Data Envelopment Analysis of Safety Performance Indicators and Economic Indicators of Bohai Rim Nuclear Power Unit based on DEA Model

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Abstract—With a history of more than 30 years in the utilization and development of civil nuclear energy, China has become a major nuclear power with the largest number of reactors under construction and the largest types of reactors in the world. In the process of development, the economy and safety of nuclear energy have formed a good momentum of spiral upward. At present, some key development regions in China are facing serious air pollution problems in the environment, and the situation of energy conservation and emission reduction is grim. Nuclear power undoubtedly becomes one of the priority energy choices to solve the current dilemma. In this paper, the safety and economy of nuclear power in the round-Bohai-sea region of China was analyzed, and using data envelopment analysis (DEA), envelope analysis safety performance indicators and economic indicators to calculate the DEA efficient of the current nuclear power unit in Bohai region. This paper analyzes and summarizes the relevant issues and hopes to provide some suggestions for nuclear power development in policy decision.

Keywords-nuclear energy; Bohai Rim; data envelopment analysis; clean energy; safety performance indicators

1 INTRODUCTION

Professor A. Charnes, W.W Cooper and E. Rhodes of the University of Texas published a paper in the journal "European Operations Research" in 1978, which claimed to open up a new chapter in operations research: Measuring the effectiveness of decision-making units. This article mainly introduces data envelopment analysis, namely DEA analysis, and the establishment of related models. The CCR model is used to evaluate the relative effectiveness of various programs, that is, whether DEA is effective. The DEA model is a mathematical model, a non-parametric model built from input and output data. DEA's advantages have attracted many users, and its use has been expanded to include military aviation, maintenance of large military bases, urban construction, and bank investment. And its application areas are still gradually expanding, such as how to choose investment projects; this method can be calculated based on relatively good conservative decision-making results. Therefore, the DEA model can be used as an evaluation tool for strategy selection.

This article will use the envelope analysis method to calculate whether the DEA is efficient for the current nuclear power plants in the Bohai Sea area, analyze the safety performance indicators and economic indicators of nuclear energy, and put forward relevant suggestions.

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2 INTRODUCTION OF BASIC DEA MODEL- CCR

2.1 Standard model

In data envelopment analysis, the evaluation object that needs to be studied is called the decision-making unit (DMU).

Assume：the of number DMU is n (j=1,2,…,n)

Each decision unit has the same m input (input) (i=1,2,…,m)

Each decision-making unit has the same s output (output) (r=1,2,…,s)

x_ij—The i-th input of the j-th DMU

y_rj—The r-th output of the j-th DMU

Evaluate whether the DEA is efficient for the j_0 DMU.

The CCR model sets the efficiency of the most efficient type of DMU as 1, which is regarded as DEA effective. Compared with other DMU, this type of unit has high value and is an important unit. The unit whose efficiency value is set between 0 and 1 is non-DEA effective. The smaller the value, the lower the efficiency of the unit, which needs to be improved.

2.2 Determining the safety performance indicators and economic indicators of nuclear power plants in the Bohai Sea Rim

First of all, the DEA method is suitable for multi-input-multi-output complex structural systems, and the comparative analysis of the safety and economics of nuclear power plants is a dynamic system that conforms to this characteristic, and the two can be presented as dynamic Spiral relationship, for nuclear power plants that are not well planned and operating, the two may also show a completely opposite relationship [1]. Therefore, in the process of analyzing nuclear energy in the Bohai Rim region, it is necessary to select multiple index data for safety and economics, and select important indicators that can fully represent the safety and economics of nuclear power plants. Here, this article selects some indicators related to unit operation benefits in the WANO and NRC Safety Performance indicators, and combines data such as on-grid tariffs to summarize a total of 12 indicators [2], as follows:

- A: The number of unplanned automatic shutdowns of the unit under critical conditions of 7000 hours, unit: times/reactor;
- B: Collective radiation dose: unit: person•Sv/year;
- C: The number of unanticipated safety system actions, including the unplanned start of the safety injection system and emergency power supply, unit: times/reactor;
- D: Effectiveness of safety functions: refers to the time share during which the three safety functions of reactivity control, core cooling, and radioactive shielding are satisfied at the same time during operation;
- E: Fuel reliability: measured by the number of fission products in the primary circuit, unit: μCi/g

- F: Power generation share, that is, the total time share of grid-connected operation in a year
- G: Abnormal prevention: the number of latent faults and defects found during operation/(the number of latent faults and defects found during operation + the actual number of faults);
- H: Reliability of operating personnel: operator related license examination, simulation machine operation performance;
- I: Unit capacity factor: The ratio of the actual electricity generated during the unit cycle to the full capacity of the nameplate power during the cycle;
- J: Waste disposal: the share of post-processed radioactive waste;
- K: Loss rate of accidental working hours: the number of days not working due to accidents caused by accidents per 200,000 person-hours [3];
- L: On-grid electricity price (including tax): On-grid electricity price within the calculation period, unit: cents/KW•h

3 DATA COLLECTION AND MODELING

3.1 Data collection statistics

Table 1 summarizes some of the relevant data we plan to perform DEA calculation and analysis, including 2018 relevant index data of HYH nuclear power plant units 1 and 3 in the Bohai Rim area, annual relevant index data of TW nuclear power plant units 1 and 2 in the East China Sea, and WANO safety performance indicators advanced values.

TABLE 1. SAFETY PERFORMANCE INDICATORS OF UNITS 1 AND 3 OF HYH NUCLEAR POWER PLANT AND 1 AND 2 OF TW NUCLEAR POWER PLANT IN 2018

SPI % Safety Performance indicators	**HYH NPP**		**TW NPP**		**WANO Benchmark value**	
	Unit 1	***Unit3***	***Unit1***	***Unit2***	***Advanced value***	***Average value***
Unit capability	99.98	91.17	86.55	87.05	93.16	83.01
Unplanned capacity loss	0.00	0.00	0.06	0.00	0.05	5.43
Forced loss rate	0.00	0.00	0.07	0.00	0.02	2.47
Grid related loss	0.00	0.00	0.00	0.00	0.00	0.06
unplanned automatic shutdowns under critical of 7000 hours	0.00	0.00	0.00	0.00	0.00	0.27
unplanned manual shutdowns under critical of 7000 hours	0.00	0.00	0.00	0.00	0.00	0.36
Safety system performance	0.0004	0.0196	0.0000	0.0000	0.0000	0.0095
Fuel reliability	0.037	3.038	0.728	0.037	0.063	14.2
Waste disposal effectiveness	1.00	1.00	1.00	1.00	1.00	1.00

Collective radiation dose	0.03	0.39	0.30	0.302	0.35	0.41
Industrial accident rate of employees	0.00	0.00	0.00	0.00	0.00	0.16
Industrial accident rate of contractor	0.00	0.00	0.00	0.00	0.00	0.28

3.2 Establishment of input-output model

Suppose there are n units for comparison, with m inputs and s outputs; denote the i-th input of the j-th unit, and denote the r-th output of the j-th unit, where, i=1,2…, m, j=1,2,…, s; If using represents the weight of the i-th input and using represents the weight of the r-th output [4], the input-output ratio of the j-th unit is:

$$\max h_{j_n} = \frac{\sum_{r-1}^{1} u_{\gamma} y_{\eta n}}{\sum_{i-1}^{m} v_i x_{\eta n}} \tag{1}$$

By appropriately selecting the weights and, ≤1, where j=1,2,...,n; the following optimization model can be used to

$$h_{j_n} = \frac{\sum_{r-1}^{1} u_{\gamma} y_{\eta n}}{\sum_{i-1}^{m} v_i x_{\eta n}} \tag{2}$$

evaluate the unit: max

$$\text{s.t.}\begin{cases} \dfrac{\sum_{r-1}^{`} u_r y_\eta}{\sum_{i-1}^{m} v_i x_\eta} \le 1 \ (j = 1,2,\ldots,n) \\ v_i \ge 0 (i = 1,2,\ldots,m), u_r \ \ge 0 (r = 1,2,\ldots,s) \end{cases} \tag{3}$$

Make a transformation so that, $\frac{1}{\sum_{i-1}^{m} v_i x_{\eta n}} = t,\ tv_i = w_i,\ \ tu_r \ = \mu_r$

Then the model (3) constitutes the following linear programming problem:

$\max h_j = \sum_{r-1}^{`} \mu_r y_{\eta_n}$

s.t.

$$\begin{cases} \sum_{i-1}^{m} w_i x_y - \sum_{r-1}^{`} \mu_r y_\eta \ge 0 \ (j = 1,2,\ldots,n) \\ \sum_{i-1}^{m} w_i x_{\eta_n} = 1 \\ w_i \ge 0 (i = 1,2,\ldots,m), \mu_r \ge 0 \ (r = 1,2,\ldots,s) \end{cases} \tag{4}$$

The dual plan is:

Minθ

s.t

$$\begin{cases} \sum_{j-1}^{n} \lambda_j x_\eta \leq \theta\, x_{\eta_n}\ (i = 1,2,\dots,m) \\ \sum_{j-1}^{n} \lambda_j y_\eta \geq y_{\eta_n}\ (r = 1,2,\dots,s) \\ \lambda_j \geq 0\ (j = 1,2,\dots,n) \end{cases} \tag{5}$$

The model (5) indicates that if the optimal value of θ is less than 1, then a nuclear power unit with such an illusion that it can obtain a higher output with a lower input than the nuclear power unit participating in the evaluation, and then it indicates that the participating nuclear power unit The operating conditions of nuclear power plants are relatively inefficient, that is, non-DEA is efficient; only when θ=1, the evaluated nuclear power plants are DEA efficient.

In order to be more representative of the selected units, below we will include the representative values of Unit 1 and Unit 3 of HYH Nuclear Power Plant in different stages, Unit 1, 2 of TW Nuclear Power Plant and WANO Advanced Unit into the data calculation, see below for details surface:

TABLE 2. TABLE2 INPUT AND OUTPUT TABLE OF 5 NUCLEAR POWER UNITS

Unit		HYH1	HYH3	TW1	TW2	WANO Advanced value
Input	staff	33．5	33.5	33.02	33.02	28
	invest	1579.5	1579.5	1703	1703	1530
output	A	0	0	0	0	0
	B	0.035	0.39	0.302	0.302	0.35
	C	0	0	0	0	0
	D	0.99	0.98	1	1	1
	E	0.037	3.038	0.728	0.037	0.037
	F	0.95	0.92	0.96	0.97	0.98
	G	0.89	0.73	0.92	0.81	0.85
	H	0.95	0.94	0.91	0.92	0.90
	I	0.99	0.91	0.86	0.87	0.93
	J	1	1	1	1	1
	K	0	0	0	0	0
	L	5.43	5.43	5.70	5.70	7.01*

The Liaoning Provincial Development and Reform Commission adjusted the on-grid tariff for the four units of the HYH Phase I project to 0.3823 yuan/kWh. Converted into the US, it is 5.43. The Jiangsu Provincial Development and Reform Commission stipulates that the on-grid power price of TW nuclear power plant is 0.401 yuan/kWh, which is converted into US 5.70.

The electricity price of WANO advanced unit adopts the American industrial electricity price standard for comparison [5].

The 4 units of the first phase of the HYH nuclear power plant have a total investment of 48.6 billion yuan. The total investment is 7.06 billion U.S. dollars based on the approved exchange rate in 2007. Each unit has a power of 1118.79MWE, a total of 1,500 employees, and a unit investment of 1579.5 U.S. dollars/kWh.

The single unit generating power of unit 1 and unit 2 of the first phase of TW nuclear power plant is 1060MWE, with a total of 2,100 employees. There are currently 6 units with an average number of employees of 33.02 people/100MWe [6]. Calculated according to the exchange rate at the time of approval, the unit investment for the construction of the first phase of the TW project (units 1 and 2) is about 1,703 US dollars per kilowatt.

4 DATA ENVELOPMENT ANALYSIS CALCULATION AND RESULTS

The input-output table of the above 5 units is shown in Table 2. Among them, "staff" means the number of employees to be hired per 100MW of installed capacity, and "investment" means the fixed investment amount per KW, and the unit is: USD/KW. This paper take Unit HYH1 as an example to determine whether it is DEA valid. According to the model (5), the linear programming model for performance evaluation of Unit HYH1 is:

Minθ

s.t.

$$\begin{cases} 33.5\lambda_1 + 33.5\lambda_2 + 33.02\lambda_3 + 33.02\lambda_4 + 28\lambda_5 \leq 33.5\theta \\ 1579.5\lambda_1 + 1579.5\lambda_2 + 1703\lambda_3 + 1703\lambda_4 + 1530\lambda_5 \leq 1579.5\theta \\ 0 \geq 0 \\ 0.035\lambda_1 + 0.39\lambda_2 + 0.302\lambda_3 + 0.302\lambda_4 + 0.35\lambda_5 \geq 0.035 \\ 0 \geq 0 \\ 0.99\lambda_1 + 0.98\lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 \geq 0.99 \\ 0.037\lambda_1 + 3.038\lambda_2 + 0.728\lambda_3 + 0.037\lambda_4 + 0.037\lambda_5 \geq 0.037 \\ 0.95\lambda_1 + 0.92\lambda_2 + 0.96\lambda_3 + 0.97\lambda_4 + 0.98\lambda_5 \geq 0.95 \\ 0.89\lambda_1 + 0.73\lambda_2 + 0.92\lambda_3 + 0.81\lambda_4 + 0.85\lambda_5 \geq 0.89 \\ 0.95\lambda_1 + 0.94\lambda_2 + 0.91\lambda_3 + 0.92\lambda_4 + 0.9\lambda_5 \geq 0.95 \\ 0.99\lambda_1 + 0.91\lambda_2 + 0.86\lambda_3 + 0.87\lambda_4 + 0.93\lambda_5 \geq 0.99 \\ \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 \geq 1 \\ 0 \geq 0 \\ 5.43\lambda_1 + 5.43\lambda_2 + 5.7\lambda_3 + 5.7\lambda_4 + 7.01\lambda_5 \geq 5.43 \\ \lambda_1\lambda_2\lambda_3\lambda_4\lambda_5 \geq 0 \end{cases} \quad (6)$$

For Unit HYH1, when the staff is the main objective function, obtain λ_1=1, λ_2=0, λ_3=0, λ_4=0, λ_5=0, θ=1, DEA is efficient. When investment is the main objective function, the solution is λ_1=0, λ_2=0, λ_3=0, λ_4=0, λ_5=1.0645, θ=1.0311, DEA is not efficient. In the same way, we can get the result whether other units' DEA is efficient.

In summary, for Unit HYH1 and TW2, from the perspective of human resource costs, the current number of personnel is the best allocation; however, the investment amount is not the optimal investment amount. The investment amount can still be controlled and reduced, and the expected good benefits can also be obtained [7].

For Unit HYH3 and TW1, from the perspective of human resource costs, the current configuration is the best number of personnel. At the same time, the investment amount has also reached the minimum investment cost. Therefore, Unit HYH3 is based on the cost of human resources and investment. It is said that they have reached the latest configuration. Maintaining the stability of the current indicators will continue to bring maximum benefits.

5 Conclusion

A. According to the DEA calculation results, the human resource cost of nuclear power plants in the Bohai Rim region of China is relatively effective and has reached a reasonable allocation. However, there is still room for further reduction in project investment costs and has not yet reached the effective allocation of DEA.

B. From the comparison of all indicators, the collective radiation doses of HYH Unit 1 and TW Nuclear Power Plant Units 1 and 2 are better than the advanced value of WANO Units, indicating that China’s nuclear power plants are already among the world’s top in terms of radiation protection. At the same time, the loss rate of accidental working hours is zero. This indicates that the safety of China's nuclear power industry is also guaranteed. Finally, compared with the advanced value of WANO units, there is still a big gap between the on-grid power price. Nuclear power on-grid power prices can still rise. The state should continue to macro-control nuclear power on-grid tariffs and adopt a regulatory policy that guarantees "price" and "quantity".

C. From the perspective of feed-in tariff, the current feed-in tariff of nuclear power is partly higher than that of thermal power, which has certain advantages, but the advantages are not obvious. At the same time, the difference in power transmission users will also affect the feed-in tariff. However, at present, China's nuclear power feed-in tariff is still far from the electricity prices of other nuclear powers in the world. Therefore, there is still room for further increase in the feed-in tariff.

In summary, at present, the safety performance indicators and economic efficiency of nuclear power units operating in the Bohai Rim region of China are good, and they have better operating benefits than thermal power units of the same power. Most of the units are DEA effective in terms of safety and economy.

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