

Research on Small Modular Reactors and the Decarbonization of China's Power and Heating Sectors

Executive Summary (2026/02/28)

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1. Research Background

1.1 Pressure on China's Coal Power Transformation under Dual Carbon Goals

Addressing global climate change, China has clearly put forward the "dual carbon" goals and established a "1+N" policy system for carbon peaking and carbon neutrality. The core of achieving this goal lies in the low-carbon transformation of the energy system, especially that the power and heating sectors need to achieve net-zero emissions around 2050. Currently, China's energy structure is highly dependent on coal, with coal consumption accounting for about 53% in 2025 and carbon emissions from coal-fired power plants accounting for about 40% of the national total. Constrained by resource endowment and energy security needs, the early retirement of coal-fired power units will face challenges such as energy supply shortage, stranded assets, local employment and economic development issues, and just transition. Meanwhile, due to the high cost of CCUS technology and the difficulty of large-scale application, and the intermittency of renewable energy sources such as wind and solar posing higher requirements for the stability and reliability of the power system, finding a safe, reliable, green, low-carbon, and cost-acceptable alternative path for coal-fired units has become an urgent topic at present.

1.2 Development Status of Small Modular Reactors

Small Modular Reactors (SMRs), due to their advantages such as high safety, flexible deployment, and proximity to the user side, are becoming an important direction for the future development of nuclear energy. According to the <Tripling Nuclear Energy Declaration> proposed at COP28, SMRs will account for a significant share in the global nuclear power installed capacity by 2050. Currently, China has taken the lead in the world in SMR technology R&D and engineering demonstration, but still faces challenges in the commercialization process, such as the need to verify technological maturity, high costs, unrecognized carbon reduction benefits, and the public's "not in my backyard" attitude.

1.3 Opportunities for Coal to Nuclear under the Goal of Carbon Neutrality

Under the goal of carbon neutrality, the scope of nuclear energy applications has expanded from single power generation to non-power sectors such as combined heat and power, industrial waste heat utilization, seawater desalination, and hydrogen production. Small light water reactors can provide a heat source of approximately 300°C to meet district heating and medium- and low-temperature industrial process heat needs, while high-temperature gas-cooled reactors (HTRs) can provide high-temperature industrial process heat above 500°C, supporting deep decarbonization in hard-to-abate industries such as petrochemicals and metallurgy.

As a zero-carbon energy source with high energy density, nuclear energy has a similar installed capacity scale and stable energy supply characteristics to coal-fired power. By building nuclear power plants at the original sites of coal-fired power plants (Coal-to-Nuclear, C2N), it can not

only reuse site resources, cooling water sources, and power transmission facilities, reducing investment costs, but also smoothly absorb employment and ease the resistance to social transformation. Internationally, the US and EU have already conducted relevant site potential assessments and typical case studies. Although China regards nuclear energy as an important part of the new energy system, national and quantitative research on the potential of C2N is still in its initial stage, and further research is needed on its specific contribution to achieving the decarbonization of China's power and heating sectors.

1.4 Research Status and Significance

Existing domestic and international research on low-carbon energy transition in China has mainly analyzed and evaluated the low-carbon transition pathways of energy systems based on a substantial increase in renewable energy, lacking a systematic evaluation of high-proportion nuclear energy scenarios. Moreover, most of the existing research that has focused on nuclear energy has mainly emphasized the power generation of large reactors (LRs), neglecting the potential of SMRs in the coordinated decarbonization of power and heating systems. In response, this study, based on the distribution of existing coal-fired power units in China, explores the contribution of high-proportion nuclear energy scenarios to the low-carbon transition of the power and heating sectors, and conducts in-depth analysis of the technical feasibility, economic viability, and public acceptance of SMRs replacing coal through typical cases. This study has important research value and practical significance for China's power and heating sectors to achieve the goal of carbon neutrality at a lower system cost, meet users' energy demand, and ensure the security of power grid operation.

2. Site Potential Assessment of Coal to Nuclear

2.1 China Coal-fired Power Generation/Heating Database

The coal power industry is a key focus for carbon emissions and air pollution control. Although existing research has established a database of Chinese coal-fired power units and classified them by installed capacity, unit age, and power plant type, data updates and dimension expansion are still needed to meet C2N requirements. The basic data for this study is sourced from the Global Coal Plant Tracker (GCPT), and GIS technology is used for spatial visualization and quantitative analysis to ensure global comparability and geographical accuracy of the data.

Based on the existing database, and in accordance with the characteristics and specific requirements of this project, the research team has developed a 2024 China Coal-Fired Power Generation/Heat Supply/CHP Database, which includes 6,078 units with a total installed capacity of approximately 1.5 billion kilowatts. Among them, 3,131 units are in service, 244 under construction, 427 planned, and 1,123 decommissioned. The database includes key information related to C2N, such as installed capacity/heat supply capacity, power generation/heat supply technology, efficiency, lifespan, plant location, geological conditions, population density, and energy (thermal and electrical) demand. Meanwhile, based on the limited information such as the total number of coal-fired power plants, installed capacity, and heating boiler capacity announced at the national and provincial levels, crosscheck and

verification was conducted, laying an accurate data foundation for subsequent carbon emission research and assessment of C2N potential.

2.2 Coal to Nuclear Site Matching Evaluation Indicators

This study draws on methods from existing literature and constructs an evaluation indicator system for C2N site suitability from both social and safety aspects, as shown in Table 1.

(1) Safety. The selection of nuclear power plant sites must strictly consider factors such as geology, water sources, and climate conditions, choosing areas with stable geology, abundant and reliable cooling water sources, and low disaster risks (such as earthquakes, floods, dangerous explosions, etc.) to ensure compliance with the safety standards and requirements for nuclear power plant site selection.

(2) Sociality. When selecting a site, it is necessary to fully consider the opinions and interests of the surrounding public, and ensure the smooth construction and operation of the project by assessing public acceptance, etc.

Table 1. Evaluation Indicator System for Site Matching of C2N Plant

Target Level	Criteria Level	Indicator Level	LRs	SMRs
Site Compatibility	Security	Seismic Geology	For earthquakes with a magnitude ≥ 6.2 , a 20 km buffer zone shall be established	For earthquakes with a magnitude ≥ 6.8 , a 20km buffer zone shall be established
		Water source conditions	A 10km buffer zone is established for rivers above the third level	A 10km buffer zone is established for rivers above the third level
	Sociality	Population Density	≥ 128 people/km ² , establish a 5km buffer zone	≥ 3185 people/km ² , establish a 1km buffer zone
		Border Line	A 20km buffer zone is established along the border line	A 20km buffer zone is established along the border line

Note: Coal-fired units within the buffer zone under the conditions of seismic geology, population density, and border lines are units that do not meet the construction standards for nuclear power plants and need to be excluded. Coal-fired units within the buffer zone under water source conditions are units that meet the construction standards for nuclear power plants and need to be retained.

Based on the above screening criteria, this study examines the site potential and transformation paths of C2N from different perspectives. The study has set up two scenario groups with different perspectives. Group 1, based on China's national conditions, takes into account the current situation and future trends of China's nuclear power, and sets up three scenarios around whether the plant site is located in coastal or inland areas and the distance from the coastline,

including the baseline scenario (S1, no restrictions on coastal, inland, and distance from the sea, maximum potential), the tightened coastline condition scenario (S2, a buffer zone is established within 5 km from the coastline, and units within the buffer zone do not meet the retrofit standards and are considered to be at risk of tsunamis), and the tightened inland nuclear power policy scenario (S3, excluding inland units in coastal provinces and pure inland units, a realistic scenario in the near term). Group 2, based on the current research status of typical global coal-to-nuclear case studies, sets up two scenarios around the replacement approach, including the site reuse scenario (R1): only the site, cooling water source, and grid connection facilities such as transmission lines and substations are retained, while all other equipment is completely demolished and rebuilt. The full reuse scenario (R2): only the coal-fired boiler is replaced, and most of the thermal system infrastructure such as steam turbines, cooling systems, and power transmission and distribution facilities are retained.

2.3 Coal to Nuclear Site Potential

Under the baseline scenario (S1), SMR demonstrates broader applicability and flexibility in site selection compared to LR. The potential of sites suitable for conversion to LR is 55.54 GW (30 sites), mainly distributed in regions with low population density around sites in Inner Mongolia Autonomous Region, Shaanxi Province, Shanxi Province, etc. in North China. The potential of sites suitable for conversion to SMR is 978.9 GW (2482 sites), mainly distributed in areas east of the Tengchong-Heihe Line (i.e., Hu Huanyong Line), among which Shandong, Inner Mongolia, and Jiangsu rank among the top three in terms of potential.

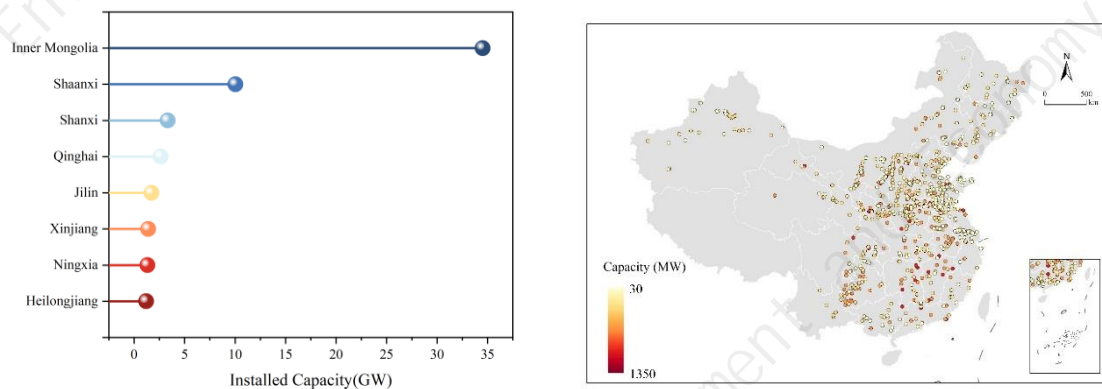


Figure 1. C2N Site Potential of LR and SMR under the Baseline Scenario

Under the tightened coastal condition scenario (S2), the potential of LR sites remains unchanged compared to the baseline scenario. The potential of SMR slightly decreases by 3.2% to 947.5 GW, with the potential in coastal provinces such as Shandong decreasing by approximately 9% - 14% due to buffer zone settings, while inland provinces in the central and western regions remain unaffected.

Under the scenario of tightened inland nuclear power policy (S3), the potential of LR drops to zero; the potential of SMR plummets by 94% to 54.85GW, with only coastal regions such as Shandong Province, Jiangsu Province, and Guangdong Province remaining. This indicates that the policy on the approval of inland nuclear power plants has a decisive impact on the site potential of C2N.

Under the scenario of site reuse (R1), the potential of LR sites is 9.96 GW, mainly concentrated in Inner Mongolia Autonomous Region and Shaanxi Province. SMRs demonstrate significant potential advantages, with the potential of eligible sites nationwide reaching 608 GW, forming multi-center clusters in coastal and inland areas.

Under the full reuse scenario (R2), the potential of LR sites drops to 5.72 GW, while that of SMR sites drops to 499 GW, due to the fact that some coal-fired power facilities are difficult to be compatible with modern nuclear energy technology standards.

In summary, compared to the LRs, SMRs demonstrate significant advantages in geographical adaptability, safety tolerance, and retrofit potential. The site reuse model (R1) is suitable for old or soon-to-be decommissioned coal-fired power plants, enabling a complete zero-carbon retrofit and upgrade at the original site. The full reuse model (R2) is more suitable for coal-fired power plants with relatively new equipment, which can reduce retrofit costs and shorten the construction period.

3. Compatibility of Technical Parameters and Safety Standards of Coal to Nuclear

3.1 Technical Parameter Compatibility

For thermal power generating units, they are mostly based on the ideal Rankine cycle, with a power cycle system composed of water pumps, boilers, steam turbines, and condensers. To improve efficiency, coal-fired power units generally follow the principle of increasing the initial steam parameters. For low-parameter units below the 50MW level, reheat cycles are usually not adopted; while for high-parameter units above the 135MW level, to ensure the dryness of the last stage blades of the steam turbine and avoid water erosion, while significantly improving thermal efficiency, complex reheat cycle systems are commonly used. The main steam pressure of current supercritical boilers has reached over 25 MPa, with the temperature stably maintained in the range of 560 - 600°C, and its complex feedwater regenerative system typically includes multi-stage high and low-pressure heaters and deaerators.

For nuclear power units, the domestically developed nuclear power units in China exhibit different characteristics in terms of parameters. Among them, the NHR200-II low-temperature heating reactor adopts an integrated layout and natural circulation scheme, with the steam generated by its main system being saturated steam, the main pressure only 1.6 MPa, the temperature 201.4°C, and it is mainly targeted at urban heating demand and medium and low-temperature process heating demand. In contrast, the HTR-PM high-temperature gas-cooled reactor, as a fourth-generation advanced nuclear energy technology, can produce superheated steam at 13.9 MPa/570°C, with its parameters already approaching those of conventional ultra-high-pressure coal-fired power units. The reactor has inherent safety, can naturally dissipate heat without emergency cooling, eliminates the possibility of core meltdown, and has the potential for high-temperature process heating and efficient power generation.

There are significant differences between nuclear reactors and coal-fired power units in terms of thermal systems and steam parameters. In thermal systems, large-capacity coal-fired units rely on reheat cycles, while pressurized water reactor nuclear power plants dehumidify through

moisture separator reheaters (MSRs), and HTR-PM ensures the safety of the last stage by virtue of its relatively high initial steam temperature without the need for reheat. In terms of parameter matching, the outlet temperature of HTR-PM can match that of subcritical coal-fired power, but its current pressure limit is approximately 13.7 MPa, far lower than the over 25 MPa of mainstream supercritical units. In addition, due to the low steam parameters of pressurized water reactors, the steam flow rate at the same power is much greater than that of coal-fired power, which leads to a sharp increase in the size of secondary loop pipes and steam turbines, and requires the use of half-speed steam turbines. It has poor compatibility with existing coal-fired power facilities and is difficult to achieve direct modular replacement.

In summary, considering the integrated thermal system, steam parameters, and equipment structure, the core technical obstacle faced by nuclear energy in replacing coal-fired units lies in the span of pressure levels. Although the high-temperature gas-cooled reactor already has the technical foundation to replace coal-fired boilers in terms of temperature parameters, the significant difference in pressure parameters limits its direct replacement of high-parameter and large-capacity units. Meanwhile, the load regulation capacity of nuclear reactors is relatively slow, making it difficult to fully simulate the characteristics of coal-fired boilers in quickly responding to grid fluctuations. Therefore, nuclear energy substitution is not simply a matter of "replacing the boiler with a reactor"; instead, customized thermal system reconstruction and steam turbine matching design must be carried out for coal-fired power units of different capacities.

Table 2. Comparison of Parameters between Nuclear Reactors and Coal-Fired Units

	Main/Reheat Steam Flow (t/h)	Main/Reheat Steam Temperature (°C)	Main/Reheat Steam Pressure (MPa)	Whether to reheat
50MW Thermal Power	220	540	9.8	No
135MW Thermal Power	440/360	541/541	13.7	is
350M Thermal Power	1204/1021	571/569	25.4	is
NHR200-II	/	201	1.6	is
HTR-PM	673	570	13.7	No

3.2 Safety Standard Compatibility

In terms of site selection, there are fundamental differences in the siting criteria between coal-fired power plants and nuclear power plants. The siting of coal-fired power plants mainly focuses on the convenience of fuel transportation, proximity to load centers, ash disposal capacity, and conventional water supply. In contrast, the siting of nuclear power plants prioritizes safety, and must specifically consider the impacts of external natural events (such as earthquakes and tsunamis) and human-induced events on the site, and strictly evaluate the environmental characteristics of the transfer of radioactive materials to the surrounding areas.

Nuclear power plants also have strict population density limits and emergency planning zones, usually requiring the establishment of a non-residential restricted area with a radius of not less than 0.5 km centered on the reactor, as well as a planned restricted area within a 5 km radius. These stringent siting criteria mean that not all existing coal power plant sites are qualified for conversion into nuclear power plants.

In terms of construction and operation, the compliance requirements for nuclear power plants during the construction and operation phases are much higher than those for coal-fired power plants. In terms of design philosophy, nuclear power follows the principle of defense in depth, needing to withstand extreme disasters and low-probability events such as aircraft crashes, and the design of its nuclear island is completely different from that of conventional boilers. At the management level, nuclear power implements a strict safety licensing system, requiring approval from the State Council and multiple permits from the National Nuclear Safety Administration. In terms of construction period, the construction duration of a nuclear power plant with the same capacity is usually 1.8 to 2 times that of a coal-fired power plant. During operation and maintenance, nuclear power also involves maintenance in radioactive environments and "three wastes" treatment, and requires the establishment of a plume and ingestion emergency linkage mechanism covering a range of 5 to 50 km, all of which are not present in the operating system of coal-fired power plants.

In the domestic and international nuclear safety standard systems, nuclear safety standards have formed a rigorous system ranging from laws to industry regulations. Internationally, the IAEA has issued safety guidelines for deterministic and probabilistic safety analysis; the US has established detailed criteria through 10 CFR part 50 and the Standard Review Plan (SRP); France has developed the RCC design and construction rules centered around engineering models. Since the 1980s, China has established a system centered around the Nuclear Safety Law, covering HAF administrative regulations, HAD guidelines, and NB/T industry standards, which regulates the entire life cycle of nuclear power plants, including siting, design, construction, operation, and decommissioning. These standards far exceed the conventional standards of the power industry followed by coal-fired units in terms of accident analysis methods, safety margins, and requirements for radioactive consequences.

4. Case Study on Typical Coal to Nuclear Conversion

This study analyzes typical cases of SMR replacing coal-fired power generation in different technology types from aspects such as technical feasibility, economic feasibility, and public acceptance, and evaluates the application advantages and practical challenges of SMR in the fields of replacing coal-fired power generation and heating.

4.1 HTR-PM Replacing Coal-fired Power Plants—Case Study 1

Case study 1 takes a coal-fired power plant in Fujian Province as a case, and assesses the feasibility of implementing "coal-to-nuclear" conversion using high-temperature gas-cooled reactors (HTR-PM). The power plant, facing issues such as aging units, increasing environmental protection pressure, and rising operating costs, is a typical case for C2N conversion. After the replacement of coal-fired units with HTR-PM, on the premise of maintaining stable power generation, zero carbon emissions in power production can be

achieved, and emissions of sulfur dioxide, nitrogen oxides, and particulate matter can be significantly reduced, making significant contribution to improving local environmental quality. This case study conducts analysis from dimensions such as technology, economy, and public acceptance.

(1) Overview of Existing Coal-fired Power Units for Nuclear Conversion

The total installed capacity of this power plant is 2720 MW, with a total of 6 units in three phases. Among them, the two 350 MW units in Phase I have reached their design service life and are planned to be shut down for renovation. This study considers building a high-temperature gas-cooled reactor at the original site for replacement.

In terms of electricity and heat demand, the existing 220 kV outgoing line system can continue to be used, eliminating the need for new power transmission facilities. Local electricity forecasts indicate that there will still be a power supply gap in the future, and the electricity generated after replacement can be effectively absorbed. This power plant also undertakes the task of regional centralized heating. As industrial boilers in industries such as printing and dyeing and textile gradually phase out, the heat demand in the surrounding industrial parks continues to increase. It is necessary to plan and lay medium and low-pressure heating pipelines to supply steam to the airport economic zone, with the maximum load of medium-pressure steam at 214 t/h and an average of 170 t/h; the maximum load of low-pressure steam at 223.1 t/h and an average of 190.8 t/h.

(2) Technical Feasibility

High temperature gas-cooled reactors are characterized by high safety and environmental friendliness. Site selection is mainly based on the Technical Specification for the Division of Non-residential Areas and Planned Restricted Areas of Small Nuclear Power Plants (T/BSRS022–2020), which requires comprehensive consideration of factors such as seismic geological conditions, engineering geological foundation, population distribution, cooling water source, transportation, and distance from airport flight paths.

The engineering plan intends to adopt six high-temperature gas-cooled reactor NSSS modules, with total thermal power of 1200 MWth, equipped with a 600 MWe-class ultra-supercritical steam turbine unit, with power generation efficiency of approximately 48%, net electric power of approximately 576 MWe, and maximum steam supply capacity of approximately 1641.6 t/h. The nuclear island modules are centrally arranged, and the conventional island is newly built at the original site.

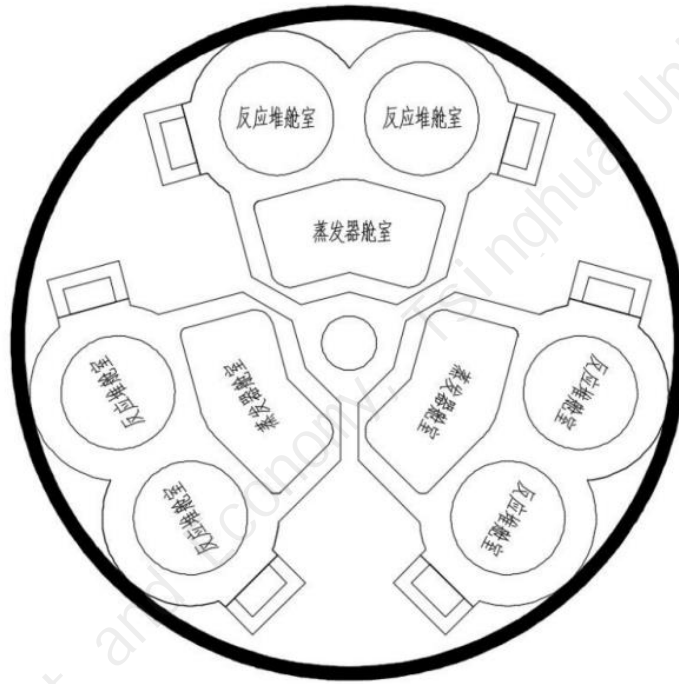


Figure 2. Layout Diagram of High-Temperature Gas-Cooled Reactor Modules

(3) Economic Feasibility

Based on the estimated unit cost of 25,000 yuan/kWe after commercialization and batch construction, the total investment is approximately 14.4 billion yuan. The annual on-grid electricity generation is 4032 GWh, and calculated at the benchmark electricity price of 0.43 yuan/kWh, the electricity revenue over 30 years is approximately 52 billion yuan; the annual maximum steam supply is 11.35 million tons, and calculated at 250 yuan/t, the steam supply revenue over 30 years is approximately 85.1 billion yuan. Since it is constructed on an existing coal-fired power plant site, it can fully utilize existing roads, port transportation facilities, transmission lines, etc., and compared with newly built high-temperature gas-cooled reactor power plants, it can save approximately 5% of the investment cost. Subsequently, in combination with technological progress and the industrial development needs in the surrounding areas of the plant site, application scenarios with higher economic value, such as industrial steam supply and hydrogen production, can be explored.

(4) Sustainable Development Benefits

Environmental Benefits: After the project is put into operation, it can reduce carbon dioxide emissions by approximately 3.8 million tons annually, and reduce SO₂, NO_x, and soot emissions by 302 tons, 564 tons, and 40 tons respectively, while reducing coal consumption by 1.36 million tons and ash and slag by 200,000 tons.

Employment Opportunities: New nuclear power projects can provide more high-tech jobs, and some coal-fired power employees can achieve job transformation after training.

Driving Industry Development: Promote the development of the entire industrial chain, such as R&D, manufacturing, and construction, and create conditions for exploring emerging business models such as hydrogen production.

Enterprise ESG: Contributes to enterprises fulfilling their social responsibilities and enhancing

their image in green and low-carbon transformation.

(5) Challenges and Response Strategies

High-temperature gas-cooled reactors have inherent safety advantages and hold significant potential in replacing coal-fired power using existing sites. However, their actual promotion still faces a series of challenges, including issues of site adaptability and system compatibility, the need to improve technological maturity, high replacement costs, imperfect relevant regulations and standards, and insufficient public acceptance. To promote the implementation of high-temperature gas-cooled reactors as a replacement for coal-fired power, it is recommended that in the future, efforts be made to strengthen research and development of key technologies and cost control, promote the update of relevant regulations and standards and enhance their pertinence, actively explore multi-energy comprehensive utilization modes such as combined power, heat, and hydrogen production, and at the same time, fully reflect their environmental benefits by improving the carbon market mechanism.

4.2 HTR-PM Replacing Coal-fired Power Plants—Case Study 2

Case study 2 evaluates the feasibility of replacing coal-fired units with high-temperature gas-cooled reactors (HTR-PM) at a coal-fired power plant in Shandong Province. The plant is located approximately 16 km from the city center and was constructed in three phases: Phase I consisted of 2×125 MW units (built in 1991 and shut down in 2008); Phase II comprises 2×320 MW subcritical cogeneration units (commissioned in 1998); Phase III includes 2×680 MW ultra-supercritical units (commissioned in 2011). The proposed replacement targets the two units of Phase II.

(1) Overview of Existing Coal-fired Power Units for Nuclear Conversion

The Phase II units have been in operation for 24 years, approaching their design life. Their rated evaporation capacity is 1025 t/h, with main steam pressure of 16.7 MPa. After multiple heating retrofits, the current rated extraction steam flow is 620 t/h, achieving a heating capacity of 23 million m². The units are connected to a 220 kV system with four outgoing lines, ensuring reliable power consumption. The heat is sold to a local thermal power group on a wholesale basis, with growing heating load demand. Cooling water is sourced from a seawater once-through cooling system with favorable intake conditions.

(2) Technical Feasibility

The site region exhibits relatively poor geological stability, with a basic seismic intensity of VII degree, necessitating a seismic safety evaluation. The proposed site is located in a bedrock area with favorable engineering geological conditions. The population within 5 km of the site is approximately 60,000, requiring enhanced public communication. Transportation is convenient, supporting the shipping of heavy and large components. The engineering plan is similar to case study 1 but twice the scale: total thermal power of 2400 MW_{th}, net electric power of 1152 MW_e, annual on-grid electricity of 8064 GWh, and maximum steam supply capacity of 22.7 million t/a, meeting the original power and heating demands. The technology is feasible.

(3) Economic Feasibility

Based on an estimated unit capacity cost of 25,000 yuan/kWe, the total project investment is

approximately 28.8 billion yuan. For pure power generation, 30-year power supply revenue could reach 104 billion yuan; for steam supply, maximum 30-year steam supply revenue could reach 170.2 billion yuan. Utilizing the existing site can save about 5% of initial investment, making it economically viable.

(4) Sustainable Development Benefits

After replacement, annual CO₂ emissions is reduced by 7.6 million tons (power supply) or 5.12 million tons (steam supply), along with substantial reductions in pollutant emissions. The project promotes green energy transition, drives the development of the nuclear power industry chain, and creates more job opportunities, delivering significant environmental and social benefits.

(5) Challenges and Response Strategies

Key challenges include: poor regional geological stability requiring in-depth seismic safety evaluation; high population density near the site necessitating enhanced public communication and environmental assessment; a high design basis flood level requiring engineering flood control measures; and the need to coordinate safety management integration between operating coal-fired units and the new nuclear island. It is recommended to strengthen special evaluations and departmental communications, optimize the general layout and emergency plans, and ensure project feasibility.

4.3 NHR200-II Replacing Coal-fired Heating in Petrochemical Industrial Park—Case Study 3

Taking a domestic petrochemical park as a case, case study 3 explores the feasibility of the in-depth coupling of the NHR200-II low-temperature heating reactor with the petrochemical park, and focuses on analyzing its potential and contributions in meeting the demand for multi-quality steam and achieving carbon emission reduction.

(1) Overview of the Petrochemical Park and Characteristics of Steam Demand

The petrochemical park takes the refining and ethylene projects as its core, focusing on the development of high-value-added petrochemical deep processing and fine chemical products. The park's energy consumption is mainly thermal energy, with a continuous and stable heating load, and the annual utilization hours exceed 7,000 hours, far exceeding that of conventional power generation equipment. Therefore, the fuel consumption and carbon emissions of the heating system dominate the park's total emissions and are the key targets for regional carbon emission reduction. Under the constraints of the "dual carbon" goals, the park faces significant emission reduction pressure, and energy conservation and carbon reduction have become a precondition for capacity expansion. Therefore, introducing clean and low-carbon energy represented by nuclear energy has become the core requirement for the park to achieve its carbon reduction goals.

Currently, steam supply in the park mainly relies on two enterprises:

Thermal Power Company: As a centralized steam supply unit, it integrates 6 heat sources including coal-fired/gas-fired power plants, boilers, and process waste heat, mainly supplying steam at three pressure levels: high pressure (4.7 MPa, 330°C), medium pressure (2.7 MPa,

326°C), and low pressure (1.32 MPa, 260°C).

Petrochemical Company: Equipped with devices such as gas boilers and gas turbine waste heat boilers, it mainly produces high-pressure steam (9.8 MPa, 510°C) for self-use, and the low-pressure steam (approximately 0.6 - 0.7 MPa, 170°C) by-produced from its process waste heat devices is also handed over to the Thermal Power Company for unified allocation.

(2) Technical Feasibility

The NHR200-II low-temperature heating reactor, with heating as its primary function, better meets the continuous and stable heating needs of industrial users, providing a reliable technical path for carbon emission reduction in the industrial sector.

Coupling Scheme. Based on the current status of heat production in the existing thermal power company and petrochemical company in the park and the requirements for steam parameters that the heat network can accommodate, while maintaining the original design of NHR200-II as much as possible, through in-depth system coupling, stable supply of superheated steam at three different pressure levels is achieved. The core of this scheme is to add a "steam compressor" and a "gas boiler". The gas boiler uses the dry gas by-produced from the petrochemical company as fuel to achieve cascading utilization of the single low-grade steam produced by NHR200-II.

The low-pressure saturated steam generated by the reactor is mainly diverted to four uses: heating the secondary-side feedwater of the steam generator; heating the high-pressure feedwater on the petrochemical side; after being pressurized by the steam compressor, it is sent to the gas boiler for superheating to supply the medium-pressure heating network; directly entering the gas boiler for superheating to supply the low-pressure heating network. The coupling system is planned to be built at a new site approximately 3 kilometers away from the heat users and will be connected to the existing heating network through a dedicated pipeline.

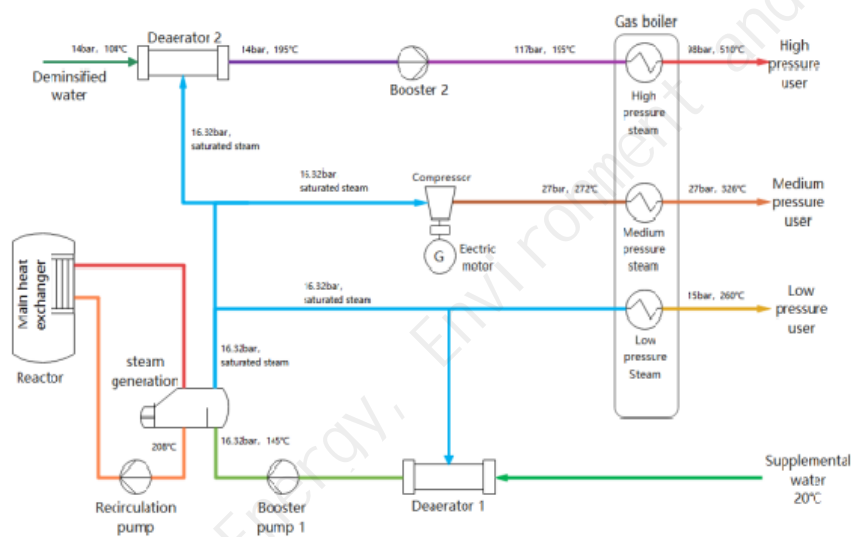


Figure 3. Schematic Diagram of Coupling Scheme

The site conditions meet the requirements of relevant geological, seismic, cooling water source, and environmental radiation protection specifications (GB 6249-2025) for SMR.

(3) Economic Feasibility

Without considering the benefits of carbon emission reduction, the costs of high, medium, and low-pressure steam produced by this project are all within the reasonable range of market prices in the petrochemical industry. However, the overall investment return rate of the project is relatively low, estimated to be approximately 2%, far lower than the industry benchmark return rate. If the benefits of carbon emission reduction (estimated at 80 yuan/ton of CO₂) are considered, the costs of medium and low-pressure steam can be reduced by approximately 11%, significantly improving the overall investment return rate of the project. Additionally, the unit heating cost of the low-temperature heating reactor is not affected by fluctuations in coal market prices, enhancing the reliability of heating and the stability of costs.

It should be noted that the current investment cost is estimated based on the first-of-a-kind demonstration project. With the advancement of standardized design and mass construction in the future, the project's economic viability is expected to be further enhanced.

(4) Carbon Emission Reduction Benefits

Through the modeling and analysis of the thermal system, based on the calculation of heat load distribution, this solution has a significant carbon reduction contribution compared to traditional coal-fired steam supply. On the premise of meeting the same steam demand of multiple qualities and heating reliability, it can achieve a substantial reduction in carbon dioxide emissions, with an annual reduction of up to 575,700 tons of CO₂, among which the carbon reduction rate of medium and low-pressure steam production exceeds 90%.

(5) Challenges and Response Strategies

Low-temperature heating reactors have broad application prospects in the field of industrial steam supply in China, and are expected to become an important solution for the clean and low-carbon transformation of industrial steam supply, contributing to the achievement of China's "dual carbon" goals. However, their large-scale promotion still faces a series of challenges, mainly including insufficient technological maturity, the need to improve economic competitiveness, and low public acceptance. To promote the practical application and implementation of low-temperature heating reactors, it is recommended to start from the following aspects: continuously promote technological optimization and innovation, strengthen policy guidance and support, improve the mechanism for realizing carbon emission benefits, and actively carry out public communication and science popularization education to enhance social awareness and acceptance.

4.4 Conclusions of Typical Case Studies

In terms of the plant site and implementation conditions, through comparative analysis of typical cases, it has been found that the feasibility of coal-to-nuclear projects not only depends on the plant site itself but is also comprehensively influenced by the structure of the regional power and thermal systems, load stability, and the degree of reusability of existing infrastructure. For example, in the case of HTR-PM replacing coal-fired power plants, the existing power transmission channels and the red-line area of the plant provide an important foundation for the layout of the nuclear power system; while in the case of petrochemical industrial park, the stable and concentrated thermal load demand becomes the key to supporting the economic feasibility of nuclear heating projects. The research further indicates that the

overall replacement of large coal-fired power units is more suitable for coastal power plants with superior site conditions and sufficient space; while small low-temperature heating reactors, with their high flexibility, are more suitable for deployment in industrial parks close to load centers. In addition, the differences in safety characteristics, construction period, and implementation rhythm among different reactor types also directly affect the implementation model and demonstration path of coal-to-nuclear projects.

Based on the analysis of comprehensive typical cases, it can be seen that there is no single standard model for coal-to-nuclear conversion. In the actual implementation process, it presents a multi-path pattern of parallel advancement of "overall replacement of coal-fired power units" and "replacement of coal-fired heating systems". In terms of emission reduction effects, coal-to-nuclear conversion can achieve significant carbon dioxide emission reduction in both the power generation and heating sectors; in terms of economic viability, considering long-term operation and carbon constraint scenarios, its full life cycle cost is competitive; from the implementation perspective, the feasibility of the project mainly depends on the matching degree of site conditions, load characteristics, and technical routes.

Overall, this study verified the feasibility of coal-to-nuclear conversion from both engineering implementation and quantitative effectiveness aspects by systematically analyzing two types of cases: high-temperature gas-cooled reactors and low-temperature district heating reactors. The results show that, under typical scenarios, coal-to-nuclear projects have clear advantages in terms of emission reduction scale, energy efficiency improvement, and long-term cost control, thus providing an actionable engineering path for the low-carbon transformation of coal-fired power and industrial heating. Research indicates that, on the premise of scientifically selecting technical routes, reasonably evaluating site conditions, and comprehensively considering emission reduction and cost-effectiveness, coal-to-nuclear conversion has practical feasibility and can play an important supplementary role in the low-carbon transformation of the future energy system.

5. Impact of Coal to Nuclear on China's Energy System Transformation under Dual Carbon Goals

5.1 Comparison of the Characteristics of Low-carbon Energy Technologies

Based on expert interviews and literature research, this study compares the characteristics of various low-carbon technologies that can replace coal-fired units, including for both electricity generation and heat provision.

Among the low-carbon electricity generation technologies, gas-fired units have lower unit installed capacity investment but high fuel costs; carbon capture and storage (CCS) technology has significant emission reduction effects but high costs; renewable energy (wind power, photovoltaic, hydropower) have strong cost competitiveness, but their intermittency and volatility pose significant challenges to the stability and reliability of the energy system. Nuclear is usually high in investment cost but advantageous in low fuel cost and reliable power output.

As for coal-fired units currently provides heat in China, they can broadly be divided into two categories: Some of them participate in the supply of low-, medium- and high-pressure steam of various qualities for industrial use, while others could provide central heating for residents in northern China during winter. Traditional low-carbon replacement of these coal-fired units could include gas-fired boilers, as well as innovative low-carbon heating technologies including CCS, biomass boilers and cogeneration nuclear, with their techno-economic characteristics similar to what is discussed above.

As a zero-carbon energy source, nuclear technology has already played a role in the low-carbon transition of industrial heating and residential heating in China by advancing from pure electricity generation units to cogeneration units. Among the different kinds of nuclear power technologies, large-scale third-generation pressurized water reactors are the most mature, while technologies such as third-generation SMRs and high-temperature reactors currently have higher unit installed capacity investment cost. Utilizing existing coal-fired power plant sites for nuclear energy substitution can reuse the original site, cooling water source, and power transmission and distribution infrastructure, significantly saving time for site selection and approval as well as the cost of power transmission projects. Combining with China's existing reserve nuclear power plant site resources, timely launching inland nuclear power and leveraging the potential of "coal-to-nuclear" conversion will contribute to optimizing the national energy strategic layout.

5.2 Key Assumptions and Scenario Settings for Energy System Transformation

To quantify the role of nuclear power and "coal-to-nuclear" in energy transition, this study sets the following key assumptions: electricity demand is projected to increase from 7.5 trillion kWh in 2020 to 16.4 trillion kWh in 2060; industrial process heat demand is estimated with reference to the statistics of industrial steam production from the National Bureau of Statistics of China and its calorific value, as well as relevant studies of industrial sector decarbonization pathway of China published by the International Energy Agency; Northern China central heating demand in the winter is adopted based on relevant research from the School of Architecture of Tsinghua University. The carbon price will gradually rise from 58 yuan/ton to above 2,700 yuan/ton to promote the low-carbon transition of the energy system. In terms of time nodes, it is assumed that large-scale development of "coal-to-nuclear" will commence in 2030, and inland nuclear deployment will be opened up in 2035. Four scenarios are included in the study: (1) Base scenario (Base): without considering coal-to-nuclear conversion; (2) Coal-to-Nuclear Slow scenario (C2NS); (3) Coal-to-Nuclear Medium scenario (C2NM); and (4) Coal-to-Nuclear Fast scenario (C2NF). The Base scenario and the C2NS scenario adopt the same upper limit for nuclear power development, and their difference lies in whether coal-to-nuclear conversion is permitted; the C2NM scenario and the C2NF scenario allow C2N like the C2NS scenario, while setting a higher nuclear power development speed than the current level in China. By comparing the energy supply structure and total system cost under different scenarios, the study evaluates the key role of "coal-to-nuclear" in energy transformation.

5.3 Model Methods and Simulation Tools

This study uses the improved China Renewable Energy Power Planning and Operation Model

(REPO Model) developed by the Institute of Energy, Environment and Economy at Tsinghua University to conduct research on the transformation path of the energy system. Based on operations research theory, this model covers all provincial-level administrative regions across the country, aiming to minimize the total cost of the considered energy system, and optimizes the installed capacity structure and planning as well as operation of the energy system from 2020 to 2060 with a 5-year time step.

In the model, nuclear power technologies are refined into four categories: Generation III large reactors, Generation III small reactors, high-temperature reactors, and fast reactors, to reflect the differences among different nuclear power technology routes in terms of cost, efficiency, and operational flexibility. Meanwhile, the model takes into account the potential of nuclear power plant sites by province and type, and sets relevant constraints for "coal-to-nuclear" conversion to reflect the associated mechanism between the decommissioning of coal-fired power units and the construction of small reactors at the original sites. To quantify the future development of nuclear heating and the impact of coal-to-nuclear conversion on it, this study further improves the original REPO model framework that previously only considered the power system by incorporating an industrial heating system and an urban residential heating system for northern China that develop synergistically.

5.4 Main Results and Conclusions

The impacts of "coal-to-nuclear" on nuclear power installed capacity, regional distribution, energy transformation path, and system cost are as follows:

(1) Nuclear power installed capacity

Under the baseline scenario, China's nuclear power installed capacity will increase from approximately 50 GW in 2020 to 435 GW in 2060. Third-generation large reactors are the main force in near- and medium-term construction, but their share in the total nuclear power installed capacity gradually declines over time, dropping to approximately 58% by 2060. Advanced reactor types such as third-generation small reactors and high-temperature reactors will develop rapidly in the medium- and long-term, with their share increasing significantly. Implementing "coal-to-nuclear" can increase China's long-term nuclear power scale by 8%-36%, reaching a maximum of approximately 590 GW under the C2NF scenario.

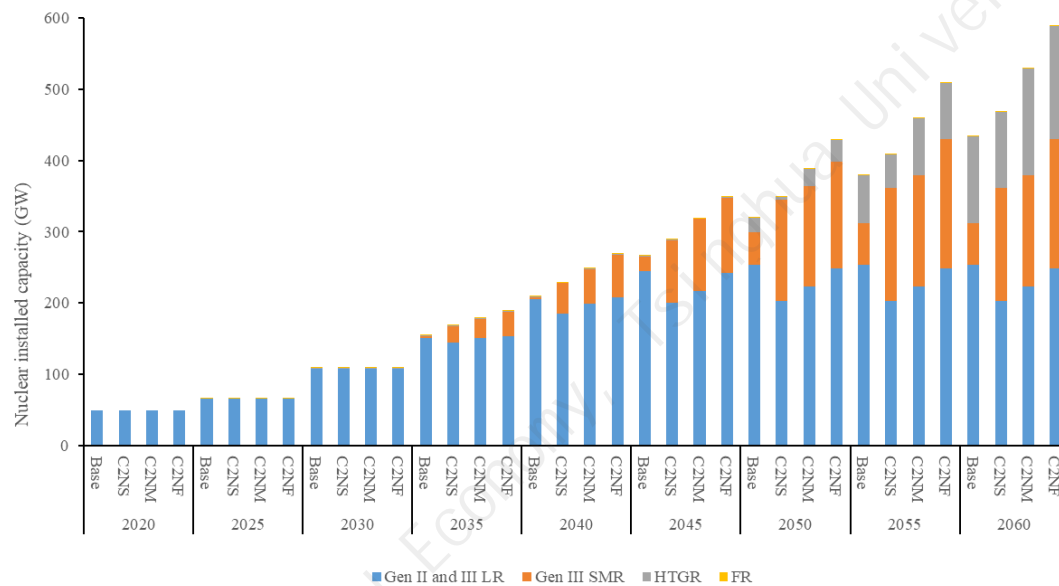


Figure 4. Nuclear installed capacity by scenario and year

(2) Regional Distribution of Nuclear Power

Opening inland nuclear power and "coal-to-nuclear" transformation will drive the expansion of China's nuclear power layout from coastal areas to more inland provinces. Among them, Shandong, Guangdong, Henan, Jiangsu and other regions will become major provinces for nuclear power installed capacity, and traditional key coal-fired power regions in the northwest are also expected to deploy nuclear power, contributing to the construction of a zero-carbon power transmission model of "wind, solar and nuclear power bundled". By 2060, China can achieve nuclear power layout in 28 provinces, municipalities and autonomous regions, an increase of 9 provincial regions compared to the baseline scenario without considering "coal-to-nuclear" transformation.

(3) Energy System Transformation Pathway

Under the "dual carbon" goals, China's power system supply structure will undergo profound transformation. Coal-fired power generation will peak around 2025 and then decline rapidly, with conventional coal-fired power basically phased out by 2060. Natural gas power generation will first increase and then decrease, mainly playing the roles of peak shaving and reserve capacity. Fossil energy coupled with biomass CCS technology will undertake part of the stable low-carbon power supply in the medium and long term. Wind and solar power will become the mainstay of power supply after 2040. As a stable zero-carbon baseload power source, under the baseline scenario, the share of nuclear power generation will steadily increase from 5% in 2020 to 17% in 2060. Under the "coal-to-nuclear" scenarios, the proportion of nuclear power can be further increased to between 20% and 25%. While replacing some low-carbon fossil energy and volatile renewable energy, it enhances the stability and reliability of the power system.

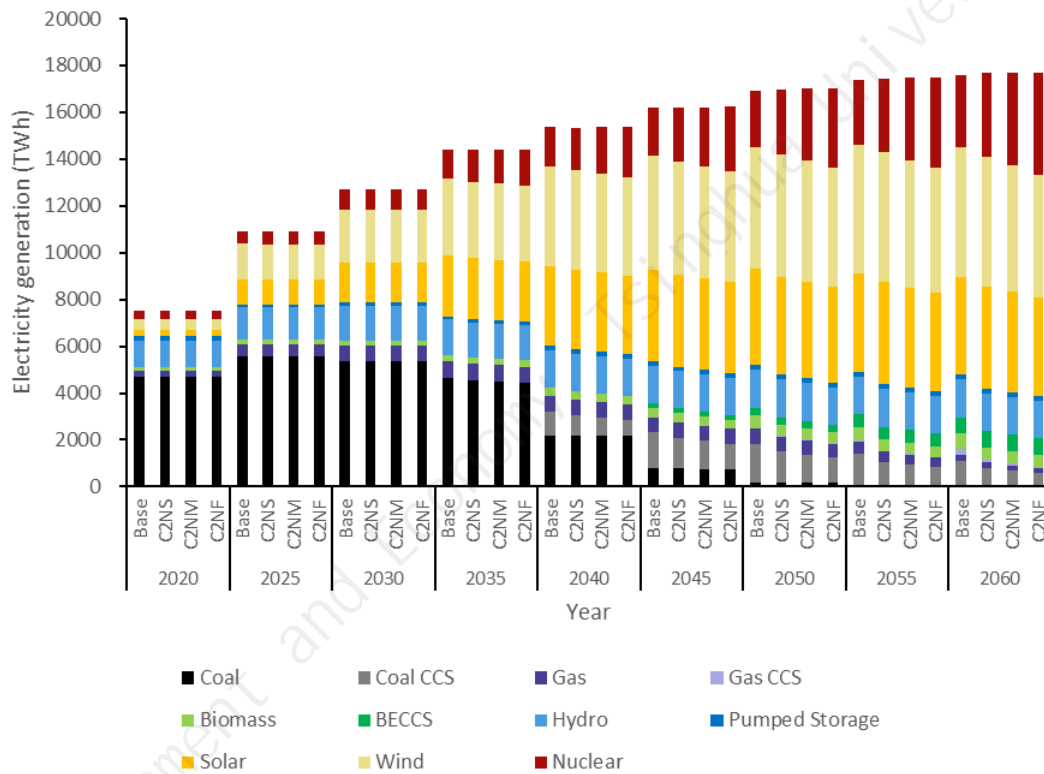


Figure 5. Electricity generation mix evolution of the scenarios

As for nuclear heat provision, the results show that by 2060, under the baseline scenario without “coal-to-nuclear” conversion, nuclear energy will be an indispensable heat source for the industry sector, accounting for approximately 14% of the supply that year (690 million GJ); while only serve as a supplementary source for urban residential heating in northern China, contributing only 1.1% (76 million GJ). After implementing “coal-to-nuclear”, the share of nuclear energy can increase by up to 8.5 percentage points (410 million GJ) for industrial process heating and up to 2.2 percentage points (150 million GJ) for urban residential heating in northern China, respectively. These increments, while demonstrating “coal-to-nuclear” significantly enhances the importance of nuclear technology, would not change its corresponding position in the two sub-energy systems.

(4) Cost-saving benefits of the total cost of the energy system

Developing "coal-to-nuclear" has economic benefits and helps reduce the construction cost of small reactors and the total cost of the energy system. By 2060, compared with the baseline scenario without considering "coal-to-nuclear", the "coal-to-nuclear" scenario can cumulatively save about 2.1 trillion to 4.1 trillion yuan in the total cost of China's energy system during 2030-2060, equivalent to 0.94%-1.75% of the cumulative total cost of the system during this period.

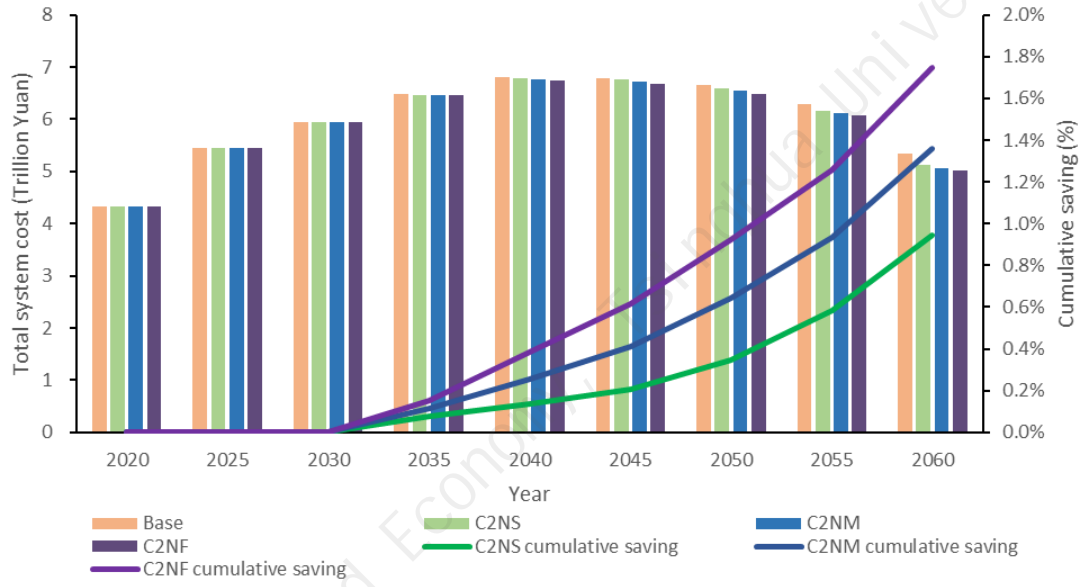


Figure 6. Total system costs and cumulative savings from Base scenario by scenarios