t) \) and the amount of abandoned water \( A(t) \) in these generation expansion planning schemes:

\[
R(t) = \frac{(H(t) + W(t) + S(t))}{G(t)}
\]

\[
A(t) = P_{gen}(t) - P_{load}(t)
\]
In formulas (5) and (6): \( H(t), W(t), S(t), G(t) \) are installed capacity of hydropower, wind power, photovoltaics, and all power sources; \( P_{\text{gen}}(t), P_{\text{load}}(t) \) are power generation, load power consumption of all power sources in the given year respectively.

Non-fossil power proportion indicators \( R_{\text{upper}}(t), R_{\text{lower}}(t) \), and the amount of abandoned water indicators \( A_{\text{upper}}(t), A_{\text{lower}}(t) \) of upper and lower envelope optimization model for each given year are obtained from equations (5) and (6). Then, these indicators form upper and lower envelope curves. The section of non-fossil power proportion indicator envelopes \( S_1 \) and the amount of abandoned water indicators \( S_2 \) are formed by these curves, as follow.

As is shown in Figure 1, if non-fossil power proportion and abandoned water indicator of the evaluated power supply scheme are located in the section \( S_1 (S_2) \), it is regarded that the evaluated plans satisfy both development of non-fossil generators and society benefits in the given year, and vice versa. For the scheme that deviated from the envelopes model, it can be adjusted by decision-makers and other related parties.

![Figure 1. Evaluation method based on envelope optimization model.](image)

### 4. Computation example

The evaluation method with the envelope optimization model proposed in this paper is used to assess a generation expansion planning scheme \( J + E(t) \) in a certain region power grid as an example. The current installed capacity of power supplies in this area is 103.67MW, and there are 13 classes planning power supplies. Take the 5th, 10th and 15th years as the forest given years from the status quo year on. Calculate power shortage in this region with current power sources installation and load forecast results of the forest year by a power balance calculation software.

Calculate some indicators such as \( Q, P_r, M_o \) and the planning power supply ranking results are shown in Table 1. The calculation result of \( Q \) is 0.67.

| Planning sources(classes)                                      | Installed capacity (MW) | \( P_r \) | \( M_o \) | Ranking results |
|---------------------------------------------------------------|-------------------------|----------|---------|----------------|
| Planning hydropower station H-a with multiyear regulating capacity | 420                     | 0.64     | 0.03    | 2              |
| Planning hydropower station H-b with multiyear regulating capacity | 300                     | 0.63     | 0.04    | 3              |
| Planning hydropower station H-c with year regulating capacity  | 180                     | 0.32     | 0.35    | 9              |
Planning hydropower station H-d with year regulating capacity 19.5 0.51 0.16 6
Planning hydropower station H-e with year regulating capacity 60 0.5 0.17 7
Planning hydropower station H-f with year regulating capacity 210 0.31 0.36 10
Planning hydropower station H-g with year regulating capacity 18 0.36 0.31 8
Planning hydropower station H-h with year regulating capacity 110 0.28 0.39 11
Planning hydropower station H-i with year regulating capacity 110 0.28 0.39 11
Planning hydropower station H-j with year regulating capacity 111 0.27 0.4 12
Planning thermal power plant T-a 1100 -- 0 1
Planning wind power (resources) W-a 1326 0.6 0.07 4
Planning solar power (resources) W-a 2590 0.55 0.12 5

According to the ranking results of planning power sources indicator $M_o$, calculate envelope optimization model schemes in the 5th, 10th and 15th year. The generation expansion planning schemes with upper and lower envelope models is as Table 2 and Table 3:

Table 2. Power planning scheme based on lower envelope optimization model.

| Generation expansion planning scheme | The status quo year | The 5th year | The 10th year | The 15th year |
|--------------------------------------|---------------------|--------------|--------------|--------------|
| Total capacity (MW)                  | 10367               | 10607        | 12227        | 13875        |
| Hydropower capacity (MW)             | 7563                | 7563         | 7983         | 8393         |
| Wind power capacity (MW)             | 930                 | 930          | 1626         | 2256         |
| Solar power capacity (MW)            | 341                 | 341          | 465          | 600          |
| Thermal power capacity (MW)          | 1533                | 1773         | 2153         | 2626         |

Table 3. Power planning scheme based on lower envelope optimization model.

| Generation expansion planning scheme | The status quo year | The 5th year | The 10th year | The 15th year |
|--------------------------------------|---------------------|--------------|--------------|--------------|
| Total capacity (MW)                  | 10367               | 10773        | 12505        | 13356        |
| Hydropower capacity (MW)             | 7563                | 7563         | 8881         | 9102         |
| Wind power capacity (MW)             | 930                 | 1216         | 1626         | 2256         |
| Solar power capacity (MW)            | 341                 | 341          | 465          | 465          |
| Thermal power capacity (MW)          | 1533                | 1653         | 1533         | 1533         |

Assuming that there is a power planning plan to be evaluated, calculate upper and lower envelope power development plans corresponding to the forecast years of this area and evaluation indicators $R(t)$, $A(t)$ of this plan. The calculated results is in Table 4:

Table 4. Power planning scheme based on lower envelope optimization model.

| $A(t)$ (MW) | The status quo year | The 5th year | The 10th year |
|-------------|---------------------|--------------|--------------|
| $J + G_{lower}(t)$ | 52                  | 10           | 11           |
It can be seen that the proportion of green power and the indicator of abandoned water power are not located in the section of this power plan in the 5th year from the calculation results, which means this power sources schemes cannot meet the goals of both non-fossil power development and social benefit optimization in this year. Moreover, the power sources schemes are in the section of envelope curves in in the 10th and 15th year, which indicates that these schemes are developed well in long-term. So it is urged that the decision-makers to find the influences and solve the problem for power source construction in a short-term period.

5. Conclusions
This paper proposes an eco-friendly generation expansion planning evaluation method based on the envelope optimization model, which improves plans’ adaptation and flexibility to external boundary conditions, and can evaluate the deviation from social benefits and eco-friendly power development goal quantitatively.

A power supply scheme of a certain regional power system is used as an example to verify the practicability of the evaluation method proposed in this paper. The result shows that deviation degree from eco-friendly power development goal of the power supply plan at various levels are different in the given years. For the forecast year closer to the present, power supply construction sequence and scale has greater influence on the scheme, which result in larger differences between planning and construction process. However, the generation expansion planning scheme under incomplete information and scattered decision-making can be adjusted more flexibly by calculating the deviation indicators.

The evaluation method proposed in this paper can be applied to the generation expansion planning and evaluation field. It can reflect the power system development goals, social benefits and the interests of all parties fully, and is benefit to guide and evaluate short-term and long-term regional generation expansion planning and construction.

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