Analysis of Nuclear Power Economy and Its Influencing Factors

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Abstract. The improvement of nuclear power economy is indispensable to the safe and efficient development of nuclear power. This paper explores the scope of economic evaluation of nuclear power based on literature and actual project operation. The evaluation scope includes power plant level, grid level and external level and this paper proposes a corresponding evaluation indicators based on the above analysis. This paper qualitatively analyzes the characteristics and influencing factors of nuclear power economy based on the current situation of nuclear power economy in China. Considering the difference between economic evaluation standard and actual operation, the typical influencing factors of economic evaluation indicators of power plant level are quantitatively evaluated. The economy of grid level and external level is analyzed by referring to foreign literature. Finally, suggestions on improving the economic efficiency of nuclear power are put forward from the aspects of economic evaluation standards and policies.

Keywords: Nuclear power economy · Evaluation scope · Evaluation indicators · Influencing factors

1 Introduction

Nuclear power is clean, low-carbon, safe and efficient high-quality energy. It plays an important role in constructing modern energy system, realizing energy transformation, protecting ecological environment, realizing carbon peaking and carbon neutrality goals, promoting scientific and technological progress, improving national comprehensive strength and guaranteeing national security.

However, in the context of the improved safety standards, the market-oriented reform of electricity, and the gradual cost reduction brought about by the large-scale development of wind power, photovoltaic and other new energy sources, the economics of nuclear power are also controversial. What is the prospect and the way out of nuclear power?

In this paper, combined with the current economic status of nuclear power, the scope and indicator system of economic evaluation will be explored, the characteristics and influencing factors of nuclear power economy will be analyzed from qualitative and quantitative perspectives, and suggestions for improving nuclear power economy will be put forward based on economic evaluation standards and policy levels.

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2 The Connotation of Nuclear Power Economics

2.1 Scope of Nuclear Power Economic Evaluation

The economic evaluation of nuclear power has cost dimension and value dimension. The core is to bring more value to investors and society with competitive cost. The level of evaluation is progressive from micro level, medium level to macro level. As shown in Fig. 1 [1], micro level refers to power plant-level assessment, medium level includes grid-level assessment, and macro-level level includes environmental and social impacts. From the perspective of cost, the micro is mainly the internal cost, while the medium and macro are used to evaluate external cost. As a clean energy that can provide stable baseload power, the external cost of nuclear power is very small, but in the market competition, only the micro internal cost is usually measured.

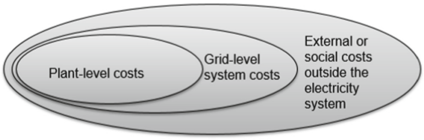

Fig. 1. Scope of nuclear power cost evaluation

2.2 Nuclear Power Economic Evaluation Indicators

Internationally, the economics of nuclear power projects are often compared and analyzed by calculating the levelized cost of electricity (LCOE) and overnight cost per kilowatt electric power. In China, the economics of nuclear power projects is evaluated by calculating the total capital cost per kilowatt electric power, the average generation cost and the on-grid electricity price during the period of operation.

The nuclear power economic evaluation indicator system corresponding to different evaluation scopes is shown in the Fig. 2 below.

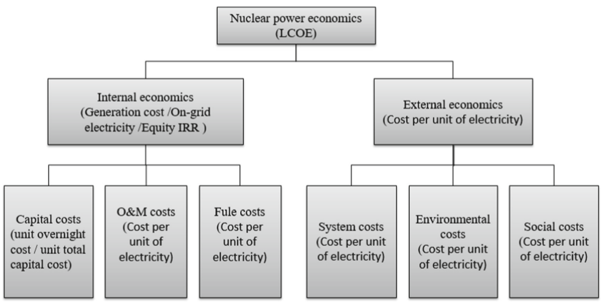

Fig. 2. Nuclear power economic evaluation indicator system diagram

3 The State of Nuclear Power Economics

Most of the Nuclear Power Plants (NPPs) in operation in China are Gen-II, and the total capital cost per kilowatt electric power is usually 11,000–14,000 yuan. Due to factors such as delays, the unit total capital cost of Gen-III First-of-A-Kind (FOAK) nuclear power units is 20,000–25,000 yuan, while the unit total capital cost of the subsequent Gen-III nuclear power units is expected to be less than 16,000 yuan.

NPPs used to adopt the "One price for one plant" electricity policy, no matter how much the cost, can always ensure a certain internal rate of return on capital. Later, the benchmark electricity price policy was adopted. The upper limit of the electricity price is 0.43 yuan/kWh or the local coal-fired benchmark electricity price (including desulfurization and denitrification price), and the return on capital depends on the cost of nuclear power. This is also the main reason why the economic efficiency of the Gen-III nuclear power plant decreases after the investment cost increases. In the future, with the continuous advancement of electricity market reform, the proportion of nuclear power participating in market-oriented transactions will gradually increase, which will further squeeze the economics of nuclear power.

4 Factors Affecting the Economics of Nuclear Power

4.1 Overview of Influencing Factors

There are many factors that affect the economics of nuclear power. The most basic factor is the technical and economic characteristics of the power plant itself. In addition, construction duration, load factor, economic life, discount rate, scale effect and learning effect will all affect the economics of nuclear power to varying degrees [2].

(1) The technical and economic characteristics of NPPs are the most important and basic factors affecting the economics of nuclear power. The constructability, operability and maintainability of the plant will affect the cost of nuclear power. The complexity, safety level, reliability requirements, achievable power plant construction period, and the power plant capacity, efficiency, availability, fuel cycle (such as UOX cycle, MOX cycle), as well as discharge fuel consumption depth, etc., will have an impact on the composition and cost of nuclear power costs as well.

(2) Nuclear power construction requires huge investment, a long construction period and a large proportion of capital cost. It is a typical capital-intensive project. Any delay in the construction of nuclear power will seriously affect the economics, such as the increased loans and the gradual rise of material costs and wages.

(3) The capital cost of NPPs is high, accounting for about 40%–60% of the generation cost. The cost related to power output is mainly fuel cycle cost, which accounts for a relatively low proportion of power generation cost, about 20%–30%, while the fuel cost of coal power and natural gas power plants accounts for more than 60%. Therefore, the economics of nuclear power is greatly affected by the load factor. The higher the annual operating rate of nuclear power, the lower the unit power generation cost.

(4) Economic life refers to the life of a nuclear power plant when it is scrapped for economic reasons, which will never be greater than its design life. The current design life of NPPs is 40–60 years. Affected by the time value of money, the benefits after 30–40 years have shrunk significantly to the present value when discounting is considered. Therefore, for the purpose of economic evaluation, the economic life of NPPs is usually set as 30 years. However, there is still a lot of profit in the later stage of actual nuclear power operation.
(5) The discount rate is an interest rate that reflects the time value of money, and is used to convert the benefits and expenses that occurred at different times into the equivalent value at the same time. It is expressed as the opportunity cost of the country or region where the power plant is built and operated. The discount rate has a great influence on the economic analysis results of NPPs with high initial investment and long life. The economic comparison of nuclear power and other power plants under different discount rates may draw diametrically opposite conclusions.
(6) The unit capital cost of nuclear power is calculated by electric power, and it is an important indicator for evaluating the economics of nuclear power. Since the proportion of unit capital cost of nuclear power in the generation cost is much higher than that of conventional thermal power, reducing unit capital cost is of great significance to improving the economics of nuclear power. When the reactor type, technical conditions and external factors are basically the same, a power plant with a smaller electric power capacity has a higher unit capital cost than those with larger power capacity, that is, NPPs have capacity scale effect, and cluster reactor construction at the same site also contributes to the total scale effect. The average unit capital cost of a series of standardized units is lower than that of a single unit with the same characteristics but designed and built separately, mainly because of the first reactor effect and the learning effect from serialized, standardized manufacturing and construction.

4.2 Analysis of Typical Influencing Factors on Internal Economy

In addition to the impact of technical solutions on the work amount, the engineering economic standard system also has a great effect on the parameters of consumption, other expenses, operation and maintenance and fuel cost, electricity price and rate of return. The following will select several typical evaluation standard parameters for detailed analysis.

(1) Impact during the economic evaluation period

At present, the principle of Gen-II plus is generally continued to be used, and the "economic evaluation period" is also considered as 30 years during the economic evaluation of the Gen-III nuclear power project. However, as the design life of the Gen-III nuclear power plant (60 years) has been significantly extended compared with that of the Gen-II plus (40 years), and most of the new domestic projects in the future are Gen-III nuclear power projects, the industry has raised the appeal of appropriately extending the economic evaluation period of the third generation nuclear power project.

Taking a domestic Gen-III reactor as an example, it is roughly estimated (according to Equity IRR (EIRR) of 9%, the electricity price of 0.430 yuan/kWh, and the total investment cost of 17,000 yuan/kW). The independent impact results of the changes in the project economic evaluation period on electricity price and total investment cost are roughly shown in the Table 1 below.

Table 1. The economic impact of nuclear power under different economic evaluation periods

No.	Economic evaluation periods (years)	Marginal change of electricity price (RMB cents /kWh)	Cumulative change of electricity price (RMB cents /kWh)
1	35	−0.72	−0.72
2	40	−0.46	−1.18
3	45	−0.32	−1.5
4	50	−0.21	−1.71
5	55	−0.14	−1.85
6	60	−0.1	−1.95

It can be seen from the above calculation that when the requirement of 9% internal rate of return on capital is met, with the extension of the project economic evaluation period, the estimated electricity price will be reduced to a certain extent, and the economy of the nuclear power plant will be further improved, but the marginal effect of extension is diminishing.

(2) The impact of loan repayment period

In the economic evaluation, the "domestic loan repayment period" refers to the past experience of operating power plants, and is generally considered as 15 years. However, with the implementation of the benchmark electricity price policy for nuclear power and the promotion of electricity market-oriented reforms, the operating income of newly-commissioned nuclear power units in my country has been affected to a certain extent, and the pressure on enterprises to repay loans has also increased relatively. In particular, the nuclear power projects to be built in the future are mainly based on the Gen-III technology route, and their economic pressure is even greater. According to the actual internal operation of the enterprise, after stress analysis and testing, the enterprise generally needs at least 25 years to complete the full repayment of the principal and interest of the domestic loan.

At present, some nuclear power projects have signed 20-year loan repayment agreements with lending banks. After communication, if there are relevant documents in the industry to support 25-year loan repayment, the bank agrees to sign an agreement with the enterprise for 25-year loan repayment.

Taking a domestic third-generation reactor as an example, it is roughly estimated (the construction price is 16,000 yuan/kW, and the capital return rate is 9% to calculate the electricity price inversely), the general situation of the on-grid electricity price under different loan repayment years is as follows (Table 2).

Table 2. The economic impact of nuclear power under different loan repayment periods

No.	Loan repayment period (years)	Electricity price (yuan/kWh)	Marginal change of electricity price (RMB cents /kWh)	Average generation cost (yuan/kWh)	Marginal change of average generation cost (RMB cents /kWh)
1	15	0.425	/	0.26	/
2	20	0.414	−1.13	0.27	1
3	25	0.406	−0.81	0.279	0.9

It can be seen from the above that with the extension of the loan repayment period, the increase in the interest repaid by the project leads to a certain increase in the average power generation cost. However, due to the reduction in the amount of loan repayment amortized to each year, and the improvement of the project's operating conditions and cash flow, the on-grid electricity price calculated at a fixed rate of return has declined to a certain extent, and the economy has improved.

(3) Impact of equity internal rate of return

At present, the reference value given in "Methods and Parameters of Economic Evaluation of Construction Projects" (Third Edition) and "Methods of Economic Evaluation of Nuclear Power Plant Construction Projects" is 9%, which is not a mandatory parameter. The value usually reflects the requirements and expectations of investors on the return of capital, which can be different due to the different requirements and expectations of investors on the return of capital. The "Standard for economic evaluation of wind farm projects" (NB/T 31085-2016) stipulates that the EIRR of wind power projects is 8%, and the EIRR when the benchmark electricity price of Gen-II nuclear power is approved is 8%. The National Development and Reform Commission estimates thermal power and other benchmark electricity price capital returns are considered by 8%.

Judging from the current overall situation of the power industry, in the context of supply-side reform, power generation enterprises can appropriately reduce the return on capital, but at the same time should reflect the basic income level. The current 10-year treasury bond interest rate (risk-free yield) is about 3.3%, while the SASAC's standard for assessing the cost of capital for central SOEs is usually 5.5%.

Taking a third-generation reactor type as an example, it is roughly estimated (the construction price is 16,000 yuan/kW, and the fixed capital rate of return calculates the electricity price inversely), the electricity price under different yields is roughly as follows (Table 3).

Table 3. The economic impact of nuclear power under different EIRR

No.	EIRR (%)	Electricity price (yuan/kWh)	Marginal change of electricity price (10^{-2} yuan /kWh)
1	9	0.425	/
2	8	0.4115	−1.35
3	7	0.3989	−1.26
4	6	0.3868	−1.21
5	5	0.3756	−1.12

It can be seen from the above that with the decline in the expectation of capital return, the electricity price level of the inverse calculation of the return on fixed capital is also declining, and the marginal effect is diminishing.

(4) Impact of lending rates

Long-term loan interest rate for nuclear power projects in our base case is implemented at 4.9% (effective interest rate 4.99%). If certain preferential loan policies are considered, such as a decrease of 5%, 10%, 15%, and 20%, take a third-generation nuclear power reactor as an example to make a rough calculation (the total capital cost is 16,000 yuan/kW, and the EIRR is 9%). The electricity price under different loan interest rates is roughly as follows (Table 4).

Table 4. The economic impact of nuclear power under different loan interest rates

No.	Effective interest rate (%)	Electricity price (yuan/kWh)	Marginal change of electricity price (10^{-2} yuan/kWh)
1	4.99	0.425	/
2	4.74	0.4212	−0.38
3	4.48	0.4172	−0.4
4	4.23	0.4134	−0.38
5	3.98	0.4096	−0.38

It can be seen from the above that based on the assumed loan interest rate, for every 5% decrease in the interest rate level, the electricity price with a fixed capital yield of 9% decreases by about 0.4 cents/kWh, that is, the preferential loan policy has a certain effect on the improvement of nuclear power economy.

(5) Impact of market power

Due to the gradual increase in the proportion of nuclear power participating in market-oriented transactions, some power plants have already been between 30% and 46%.

Taking a domestic Gen-III nuclear power reactor as an example, it is roughly estimated (the total capital cost is 16,000 yuan/kW, and the annual utilization is 7,000 h), of which the benchmark electricity price of nuclear power (0.43 yuan/kWh) is used for 5,000 h, and the remaining 2,000 h are based on market bidding (considering 0.43 yuan, down 5%, 10%, 15%, 20%, 25%, 30%), the EIRR is as follows.

Table 5. Indications of the impact of market electricity prices

No.	Planned power (h)	benchmark electricity price (yuan/kWh)	Market power (h)	market electricity price (yuan/kWh)	EIRR (%)	Marginal change of EIRR (%)
1	5000	0.430	2000	0.430	10.44	–
2	5000	0.430	2000	0.409	9.97	−0.47
3	5000	0.430	2000	0.387	9.51	−0.46
4	5000	0.430	2000	0.366	9.02	−0.49
5	5000	0.430	2000	0.344	8.57	−0.45
6	5000	0.430	2000	0.323	8.09	−0.48
7	5000	0.430	2000	0.301	7.58	−0.51

As can be seen from the above table, every 5% drop in the market electricity price for 2000 h will affect the internal rate of return of the project capital by about 0.47%, and the decline rate is about 5%, which has a greater impact on the economics of nuclear power. Due to the high cost of nuclear power construction, it is necessary to ensure a certain number of annual utilization hours and electricity prices to recover fixed costs.

(6) Impact of batch

The international experience of nuclear power development shows that in the process of standardization and batch construction of nuclear power units, due to various factors such as proficiency in skills, accumulation of experience, and improvement of management, the productivity will increase, and the unit total capital cost of nuclear power units will gradually decline. This phenomenon is called the learning effect. The cost reduction due to the learning effect can be described by a learning curve. Different product series have different learning curves and learning rates. For nuclear power, the construction frequency, the number of constructions on a single site, the construction market conditions, the degree of standardization and the level of construction management will all have a certain impact on the learning rate.

Due to the scheme effect of nuclear power, that is, the development surcharge involved in the FOAK project. This is necessary to complete the design, development, qualification, testing of new systems, new equipment, and obtain manufacturing, construction licenses and authorizations. It varies with technological progress and the degree of standardization and procurement policies, but it has nothing to do with the number of units in the standardized series and is relatively fixed, which is a one-time cost.

If it is expected that a certain model can be developed in batches, such as about 8 units, then the additional one-time cost of FOAK can be shared among the series of units, thereby improving the overall economy of the model. For recurring costs, it can be reduced by learning effects, with a learning rate of 3%–10%. Even if it is a recurring cost, if considering the construction of multiple reactors at a single site, the site-related costs can be allocated within a small area. If the multi-site group reactors are located in the same area, the shared off-site emergency facilities costs can also be shared, so that there is a possibility of further economic improvement.

4.3 External Cost and System Cost

4.3.1 External Cost

The external cost of nuclear power is relatively small. According to “synthesis on the economics of nuclear energy WPEN2013-14”, the external cost of nuclear power in the case of no nuclear accident is compared with other forms of power generation as in Fig. 3 [3].

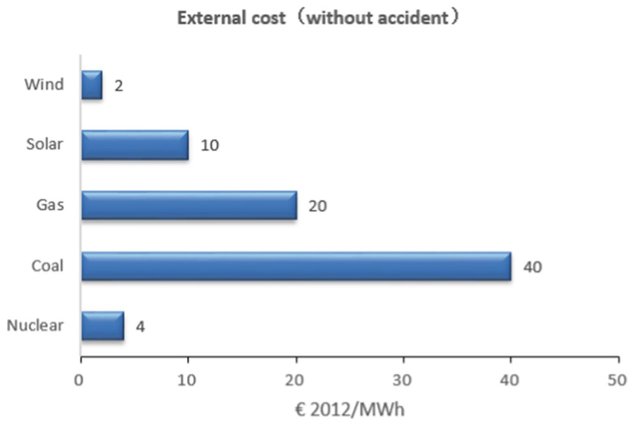

Fig. 3. Different energy external costs

After considering a certain risk of nuclear accident, the added value of the external cost of nuclear power is about 0.1–3 EUR/MWh (EUR 2012).

As the internal cost of nuclear power has taken into account the cost of post-treatment of spent fuel, the cost of treatment and disposal of medium and low radioactive waste, decommissioning fund and insurance, etc., that is, some external costs have been internalized and not all countries include costs such as greenhouse gas emissions in the internal costs of power plants.

The external costs of nuclear power are still significantly better than those of fossil fuel power plants.

4.3.2 System Cost

The so-called system cost in foreign literature mainly refers to backup, balancing cost, grid connection, grid strengthening and extension, etc. Domestic auxiliary services refer to the services needed to maintain the safe and stable operation of the power system or restore system security, ensure the safe, high-quality, and economical operation of the power system, maintain the legitimate rights and interests of power companies, and ensure the supply of electrical energy and meet the requirements of voltage, frequency, and quality. It includes basic auxiliary services and paid auxiliary services (basic auxiliary services include primary frequency regulation, basic peak regulation, and basic reactive power regulation. Paid auxiliary services include automatic generation control (AGC), paid peak regulation, paid reactive power regulation, and automatic voltage control. (AVC), spinning reserve, hot spare, black start). The connotation of foreign system cost is greater than that of domestic auxiliary services.

Although nuclear power usually operates at base load for economic reasons, it has a certain load-following capability from a technical point of view, which gives it an advantage in system cost compared with new energy sources such as wind power and photovoltaics. Please see Table 6 [3] for details.

As shown in Table 7 [3] and Table 8 [3], nuclear power has a smaller system cost, higher than coal and gas-fired power plants, but much lower than wind and photovoltaics. At the same time, with the increase in the proportion of power sources, the system costs of nuclear power, coal-fired and gas-fired power plants remained unchanged or slightly decreased, while the system costs of wind power and photovoltaics increased significantly.

Table 6. Load tracking capabilities of different energy sources

	Start-up time	Maximal change in 30 s	Maximum ramp rate
Open cycle gas turbine (OCGT)	10–20 min	20–30%	20%/min
Combined cycle gas turbine (CCGT)	30–60 min	10–20%	5–10%/min
Coal plant	1–10 h	5–10%	1–5%/min
Nuclear power plant	2 h–2 days	up to 5%	1–5%/min

Table 7. Comparison of system costs of different energy sources in Germany1 (2011 USD/MWh)

Technology	Nuclear		Coal		Gas	
Penetration level	10%	30%	10%	30%	10%	30%
Back-up costs (adequacy)	0.00	0.00	0.04	0.04	0.00	0.00
Balancing costs	0.52	0.35	0.00	0.00	0.00	0.00
Grid connection	1.90	1.90	0.93	0.93	0.54	0.54
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00
Total grid-level system costs	2.42	2.25	0.97	0.97	0.54	0.54

Table 8. Comparison of system costs of different energy sources in Germany2 (2011 USD/MWh)

Technology	Onshore wind		Offshore wind		Solar	
Penetration level	10%	30%	10%	30%	10%	30%
Back-up costs (adequacy)	7.96	8.84	7.96	8.84	19.22	19.71
Balancing costs	3.30	6.41	3.30	6.41	3.30	6.41
Grid connection	6.37	6.37	15.71	15.71	9.44	9.44
Grid reinforcement and extension	1.73	22.23	0.92	11.89	3.69	47.40
Total grid-level system costs	19.36	43.85	27.89	42.85	35.65	82.96

5 Conclusions

In order to cope with climate change, it is necessary to establish a clean and efficient energy supply mix. Nuclear power, which is clean, safe, stable and flexible, will be an important option in the energy mix. At present, economy seems to be the factor restricting its development.

The current cost of Gen-III nuclear power is relatively high, but its inherent technical and economic characteristics show a good economic potential. In addition, with the breakthrough of advanced fuel and material technologies, as well as the application of digital and intelligent technologies, nuclear power will achieve an effective balance between technology and economy and have a better economic prospect.

From the perspective of the full range of costs, nuclear power has a certain economic advantage, but the current economic evaluation focuses on internal costs, and the internal cost advantage is not prominent. Therefore, to improve the economy of nuclear power, one solution is to better control the internal cost, the other solution is to internalize the external cost, reflecting the comprehensive cost advantage.

Based on the above analysis, it is suggested to improve the economy of nuclear power:

(1) Appropriately extend the economic evaluation period of Gen-III advanced nuclear power. It is recommended to be clearly stated in the standard specification that the

economic evaluation period of the Gen-II plus project is still considered as 30 years, while that of the Gen-III project is considered as 40 years.

(2) Provide low-interest loans or discount policies for NPPs, explicitly support appropriate extension of loan repayment terms, but the longest term should not exceed 25 years which may better match the depreciation life.
(3) Nuclear power investors appropriately reduce the EIRR. It is specified in the standard specification that each unit can choose the EIRR by itself based on its own capital cost and investment expectation.
(4) Create a good policy and regulatory environment to promote the sustainable and stable development of nuclear power and moderate mass production, so as to obtain a better learning effect and reduce the cost of subsequent units.
(5) In the context of electricity marketization, research and introduce carbon pricing strategies to take advantage of the lower external cost of nuclear power.
(6) Internalize grid system costs when feasible and necessary.

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