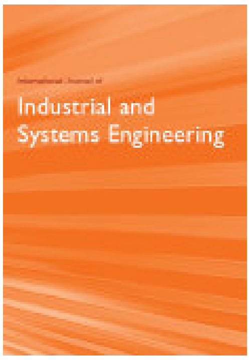

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Investment efficiency evaluation of electric power substation projects by stages using the EWM-DEA model

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Abstract: Power grid construction projects are crucial for national industrial development. To improve the investment efficiency (IE) of substation engineering construction, this study determines the influencing factors of the input and output of substation construction projects through the entropy weight method (EWM) principle and constructs the evaluation model of IE of substation engineering construction by using data envelopment analysis (DEA) theory. Considering substation projects of a power grid company as an example, this article evaluates and compares the investment economy of one-time and phased construction to maximise the economic efficiency of substation project construction. Hence, our study provides scientific reference for investment decision-making involving substation projects and promotes collaborative planning of various regions, projects, and assets under the construction of substation projects. The results show that the IE of phased substation construction projects is higher than that of one-time construction. This effectively improves the IE of power grid companies.

Keywords: substation project; data envelopment analysis; DEA; entropy weight method; EWM; input–output index; construction by stages; investment efficiency; IE.

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1 Introduction

Power engineering construction is the basic guarantee of a country's urbanisation process (Mittelviefhaus et al., 2021; Wang et al., 2021). Scientific evaluation of IE of power grid construction projects can guide the investment decision-making and optimise IE, avoid high investment costs, meet the increasing power demand, and ensure that power grid enterprises maximise IE while considering socio-economic benefits (Schreiner and Madlener, 2021; Tao et al., 2021; Xin et al., 2021). In power grid construction, construction time interval of some phased projects can be short, burdening the participating units and personnel and affecting the safe operation of the grid. Therefore, a comparative study on the IE of one-time and phased construction and planning the power grid investment scientifically is vital.

Generally, the efficiency evaluation of power grid project construction can scientifically demonstrate whether the project meets investment expectations and provides reference for investment decision (Greiml et al., 2021; Coady and Duquette, 2021; Castellini et al., 2020). Considering the economy and efficiency of substation investment by stages as the starting point, we first examine relevant literature and summarise common methods for measuring efficiency and the economic applicability of each method. Second, we analyse the uniqueness of DEA in research on IE of phased construction. We consider the regional economic and technical impact of power grid project construction, identify key factors, and use the EWM to select input–output factors. Third, according to the determined input–output elements, DEA is used to calculate and compare the IE of one-time and phased construction of power grid projects. Improvement and optimisation methods are proposed under various efficiency conditions from the aspects of both pure technical efficiency (PTEs) and scale efficiencies (SEs), to guide the decision-making of power grid companies. Finally, several conclusions and suggestions are given.

2 Literature review

In power grid IE research, Pierluigi summarised the potential benefits of disaster recovery in smart grids and built the coordination degree model of smart grid operation efficiency and power grid disaster benefit recovery (Siano, 2014). He built a linkage model of transmission and distribution price and electric power substation investment based on sustainable development, which is suitable for the actual situation of China's power market (He et al., 2015). Considering the complexity of power grid investment demand, Li et al. (2018) proposed a hybrid forecasting model of EMD–GASVM–RBFNN based on EMD, which can accurately predict investment demand of the power grid and improve IE. Based on cost–benefit analysis, intending to maximise net profit in the entire life cycle, Han established a microgrid generation planning model including a low-carbon economy (Han et al., 2016). Zhen determined that electric power substation infrastructure is a good policy tool for driving regional economic development at the present stage; however, regions have different investment priorities (Xu et al., 2021). Ahmet investigated the economic benefits and efficiency of smart grid automation investments (Onen et al., 2015). Poudineh and Jamasb (2014) summarised the benefits of disaster recovery in smart grids and built the coordination degree model of smart grid operation efficiency and disaster benefit recovery. Citing

Ghana, Abdulsalam demonstrated the importance of cost efficiency in substation planning (Abdul-Salam and Phimister, 2016). Based on the three-stage DEA model, Sun researched the IE evaluation of China's provincial power grid enterprises under the new power market reform and put forward relevant investment policy suggestions.(Sun et al., 2019). Considering the investment benefits of solar photovoltaic and supply-side energy storage, Raziei et al. (2016) conducted a study on the clean energy utility of multifamily residential buildings in the energy market. Wang et al. (2018) determined the joint effects of clean power on regional total-factor energy IE.

Existing literature is useful for studying the IE of power grid projects; however, it only focuses on analysing their economic benefits.

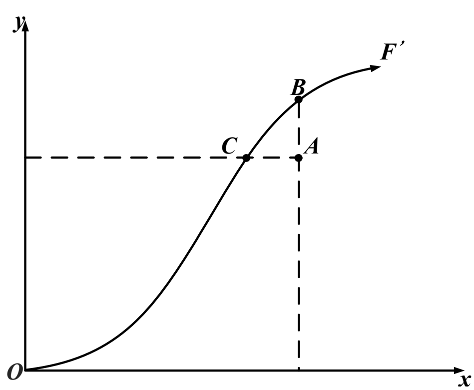
3 Efficiency method

3.1 Efficiency types

Efficiency essentially follows the Pareto optimal state of economic efficiency theory, which is the ratio of output to input. Three different concepts of main efficiency types are provided below.

1 Technical efficiency (TE): From the output perspective, TE reflects an enterprise's ability to obtain maximum output under the condition of constant input. From the input perspective, TE is the ability to input the minimum required when output is provided. When return to scale (RTS) remains unchanged, distance between the enterprise and forefront of production is TE. TE can be divided into PTEs and SEs. Combined with production function theory, the production process under the condition of single input and single output can be represented as shown in Figure 1.

Figure 1 Production function curve



Production frontier refers to the maximum output corresponding to each input level, as represented by the curve OF' in Figure 1. A manufacturer on the production boundary is technically effective as demonstrated in points B and C. Under the production boundary is invalid, as shown in point A.

2 Pure TE (PTE): This refers to the distance measure between the decision-making unit (DMU) and the production frontier when the RTS is variable.

3 SE: This refers to productivity increase when the unit production scale changes. SE is measuring the relationship between the DMU and the production frontier when the RTS is variable.

3.2 Basic formula of efficiency analysis

According to efficiency theory, some interaction between the above three efficiency indicators to measure the production state, and the value and significance of production and operation activities can be fully reflected through three aspects of TE, PTE, and SE. Therefore, in this study, the phased construction investment of substation project must consider TE. Equation (1) presents the relationship between PTE and SE:

$$SE = \frac{TE}{PTE} \tag{1}$$

According to the input–output index, this study builds the DEA model of IE of phased substation construction projects, calculates technical and PTEs, and calculates the SE according to equation (1).

4 DEA theory and it is applications

DEA is a nonparametric method evaluating the relative effectiveness of multi-input and multi-output DMUs (Sueyoshi and Wang, 2017; Mohsin et al., 2021; Mohd et al., 2021; Pessanha and Melo, 2021; Almeida Neves et al., 2020; Wang et al., 2020). DEA can effectively calculate and analyse the IE of power grid project construction, to study the economy of power grid project construction and make an important reference for later power grid investment decision-making. Currently, CCR and BCC are the two most basic models, and the two most widely used models in recent years, as demonstrated in equation (2) and equation (3):

1 CCR model

$$(CCR)\begin{cases} \max \mu^T y_0, \\ s.t. \quad \omega^T x_j - \mu^T y_j \geq 0, j = 1, 2, \ldots, n, \\ \omega^T x_0 = 1, \\ \omega \geq 0, \mu \geq 0. \end{cases} \tag{2}$$

2 BCC model

$$(BCC)\begin{cases} \max(\mu^T y_0 + \mu_0), \\ s.t. \quad \omega^T x_j - \mu^T y_j - \mu_0 \geq 0, j = 1, 2, \ldots, n, \\ \omega^T x_0 = 1, \\ \omega \geq 0, \mu \geq 0. \end{cases} \tag{3}$$

Referring to the calculation method of the above model, the TE of the DMU can be obtained according to input and output element index.

The above two classic DEA models constitute a complete system for the study of returns to scale evaluation in efficiency, which is expressed in a general form, as in equation (4):

$$(P)\begin{cases} \max\left(\mu^T y_0 + \delta_1\mu_0\right) = V_P, \\ s.t. \quad \omega^T x_j - \mu^T y_j - \delta_1\mu_0 \geq 0, j = 1, 2, ..., n, \\ \omega^T x_0 = 1, \\ \omega \geq 0, \mu \geq 0, \delta_1\delta_2(-1)^{\delta_3}\mu_0 \geq 0. \end{cases} \tag{4}$$

Definition 1: If the optimal value V_p of linear programming (*P*) is 1, the decision unit j_0 is labelled as weak DEA efficient.

Definition 2: If the linear programming (*P*) has an optimal solution, ω^0, μ^0, μ_0^0 satisfies equation (5):

$$\omega^0 > 0, \mu^0 > 0, V_P = \mu^{0T} y_0 + \delta_1\mu_0^0 = 1. \tag{5}$$

The DMU j0 is then called DEA efficient,

When $\delta_1 = 0$, model (*P*) is a CCR model. When $\delta_1 = 1$, $\delta_2 = 0$, model (*P*) is a BCC model.

It can be seen from the above calculation process that when using DEA to evaluate the efficiency of power grid construction projects, DEA is effective if the TE of the evaluation object is 1, otherwise, it is invalid.

Combining the CCR and BCC model can effectively calculate the TE of the DMU and calculate the SE according to both PTEs and TEs. Based on the above characteristics, CCR and BCC models are used to calculate the TEs and PTEs of phased construction of power grid projects in this study. On this basis, SE value (EV) is calculated by equation (1) and the IE of substation projects is studied.

5 Selection of index

Power grid engineering construction projects entail huge investments, long construction cycles, and high uncertainties. This study scientifically screens and determines the adequate input–output elements, analyses the influencing factors of input–output elements, and selects specific indexes to establish the index system.

This chapter selects the evaluation index of IE of phased construction of substation projects based on the EWM. Moreover, it includes selecting the DMU, determining influencing factors of input and output, and selecting the evaluation indicators of IE of phased power grid project construction to provide a theoretical basis for the case analysis in the next chapter.

5.1 Influencing factors of input–output indicators

Under normal circumstances, the input–output elements depend on the investment decision-making and construction process of the construction project itself. However, they will be comprehensively affected by various factors in the actual investment decision-making process. This study analyses these items by from the following four aspects.

1 Macroeconomy: The change of national macro-economy plays a guiding role in power grid development.

2 Power grid construction planning: Constructing transmission lines is significant in ensuring power supply, promoting clean energy development, and improving the security level of the power grid.

3 Engineering project management: Every aspect of the project management process for power grid projects should be strictly controlled to achieve the set objectives.

4 Technical level: At this stage, the electric power construction industry has a wide range of technological upgrades, and technologically advanced power grid construction projects will promote social progress.

5.2 Selection principle of input–output indicators

Identifying and analysing input–output factor indexes is instrumental in ensuring the accuracy and validity of IE evaluation results of power grid projects. Therefore, we summarise the existing relevant research literature and determine that the input–output factors of IE evaluation of power grid projects should follow four principles:

1 The comprehensive scope of indicators.

2 Index is quantifiable.

3 The indicators are objective and standardised.

4 The number of indicators is adequate.

Referring to the above four basic principles, based on indicators in the data of power grid construction projects in Hubei Province, China, and combined with the influencing factors of power grid construction, input–output indicators studied in this study can be determined.

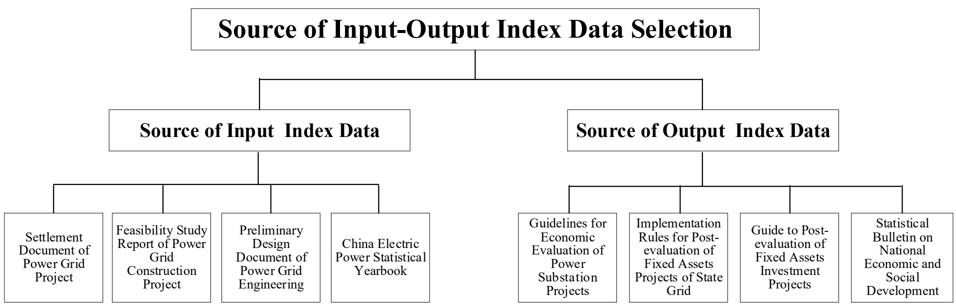
5.3 Acquisition and processing of element index data

5.3.1 Case background and source of indicator data

This section screens targeted indicators based on early-stage data and documents. Substation projects can be constructed in stages according to the investment situation. On one hand, it can alleviate capital pressure of the investor. On the other hand, if the regional load situation does not require simultaneous installation of multiple transformers, phased installation can reduce the idle rate of the equipment. When the regional economic development is high and power demand is greater, the main transformer of the substation can be expanded. In this study, the IE analysis of phased construction of substation projects is based on the DEA model of one-time construction and phased construction of substation projects, respectively. The results are compared to analyse the economy of substation construction.

Owing to different economic environments, geographical characteristics, and local power grid planning, screening input–output indicators of power grid construction projects will be different. To maintain consistency of input–output indicators and build a better DEA model, this study examines data from Hubei Province, China. Owing to the large number of recently constructed 220kV substation projects, the relevant data of 220kV substation projects are collected. To reduce the gap between projects and ensure model construction accuracy, the scope of new 220kV substations is reduced to the capacity of a single main transformer 1×180MVA. To ensure the data comparability, the phased construction of substation projects combines new construction and later expansion. Because of project screening limitations, available reference data are limited. In this study, eight new 220kV substation projects are considered one-time construction projects, and one new 220kV substation project is added to the later expansion project, respectively, and 1×180MVA main transformer project is a phased construction project. Figure 2 shows the selection source of input–output index data for measuring IE of substation construction.

Figure 2 Source of input–output index data selection



5.3.2 Screening indicators with EWM

Based on an extensive collection of input–output element index data and qualitative analysis, quantitative analysis is conducted according to index weight to screen reasonable input–output element indexes and ensure that indexes used in modelling accurately reflect the characteristics of the substation engineering project. In this section, EWM is used for index screening.

5.3.2.1 Connotation of EWM

Entropy was originally a thermodynamic concept. Later, C.E. Shannon introduced information theory and proposed information entropy. After years of development, it was widely used in engineering and economic fields (Cui et al., 2021; Kumar et al., 2021; Davoudabadi et al., 2019; Ghosh et al., 2017). The EWM determines the objective weight according to the index variability (entropy value). Hence, according to the data difference degree of indexes, the entropy weight of each index is obtained using information entropy. Moreover, the weight is corrected by entropy weight, and an objective weight index is obtained by mathematical analysis.

According to the information theory, information measures the order degree of a system. In contrast, entropy measures the disorder degree of a system. Assuming that a system may be in different states and the corresponding probability of each state is $p_i (i = 1, 2, \dots, m)$, system entropy is defined as shown in equation (6):

$$e_i = -\sum_{i=1}^{m} p_i \ln p_i \tag{6}$$

According to the above analysis, when $p_i = 1/m$ ($i = 1, 2, \ldots, m$), that is, the probability of various states is the same, maximum entropy is shown in equation (7) as follows:

$$e_{\max} = \ln m \tag{7}$$

From the definition of information entropy, the smaller the entropy e_j of an index, the greater the degree of change of the index between different observation objects and the more information can the index provide. In evaluation activities, the greater the role the index can play in measuring and distinguishing different objects to be evaluated, the greater the weight of the corresponding index, and vice versa.

5.3.2.2 Basic steps of EWM

According to the above, the number of DMU efficiency evaluation of power grid project construction is m. Moreover, each evaluated DMU has *n* element indexes (input or output elements, respectively), which can form the original matrix of input–output elements, as shown in equation (8):

$$R = (r_{ij})_{\max} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{21} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}_{\max} \tag{8}$$

where r_{ij} is the evaluation value of the ith substation project construction under the jth factor index.

The EWM consists of seven basic steps:

The first is normalising and calculating the relative proportion P_{ij} of the index value of the ith substation construction project factor under the jth factor index, as shown in equation (9):

$$P_{ij} = r_{ij} \Big/ \sum_{i=1}^{m} r_{ij} \tag{9}$$

The second is calculating the entropy e_j of the jth index:

$$e_j = -\frac{1}{\ln m} \sum_{i=0}^{m} P_{ij} \ln P_{ij} \tag{10}$$

As can be seen from equation (10), the smaller the index entropy e_j, the greater the variability of the index, the more effective information it provides, and the greater the role it plays in the later DEA model calculation process. Hence, this should be retained or otherwise eliminated.

The third is to calculate the entropy weight w_j of the jth factor index, as shown in equation (11):

$$w_j = (1-e_j) \Big/ \sum_{j=1}^{n} (1-e_j) \tag{11}$$

The fourth is to calculate the discrimination of the index, as shown in equation (12):

$$\eta_j = \frac{1-e_j}{\left(n - \sum_{j=1}^{n} e_j\right) e_j} \tag{12}$$

The fifth is that the smaller the index entropy, the greater the degree of discrimination. Hence, the index should be retained. Therefore, the indexes are sorted according to the discrimination value η_j, and the factor indexes with larger η_j are selected to form the final input–output factor index system.

The sixth uses the discrimination value to determine the input–output index according to the solution results of the above steps, which can be used as the basis for the analysis and research of the DEA model of the power grid construction project.

Table 1 Input index data of one-time construction projects

Substation	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
A	9176	3103	3224	1058	214	753	272	509.78
B	8961.14	2694.85	3191.47	996.61	209.65	1109.4	301.86	497.84
C	12732	4839	4966	1302	256	668	365	687.06
D	10739	5043	2900	1027	216	589	326	596.61
E	13169	4049	4641	1026	196	2391	349	712.22
F	15534	4450	4769	1636	328	770	394	768.39
G	15683	5592	5276	1572	249	1053	437	871.28
H	8473	3126	2726	1204	123	458	156	470.72

5.4 Measurement of index of one-time construction project

5.4.1 Input indicators

Data that may obviously cause calculation problems are eliminated. Eight input index data are retained for each new 220kV substation project, which is as follows: X_1, is the total investment of the construction project (1×10^4 yuan); X_2, the construction and installation engineering cost (1×10^4 yuan); X_3, the equipment purchase cost (1×10^4 yuan); X_4, other costs (1×10^4 yuan); X_5, basic reserve cost (1×10^4 yuan); X_6, the construction site acquisition and cleaning cost (1×10^4 yuan); X_7, the loan interest during the construction period (1×10^4 yuan); and X_8, the unit investment (yuan/kVA). The input index data are shown in Table 1.

We calculate data in Table 1 using the EWM and normalise the data of eight one-time substation construction projects. Table 2 shows the calculation results.

Table 2 Calculation results of relative proportion P_{ij} of one-time construction investment index value

P_{ij}	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
A	0.10	0.09	0.10	0.11	0.12	0.10	0.10	0.10
B	0.09	0.08	0.10	0.10	0.12	0.14	0.12	0.10
C	0.13	0.15	0.16	0.13	0.14	0.09	0.14	0.13
D	0.11	0.15	0.09	0.10	0.12	0.08	0.13	0.12
E	0.14	0.12	0.15	0.10	0.11	0.31	0.13	0.14
F	0.16	0.14	0.15	0.17	0.18	0.10	0.15	0.15
G	0.17	0.17	0.17	0.16	0.14	0.14	0.17	0.17
H	0.09	0.10	0.09	0.12	0.07	0.06	0.06	0.09

According to the calculation results of the relative proportion P_{ij} of element index value in Table 2 and equations (10), (11), and (12), we calculate the entropy e_j, entropy weight w_j, and discrimination of the index η_j, as shown in Table 3.

Table 3 Calculation results of EWM for input indexes of one-time construction projects

Index	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
e_j	0.987	0.986	0.985	0.991	0.985	0.932	0.984	0.989
w_j	0.079	0.087	0.093	0.055	0.092	0.427	0.101	0.066
η_j	0.080	0.089	0.094	0.055	0.093	0.458	0.103	0.067

According to the calculation results of the above EWM, the eight indexes are distinguished η_j after ranking from large to small, and we select the value with large discrimination as the input index of the one-time construction of substation projects. The ranking is as follows: X_6, X_7, X_3, X_5, X_2, X_1, X_8, and X_4.

5.4.2 Output indicators

Referring to the screening and elimination principle of input indicators, the output indicators of substation construction project are as follows: Y_1 is the financial net present value (1×10^4 yuan), Y_2 is the financial internal rate of return IRR (%), Y_3 is the static investment payback period (year), Y_4 is the total return on investment (%), Y_5 is the regional GDP growth rate (%), Y_6 is the GDP industrial composition index (%), and Y_7 is the score of technical indicators, Y_8 is the score of environmental protection index.

Table 4 Output index data of one-time construction projects

Substation	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8
A	3290.62	9.85	11.6	4.39	11.4	57.7	64.2	87
B	4593.73	10.89	10.34	5.27	13.5	55.3	71.4	92
C	5229.36	9.65	11.87	4.22	8.5	43.7	65.5	88
D	4674.72	9.95	11.48	4.47	9.1	36.4	59.6	92
E	6980.22	11.06	10.11	5.46	8.8	45.7	67.6	95
F	6270.65	9.77	11.71	4.32	9.5	50.81	68.6	80
G	4718.35	8.43	13.64	3.21	9.9	35.79	68.2	73
H	4430.86	11.01	10.2	5.38	8.5	43.7	64.1	85

Table 4 shows the output index data of the one-time substation construction projects.

The data in Table 4 is calculated using the EWM. First, the eight-output data of one-time substation construction projects in Table 4 is normalised. Table 5 presents the calculation results.

Table 5 Calculation results of relative proportion P_{ij} of one-time construction output index value

P_{ij}	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8
A	0.08	0.12	0.13	0.12	0.14	0.16	0.12	0.13
B	0.11	0.14	0.11	0.14	0.17	0.15	0.13	0.13
C	0.13	0.12	0.13	0.11	0.11	0.12	0.12	0.13
D	0.12	0.12	0.13	0.12	0.11	0.10	0.11	0.13
E	0.17	0.14	0.11	0.15	0.11	0.12	0.13	0.14
F	0.16	0.12	0.13	0.12	0.12	0.14	0.13	0.12
G	0.12	0.10	0.15	0.09	0.13	0.10	0.13	0.11
H	0.11	0.14	0.11	0.15	0.11	0.12	0.12	0.12

Calculation parameters e_j, w_j and η_j. Our results are shown in Table 6.

Table 6 Calculation results of EWM for output indicators of one-time construction projects

Substation	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8
e_j	0.989	0.998	0.998	0.994	0.994	0.994	0.999	0.999
w_j	0.307	0.047	0.062	0.168	0.174	0.182	0.018	0.042
η_j	0.310	0.047	0.062	0.169	0.175	0.183	0.018	0.042

According to the calculation results of the above EWM, after sorting the eight indexes from large to small, we select the value with large discrimination as the output index of the one-time substation construction projects, and the order is as follows: Y_1, Y_6, Y_5, Y_4, Y_3, Y_2, Y_8, and Y_7.

5.5 Measurement of index of phased construction project by EWM

Research on the phased construction of substation projects involves two or more construction periods. Therefore, selecting indicators requires more specific analyses. Carefully analysing each indicator and reasonably analysing and processing the multi-phase data are necessary to ensure the accuracy of later DEA model measurement. Therefore, the selection of phased construction index of substation projects is extremely significant.

5.5.1 Input indicators

According to the EWM analysis of one-time construction project indicators, the eight indicators are organised from large to small, and the value with large discrimination is selected as the investment index of the phased construction of substation projects. The order is as follows: X_6, X_2, X_5, X_7, X_1, X_3, X_8, and X_4.

5.5.2 Output indicators

According to the analysis of the one-time construction project index EWM, after ranking the above eight indexes from large to small, we select the larger value as the output index of the one-time construction of substation projects. The ranking is as follows: Y_1, Y_5, Y_6, Y_4, Y_3, Y_7, Y_2, and Y_8.

5.6 Integration of input–output indexes of one-time and phased construction projects

The appropriate number of indicators should be determined in indicator selection. The rule of thumb in DEA theory stipulates that the number of evaluation indicators should not be more than half the number of DMU. Too many indicators lead to a large number of effective DMUs, greatly reducing differentiation and effectiveness of the DEA mode, while too few indicators do not provide enough information for decision-makers. Therefore, in the case analysis of eight 220kV substation projects, this study selects four input and four output indexes.

To maintain consistency of input indexes between a one-time construction project and phased construction of substation projects, to reduce the model difference and enhance the comparability, overlapping items of the top 5 indexes of the two input index systems are considered the input indexes of DEA model in this study, which is as follows: X_2, X_5, X_6, and X_7.

The top four indicators of the two output index systems of one-time and phased substation construction projects completely coincide. Therefore, these four indicators are determined to be output indicators of the DEA model in order: Y_1, Y_4, Y_5, and Y_6.

6 Case analysis

Using substation projects in China's Hubei Province as an example, this chapter selects the corresponding DMU and uses BCC and CCR models to calculate PTEs and TEs of the one-time and phased construction models, respectively, and then calculates the SE. Hence, the IE results of the two DEA models are compared and analysed, the invalid DMU of DEA is highlighted, and the improvement suggestions are proposed.

6.1 IE of one-time construction

6.1.1 Calculation of one-time construction IE

The data of eight indicators of one-time construction input and output of substation project are shown in Table 7.

Substituting the input and output index data of the one-time construction of substation projects in Table 7 into the CCR and BCC models, provides the TEs and PTEs of the one-time construction of substation projects. According to equation (1), TEs and PTEs, the SE and RTS of the one-time construction of substation projects can be calculated. The IE of the one-time project construction is presented in Table 8.

Table 7 Data of input–output indicators for one-time construction of substation projects

Substation	X_2	X_5	X_6	X_7	Y_1	Y_4	Y_5	Y_6
A	3103	214	753	272	3290.62	4.39	11.40	57.70
B	2695	210	1109	302	4593.73	5.27	13.50	55.30
C	4839	256	668	365	5229.36	4.22	8.50	43.70
D	5043	216	589	326	4674.72	4.47	9.10	36.40
E	4049	196	2391	349	6980.22	5.46	8.80	45.70
F	4450	328	770	394	6270.65	4.32	9.50	50.81
G	5592	249	1053	437	4718.35	3.21	9.90	35.79
H	3126	123	458	156	4430.86	5.38	8.50	43.70

Table 8 Analysis results of IE of one-time construction of the substation

DMU	*TE*		*PTE*		*SE*		*RTS*
	EV	*sort*	*EV*	*sort*	*EV*	*sort*	
A	1	1	1	1	1	1	-
B	1	1	1	1	1	1	-
C	0.809	7	0.888	7	0.911	6	DRS
D	0.832	6	0.949	6	0.878	7	DRS
E	1	1	1	1	1	1	-
F	0.974	5	1	1	0.974	5	DRS
G	0.585	8	0.672	8	0.870	8	DRS
H	1	1	1	1	1	1	-

Table 8 shows that the TE of substations A, B, E, and H is one, which is DEA effective. The investment index of substation project construction can be utilised for maximising the output effect. The TE of the other four substations is less than one, which is DEA invalid. The higher the TE value, the higher the utilisation efficiency of the input index. Therefore, the lowest TE of substation G in the remaining four substations is 0.585. This indicates that the IE of this substation project is the lowest. The PTE of substations A, B, E, F, and H is one. This indicates that these five substations are on the production function surface, and the technical IE is very high. Hence, further improvement is not needed. The PTE of the other three substations is less than one. This indicates that some resources are wasted because of the technical level. Among them, PTE of substation G is 0.672. This indicates that the resource investment of 0.328 because of the technical level is invalid, and a large scope for improvement remains.

SE is the ratio of TE to PTE. This reflects the gap between the current and optimal investment scales. The SE of substations A, B, E, and H is one. This indicates that SE has reached the optimal level. SE of the other four substations is distributed between 0.870–0.974. This indicates that the overall SE has scope for improvement. Although substation F is effective in PTE, it is ineffective in SE. This indicates that the investment scale of substation F is too large, and the IE can be optimised by reasonably adjusting its scale.

Data in Table 8 shows that substations C, D, F, and G are diminishing returns to scale (DRS). This indicates excess input resources, that is, the proportion of output increase, is less than that of input increase. Therefore, IE of the DMU should be improved.

6.1.2 Analysis on the improvement of one-time construction IE

After using the EWM-DEA model to calculate IE of substation projects, the main reference basis for improvement suggestions is to increase (or decrease) output (or input) while input (or output) remains unchanged. When calculating the CCR model of one-time construction of substation projects, the projection can be calculated. Projection value of the DEA-effective DMU is equal to index value, and improvement is not necessary. The projection value of the DEA-invalid index is the improved optimal value. Hence, the difference between the index value and the projection value is the improvement amount. Moreover, the proportion of the improvement amount in the index value is the improvement proportion.

In the one-time construction, substation C with invalid DMU DEA is used as the analysis object. The actual input value of input index X_2 of substation C is 48.39 million yuan, the projection value is 36.8935 million yuan, the improvement method is to reduce the investment of 11.4965 million yuan, and the improvement proportion is 23.76%. Actual input value of X_5 is 2.56 million yuan, and projection value is 1.4517 million yuan. The improvement method reduces investment by 1.1083 million yuan, and improvement proportion is 43.29%; The actual input value of X_6 is 6.68 million yuan, and projection value is 5.454 million yuan. The improvement method reduces the investment by 1.2746 million yuan, and the improvement proportion is 19.08%. The actual input value of X_7 is 3.65 million yuan, and projection value is 1.8411 million yuan. The improvement method reduces the investment by 1,889 million yuan, and improvement proportion is 49.56%. Actual value of Y_1 in the output index is similar to the projection target value. Thus, improvement is unnecessary. However, the actual output value of Y_4 is 4.22%, the projection target value is 6.35%, the improvement method is to increase by 2.13%, and the improvement proportion is 50.46%. Actual output value of Y_5 is 8.5%, projection target value is 10.03%, improvement mode is increased by 1.53%, and improvement proportion is 18.02%. The actual output value of Y_6 is 43.7%, the projection target value is 51.58%, the improvement mode is increased by 7.88%, and the improvement proportion is 18.02%. Above is the improvement analysis of one-time construction IE of substation C based on projection value. Table 9 shows the improvement analysis of IE of the one-time construction of eight substation projects.

Table 9 Improvement analysis of one-time construction IE of eight substation projects

Indicator type of DMU	*Index*	*Data*	*Projection*	*Improvement quantity*	*Improvement ratio*
A		*1*			
Input index	X_2	3103	3103	0	0.00%
	X_5	214	214	0	0.00%
	X_6	753	753	0	0.00%
	X_7	272	272	0	0.00%

Table 9 Improvement analysis of one-time construction IE of eight substation projects (continued)

Indicator type of DMU	*Index*	*Data*	*Projection*	*Improvement quantity*	*Improvement ratio*
Output indicators	Y_1	3290.62	3290.62	0	0.00%
	Y_4	4.39	4.39	0	0.00%
	Y_5	11.4	11.4	0	0.00%
	Y_6	57.7	57.7	0	0.00%
B		*1*			
Input index	X_2	2694.85	2694.85	0	0.00%
	X_5	209.65	209.65	0	0.00%
	X_6	1109.4	1109.4	0	0.00%
	X_7	301.86	301.86	0	0.00%
Output indicators	Y_1	4593.73	4593.73	0	0.00%
	Y_4	5.27	5.27	0	0.00%
	Y_5	13.5	13.5	0	0.00%
	Y_6	55.3	55.3	0	0.00%
C		*0.809*			
Input index	X_2	4839	3689.35	–1149.65	–23.76%
	X_5	256	145.17	–110.83	–43.29%
	X_6	668	540.54	–127.46	–19.08%
	X_7	365	184.11	–180.89	–49.56%
Output indicators	Y_1	5229.36	5229.36	0	0.00%
	Y_4	4.22	6.35	2.13	50.46%
	Y_5	8.5	10.03	1.53	18.02%
	Y_6	43.7	51.58	7.88	18.02%
D		*0.832*			
Input index	X_2	5043	3346.66	–1696.34	–33.64%
	X_5	216	131.68	–84.32	–39.04%
	X_6	589	490.33	–98.67	–16.75%
	X_7	326	167.01	–158.99	–48.77%
Output indicators	Y_1	4,674.72	4,743.63	68.91	1.47%
	Y_4	4.47	5.76	1.29	28.85%
	Y_5	9.1	9.1	0	0.00%
	Y_6	36.4	46.78	10.38	28.53%
E		*1*			
Input index	X_2	4049	4049	0	0.00%
	X_5	196	196	0	0.00%
	X_6	2391	2391	0	0.00%
	X_7	349	349	0	0.00%

Table 9 Improvement analysis of one-time construction IE of eight substation projects (continued)

Indicator type of DMU	*Index*	*Data*	*Projection*	*Improvement quantity*	*Improvement ratio*
E		*1*			
Output indicators	Y_1	6980.22	6980.22	0	0.00%
	Y_4	5.46	5.46	0	0.00%
	Y_5	8.8	8.8	0	0.00%
	Y_6	45.7	45.7	0	0.00%
F		*0.974*			
Input index	X_2	4450	4336.11	–113.89	–2.56%
	X_5	328	187.29	–140.71	–42.90%
	X_6	770	750.29	–19.71	–2.56%
	X_7	394	243.33	–150.67	–38.24%
Output indicators	Y_1	6,270.65	6270.65	0	0.00%
	Y_4	4.32	7.56	3.24	75.10%
	Y_5	9.5	12.78	3.28	34.57%
	Y_6	50.81	63.45	12.64	24.88%
G		*0.585*			
Input index	X_2	5592	3269.77	–2322.23	–41.53%
	X_5	249	145.60	–103.40	–41.53%
	X_6	1053	595.88	–457.12	–43.41%
	X_7	437	190.54	–246.46	–56.40%
Output indicators	Y_1	4,718.35	4,761.18	42.83	0.91%
	Y_4	3.21	5.73	2.52	78.53%
	Y_5	9.9	9.9	0	0.00%
	Y_6	35.79	48.59	12.80	35.77%
H		*1*			
Input index	X_2	3126	3126	0	0.00%
	X_5	123	123	0	0.00%
	X_6	458	458	0	0.00%
	X_7	156	156	0	0.00%
Output indicators	Y_1	4,430.86	4,430.86	0	0.00%
	Y_4	5.38	5.38	0	0.00%
	Y_5	8.5	8.5	0	0.00%
	Y_6	43.7	43.7	0	0.00%

6.2 IE of phased construction

6.2.1 Calculation of IE of phased construction

The input–output index data of phased construction projects are shown in Table 10.

Table 10 Input–output index data of phased construction of substation projects

Substation	X_2	X_5	X_6	X_7	Y_1	Y_4	Y_5	Y_6
A	3,501.80	1,212.53	247.64	753.00	4,378.93	5.05	13.01	56.12
B	3,265.11	1,278.67	273.38	1,109.40	6,531.13	5.86	17.27	52.47
C	5,382.31	1,661.18	256.00	688.86	6,808.50	4.70	9.98	43.77
D	6,829.91	1,523.09	376.43	589.00	7,973.74	5.54	12.22	35.00
E	5,771.45	1,641.87	196.00	251,4.36	9,753.74	5.90	11.44	45.20
F	4,631.78	1,707.30	347.59	770.00	6,745.76	4.53	9.80	50.53
G	5,908.40	1842.13	249.00	1,053.00	5,947.30	3.70	10.89	35.54
H	3,238.71	1,287.09	149.33	485.97	5,304.55	5.84	9.56	42.88

Substituting the input and output indexes of the phased construction of substation projects in Table 10 into the CCR and BCC models, provides the TEs and PTEs of the phased substation construction projects. According to equation (1), TEs and PTEs, the SE and scale return of phased construction of substation projects can be calculated. Table 11 demonstrates the IE of the phased construction of substation projects.

Table 11 Analysis of IE value of phased construction of substation projects

DMU	*TE*		*PTE*		*SE*		*RTS*
	EV	*sort*	*EV*	*sort*	*EV*	*Sort*	
A	1	1	1	1	1	1	–
B	1	1	1	1	1	1	–
C	0.911	6	1	1	0.911	7	DRS
D	1	1	1	1	1	1	–
E	1	1	1	1	1	1	–
F	0.903	7	1	1	0.903	8	DRS
G	0.717	8	0.718	8	0.999	6	IRS
H	1	1	1	1	1	1	–

Table 11 shows that the TE of substations A, B, D, E, and H of the phased construction project is one, which is effective for DEA. This indicates that the investment indicators of the construction of these five substations can be utilised for maximising the output effect. The TE of the other three substations is less than one, which is invalid for DEA. As the higher the TE value, the higher the utilisation efficiency of the input index, the lowest TE of substation G in the remaining three substations is 0.717. This indicates that the IE of this substation is the lowest. Only the PTE of substation G is 0.718. This does not reach DEA effectiveness and indicates that the technical level leads to the waste of resources invested by substation G and has no impact on the output. This invalid input is 0.382; hence, the technical level has large scope for improvement. Additionally, the PTE of the seven substations is one, indicating that the seven substations are on the production function surface, and the technical IE is very high, so there is no need for further improvement. The SE of substations A, B, D, E, and H is one, indicates optimal SE. SE of the other three substations is distributed between 0.903 and 0.999. This indicates that the overall SE is high; however, large scope for improvement remains. Although substations C and F are effective in PTE, they are ineffective in SE. This indicates that the investment scale of these two substations is too large. For this project, optimising IE can be realised only by reasonably adjusting their investment scale.

Table 11 shows that the returns to scale of substations C and F are decreasing, indicating excess input resources. The proportion of output increase is less than the proportion of input increase, indicating that directly increasing input is not proportional to output. Hence, improving the IE of DMUs is necessary. Substation G is increasing returns to scale (IRS), which shows that the increased proportion of output results is greater than that of input factors. Therefore, increasing input is an efficient way to increase output.

6.2.2 Analysis on improvement of IE of phased construction

The phased construction of substation G, whose DMU DEA is invalid, is the improvement analysis object. The input index X_2 of substation G, the actual input value is 59.084 million yuan, the projection value is 35.801 million yuan, the improvement method reduces investment by 23.283 million yuan, and the improvement proportion is 39.41%. The actual input value of X_5 is 18.4213 million yuan, and the projection value is 13.2133 million yuan. Improvement reduces investment by 5.2080 million yuan, and improvement proportion is 28.27%. The actual input value of X_6 is 2.49 million yuan, and projection value is 1.786 million yuan. The improvement method reduces investment by 70.40 yuan, and improvement proportion is 28.27%. The actual input value of X_7 is 10.53 million yuan, and projection value is 7.553 million yuan. The improvement method reduces investment by 2.977 million yuan, and improvement proportion is 28.27%. In the output indicators, the actual values of Y_1 and Y_5 are similar to the projection target value, and improvement is not necessary. In contrast, the actual output value of Y_4 is 3.7%, the projection target value is 5.82%, the improvement method is to increase by 2.12%, and the improvement proportion is 57.29%. The actual output value of Y_6 is 35.54%, the projection target value is 44.07%, the improvement mode is increased by 8.53%, and the improvement proportion is 24.00%. The above is the IE improvement analysis of phased construction of the substation G based on projection value. Similarly, other substations with invalid DEA can refer to improvement analysis of substation G to find a reasonable method for improving IE. Table 12 shows the improvement analysis of IE of phased construction of eight substation projects.

6.3 Comparative of IE between one-time construction and phased construction

According to the results, the IE of the phased construction project is significantly different from that of the one-time construction project. In this section, we conduct comparative analysis according to efficiency value and DMU.

Table 12 Improvement analysis of phased construction IE of eight substation projects

Indicator type of DMU	*Index*	*Data*	*Projection*	*Improvement quantity*	*Improvement ratio*
A		*1*			
Input index	X_2	3,501.8	3,501.8	0	0.00%
	X_5	1,212.53	1,212.53	0	0.00%
	X_6	247.64	247.64	0	0.00%
	X_7	753	753	0	0.00%
Output indicators	Y_1	4,378.93	4,378.93	0	0.00%
	Y_4	5.05	5.05	0	0.00%
	Y_5	13.01	13.01	0	0.00%
	Y_6	56.12	56.12	0	0.00%
B		*1*			
Input index	X_2	3,265.11	3,265.11	0	0.00%
	X_5	1,278.67	1,278.67	0	0.00%
	X_6	273.38	273.38	0	0.00%
	X_7	1,109.4	1,109.4	0	0.00%
output indicators	Y_1	6,531.13	6,531.13	0	0.00%
	Y_4	5.86	5.86	0	0.00%
	Y_5	17.27	17.27	0	0.00%
	Y_6	52.47	52.47	0	0.00%
C		*0.911*			
Input index	X_2	5,382.31	4,716.56	–665.75	–12.37%
	X_5	1,661.18	1,513.55	–147.63	–8.89%
	X_6	256	233.25	–22.75	–8.89%
	X_7	688.86	627.64	–61.22	–8.89%
Output indicators	Y_1	6,808.5	6,808.50	0	0.00%
	Y_4	4.7	6.43	1.73	36.81%
	Y_5	9.98	11.48	1.50	15.05%
	Y_6	43.77	45.80	2.03	4.65%
D		*1*			
Input index	X_2	6,829.91	6829.91	0	0.00%
	X_5	1,523.09	1,523.09	0	0.00%
	X_6	376.43	376.43	0	0.00%
	X_7	589	589	0	0.00%
Output indicators	Y_1	7,973.74	7,973.74	0	0.00%
	Y_4	5.54	5.54	0	0.00%
	Y_5	12.22	12.22	0	0.00%
	Y_6	35.6	35.6	0	0.00%

Table 12 Improvement analysis of phased construction IE of eight substation projects (continued)

Indicator type of DMU	*Index*	*Data*	*Projection*	*Improvement quantity*	*Improvement ratio*
E		*1*			
Input index	X_2	5,771.45	5,771.45	0	0.00%
	X_5	1,641.87	1,641.87	0	0.00%
	X_6	196	196	0	0.00%
	X_7	2,514.36	2,514.36	0	0.00%
Output indicators	Y_1	9,753.74	9,753.74	0	0.00%
	Y_4	5.9	5.9	0	0.00%
	Y_5	11.44	11.44	0	0.00%
	Y_6	45.2	45.2	0	0.00%
F		*0.903*			
Input index	X_2	4,631.78	4,182.51	–449.27	–9.70%
	X_5	1707.3	1,541.70	–165.60	–9.70%
	X_6	347.59	220.82	–126.77	–36.47%
	X_7	770	695.31	–74.69	–9.70%
Output indicators	Y_1	6,745.76	6,745.76	0	0.00%
	Y_4	4.53	6.87	2.34	51.67%
	Y_5	9.8	12.93	3.13	31.91%
	Y_6	50.53	51.64	1.11	2.19%
G		*0.717*			
Input index	X_2	5,908.4	3,580.10	–2,328.30	–39.41%
	X_5	1,842.13	1,321.33	–520.80	–28.27%
	X_6	249	178.60	–70.40	–28.27%
	X_7	1,053	755.30	–297.70	–28.27%
Output indicators	Y_1	5,947.3	5,947.30	0	0.00%
	Y_4	3.7	5.82	2.12	57.29%
	Y_5	10.89	10.89	0	0.00%
	Y_6	35.54	44.07	8.53	24.00%
H		*1*			
Input index	X_2	3,238.71	3,238.71	0	0.00%
	X_5	1,287.09	1,287.09	0	0.00%
	X_6	149.33	149.33	0	0.00%
	X_7	485.97	485.97	0	0.00%
Output indicators	Y_1	5,304.55	5,304.55	0	0.00%
	Y_4	5.84	5.84	0	0.00%
	Y_5	9.56	9.56	0	0.00%
	Y_6	42.88	42.88	0	0.00%

6.3.1 Comparative analysis of EV

From the DEA model efficiency value analysis perspective, the one-time construction project and phased construction of substation projects are comparable in the following four aspects:

1. TE: The number of DEA-effective decision units for one-time construction projects and phased construction projects of substation projects is 4 and 5, respectively, and the number of phased construction projects is more than that of one-time construction projects. After calculation, the average TE of a one-time and phased construction of substation projects is 0.900 and 0.941, respectively. This indicates that the average TE of the phased construction of substation projects is significantly higher than that of the one-time construction project and proves the higher overall IE of phased construction of substation projects.
2. PTE: The number of projects with DEA PTE of the one-time construction project and phased construction project DMU of substation project is 5 and 7, respectively, and the number of phased construction projects is significantly more than that of one-time construction projects. The proportion of projects with PTE of 1 in phased construction projects accounts for 87.25%. This shows that phased construction projects have a very high technological level. The average net TE of the one-time construction project and phased construction of substation projects are 0.939 and 0.965, respectively. This indicates that the average TE of the phased construction of substation projects is significantly higher than that of the one-time construction project. Therefore, the phased construction of substation projects is closer to the forefront of DEA production.
3. SE: The number of projects whose SE of DMUs of one-time construction projects and phased construction projects of substation project reaches 1 is 4 and 5, respectively. The number of phased construction projects is greater than that of one-time construction projects. Moreover, the average SE of phased construction projects is 0.977; higher than that of one-time construction projects by 0.954. This shows that the SE of the phased construction of substation projects is significantly higher than that of the one-time construction project.
4. RTS: In the DMU of the one-time construction of substation projects, four projects have a constant return to scale, and four have decreasing RTS (excess input resources). In the DMU of phased construction projects, five projects have constant returns to scale; two, decreasing returns to scale; and one, IRS (insufficient input resources). Compared with a one-time construction, phased construction has more projects with constant returns to scale. This indicates that phased construction has better IE, more projects to achieve the optimal allocation, and fewer projects to be improved.

6.3.2 Comparative analysis of DMU

From the decision-making perspective, comparing IE between phased construction and one-time construction of substation projects has the following characteristics:

1 Substations A, B, H, and E achieved DEA effectiveness in one-time construction and phased construction. This indicates that the IE of these four substation projects is quite high, which can be used as a reference for other substation construction projects and is worthy of popularisation and reference.

2 Substations C, F, and G have not reached DEA effectiveness in a one-time construction and phased construction. Moreover, the technical and PTE values of substation G are lowest among the eight substations. This indicates that substation G still has a lot of investment optimisation space, which can be further analysed to improve IE.

3 Substation D did not achieve DEA effectiveness during construction of phase I. After the optimisation of phase II construction, DEA effectiveness was achieved as a phased construction project. This indicates that the substation can improve its IE after reasonable phased construction. This will guide future project planning. The IE of phased-in substation construction is higher than that of one-time construction; therefore, priority must be given to phased construction in planning.

7 Conclusions

In this study, we selected eight 220 kV substation projects built by Hubei Electric Power Company in China as the research objects. The DMU multi-input multi-output indicators are organised, and EWM is used to calculate and process the input–output indicator data and an input-output indicator system is constructed. Secondly, IE of substation engineering construction is measured based on the DEA model, TEs, PTEs, and SEs of one-time and phased substation construction projects are analysed according to the results. We compare the IE of the two project types and propose improvements for those with invalid DEA to provide an important reference for future power grid investment decision-making. Finally, through the analysis and demonstration of the same DMU, the IE of the phased construction of substation projects is better than that of the one-time construction project. The EWM-DEA model method proposed in this study can scientifically guide power grid companies to make reasonable investment decisions, effectively improve the economic and social benefits of regional power grid construction projects and promote the sustainable development of power grid companies and economy and society.

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