Analysis of the Economic Prospect of Nuclear Heat Supply by Megawatt-Class Nuclear Power Units from the Perspective of Carbon Peaking and Carbon Neutrality

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Abstract. Under the vision of carbon peaking and carbon neutrality, clean heat supply as one of the important ways to realize low-carbon transition, will face a broad market, and replacing some conventional heat sources with nuclear energy is an effective means to reduce pollutants and a priority choice to optimize energy structure. Based on the current situation of heat supply in China, this paper first analyzes the necessity of nuclear heat supply (NHS) by megawatt-class nuclear power units from the demand side and supply side respectively. The paper then constructs an economic model and based on the opportunity cost theory, uses the power loss method to carry out financial calculation after apportioning the cost of thermal power. It will analyze the impact of nuclear feed-in/cost tariff, heating load, and distance of heat supply network on the cost-effectiveness of NHS by megawatt-class nuclear power units in the case of low-pressure steam supply, as well as the range of heat price variation caused by related factors within a certain controllable range. The study shows that the cost-effectiveness of NHS is most sensitive to feed-in/cost tariff, and that at the current level of nuclear feed-in/cost tariff, the price of NHS is significantly lower than the price level set by the Development and Reform Commissions in most regions of China. Therefore, NHS by megawatt-class nuclear power units has a very good market prospect in terms of both price competitiveness and policy support.

Keywords: Nuclear heat supply (NHS) · Low-pressure steam · Heat price · Feed-in/cost tariff · Cost-effectiveness

1 Introduction

The proposal of carbon peaking and carbon neutrality provides a great opportunity for the development of nuclear energy. As a low-carbon, safe and stable localized non-fossil energy, nuclear energy can not only provide electricity, but also replace a part of fossil energy such as natural gas and coal through nuclear heating, so nuclear power can reduce emissions on a massive scale. In November 2019, with the successful implementation of the China's first nuclear power civil central heating commercial project in Haiyang,

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Shandong province, which means that the technology of cogeneration of nuclear power units has achieved a breakthrough, and it has become economically competitive with coal heating because that the heating price of single square meter is 1 yuan lower than in previous years. Meanwhile, the safety of using nuclear power units to provide heating for residents has also been recognized. Since CNNC Tianwan steam energy supply project officially started, China started its first industrial nuclear energy steam supply project research and exploration. The main factors affecting the economy of nuclear heating retrofit project is different from the normal heating project, to study and explore the competitiveness of nuclear energy supply industrial steam projects in the market is conducive to promoting the coupling development of active nuclear power units and high energy consumption industries, and further realizing the coordinated development of energy, economy, and ecological environment.

2 Great Opportunities for Nuclear Heating Under Carbon Peaking and Carbon Neutrality Targets

2.1 Analysis of China Heating Status

From 2011 to 2020, China's heating area keeps growing, and the hot-water heating capacity and total heating volume keep rising. In contrast, the steam heating capacity and total heating volume are relatively small, in which the annual steam heating volume only accounts for about 16% of the total urban heating volume and presents a downward trend.

On the demand side, with the acceleration of China's urbanization process and the rapid development of industry, the area of central heating keeps increasing, and the demand for industrial heat also rises every year. High energy consumption industries such as petrochemical and steel mainly rely on fossil energy such as natural gas and coal for a long time, which inevitably leads to high carbon emissions. Therefore, it is appropriate to develop the central heating mode based on nuclear waste heat utilization, which is a new way to solve the petrochemical industry's demand for steam, reduce comprehensive energy consumption and reduce environmental pollution. According to experts' forecasts, the use of waste heat from coastal nuclear power is expected to meet the winter heating demand of nearly 7 billion square meters of buildings within 200–300 km from the coast to the hinterland.

2.2 The Government Issued Relevant Policies, the Development of Nuclear Heating Sustains Positive

In recent years, China has gradually increased the policy support for nuclear heating and issued several policies. In 2017, the Plan for "Clean Winter Heating in Northern China (2017–2021)" which issued by ten ministries and commissions, made it clear that nuclear, geothermal, and solar energy are important forms of clean heating. In 2018, the National Energy Administration pointed out in the "Guidance on Energy Work in 2018" and the "Five-year Action Plan for Nuclear Energy Heating in Northern China" (draft for comments) that the pilot work of nuclear energy heating in northern China

should be actively studied and promoted, and the demonstration project of nuclear energy heating should be promoted as a key project. "The Guidance Catalogue for Industrial Restructuring (2019 Edition)" which took effect in January 2020, also includes the comprehensive utilization of nuclear energy in heating, steam supply and other fields in the "encouraged category" of the catalogue.

In September 2020, as CPC General Secretary clearly proposed the ambitious goal of "striving to achieve carbon peak by 2030 and carbon neutral by 2060" at the general debate of the seventy-fifth Session of the United Nations General Assembly, the development of nuclear energy has once again become the focus of local government arrangements. In 2021, "Opinions of the CPC State Council on Fully, accurately and comprehensively Implementing the New Development Concept to achieve carbon peak and Carbon Neutral Work" proposed that "Actively and prudently carry out nuclear waste heat for heating". In that year's government work report, it was clearly stated that "Nuclear power should be actively and orderly developed on the premise of ensuring safety". Nuclear energy heating has been listed by many local governments as an important expansion direction of the "14th Five-year Plan" and the medium- and long-term comprehensive utilization of nuclear energy, nuclear energy heating has a promising future.

3 The Main Factors Affecting the Economy of Nuclear Heating Retrofit Project

The economy of nuclear heating retrofit project should consider heating mode, matching relation of heat load, distance of heating pipe network and parameters optimization, etc. Therefore, it is necessary to optimize and analyze the whole system including heating scale, heat source and heat network, and analyze the economics of nuclear heating retrofits based on the investment and cost of different heating scales [1]. The main factors affecting economy are as follows:

(1) Heating scale: It is related to the demand of heat users, the demand of heat users further determines the heating load, heating parameters, heating pipe network parameters and the loss of reactor power generation, etc. The short-term heat load requirements of heat users should be determined based on the heat requirements from existing, under construction and approved industrial projects.
(2) Heating parameters: It is related to the industrial type of heat users. Due to the difference of raw materials, technology and products, different industrial enterprises have different requirements for steam heating parameters. Generally, 1.6 MPa can meet the heating requirements of machinery, pharmaceutical, while petrochemical enterprises need pressure grade parameters such as 2.2, 3, 5 and 4.0 MPa to meet the heating requirements [2].
(3) Distance of heating pipe network: It is related to the distribution characteristics of nuclear power units and chemical industrial parks. Nuclear power units in China are all distributed in developed coastal areas in the east and south, and chemical parks are also generally far from central cities. As the larger the heating radius is, the higher the cost required by burying pipes is, and the greater the heating loss is

[3]. There may have problems that the steam parameters cannot meet the needs of the user when the steam is transported over a long distance of more than 35 km. Therefore, we should consider the reasonable distance of heating network to select hot users. Meanwhile, we can also further optimize the initial parameters of steam, the diameter of heating pipe, the thickness of pipe insulation and the layout of pipe to reduce the heat loss in steam transportation [4].

(4) Reactor generation losses: It is related to the demand of heat users and the operating status of nuclear power plants. Because nuclear energy heating needs to extract steam from the second loop of the main steam pipe of the original nuclear power unit, the generation of electricity is reduced. From the analysis of the opportunity cost theory of economic, the less electricity produced here should be the cost of heating. Therefore, we need to determine the loss rate of power generation caused by steam extraction heating and then obtain the reduced power generation of nuclear power units, and the consumption of reactor power, etc.

(5) Feed-in/cost tariff: The type of electricity price is related to the operation of nuclear power units in service. If the nuclear power unit reactor works in TMCR(turbine maximum continuous rating) condition, that is, the annual power generation is at full capacity, then the reduction of generating capacity due to steam extraction will only affect the Feed-in generation of the unit, and the electricity price should be considered according to the Feed-in tariff. If the reactor of a nuclear power unit doesn't work in TMCR condition, that is, the annual power generation isn't at full capacity, then the effect of main steam extraction on the reactor will be divided into two parts: if the reduction of electric quantity affects the Feed-in generation part of the unit, the cost should be considered according to the Feed-in price; if the reactor is consumed because of the additional work done by the extraction of steam, according to the opportunity cost theory of economic theory, the cost of additional consumption of reactor should be compensated based on cost tariff (Table 1).

4 Calculate the Financial Benefit of Different Heating Demands in the Case of Low-Pressure Steam Supply

Pressurized water reactor (PWR) has good operation stability and large thermal production capacity. Taking an active million-kilowatt pressurized water reactor nuclear power units as the model, the units were put into a hypothetical low-pressure industrial steam supply system, the steam conversion scheme is adopted to produce industrial steam by using the main steam of the second loop of the original nuclear power unit through the steam conversion device, and to provide low pressure industrial steam to the thermal users of the industrial park through the long transmission pipeline. At this time, the original pure condensing generator unit is transformed into a combined heat and power supply unit, and the former nuclear power plant is transformed into a nuclear thermal power plant. The modified nuclear thermal power plant consists of a nuclear power generation system and a steam extraction heating system, Since the nuclear power unit in service is already in economical operation state, the cost-effectiveness of the transformed nuclear thermal power plant will depend on the extraction steam heating system.

Table 1. Overview of the main parameters of nuclear energy heating renovation project

Main factors	Related factors	Conformation method
Heating scale	It is related to the demand of heat users	Based on the heat requirements from existing, under construction and approved industrial projects
Heating parameters	It is related to the industrial type of heat users	The enterprise type of heat users determines the steam pressure level
Distance of heating pipe network	It is related to the distribution characteristics of nuclear power units and chemical industrial parks	Consider the reasonable distance of heating network to select hot users
Reactor generation losses	It is related to the demand of heat users and the operating status of nuclear power plants	Determine the loss rate of power generation caused by steam extraction heating and then obtain the reduced power generation of nuclear power units, and the consumption of reactor power, etc.
Feed-in/cost tariff	The type of electricity price is related to the operation of nuclear power units in service	The nuclear power unit reactor works in TMCR condition

This paper take a study based on the nuclear heating retrofit project. Taking the extraction point as a cut-off point, The steam extraction heating system on the steam supply side as a nuclear energy heating renovation project, which includes heat source engineering and heat network engineering. The heat source engineering includes steam energy supply system, chemical water treatment system, instrument and control system, electrical system, etc. the cost of a ton of steam is about 120 yuan/t; Heat network engineering includes thermal system, thermal control system and ancillary production engineering, etc. The investment cost is about 25,000 yuan/m. Other main parameters can be seen as follows (Table 2).

Based on《Economic Evaluation Methods and Parameters of Construction Projects》(The Third Edition) to make economic calculations, the impact of nuclear feed-in/cost tariff, heating load, and distance of heat supply network on the cost-effectiveness of NHS by megawatt-class nuclear power units in the case of low-pressure steam supply was analyzed one by one. The study shows that the cost-effectiveness of NHS is most sensitive to feed-in/cost tariff, followed by heating load, and the distance of long-distance transmission network has a relatively small impact on the cost-effectiveness (Fig. 1). The main reason is that in the process of heating project transformation, the loss cost of reactor power generation is relatively high, accounting for about 80–90% of the total operating cost. The change of Feed-in/cost tariff price will directly cause the change of the loos cost, and then it affects the heat price.

Table 2. Details of the main parameters of nuclear energy heating renovation project

Main parameters	Unit	Quantity
Heating scale	t/h	600
Heating hours	h	8000
Distance of heating pipe network	km	27
Loss of reactor power	MW	175
Feed-in tariff	¥/kWh	0.43
Heating parameters	–	Low-pressure steam
Internal rate of return of capital	%	10
Other fees	¥/t	20.8×10^4
Operation Hours of reactor	H	7000
Cost tariff	¥/kWh	0.21

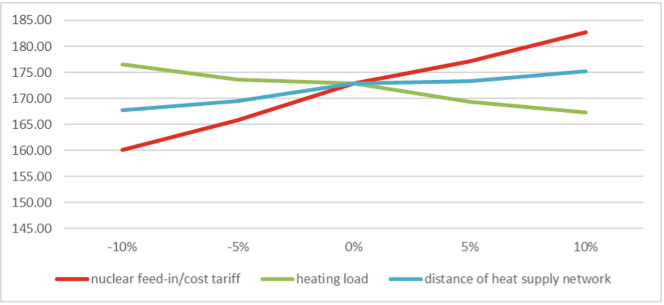

Fig. 1. Sensitivity analysis

In the most unfavorable case, the nuclear power unit reactor works in TMCR condition, that is, the annual power generation is at full capacity. At this time, the cost of making up for the loss of reactor power generation is calculated according to the benchmark electricity price of 0.43 yuan/kWh (the highest value) approved by the National Development and Reform Commission in June 2013. Refer to "Guidelines for economic evaluation of fossil-fired power plant" (DL/T5435-2019), the heat price was calculated based on 10% internal rate of return of capital, and the heat price is about 172.83 yuan/t on the user side. If the nuclear power unit reactor does not work in TMCR condition, Cost tariffs will be applied to the reactor loss caused by the extraction of main steam, and the average cost per kWh will reduce 0.21 yuan/kWh, and the heat price to the user side will be further reduced. According to the Interim Measures for The Administration of Urban Heating Price (No. 1195 [2007]), the heat price shall be fixed or guided by the government in principle. At present, Jiangsu, Zhejiang and Shandong are the three provinces which have the largest number of national economic development zones in China, those provinces have many industrial heat users. The average price of low-pressure steam published by the National Development and Reform Commission is

about 176–222 yuan/t. The calculated heat price of the project is lower than the guiding price level of the National Development and Reform Commission in most regions of China, indicating good market economic competitiveness.

5 Summary

At present, there is no nuclear energy heating project for industrial steam in China, Retrofitting the existing million-kilowatt pressurized water reactor nuclear power unit to Provide low pressure steam for thermal users in industrial parks, to satisfy China's growing energy demand, and to realize the energy and coordinated development between economy and ecological environment. The calculation results show that the biggest influence on heat price is the Feed-in/cost tariff of nuclear power units. Based on the benchmark electricity price of 0.43 yuan/kWh (the highest value) verified by NDRC, heat price is still lower than the guiding price level of NDRC in most regions of China. To sum up, no matter in terms of price competitiveness or policy support, NHS by megawatt-class nuclear power units has a very good market prospect in terms of both price competitiveness and policy support.

Later we will use post evaluation model constructed by this paper to demonstrate the construction achievements of the example project [5], and then put forward the evaluation results.

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