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Role of Coal-to-Nuclear Conversion in China's Electricity System Decarbonization

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ABSTRACT

In recent years, the replacement of retired coal-fired power plants with nuclear power plants (also known as coal-to-nuclear conversion, C2N) has been considered a particularly cost-effective solution for power system decarbonization amid global climate change mitigation goals. In this study, we improved a power system model of China equipped with provincial spatial resolution. Specifically, we expanded the classification of nuclear technologies from one to four types, based on generation and reactor design, and incorporated relevant C2N conversion constraints. This improvement allows quantification of C2N's potential role in decarbonizing China's power system, following the identification of its maximum conversion potential. The results indicate that by utilizing conventional site resources in both coastal and inland China, a major growth of nuclear capacity is possible under China's carbon peaking and neutrality goals, reaching 422 GW by 2060, with 42% of this capacity being small modular reactors that offer greater operational flexibility. In 2060, nuclear power will become an important source of electricity generation in China, accounting for 18% of total supply. Site resource availability represents a major constraint to this development: Expanding site availability through C2N has the potential to further increase nuclear capacity in 2060 by 13%–23%, while raising nuclear's share of total electricity supply that year by 2–4 percentage points. Expanding nuclear energy's share in China's decarbonization via C2N will yield cost savings of 0.22%–0.69% of system cost from 2030 to 2060.

1. Introduction

Global climate change has urged countries worldwide to actively pursue the realization of energy system decarbonization [1], with immediate focus on the clean transformation of electric power supply, as some study suggests that the supply of such secondary energy to fully decarbonize before the entire energy system [2]. Recently, the power system decarbonization has been more actively addressed through the increased adoption of renewable and other non-fossil sources of electricity [3]. This has been true especially for China, the world's largest CO_2 emitter [4]. However, the existing electricity system of China poses some tremendous challenges. On the one hand, the electricity supply of China has a large number of young coal-fired power plants constituting its energy supply, which may face a greater risk of asset stranding if they are forced to retire early [5]. On the other hand, although intermittent renewables are being and can be added and are being added to the electricity system, dispatchable and firm sources remain necessary to maintain its supply side flexibility [6,7].

In this context, the replacement of to be retired coal-fired power plants with nuclear ones, often considered as small modular reactors (SMRs), has been recently discussed as a promising technology pathway. This process, also known as coal-to-nuclear conversion (C2N) or repowering/repurposing, can be done by retaining the existing site resources (and preferably facilities) of

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the coal-fired power plants and converting them to nuclear ones, potentially reducing the efforts and expenses required for introducing such technologies. This process is classified into three categories (in the order of increase in costs): heat source replacement, which only replaces coal-fired boilers with nuclear reactors; partial replacement, which additionally replaces steam turbines; and complete replacement, which only retains the site and grid facilities [8].

Many early studies on C2N concentrated on Europe, the United States, and Republic of Korea. Qvist et al. [9] examined the cost effectiveness of C2N for the development of nuclear technologies in Poland and suggested that this technology pathway could reduce the capital costs of nuclear technologies by 28%–35% and the levelized cost of electricity by 9%–28% compared to that of greenfield plants, while maintaining the existing infrastructure and avoiding stranded assets. Bartela et al. [10] performed a techno-economic assessment of retrofitting a 460-MW supercritical coal power plant with Kairos power fluoride-salt-cooled high-temperature reactors and concluded a net present value of 1205.5 million EUR and a discounted payback period of 10 years. Hansen et al. [11] studied the benefits of performing C2N in the United States and determined that it can reduce nuclear construction costs by 15%–35% and increase the local economic activity by up to 275 million USD. Haneklaus et al. [12] argue that coal plants should be readily converted to nuclear plants, in which SMRs are best suited for their similar capacities, leveraging the existing infrastructure to reduce costs and accelerate decarbonization. Chmielewska-Śmietanko et al. [13] studied the development of a ranking list through the identification of legal framework, safety requirements, and site selection criteria in Poland. Ochmann et al. [14] analyzed the conversion of existing inland coal-fired power plants to nuclear power plants at four sites in Poland, focusing on the hydrological conditions and cooling water requirements for large-scale Generation III reactors and suggested the necessity of further assessments for Generation IV reactors. The techno-economic feasibility of C2N in Republic of Korea was examined by Joo et al. [15], who argued that nuclear power is more suitable than renewables to replace coal considering their significantly lower need for energy storage systems, which could maintain the cost of electricity generation within a reasonable range. The technological feasibility of this transition was also analyzed for different reactor types, including both the high-temperature gas-cooled reactors (HTGRs) and small modular pressurized water reactors. Furthermore, the existing regulatory framework should also be adjusted for such development [15]. Abdussami and Verma [16] used a Geographic Information System (GIS)-based tool and determined that the most economical option to replace existing coal plants is coal-to-integrated energy systems, with a potential of reducing the cost of energy by 65%.

Some studies have also analyzed the techno-economic feasibility of C2N in China. Xu et al. [17] identified a three-stage strategy for the development of C2N and suggested a technical potential of up to 640 GW. An economic saving of 300 billion USD was deemed possible if HTGRs were used. Luo et al. [18] analyzed the technical feasibility of C2N and suggested a high feasibility of using the 200-$\mathrm{MW_e}$ HTGR to replace the 300-MW class coal-fired power plants. Weng et al. [19] further evaluated the impact of C2N in Guangdong Province using the EnergyPLAN simulation model and suggested that C2N will enable higher reductions in fuel and societal costs and $\mathrm{CO_2}$ emissions compared to using alternative sources.

In summary, although the existing studies on C2N have analyzed its techno-economic feasibility, to the best of our knowledge, no analysis has been performed on the optimal power system decarbonization pathway considering both C2N and the diversification of different nuclear technologies. Therefore, this study is innovative for its techno-economic analysis on the cost-effectiveness of C2N (in which coal plants are replaced by SMRs) in China, where a power system model with provincial-level spatial details and the technological discrepancy of nuclear technologies by four different reactor types were used in the planning and operation of its electricity system. Nuclear technologies were differentiated by reactor types with discrepancies in their techno-economic characteristics. The results were quantified under different C2N scenarios in the following aspects: the installed capacities of the nuclear power-generation technologies by reactor type, the regional level nuclear capacity, electricity generation mixes by fuel type, and the total system costs.

The remainder of the paper is organized as follows: Section 2 discusses the methodology and key assumptions to this study and highlights the contributions of the study. Section 3 provides the major results. Section 4 concludes the study and presents relevant policy recommendations and research outlooks.

2. Methodology

2.1. REPO model

The power system model used in this study is the Renewable Electricity Planning and Operation (REPO) model. Despite the name, it contains fossil fuel-based and other electricity sources including nuclear [20]. The model was built based on the Balmorel framework [21] and was customized to study the power system transition of China, with detailed consideration of its unique characteristics (techno-economic parameters, demand and load duration curves, relevant policies, etc.) [20,22–24]. The model considers aspects including the development of flexible district heating technology, ultra-high voltage transmission technology and complete spot-marketization of the power sector [20], development of the emission trading scheme and renewable portfolio standard [23,25], effect of implementing demand response in China's industrial sectors [22], and development of a synergistic hydrogen supply system [24].

The base version of the REPO model can determine the cost optimal planning and operation of a power system (lowest total discounted cost) for each model simulation year. Spatially, the model includes 32 provincial-level grid regions, representing all the provincial administrative regions in China except Hong Kong, Macao, and Taiwan (with Inner Mongolia divided into eastern and western Inner Mongolia, denoted as East-IM and West-IM, considering the electricity grid structure). The energy demand, resource potential, existing generation capacity, and transmission line capacities are considered with at least this level of spatial discrepancy (with renewable potential at sub-provincial level). The model uses 2020 as the base year and optimizes the energy system transition pathway in five-year time steps through 2060.

The generation technologies in the model include those by coal, gas, nuclear, hydro, wind, solar, and biomass, and the storage technologies include chemical and compressed air energy storages. Exogenously considered technology advancements are depicted by the associated changes in techno-economic parameters. The key constraints in the base version of the model include electricity balance constraints, interprovincial electricity transmission constraints, renewable availability and variability constraints, unit commitment constraints for dispatchable units, and energy storage cyclical constraints. The renewable availability and variability data are inherited from its previous iteration [23], which considered the hourly and sub-provincial variations in China, represented in the form of unitless capacity factors between 0 and 1. The provincial-level electricity system planning and operation could be determined under this set of constraints and additional policy constraints [25]. The model uses carbon price as the climate mitigation policy, with this study adopting the values from an energy economy model, increasing the cost per tonne CO_2 as follows: from 58 CNY in 2020 to 68 CNY 2025, 104 CNY in 2030, 178 CNY in 2035, 287 CNY in 2040, 435 CNY in 2045, 751 CNY in 2050, 1363 CNY in 2055, and 2732 CNY in 2060 [26].

2.2. Major contributions and adjustments to the model

Fig. 1 depicts the updated modeling structure of the REPO model considering our latest contributions. The model now includes a wider range of technologies, where the modeling of nuclear technologies has been enhanced considering the discrepancies between different reactor types (elaborated in Section 2.2.1). We also made specific considerations to C2N in the model, as presented in Section 2.2.2. Subsequently, the key techno-economic parameters in the model are presented in Section 2.3 and the scenario design in Section 2.4.

2.2.1. Technologies considered

In the base versions of the REPO model, nuclear technologies were modeled as a single set [23]. Some version additionally considers Gen IV HTGRs and highlights their use in hydrogen production [24]. The improved REPO model now includes four types of nuclear technologies in addition to the existing Gen II reactors installed in China, which we assume will not be newly built anymore. The nuclear technologies considered with endogenous capacity are classified below with their abbreviations listed in Table 1.

Gen III LR and Gen IV FR are considered as large reactors. The Gen III LR is modeled after averaging several Gen III LR designs domestically (led by Hua-long Pressurized Reactor (HPR)-1000 and China Advanced Pressurized Water Reactor (CAP)-1400), whereas the FR is modeled after CFR-600 (Xiapu Fast Reactor Pilot project); these designs have above 500 MW_e of capacity per reactor. The Light Water Small Modular Reactor (LW-SMR) is modeled after the light water small modular reactor design ACP-100 (Linglong One) developed in China, below the commonly used 300 MW_e threshold. The HTGR is also considered an SMR with its multi-modularity and is modeled after HTR-PM600 (600-MW_e HTGR nuclear power plant).

2.2.2. Coal-to-nuclear conversion

The REPO model now considers C2N in China's electricity system through the installation of SMRs by retrofitting the coal power plants as an additional set of technologies, assuming higher safety measures and operational flexibilities over large reactors. The use of two SMRs, namely, Gen III LW-SMR and Gen IV HTGR, was considered.

Table 1
Nuclear technologies considered in the REPO model with endogenous capacity.

Reactor classification	Reactor type
Large reactor	Gen III Large Reactor (LR) Gen IV Fast Reactor (FR)
Small modular reactor	Gen III Light Water Small Modular Reactor (LW-SMR) Gen IV HTGR

Additional constraints were added to assess the capacities of C2N that can occur in each model simulation year. The model first incorporates the technically feasible coal capacity for nuclear conversion (further discussed in Sections 2.3.3 and 2.4). The total installed capacity of the coal-fired power plants that is technically feasible to be converted to nuclear power plants in each province R currently (at the time of writing) was first incorporated as a parameter into the REPO model, P_R.

The REPO model also includes the total capacity of coal-fired power plants that will naturally retire each year Y owing to the end of their assumed planned lifespan [23], which is denoted by $N_{Y,R}$, it could determine the total capacity of the coal-fired power plants that is economically favorable (resulting in lower system cost) to retire before the end of its lifespan in each year, denoted as $\upsilon E_{Y,R}$. This indicates that the total capacity of coal-fired power plants that actually retire in each year from both natural (end of lifespan) and economic (premature retirement) considerations, denoted as $\upsilon \mathrm{TR}_{Y,R}$, is the sum of these two terms, as shown in Eq. (1).

$$\upsilon \mathrm{TR}_{Y,R} = N_{Y,R} + \upsilon E_{Y,R} \tag{1}$$

Furthermore, in each model optimization year, as C2N conversion must occur after the coal-fired power plants retire (because a power plant cannot be both coal-fired and nuclear-powered simultaneously), there exists a total capacity of power plants that either can be converted from coal-fired into nuclear ones, or has already been through the conversion, in each year. This installed capacity is denoted as υB. This capacity is the intersection of the following: the initial installed capacity of the coal-fired power

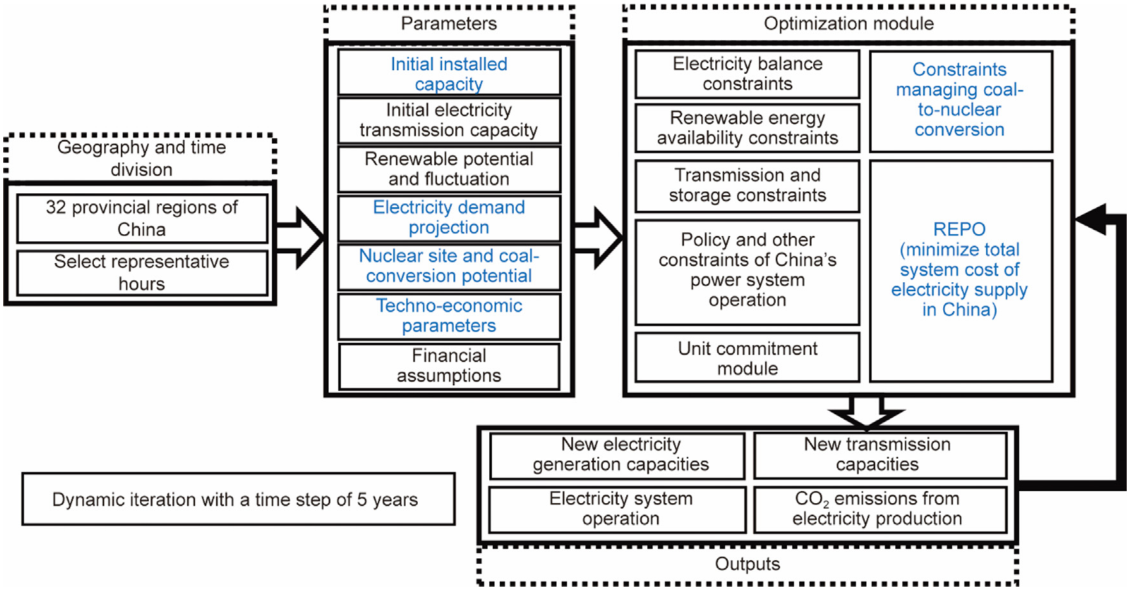


Fig. 1. Updated modeling structure for the REPO model (with dark blue texts outlining the key differences with its base version).

plants that is technically feasible to be converted to nuclear power plants P_R, and the total capacity of the coal-fired power plants that actually retires in each year from both natural and economic consideration, $\upsilon \mathrm{TR}_{Y,R}$. This is shown by Eq. (2).

$$\upsilon B_{Y,R} = \upsilon \mathrm{TR}_{Y,R} \cap P_R \tag{2}$$

Finally, in each model optimization year, the actual capacity of C2N that occurs, denoted as υC2N, is determined. This will be no more than the remaining capacity available for conversion, that is, the difference between the total capacity of power plants that can be either converted from coal-fired to nuclear or have already been converted (υB), and the cumulative installed capacity of C2N already performed in each year (denoted as CC). This calculation is shown by Eq. (3).

$$\upsilon \mathrm{C2N}_{Y,R} \leq \upsilon B_{Y,R} - \mathrm{CC}_{Y,R} \tag{3}$$

As the model stores the results from each previous model optimization year, the dynamic iterative optimization of the electricity system is considered with these C2N constraints.

2.3. Parameters

2.3.1. Techno-economic parameters

The technologies in the REPO model are differentiated using techno-economic parameters. These parameters were acquired by referencing published books and reports, international databases [27–33], and consulting with experts from The Institute of Nuclear and New Energy Technology of Tsinghua University and the China National Nuclear Corporation. The complete details are presented in Appendix A.

Table 2 lists the economic parameters for the nuclear technologies. A minor investment was considered as cost saving if the nuclear plants were to go through C2N. For simplification, "C2N" was added in parentheses to indicate those that went through this process. Only a modest cost saving was considered from the conversions, as expert consultation suggested that it would be more challenging to replace only the heat source (reactor).

2.3.2. Electricity demand

For the modeled electricity system, demands are a set of key parameters. The national total value was set according to an energy economic (computable general equilibrium, CGE) model [34], reaching 10.4, 12.0, 13.5, 14.3, 15.1, 15.8, 16.2, and 16.4 PW·h in 2025, 2030, 2035, 2040, 2045, 2050, 2055, and 2060, respectively. The provincial-level distribution follows another energy economic model with the provincial-level details of China [35].

2.3.3. Nuclear site resources and C2N potential

In this study, the greenfield nuclear site resources in China are adopted from Ref. [36], totaling 491 GW if the inland nuclear power plants are allowed. It is assumed that China allows their planning after 2035 and operation (appearing in modeling results) beginning in 2040. For C2N, the theoretical potential was first derived from screening the installed capacity of operational coal-fired power plants in China from the Global Coal Plant Tracker (January 2024 version) [37]. Seismic activity, national border proximity, residential areas, and water resources were considered to filter the coal-fired power plants by applying the relevant buffering zones. Thereafter, the impact of cooling water availability was considered by excluding air-cooled coal power plants (that is, accounting for the proportion of such plants that is assumed to have limited water resource nearby, meeting the cooling needs). The installed capacity of non-air-cooled coal power plants after the filtering for buffering zone for each of the province was then entered into the REPO model as a parameter.

2.4. Scenario design

Three C2N scenarios were considered in the energy system modeling, where the candidates for the replacements of the eligible retired coal plants were SMRs (LW-SMR and HTGR). The first scenario is a Base scenario that did not include such a conversion. The second scenario enables the conversion of coal-fired power plants to SMRs but imposes a stringent set of rules (more closely resembling those for large reactors) in the filtering of eligible coal plants and is therefore referred to as the LargeReactorPrinciple (LRP) scenario. The third scenario is the SmallReactorPrinciple (SRP) scenario, which facilitates the filtering of coal plants following more lenient requirements. The differences of distances governing the corresponding buffering zones for the different factors in the two scenarios are listed in Table 3. The relevant rules and regulations for these buffering zones are presented in Section S3.6 in Appendix A, based on the available national regulations and standards on siting of nuclear plants, and are also supported by expert interviews. The coal power plants outside the buffering zone of the first three criteria will be selected and those within will be omitted, whereas the opposite is true for water resources, to ensure the availability of cooling water. Therefore, the criterion specifies a shorter distance/higher population density for the SRP scenario compared to the LRP scenario, whenever applicable. Air-cooled coal plants were also filtered as an additional consideration of cooling resource availability. Both the LRP and the SRP scenarios assume that China will start planning for C2N from 2030, and therefore, they will be available in model results at the earliest by 2035 after accounting for the 3–5-year installation period for nuclear plants in China.

These requirements were first applied into GIS; operational coal power plants were filtered and a set of conversion potentials were identified. The potential of C2N in the LRP scenario after these steps was 137 GW, distributed across 19 provincial grid regions. In the SRP scenario, the site resources were 199 GW across 27 provincial grid regions. Even though these potentials account for the availability of cooling water, expert interviews were further performed and the potential of each province was reduced by the

Table 2
Economic characteristics of modelled nuclear reactors.

Reactor type	Investment ($\mathrm{CNY \cdot W^{-1}}$)			Variable O&M ($\mathrm{CNY \cdot (MW \cdot h)^{-1}}$)	Fixed O&M ($\mathrm{CNY \cdot (kW \cdot a)^{-1}}$)	Fuel ($\mathrm{CNY \cdot GJ^{-1}}$)			Life (year)
	2020	2035	2060			2020	2035	2060	
Gen III LR	15.6	15.4	15.4	14.7	629	4.9	4.9	4.9	60
LW-SMR	70.0	20.6	17.9	14.7	629	4.9	4.9	4.9	60
LW-SMR (C2N)	69.8	20.4	17.7	14.7	629	4.9	4.9	4.9	60
HTGR	55.0	34.8	14.8	14.7	690	14.7	9.7	4.9	60
HTGR (C2N)	54.8	34.6	14.6	14.7	690	14.7	9.7	4.9	60
FR	69.9	51.1	20.5	14.7	1388	7.4	7.4	7.4	40

O&M: operations and maintenance.

Table 3
Buffering zone of filtering conversion candidates.

Factor	Criteria	LRP scenario	SRP scenario
1. Seismic activity	1.1 Earthquakes (magnitude ≥ 5, between 1980 and 2024, according to United States Geological Survey (USGS) Earthquake Catalog)	20 km	15 km
	1.2 Active faults	20 km	10 km
2. Border proximity	2.1 Land borders	20 km	20 km
	2.2 Coastlines	5 km	No requirements
3. Residential areas	3.1 Densely populated areas	5 km from ≥ 500 people·km^{-2}	5 km from ≥ 1000 people·km^{-2}
4. Water resource	4.1 Distance from rivers of third grade and above	10 km	10 km

percentage of air-cooled coal power units to ensure a higher likelihood of replacing the selected coal plants by nuclear ones, which require cooling water as a key operational constraint. The corresponding conversion potentials after the aforementioned two layers of considerations reduced to 39 and 91 GW for the LRP and SRP scenarios, respectively. The sensitivity analyses of these scenarios, accounting for sensitivities of variations in electricity demand, carbon prices, and continuous prohibition of inland nuclear power plants, is presented in Section S4 of the Appendix A.

3. Results and discussion

3.1. Nuclear power capacity

The installed nuclear capacity from 2020 to 2060 in five-year time steps is shown in Fig. 2. The scenarios are identical from 2020 to 2030 as it was assumed that the conversion of coal power plants would start only after 2030, which is a reasonable assumption given the relatively long planning periods required for nuclear in comparison to other electricity sources. By 2030, the majority of nuclear power plants in China are Gen II and Gen III LRs, with a small number of LW-SMRs, HTGRs, and FRs as early demonstration projects that have already been announced for construction. The total installed capacity of these nuclear power plants reaches approximately 110 GW by 2030.

In the Base scenario, the nuclear capacity reaches 155 GW by 2035 and reaches 320 and 422 GW in 2050 and 2060, respectively. For the four different types of nuclear power plants, LRs increase steadily and gradually slow down, with the share of LRs in the nuclear fleet capacity declining over time: from 153 GW in 2035 (99%) to 245 GW in 2050 (77%) and to 245 GW in 2060 (58%), which constitute the majority of China's nuclear fleet. LW-SMRs will pick up their growth momentum from 2040, reaching 50 (16%) and 62 (15%) GW in 2050 and 2060, respectively. Owing to their fuel cost disadvantages compared to LW-SMRs and delayed development, HTGRs grow significantly from 2050 and reach 25 GW in 2050 (8%) and 113 GW in 2060 (27%). FRs remain uneconomical for them to be built additionally because of their relatively high operational costs and short lifespans. The assumed shorter lifespan in particular would therefore result in a shorter time for FRs to recover their investment costs. Therefore, the installed capacity of FRs remains the same as their value in 2030 (1.2 GW).

In the LRP scenario, a faster growth rate of nuclear capacity is observed. By 2035, the total installed capacity of nuclear reaches 172 GW, followed by 377 GW in 2050 and 477 GW in 2060. The value in 2060 represents an increment of 13% (55 GW) over the value in the Base scenario. The share of LRs in this scenario is slightly lower owing to additional C2N for SMRs and reaches 250 GW in 2050 (66%) and 250 GW in 2060 (52%). The capacity in 2060 represents an increase of 5 GW (2%) over the value in the Base scenario. LW-SMRs have now flourished since 2035, reaching a capacity of 98 GW in 2060 (21%). The value in 2060 represents more than 50% growth compared to that of the Base scenario. The growth of HTGRs also improves in this scenario, with major growth post 2040, and reaches 128 GW in 2060 (27%). The installed capacity of FRs remains at 1.2 GW with their economic competitiveness unchanged.

The SRP scenario shows an even larger nuclear capacity from additional SMRs and therefore, a lower share of LRs in the long run. By 2035, the total nuclear capacity reaches 181 GW, an increment of 25 GW over the value in the Base scenario, representing a 17% growth. It reaches 421 GW (101 GW, 32% more than that of the Base) in 2050, and 518 GW in 2060 (96 GW, 23% more). The share of LRs decreases further from that of the LRP scenario: 153 GW in 2035 (85% of total nuclear), 253 GW in 2050 (60%), and 253 GW in 2060 (49%). The growth of LW-SMRs post 2035 is stronger than before, reaching 26 GW (14%) in 2035, increasing to 118 GW in 2050 (28%) and 130 GW in 2060 (25%). This installed capacity almost doubles the value of the Base scenario. Higher growth of HTGRs is also observed, reaching 48 GW in 2050 (11%) and 133 GW in 2060 (26%). Compared to the Base scenario, the capacity of HTGRs increases by 19 GW (17%). The capacity of FRs is identical to that in the other two scenarios.

3.2. Spatial discrepancies of nuclear capacities

The provincial-level installed capacity of nuclear technologies in electricity system decarbonization in 2040, 2050, and 2060 was analyzed further. The full result by year for each of the three scenarios is shown in Fig. 3. In 2040 (Fig. 3 (a)) of the Base scenario, major nuclear development occurs in coastal provinces with some early expansion into inland ones, where the coastal province of Guangdong leads with a total capacity at 59 GW. The inland province of Henan develops over 20 GW of nuclear (23 GW). Other inland provinces, including Hunan (10 GW), Jiangxi (6 GW), and Chongqing (5 GW), also experience major growth early on. With slightly more freedom in nuclear siting in the LRP scenario, the top five provinces by installed nuclear capacity remain unchanged from the Base scenario (Guangdong, Henan, Shandong, Zhejiang, and Fujian). Although Guangdong experiences additional growth, West-IM, a grid region with no known greenfield sites [36], also develops more than 5 GW of nuclear capacity. Even though many regions implement C2N in the most lenient SRP scenario, some of the notable provinces with C2N development now include West-IM (7 GW), East-IM (3 GW), and Shaanxi (3 GW); these previously had large coal power capacity and such capacity represents a minimal share of such capacity.

Full details in 2050 are shown in Fig. 3(b). Under the Base scenario, the top five regions in nuclear capacities have a combined capacity of 176 GW, which are Guangdong (73 GW), Zhejiang (30 GW), Henan (27 GW), Anhui (24 GW), and Shandong (22 GW)—a mixture of coastal and inland provinces. C2N in the LRP scenario now enables the presence of nuclear fleets in 26 provinces. Although the provinces in northwestern China face limitations in cooling water availability to a certain degree, they have a combined nuclear capacity of 28 GW across Inner Mongolia,

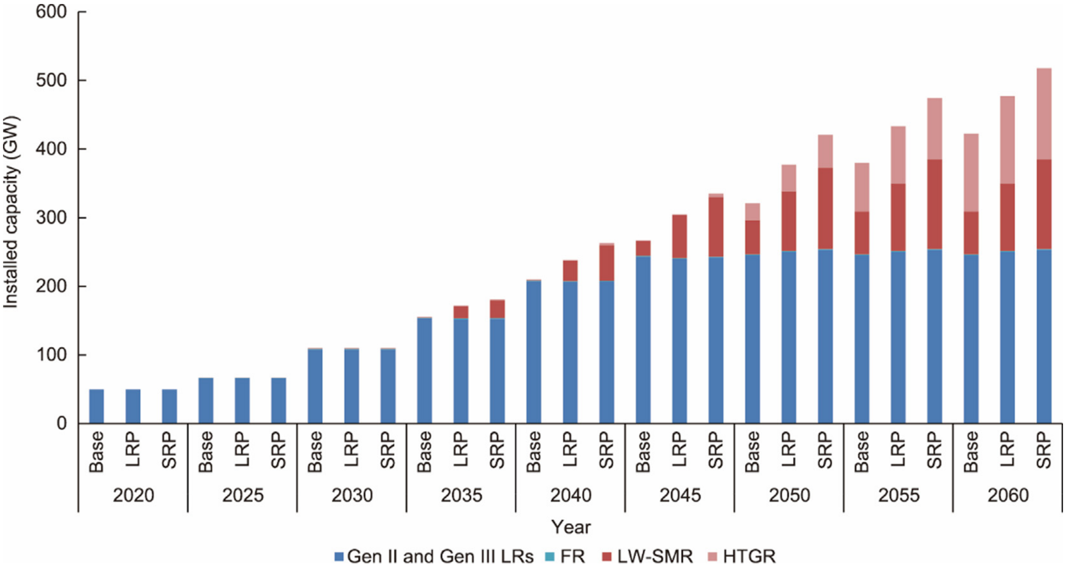


Fig. 2. Nuclear installed capacity by scenario and year.

Xinjiang, Shanxi, and Shaanxi, illustrating the potential of C2N in these inland provinces/regions. Further relaxation of the requirements in the SRP scenario expands the nuclear capacity to 28 provinces, with the capacity of Guangdong slightly exceeding 80 GW and a total of eight provinces having total nuclear capacity exceeding 20 GW.

The full details of nuclear distribution in 2060 are shown in Fig. 3(c). Without C2N, the top five provinces are now Guangdong (73 GW), Jiangxi (39 GW), Guangxi (30 GW), Zhejiang (30 GW), and Hunan (30 GW)—a combination of coastal and inland provinces (19 in total). In the LRP scenario, the top five provinces in nuclear capacities are Guangdong (76 GW), Jiangxi (39 GW), Hunan (35 GW), Guangxi (32 GW), and Zhejiang (30 GW). C2N development in northwestern China is less than 10 GW per province, and the nuclear capacity is distributed across 27 provinces. The SRP scenario has Guangdong (80 GW), Jiangxi (43 GW), Hunan (38 GW), Guangxi (35 GW), and Zhejiang (35 GW) as the top five provinces. In total, now 28 provinces possess nuclear capacities, with 16 of them exceeding 10 GW (totaling 467 GW), providing a much more diversified deployment of nuclear technologies across China.

Comparing the three scenarios across different years, in the Base scenario, nuclear power development in inland provinces becomes increasingly important: Henan is the frontrunner, followed by Anhui, Jiangxi, and Hunan, expanding the nuclear fleet from 14 to 19 provinces. With slightly more flexibility in nuclear siting in the LRP scenario, the northwestern provinces are major beneficiaries of such additional nuclear development, an outcome that would be unable to achieve without C2N; up to 27 provinces now have nuclear fleets. By 2060, with the most lenient C2N development criteria in the SRP scenario, the top provinces in nuclear capacities are those rich in greenfield sites (led by Guangdong). This suggests that while C2N fosters nuclear growth in northwestern provinces with large coal capacity, it would not fundamentally shift the center of nuclear development in China toward these regions.

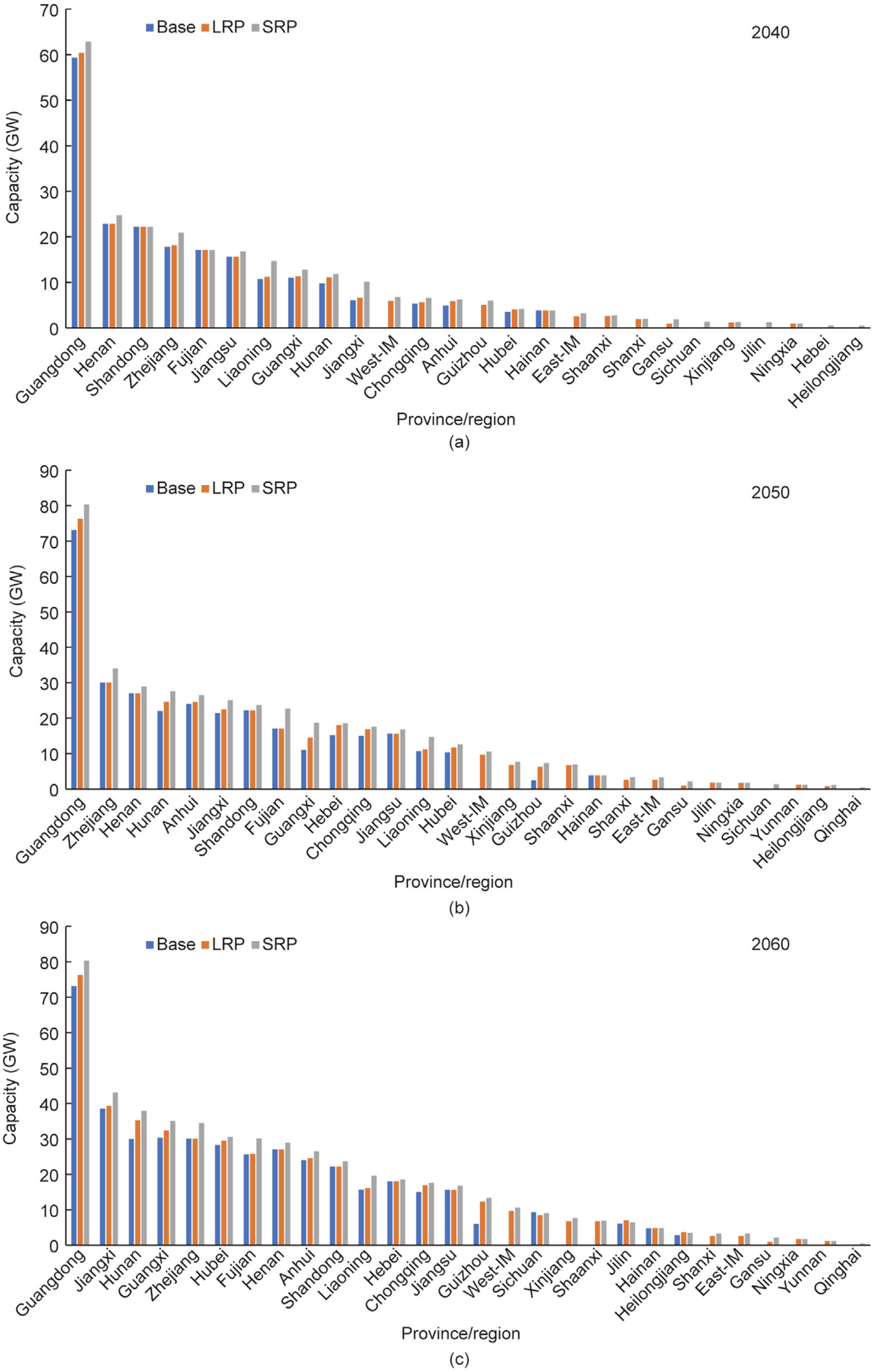
3.3. Electricity generation mixes

The electricity generation mix in China will undergo major changes over time, as shown in Fig. 4. In the Base scenario, coal-fired generation will reach its peak at approximately 5.6 PW·h in 2025, with a minor decline to 5.5 PW·h in 2030. After 2050, generation from unabated coal-fired power plants becomes negligible. Gas-fired generation follows a similar trend and reaches its peak later, increasing from 0.3 PW·h in 2020 to 0.7 PW·h by 2035, and then declining to 0.6 PW·h by 2050 and 0.2 PW·h by 2060. This suggests that the unabated fossil-fuel-based plants will increasingly serve as reserve units as climate policies become stringent. However, fossil-fuel-based power plants with carbon capture and storage (CCS) will increase in terms of their importance. Coal-fired power plants with CCS will be commercialized by 2040, accounting for 8% of electricity generation in that year. Their total generation will reach 1.9 PW·h (11%) by 2050, and 1.6 PW·h (8%) by 2060. By 2060, total fossil-fuel-based generation will only account for approximately 9% of total generation.

Wind and solar power are the main sources of future growth in non-fossil-fuel-based electricity generation and will steadily increase. Wind power generation will increase to 2.1 PW·h in 2030 and 5.3 PW·h in 2060. Solar power generation will increase to 1.6 PW·h in 2030 and 4.2 PW·h in 2060. Their share in total electricity generation also increases from 10% in 2020 to approximately 30% in 2030, represent the majority of China's electricity supply after 2040. Although hydropower generation will continue to increase in the future, its growth will be limited owing to limited resources, increasing from 1.4 PW·h (18%) in 2020 to 1.8 PW·h (slightly more than 10%) in 2060, offering both electricity generation and buffering capacity in the system. Biomass-based generation without CCS will increase from 0.14 PW·h in 2020 to 0.69 PW·h in 2060 (slightly less than 4% of the total). Biomass energy with carbon capture and storage (BECCS), a net-negative emissions electricity source that will develop in the long run and convert the electricity system into a carbon sink, will see its electricity generation capacity reaching 0.69 PW·h in 2060 (4%).

Nuclear power generation could see continuous growth, with increases from 0.37 PW·h in 2020 to 0.89 PW·h in 2030, 1.7 PW·h in 2040, 2.5 PW·h in 2050, and 3.2 PW·h in 2060. Its share in total electricity generation will gradually increase from 5% in 2020, exceeding 10% in 2040, reaching 15% in 2050, and rising to 18% in 2060.

In the LRP scenario, with a larger nuclear capacity, nuclear power generation sees a slight boost. The total nuclear power generation rises to 1.9 PW·h in 2040, 3.0 PW·h in 2050, and 3.6 PW·h in 2060. The share of nuclear power in total electricity generation reaches 12% in 2040, 17% in 2050, and further increases to 20% in 2060, a 2-percentage-point increase compared to the Base scenario.



(a)

(b)

(c)

Fig. 3. Nuclear capacities of provincial-level regions by year: (a) 2040, (b) 2050, and (c) 2060.

The electricity generation mix of the SRP scenario reveals an even larger increment of nuclear power generation, with values of 3.3 PW·h in 2050 and 3.9 PW·h in 2060. By 2060, nuclear accounts for 22% of the total power generation, a nearly 4-percentage-point increase over that of the Base scenario. The three scenarios face similar levels of renewable curtailment, with rates ranging from 2% to 5% for solar and 3% to 6% for wind between 2030 and 2060.

A comparison of the generation mixes across the scenarios reveals that because nuclear power generation in the LRP and SRP scenarios is higher, both renewable-based and fossil-fuel-based generation would be displaced. In 2040, the LRP scenario exhibits an increase of 221 TW·h in nuclear power generation, whereas fossil-based generation decreases by 145 TW·h, and wind and solar generation decreases by 81 TW·h, suggesting early additional C2N has a substantial role in representing firm electricity source under energy transition. By 2060, the increment of nuclear power generation is 410 TW·h in the LRP scenario; this is offset by a 239 TW·h reduction in electricity generation from solar and wind

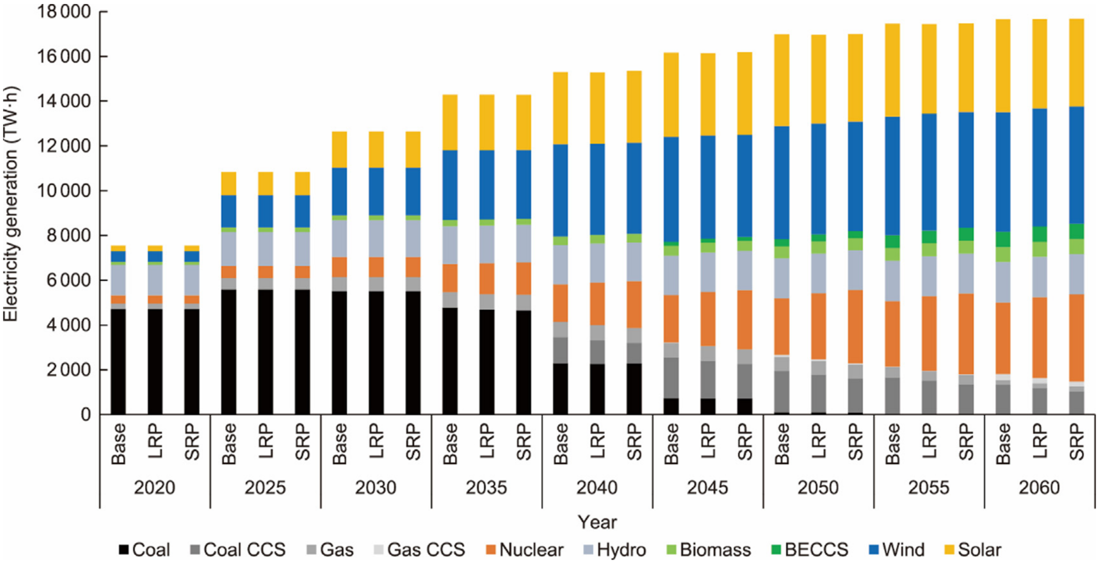


Fig. 4. Electricity generation mix evolution of three scenarios. BECCS: biomass energy with carbon capture and storage.

technologies and a 176 TW·h reduction from fossil-fuel-based generation with CCS. A further comparison of the SRP and LRP scenarios in 2060 shows that the additional increment of 289 TW·h of nuclear power generation is offset by 108 TW·h of power generated from variable renewables and 159 TW·h of power from fossil fuels with CCS. This suggests that flexible SMRs from C2N play a crucial role in a heavily decarbonized power system.

3.4. Total system costs

The total system cost of the electricity system in the Base scenario is shown in Fig. 5; the total system cost is decomposed into the following in each optimization period: investment, operational and maintenance (including both fixed and variable costs), and transmission costs. This suggests that the cost structure of China's power system will transition from operation-heavy (dominated by fossil fuels) to investment-heavy (dominated by renewables), while the share of transmission remains low. Therefore, the model inherently considers capacity utilization and its impact on the economic competitiveness of coal power plants (with greater operational flexibility) relative to nuclear power plants (with more base-load characteristics).

The comparison of total system costs across the three scenarios is shown in Fig. 6. With LRP and SRP scenarios being flexible and adaptable to nuclear development, the system costs decrease over time. By 2060, cumulative savings in the LRP scenario amount to 0.44 trillion CNY, or 0.22% of the cumulative cost of the Base scenario from 2030 to 2060. An additional 0.95 trillion CNY is cumulatively saved as seen from the comparison of the SRP and LRP scenarios, representing an additional 0.47% of the Base scenario's cumulative cost. This suggests that the development of C2N promotes nuclear technology development and is an effective tool for transitioning the energy system at a relatively lower total cost.

4. Conclusions and policy recommendations

In this study, the power system model of China was improved and the role of C2N was identified in China's cost-optimal electricity system decarbonization pathway. The results show that by utilizing the greenfield site resources in both the coastal and inland provinces, China could have a nuclear installed capacity of 422 GW in 2060, with 42% of this capacity from SMRs with higher operational flexibility. Nuclear power would emerge as an important electricity source, contributing to 18% of the supply in 2060. The availability of nuclear site resources presents a major bottleneck to the growth of nuclear technologies. The expansion of site availability via C2N could further raise the nuclear capacity by 13%–23%, while elevating nuclear power's share in electricity generation by 2–4 percentage points, at similar levels of renewable curtailments not exceeding 7% by 2060. This expansion of nuclear capacity can be a cost-effective solution for China's decarbonization, reducing the cumulative total system costs between 2030 and 2060 by 0.22%–0.69%. The techno-economic conclusions of this study can be further improved through a technical feasibility analysis of the C2N through satellite imagery and on-site inspections/evaluations, whenever applicable. Future studies can further improve the holisticity of the analysis and refine the considerations of other aspects such as nuclear waste management, radiation safety, and public acceptance. For the first two aspects, combining the typical scenarios in the arid northwest region of China can be considered to perform localized environmental impact analysis, such as between water consumption for nuclear power and ecological water use, and the impact of radioactive waste treatment on groundwater in arid areas. For analyzing public acceptance, questionnaire surveys and semi-structured interviews can be adopted to collect public perceptions of nuclear safety and environmental risks in the associated regions, before C2N is adopted as a technology pathway under decarbonization at a large scale.

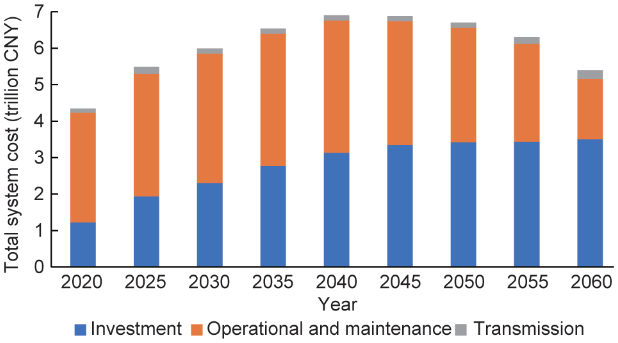


Fig. 5. Decomposition of total system cost for the Base scenario.

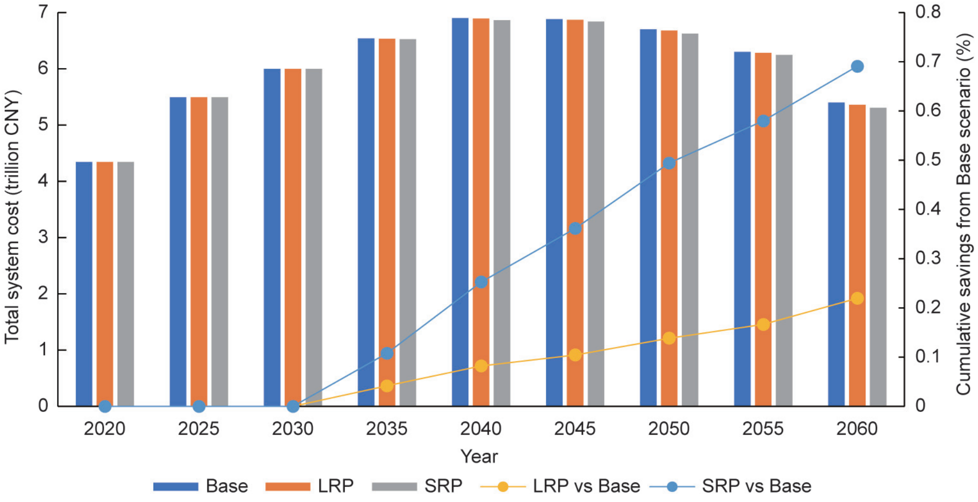


Fig. 6. Total system costs and cumulative savings from Base scenario by scenario in each year.

Based on the study, several policy recommendations are made: ① prioritize the protection of the surveyed greenfield nuclear sites to ensure their effective use under the carbon peaking and neutrality goals; ② promote the construction of pilot projects for C2N, and facilitate the appropriate acceleration of nuclear power development as decarbonization progresses. Assuming that the sites of the filtered coal plants in this study can be protected and remain suitable for C2N, northwestern China could particularly benefit from considering both the coal-fired power plant retirements and growing electricity demand after 2035 if inland nuclear development opens up, presenting a golden opportunity for C2N deployment. Introducing supporting policies such as land-use rights conversion and simplified nuclear safety approvals will significantly enhance the economic viabilities of C2N projects; ③ expand and promote the growth of manufacturing capacity for key equipment and components for nuclear power plants to meet their potential requirement in energy transition; and ④ support the research and development of advance nuclear technologies to significantly lower their costs and enhance their operational flexibility.

CRediT authorship contribution statement

Daiwei Li: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Hongyu Zhang:** Writing – review & editing, Software, Methodology, Formal analysis. **Ying Zhou:** Writing – review & editing, Visualization, Software, Investigation, Data curation. **Sheng Zhou:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Siyue Guo:** Writing – review & editing, Methodology. **Junling Huang:** Supervision, Funding acquisition. **Xiliang Zhang:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2025.11.025.

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