

Unit-level geospatial assessment of coal-to-nuclear repowering potential in China: Siting suitability and constraint attribution

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ABSTRACT

Coal-to-nuclear (C2N) repowering, which replaces coal-fired units with nuclear reactors while reusing existing site infrastructure, offers a unique solution to the challenge of large-scale coal retirement in China's low-carbon transition. However, the availability of suitable sites, which fundamentally determines C2N potential, remains insufficiently quantified at high spatial resolution, and the key factors constraining siting suitability remain poorly understood. This study develops a unit-level C2N siting model integrating a database of coal-fired units with multi-source geospatial constraint layers at 1-km resolution. A four-dimensional framework encompassing geological stability, cooling water availability, population distribution, and unit capacity is applied to screen candidate sites for large reactors (LRs) and small modular reactors (SMRs). Results show that 44 units (30.80 GW) pass the geospatial screening criteria for LR, while 1,657 units (718.36 GW) pass the criteria for SMRs in China, indicating SMRs may represent a potentially suitable option under geospatial constraints. Shapley-value decomposition quantitatively attributes each constraint's contribution to site exclusion, identifying population as the dominant factor. Plant capacity is the second-largest contributor for LR, whereas cooling water and geological conditions are the next most influential factors for SMRs. Regional Shapley analysis reveals pronounced spatial heterogeneity in binding constraints across China's seven power regions. Sensitivity analyses across alternative population regulatory frameworks and cooling-water distance thresholds confirm the robustness of SMR siting advantages while showing that shifts in these standards can substantially reshape regional technology mix and siting patterns. These findings provide high-precision spatial inputs for power system planning and differentiated policy design toward decarbonization of coal-fired power plants in China.

KEYWORDS

Coal-to-nuclear repowering, small modular reactors, coal power transition, nuclear energy policy, power system planning, siting regulation.

1 Introduction

To limit global warming to well below 2 °C, substantial reductions in carbon emissions from coal-fired power plants (CPPs) are urgently required^[1–4]. This challenge is particularly acute for China, where the coal-dominated energy structure persists, with coal-fired generation still accounting for 53.5% of total electricity production^[5,6]. Several decarbonization strategies have been proposed for CPPs, but each faces some limitations. Carbon capture and storage (CCS) represents a relatively mature technological pathway, but remains commercially unproven at scale and imposes energy penalties^[7,8]. Biomass co-firing offers emission reductions at comparatively low cost, but the deployment potential is constrained by limited biomass resources^[9,10]. Compulsory early retirement of CPPs can directly reduce emissions, but may lead to substantial stranded assets, disrupt local employment, and undermine economic stability in coal-dependent regions, which should be considered in the energy transition process^[11,12]. These limitations call for an alternative transition pathway that can simultaneously deliver deep decarbonization, preserve existing energy infrastructure value, and mitigate socio-economic disruption.

Coal-to-nuclear (C2N) repowering has emerged as a promising solution to the large-scale retirement challenge of CPPs in the low-carbon transition process^[13]. By replacing coal-fired units with nuclear reactors while reusing existing plant infrastructure, C2N offers a unique opportunity to leverage site assets such as substations, transmission connections, transport facilities, and cooling-water systems. This infrastructure reuse can significantly reduce capital investment requirements, preserve local employment, and alleviate resistance to stringent climate policies, thereby supporting a just energy transition^[14,15]. Meanwhile, nuclear power provides stable and dispatchable generation that complements variable renewable resources such as wind and solar, enhancing system reliability and energy security. As a near-zero-carbon technology, nuclear power emits only about 6.5 g CO₂ per kWh, roughly 1% of the emissions intensity of conventional coal-fired power, and can thereby play a critical role in the low-carbon transition process^[16,17].

However, not all coal sites are suitable for nuclear repowering, as nuclear facilities are subject to stringent siting requirements owing to their potential safety risks. Understanding these site-specific constraints has prompted a growing body of international research. In the United States, the U.S. Department of Energy has

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conducted detailed assessments of C2N geospatial screening potential using the OR-SAGE siting model. They evaluated 157 retired and 237 operating CPP sites, finding that approximately 80% possess the basic requirements to host advanced reactors, with a total capacity of 263 GW^[18,19]. Complementary work employing the STAND evaluation framework ranks 245 operating U.S. CPPs by C2N siting suitability, revealing substantial heterogeneity driven by safety, socioeconomic, and proximity-related indicators^[20]. In Europe, since the number of CPPs is relatively small, most of the research remains largely at the case-study stage^[21,22]. For China, early studies are largely qualitative or confined to individual case analyses, falling short of systematically identifying siting-compatible C2N candidate sites at the national scale^[23,24]. A recent study represents an important step forward in quantifying provincial C2N geospatial screening potential, yet several limitations remain^[25]. First, the constraint characterization is simplified to some extent: geological screening considers only seismic hazard, overlooking flood risk, landslide susceptibility, and terrain slope, which should be considered in the nuclear siting standards^[26]; cooling water eligibility relies on river grade classification rather than quantitative discharge thresholds; and the total population limit is simplified to a density limit, which may introduce inaccuracy particularly in areas with heterogeneous population distributions. Furthermore, the relative contributions of individual constraints to site exclusion have not been quantified, and the population and cooling-water standards have not been discussed. This is a notable gap given that China is one of the world's most densely populated countries, where even modest changes in population requirements could substantially alter the scale and spatial pattern of viable C2N candidate sites.

To address these gaps, this study develops a unit-level C2N siting model for China integrating a database of coal-fired units

with multi-source geospatial constraint layers at 1-km resolution. There are three contributions in this research. First, we construct a four-dimensional siting framework that extends existing geological screening to include peak ground acceleration, flood risk, landslide susceptibility, and slope, specifies cooling water requirements using quantitative river discharge thresholds, and applies population constraints consistent with Chinese regulatory standards, thereby providing a more rigorous and complete characterization of physical siting constraints. Second, we introduce Shapley-value decomposition to quantitatively attribute each constraint's marginal contribution to site exclusion, both nationally and across China's seven power regions, enabling systematic identification of the key limiting factors and revealing pronounced regional heterogeneity in binding constraints. Third, we conduct sensitivity analyses with respect to population and cooling-water distance thresholds, comparing Chinese and international regulatory frameworks to assess how changes in these standards reshape the scale, technology mix, and spatial pattern of C2N deployment. These contributions provide the high-precision spatial foundation needed to support power system planning and differentiated regional policy design for coal infrastructure decarbonization in China.

2 Methodology

2.1 Methods

2.1.1 Site selection method

This study identifies candidate C2N sites by spatially matching unit-level coal plant data with multi-source geospatial constraint layers at 1-km resolution. The overall technical roadmap is illustrated in Figure 1.

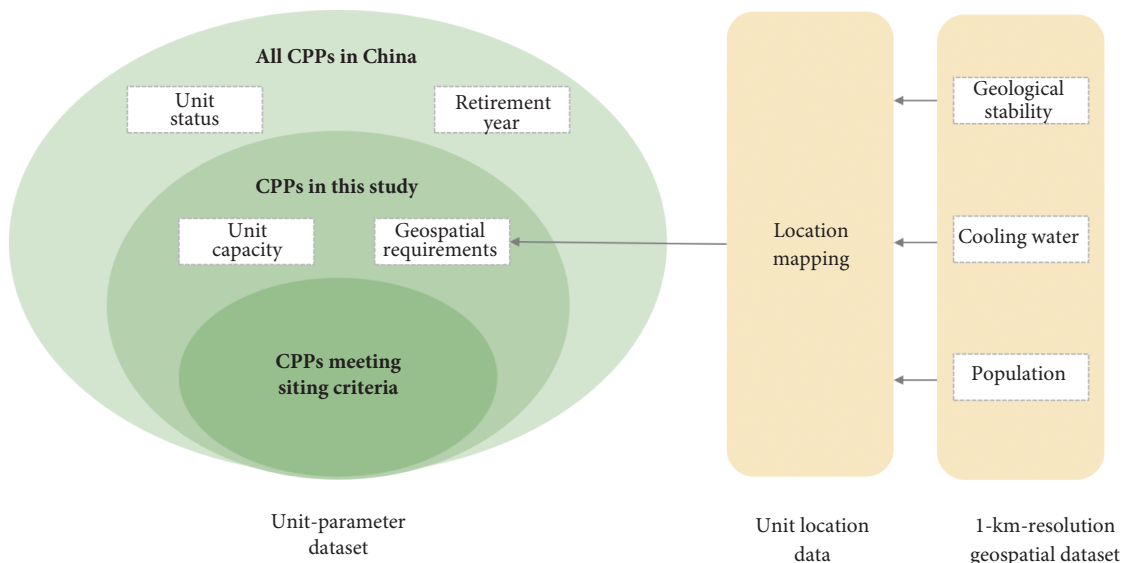


Fig. 1 Technical roadmap for C2N site screening.

The screening procedure is implemented in three steps. In the first step, geospatial constraints are evaluated at the grid-cell level. For each of the K nuclear siting constraints, a binary variable x_{ij}^k is defined for every 1-km² grid cell (i, j) , where input rasters with other resolutions are resampled to 1 km. A cell is assigned $x_{ij}^k = 0$

if it satisfies constraint k , and $x_{ij}^k = 1$ otherwise. The geospatially suitable candidate area for nuclear siting is defined in Eq. (1):

$$G = \left\{ (i, j) \in I \times J \mid \sum_{k=1}^K x_{ij}^k = 0 \right\} \quad (1)$$

where $x_{ij}^k \in \{0, 1\}$, $\forall k = 1, \dots, K$; $i = 1, \dots, I$; $j = 1, \dots, J$.

In the second step, the location of each coal-fired unit is mapped to the constraint grid via a coordinate-mapping function Ψ . Using a consistent spatial projection, the latitude and longitude ($\text{lat}_{mn}, \text{lon}_{mn}$) of unit (m, n) are converted to grid indices (i, j) as Eq. (2):

$$\Psi: (m, n) \mapsto (i, j) = \left(\left\lfloor \frac{\text{lat}_{mn} - \text{lat}_{\text{origin}}}{\Delta} \right\rfloor, \left\lfloor \frac{\text{lon}_{mn} - \text{lon}_{\text{origin}}}{\Delta} \right\rfloor \right) \quad (2)$$

$$y_{mn}^k = x_{\Psi(m,n)}^k = x_{ij}^k, \forall k = 1, \dots, K$$

where $\text{lat}_{\text{origin}}, \text{lon}_{\text{origin}}$ are the coordinates of the grid origin, and Δ is the grid resolution.

Finally, for unit-level parameters, a binary variable z_{mn}^t is defined for each unit (m, n) under parameter constraint t , where $z_{mn}^t = 0$ if the unit satisfies constraint t , and $z_{mn}^t = 1$ otherwise. A coal-fired unit is included in the preliminary C2N candidate set S only if its corresponding grid cell satisfies all K geospatial constraints and the unit itself satisfies all T parameter constraints, as shown in Eq. (3):

$$S = \left\{ (m, n) \in M \times N \mid \sum_{k=1}^K y_{mn}^k + \sum_{t=1}^T z_{mn}^t = 0 \right\} \quad (3)$$

where $z_{mn}^t \in \{0, 1\}$, $\forall t = 1, \dots, T$; $m = 1, \dots, M$; $n = 1, \dots, N$.

2.1.2 Shapley analysis method

To quantify the contribution of each siting constraint to the exclusion of coal-fired units, we employ the Shapley value method. The Shapley value computes, over all possible subsets of constraints, the average marginal effect of adding a given constraint to an existing subset, thereby providing a theoretically grounded and fair attribution of influence. Compared with conventional one-at-a-time sensitivity analysis, the Shapley approach explicitly accounts for interactions among constraints,

making it particularly well suited to multi-constraint siting problems in which different factors often co-occur and interact spatially.

For each constraint variable $i \in N$, the Shapley value ϕ_i represents the average marginal contribution of variable i to the outcome and is calculated as Eq. (4).

$$\phi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|! (|N| - |S| - 1)!}{|N|!} \cdot [v(S \cup \{i\}) - v(S)] \quad (4)$$

where N denotes the full set of constraint variables, with $N = \text{Unit, Geology, Water, Population}$; S denotes a subset of N that does not contain variable i ; $v(S)$ denotes the number of coal-fired units excluded under constraint set S ; $v(S \cup \{i\})$ denotes the number of units excluded after further adding constraint i to S .

To facilitate comparison across constraints, the Shapley values are normalized as Eq. (5).

$$\phi_i^{\text{norm}} = \frac{\phi_i}{\sum_j \phi_j} \quad (5)$$

The analysis is conducted both at the national level and separately for each of China's seven power regions, enabling identification of region-specific binding constraints and spatial heterogeneity in limiting factors for C2N siting.

2.2 Site selection criteria

Siting criteria for C2N geospatial screening comprise two broad categories: (1) safety-related geospatial constraints governing the suitability of CPP sites to host nuclear power plants (NPPs), and (2) unit-capacity conditions determining whether a CPP site possesses sufficient infrastructure to accommodate a given reactor type. The full set of criteria and parameter settings is summarized in Table 1.

Table 1 C2N site selection criteria and parameter settings.

Dimension	Indicator	Parameter	Criteria reference	Data source
Geological stability	Seismic	LR: peak ground acceleration (PGA) > 0.3 g excluded (2,475-year return period, 2% exceedance in 50 years); SMR: PGA > 0.5 g excluded	[27,28]	[29]
	Flood	Flood depth > 0.1 m excluded (100-year return period)	[26]	[30]
	Landslide	LR: sites with medium/high risk excluded; SMR: sites with high risk excluded	[26]	[31]
	Slope	LR: slope > 12% excluded; SMR: slope > 18% excluded	[18]	[32]
Cooling water	Freshwater	LR: within 30 km of river with flow > 5.83 m ³ /s; SMR: within 30 km of river with flow > 1.5 m ³ /s	[18,20,26]	[33,34]
	Marine water	Within 30 km of coastline		[35]
Population	Chinese standard	LR: total population within 5 km > 10,000 excluded; SMR: total population within 1 km > 10,000 excluded	[36]	[37]
	International standard	LR/SMR: population density > 193 persons/km ² within exclusion zone excluded (radius depends on reactor size)	[38]	
Unit	Capacity	LR: plant total capacity ≥ 1,000 MW; SMR: plant total capacity ≥ 50 MW	[20,26]	[39]

2.2.1 Geological stability

To reduce the risk of radioactive release, areas with poor geotechnical conditions are excluded. Following the Electric

Power Research Institute (EPRI) siting guidance, LRs are generally screened using a PGA threshold of 0.3 g, while advanced reactor siting studies suggest that smaller advanced reactors and SMRs may tolerate PGA values up to 0.5 g due to their enhanced seismic

mitigation capabilities, including smaller structural footprints, shorter and less complex piping systems, passive safety features, underground installation configurations, and improved seismic isolation performance^[27,28]. Sites with flood depths exceeding 0.1 m under a 100-year return period, or with medium to high landslide susceptibility for LRs or high susceptibility for SMRs, are also excluded to prevent accident escalation^[26]. Steep terrain significantly increases construction costs and is generally avoided in nuclear siting practice; accordingly, slope thresholds of 12% (approximately 6.84°) and 18% (approximately 10°) are applied for LRs and SMRs, respectively^[18].

2.2.2 Cooling water availability

Reliable access to cooling water is essential for both normal reactor operation and emergency cooling. A site is retained if it lies within the specified distance of at least one qualifying water source, with freshwater and seawater treated as alternatives. For freshwater, the minimum required river flow for LRs is derived as the average of the thresholds adopted in the current research^[18,20], while the SMR threshold is obtained by linear interpolation^[26]. For marine water, sites within 30 km of the coastline are considered to have adequate seawater access, consistent with the siting practice of all currently operating nuclear plants in China.

2.2.3 Population distribution

Given the potentially severe public health and safety consequences of nuclear accidents, sites in densely populated areas are excluded. Population-related siting requirements are central to nuclear policy debates, with domestic and international standards differing substantially. This study therefore evaluates screening outcomes under two sets of population criteria. In the baseline scenario, we apply the Chinese national standard GB 6249-2025 issued by the Ministry of Ecology and Environment^[36]. Under this standard, a site is retained only if the total population within the exclusion zone is no more than 10,000, with exclusion-zone radii of 5 km and 1 km for LRs and SMRs, respectively. This approach directly applies the regulatory population count requirement rather than converting it to an equivalent density threshold, thereby avoiding the simplification errors that may arise in areas with heterogeneous population distributions. In the extended analysis, an international regulatory scenario is constructed based on U.S. Nuclear Regulatory Commission Regulatory Guide 4.7 (NRC RG 4.7), which specifies a population density limit of 500 persons per square mile (approximately 193 persons/km²) within the exclusion zone^[38]. Exclusion-zone radii are determined according to IAEA guidance for each reactor capacity class. Starting from a 1-km radius, we incrementally expand the radius in 1-km steps, checking in each ring whether the population density meets the limit, and repeat this process until the required radius is reached. As these international criteria were originally developed for LRs and no official SMR-specific population standard has yet been published, the LR international density limit is applied to SMRs in this scenario^[20].

2.2.4 Unit capacity

The suitability of a CPP site for nuclear repowering depends in part on the aggregate generating capacity of the plant, as a single site typically hosts multiple units whose combined infrastructure determines the candidate nuclear capacity it may accommodate at the screening stage. This study focuses on a full-replacement scenario in which only the plant site and grid connection

infrastructure are reused, reflecting the ongoing uncertainty regarding the extent to which other CPP components such as boilers can be repurposed for nuclear operation. Capacity screening is therefore assessed at the plant level using the sum of nameplate capacities of all units at a given site. Plants with a total capacity of at least 1,000 MW are retained as LR candidates in the geospatial screening, while those with a total capacity of at least 50 MW are retained as SMR candidates^[20,26].

2.3 Data collection and processing

2.3.1 Geospatial data preprocessing and validation

All geospatial layers were harmonized to WGS84 coordinates (EPSG:4326) and an approximately 1 km grid (0.008333° × 0.008333°). The final constraint layers were converted into binary screening layers, where 0 indicates cells passing the criterion and 1 indicates excluded cells. Missing or invalid cells were coded as 999, without interpolation or imputation, to avoid introducing artificial constraint information. Given their limited coverage, this treatment is unlikely to materially affect the screening results. Because the final layers are categorical, nearest-neighbor resampling was used for all reprojection and grid-alignment steps.

The original seismic layer has a resolution of approximately 0.05°, while the flood layer has a resolution of 0.008333°. The landslide susceptibility, slope, population, and river-discharge layers were provided at 30 arc-second resolution. Seismic, flood, landslide, and slope layers were checked and converted into binary exclusion layers according to Table 1. For freshwater and marine-water constraints, Euclidean distances were calculated from each grid cell to the nearest eligible river cell and coastline, respectively. For population constraints, moving-window calculations were used to estimate population within the required surrounding area. Coal-plant coordinates were matched to the harmonized grid using their reported longitude and latitude.

Quality checks included verification of coordinate reference systems, spatial extent, raster resolution, NoData values, and grid alignment after resampling. Representative point checks were also performed for population, river distance, coastline distance, and coal-plant coordinate extraction.

2.3.2 Coal-plant dataset and unit classification

The model covers 30 provincial administrative areas in China (Xizang Autonomous Region, Hong Kong Special Administrative Region, Macao Special Administrative Region, and Taiwan Province are not represented due to data limitations). The primary CPP data are drawn from the 2025 China dataset of the Global Coal Plant Tracker (GCPT), which provides comprehensive unit-level coverage of China's coal fleet across nine status categories: announced, construction, mothballed, operating, permitted, pre-permit, shelved, canceled, and retired^[39]. Units with shelved or canceled status are excluded, as these sites have generally been repurposed and no longer represent viable C2N candidates. GCPT systematically excludes coal-fired units below 30 MW, which may lead to the omission of some multi-unit plants that would otherwise meet the plant-level capacity threshold, thereby underestimating the screening potential. However, for operating plants, our dataset covers more than 95% of the total coal-fired capacity reported by the China Electricity Council. Given the limited contribution of sub-30 MW units to China's total coal-fired capacity, this data limitation is unlikely to materially affect our main conclusions. Units retired more than 10 years prior are

also excluded on the grounds that prolonged decommissioning renders site reuse impractical. The final sample comprises 4,440 coal-fired units with a combined installed capacity of 1,658.64 GW, whose provincial distribution is shown in Figure 2. These units are classified into four groups: operating (1,171.36 GW, 70.62%), under construction (204.21 GW, 12.31%), planning (216.61 GW, 13.06%; comprising announced, permitted, and pre-

permit units), and deactivated (66.47 GW, 4.01%; comprising mothballed units and recently retired units decommissioned within the past 10 years). For operating units, the expected retirement year is estimated as 2025 plus the reported remaining plant lifetime and is grouped into three windows: before 2040, 2040–2049, and 2050–2060. The screening methods and criteria described above are applied to each group.

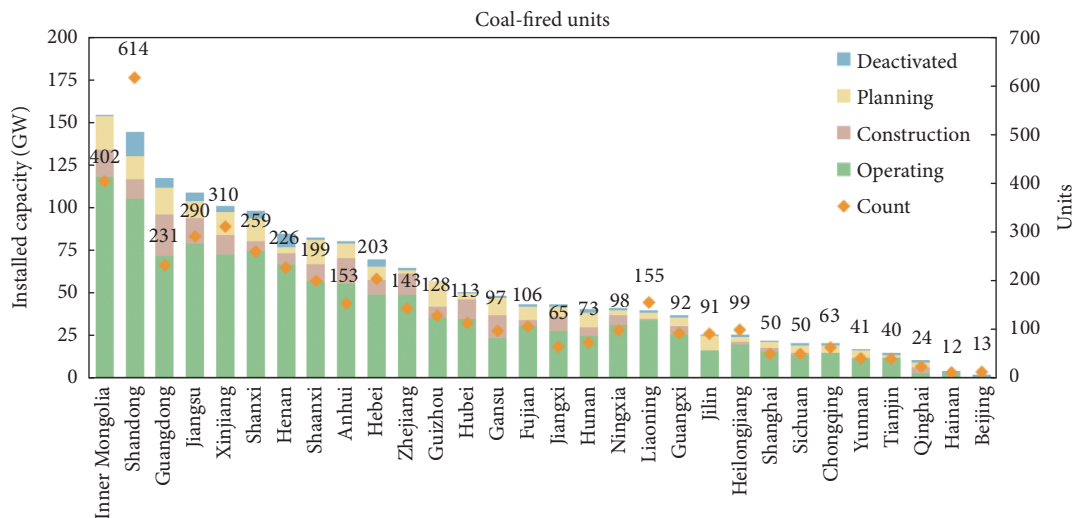


Fig. 2 Provincial distribution of coal-fired units by project status in China.

3 Results and discussion

3.1 Geospatial screening potential for C2N in China

3.1.1 Overall screening results

Screening results indicate that China possesses substantial site resources for C2N repowering, with SMRs exhibiting particularly broad siting compatibility under the selected screening assumptions. A total of 44 coal-fired units with a combined

capacity of 30.80 GW pass the geospatial screening criteria for LR, while 1,657 units totaling 718.36 GW pass the criteria for SMRs. The national siting-compatible candidate capacity and composition of LR and SMR candidates are summarized in Figure 3. Relative to the total coal-fired capacity considered, 43.31% is retained as SMR candidates, compared with 1.86% retained as LR candidates, confirming that coal-to-SMR (C2S) conversion offers considerably broader geospatial screening space than coal-to-LR (C2L) conversion.

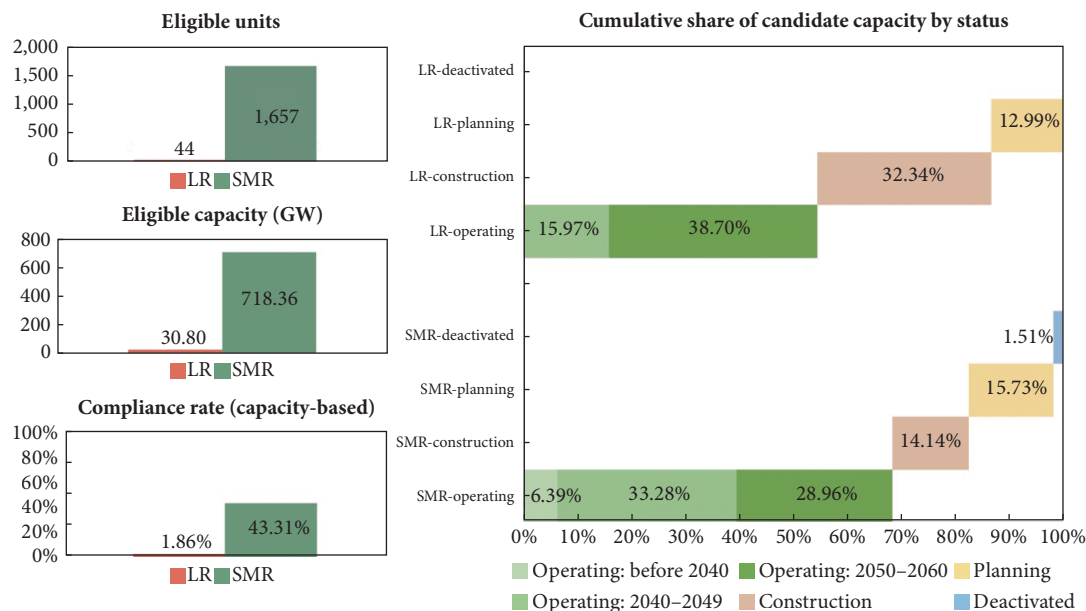


Fig. 3 National C2N geospatial screening results for LR and SMR candidates in China.

The status composition of candidate units has important implications for deployment timing. Operating units account for 54.68% of LR-eligible capacity and 68.63% of SMR-eligible capacity. Construction and planning units account for 32.34% and 12.99% of LR-eligible capacity, respectively, compared with 14.14% and 15.73% for SMRs. Deactivated units contribute no LR-eligible capacity and only 1.51% of SMR-eligible capacity. Among operating candidates, 100% of LR-eligible capacity and 90.69% of SMR-eligible capacity fall within the 2040–2060 retirement window. Given the sunk costs of existing coal assets and the learning costs associated with early-stage C2N demonstration and assessment, large-scale repowering is therefore likely to materialize primarily in the later phases of China's carbon neutrality transition, when it could make a significant contribution to achieving the 2060 carbon neutrality target while supporting a just energy transition for coal-dependent communities.

From a power system perspective, China's currently installed and planned nuclear capacity falls well short of the C2N potential identified in this study. Even partial realization of this potential would substantially increase the share of near-zero-carbon firm generation in the power system over the medium to long term. Relative to greenfield nuclear development, C2N leverages existing transmission and distribution infrastructure and avoids additional land acquisition and population resettlement, advantages that become increasingly valuable under tightening land-use and environmental regulations. Quantifying C2N siting-compatible candidate capacity at high spatial resolution therefore helps clarify the preliminary scale and geography of candidate sites and provides the spatial boundary conditions required for power system planning and the advancement of a regionally differentiated just transition.

3.1.2 Regional distribution of geospatial screening potential

In terms of regional distribution, more than 70% of LR candidate capacity and approximately 60% of SMR candidate capacity are located in inland provinces. Figure 4 presents cumulative LR and SMR candidate capacities and unit counts by province. Based on coastal location and the presence of operating NPPs, provinces are classified into three categories:

1. Category I: coastal provinces with existing NPPs, where established nuclear operations and regulatory experience are expected to facilitate public acceptance of C2N projects;

2. Category II: coastal provinces without existing NPPs, which lack an operational nuclear base but benefit from coastal location, proximity to Category I provinces, and relatively strong emergency response infrastructure, implying moderate public acceptance barriers;

3. Category III: inland provinces, where no inland NPPs are currently in operation in China and public resistance to C2N is likely to be higher in the near term.

LR candidate capacities in the three categories are 4.64, 3.84, and 22.32 GW, respectively, while the corresponding SMR capacities are 229.44, 36.30, and 452.62 GW. The concentration of candidate capacity in inland provinces implies that the ultimate scale of C2N implementation will depend critically on future policy decisions regarding inland nuclear power. Nonetheless, SMR candidate capacity in Category I provinces alone exceeds 200 GW, indicating that C2N retains considerable near- to medium-term geospatial potential even under conservative inland nuclear policies.

At the provincial level, the limited total LR candidate capacity means that LR candidates are confined to only seven provinces. Inner Mongolia, characterized by low population density, vast

territory, and a large coal fleet, accounts for approximately half of all LR candidate capacity, making it the province with the greatest C2L geospatial potential. SMR siting-compatible potential is more geographically dispersed, with candidates present in 29 provinces. Inner Mongolia, Guangdong, Guizhou, Xinjiang, and Shanxi rank as the top five provinces by SMR candidate capacity, broadly coinciding with major regional load centers and coal resource bases. Notably, Inner Mongolia also possesses substantial uranium reserves, which could support domestic nuclear fuel supply and reinforce its status as a priority region for further inland NPP development. By contrast, Shandong, which hosts the largest number of coal plant sites and the second-largest coal capacity in China, exhibits relatively low C2N qualification rates possibly due to its high population density, with approximately 1% of its coal-fired capacity qualifying for LR deployment and 20% for SMR deployment.

3.2 Key limiting factors for C2N in China

To systematically identify the factors constraining C2N geospatial screening potential and characterize their regional heterogeneity, Shapley-value decomposition is applied to quantify the contribution of each constraint to site exclusion at both national and regional scales, as shown in Figure 5.

The results reveal marked differences in the relative influence of the four constraint categories, with population-related requirements emerging as the dominant limiting factor for C2N siting in China. Across all possible constraint combinations, population constraints account on average for nearly 50% of excluded LR and SMR sites nationwide. The influence of unit-capacity constraints differs sharply between reactor types: for LRs, unit capacity ranks as the second most important limiting factor after population, whereas for SMRs the much greater flexibility in site-size requirements means that capacity constraints contribute negligibly to site exclusion. As most coal plant sites are located in areas with relatively stable geological conditions and adequate water access, cooling-water and geological constraints are broadly similar in magnitude and smaller than population and capacity constraints, collectively constituting secondary limiting factors for C2N siting in China.

The relative contributions of these constraints vary across regions. In North China, Northeast, and Northwest regions, population and cooling-water constraints are co-dominant. These regions are largely situated in arid and semi-arid climate zones, where limited surface water availability constitutes a critical bottleneck for nuclear siting in addition to population considerations. In East and South China, population and geological constraints are more prominent, reflecting the higher exposure of these regions to landslide and flood hazards, which renders geological conditions a non-negligible limiting factor. In Central and Southwest China, population constraints predominate, while geological and cooling-water conditions are generally favorable, which further amplifies the relative importance of population as the binding constraint. Unit-capacity Shapley values additionally reveal that average coal-fired unit sizes are smaller in the Northeast, Northwest, Southwest, and North China regions than elsewhere, significantly restricting C2L geospatial potential in these areas, as many sites do not meet the capacity threshold for LR candidacy. The majority of these sites nonetheless satisfy SMR capacity requirements, confirming that unit capacity is not a binding constraint for C2S conversion in these regions.

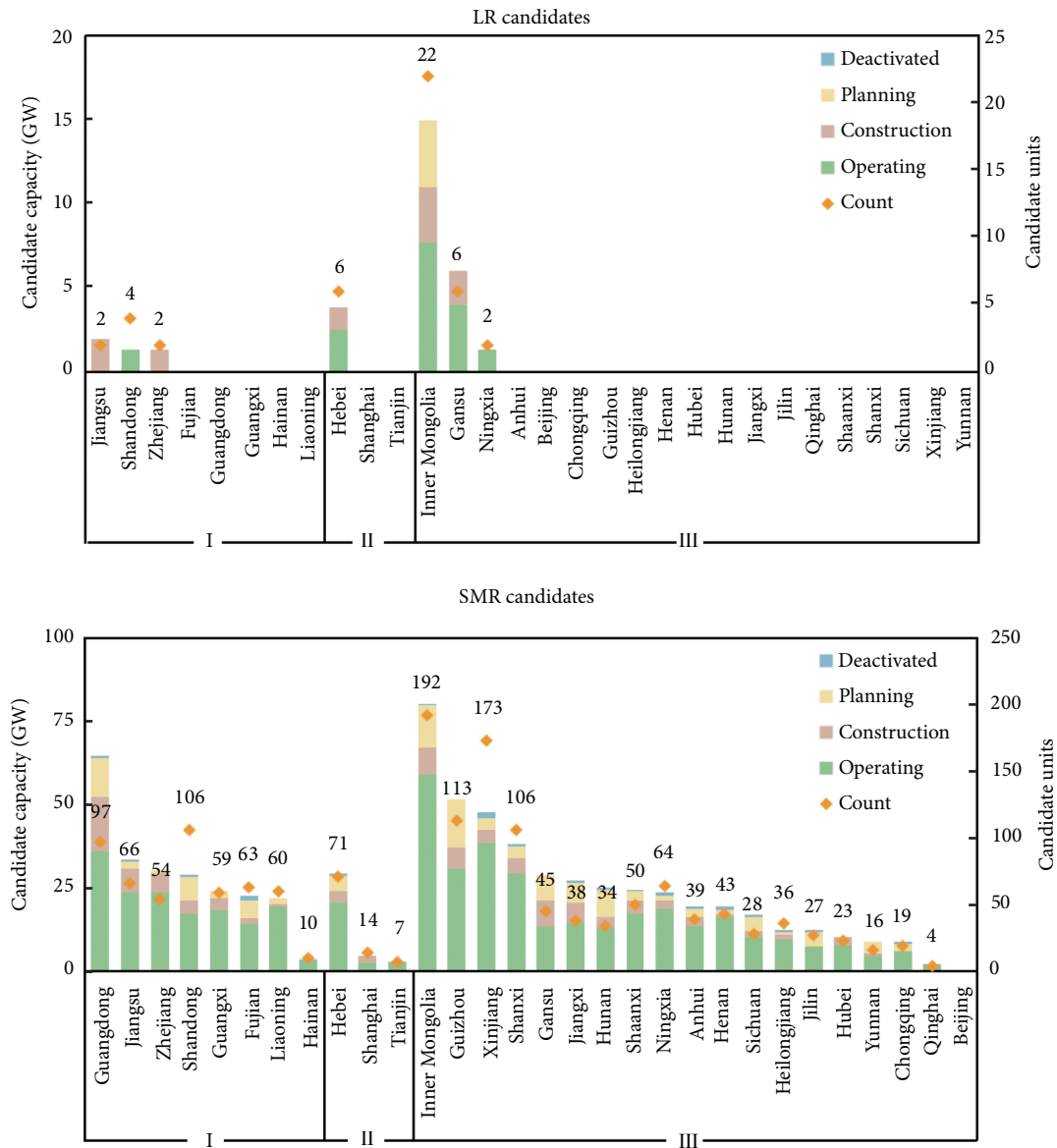


Fig. 4 Provincial distribution of LR and SMR candidate capacity. (Category I: coastal provinces with existing NPPs; Category II: coastal provinces without existing NPPs; Category III: inland provinces)

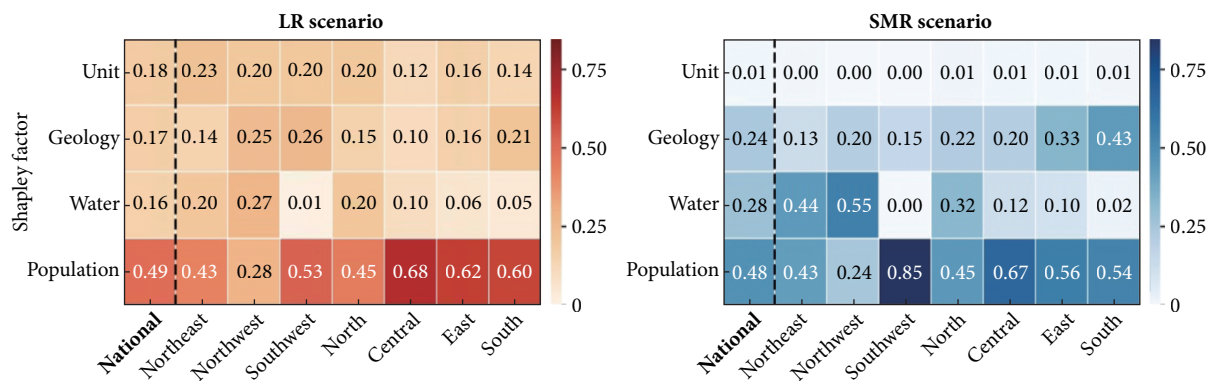


Fig. 5 Normalized Shapley values for limiting factors by reactor type and power region.

3.3 Sensitivity analysis

To assess the robustness of the siting results and examine how changes in key assumptions affect the technology mix and spatial pattern of C2N candidate sites, sensitivity analyses are conducted with respect to population constraint standards and cooling-water distance thresholds. These two constraints are selected for two reasons. First, Shapley decomposition identifies them as the primary drivers of site exclusion and thus the principal limiting factors for C2N siting. Second, relative to geological stability and unit nameplate capacity, which are largely fixed in the short term, population and cooling-water standards are more amenable to policy and engineering adjustment, such as through revisions to exclusion-zone requirements, adoption of SMR-specific population criteria, or adoption of water-saving cooling technologies.

3.3.1 Sensitivity to population constraints

Given that population is the primary siting constraint in China and that substantial discrepancies exist between domestic and international population standards, particularly for SMRs for which no international consensus has yet been established, a systematic sensitivity analysis is conducted across multiple regulatory scenarios. The Chinese baseline scenario (CNS) applies the requirement that total population within the exclusion zone must not exceed 10,000 persons, corresponding to effective density thresholds of 127 persons/km² for LRs and 3,185 persons/km² for SMRs. The international standard scenario applies the NRC Regulatory Guide 4.7 population density limit of 500 persons per square mile (approximately 193 persons/km²).

To account for the possibility that population standards in China may evolve as nuclear technology matures and public acceptance improves, additional sensitivity scenarios are constructed for each reactor type. For LRs, current population densities within 5 km of the first five commercial NPPs in China

(Qinshan, Tianwan, Daya Bay, Ling'ao, and Ningde) are surveyed and found to range from 150 to 450 persons/km², reflecting population growth that has occurred since construction. Two relaxed LR scenarios are defined on this basis: "LR CNS-Average" with a threshold of 300 persons/km² and "LR CNS-Upper" with a threshold of 450 persons/km², both replacing the baseline condition ceiling of 10,000 persons within 5 km. For SMRs, recognizing that many regulatory authorities currently apply conservative population standards to this less-mature technology, two tightened scenarios are constructed: "SMR CNS-50% Stricter", which halves the baseline density threshold to 1,600 persons/km², and "SMR CNS-LR", which applies the LR threshold of 127 persons/km².

As shown in Figure 6, switching from the Chinese standard to the international standard of 193 persons/km² increases LR candidate capacity from approximately 31 GW to 41 GW, while SMR potential falls sharply from 718 GW to 102 GW. This divergent response reflects the large asymmetry in effective density thresholds: the Chinese SMR threshold of 3,185 persons/km² is approximately 16.5 times more permissive than the international threshold of 193 persons/km², whereas the Chinese LR threshold of 127 persons/km² is approximately 34% stricter than its international counterpart. Under the Chinese sensitivity scenarios, LR candidate capacity increases substantially as the population threshold is relaxed, rising to 84 GW and 134 GW under the CNS-Average and CNS-Upper scenarios, respectively. Conversely, tightening population standards for SMRs reduces candidate capacity to 440 GW under the 50% stricter scenario and to 96 GW under the CNS-LR scenario. Across all scenarios considered, C2S geospatial screening potential consistently exceeds LR potential, confirming the robustness of the finding that SMRs offer superior siting flexibility. Population constraint also remains the primary driver of site exclusion across all scenarios, consistent with the national Shapley results.

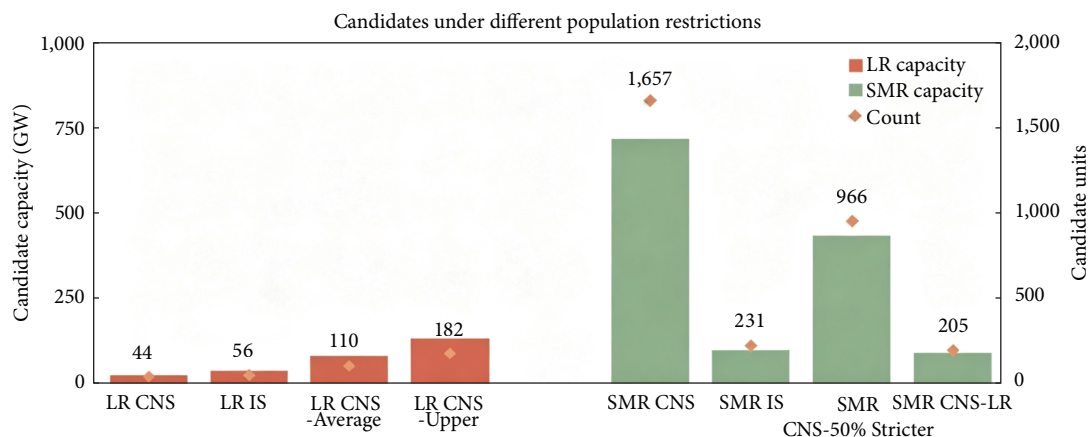


Fig. 6 C2N geospatial screening potential under alternative population criteria. (CNS: Chinese national standard; IS: international standard)

The spatial implications of alternative population scenarios are also pronounced. As LR thresholds are relaxed, additional LR capacity emerges predominantly in coastal and south-central provinces such as Guangdong, Guangxi, and Fujian, which were previously excluded under stringent population standards. The regional composition of LR candidates shifts from being concentrated in a small number of inland bases in North and Northwest China toward a more geographically balanced distribution across coastal and inland provinces. Under stricter

SMR standards, candidate capacity retreats from densely populated provinces such as Guangdong, Jiangsu, and Henan, and becomes concentrated in sparsely populated regions including Inner Mongolia, Xinjiang, Gansu, Ningxia, and Shaanxi, shifting the SMR candidate-site distribution from a nationwide distribution to one dominated by the Northwest and North. Changes in population thresholds therefore not only alter the relative roles of LRs and SMRs, but also reshape regional choices between C2L and C2S transition pathways.

3.3.2 Sensitivity to cooling water constraints

In China, there is a long-standing caution regarding inland nuclear power, which is closely related to cooling-water concerns. Inland rivers exhibit strong seasonal variability in flows, climate change increases the frequency of extreme drought events, and ecological flow requirements are becoming more stringent, which cast uncertainty on the ability of nuclear units to secure reliable cooling water over their full lifetimes. Meanwhile, LR and SMRs differ markedly in their water demands. LRs require high-parameter steam cycles and large-scale circulating-water systems and are therefore highly sensitive to continuous water availability, whereas certain SMR designs employ air cooling, hybrid cooling, or high-efficiency cooling towers, substantially reducing per-unit water consumption and dependence on large water bodies.

Against this background, a sensitivity analysis is conducted using four cooling-water distance thresholds. The baseline scenario adopts a 30-km buffer from qualifying water bodies, reflecting a range that is broadly acceptable in current engineering practice in terms of water-intake distance and conveyance costs, and is consistent with the general principle that large power plants should be located near stable water sources. Three progressively stringent scenarios are then defined with thresholds of 20, 10, and 5 km, respectively. The 20-km scenario represents moderate tightening under more constrained hydrological conditions or

when additional control of pumping energy use and pipeline risks is desired; the 10-km and 5-km scenarios represent strict and very strict requirements, corresponding to higher safety margins and stronger ecological protection for cooling water.

As shown in Figure 7, tightening the cooling-water distance standard from 30 km to 20, 10, and 5 km leads to systematic reductions in candidate capacity for both reactor types. Relative to the 30-km baseline, total LR candidate capacity declines by approximately 30%, 60%, and 77%, respectively, while SMR candidate capacity declines by 12%, 31%, and 47%. LR deployment is therefore considerably more sensitive to cooling-water distance restrictions than SMR deployment. In spatial terms, as distance thresholds are tightened, remaining LR capacity becomes concentrated in a small number of coastal provinces such as Jiangsu, Zhejiang, and Hebei, which benefit from simultaneous proximity to major rivers and the coastline, while the majority of inland LR candidates are eliminated. SMR capacity also declines substantially under stricter thresholds, with the largest reductions occurring in arid and semi-arid provinces such as Inner Mongolia, Shanxi, Gansu, Xinjiang, and Guizhou, whereas coastal provinces such as Guangdong, Fujian, and Guangxi are comparatively less affected. Tightening cooling-water standards therefore shifts both the technological and spatial distribution of C2N candidate sites toward water-abundant coastal regions and toward SMR technologies with lower water dependency.

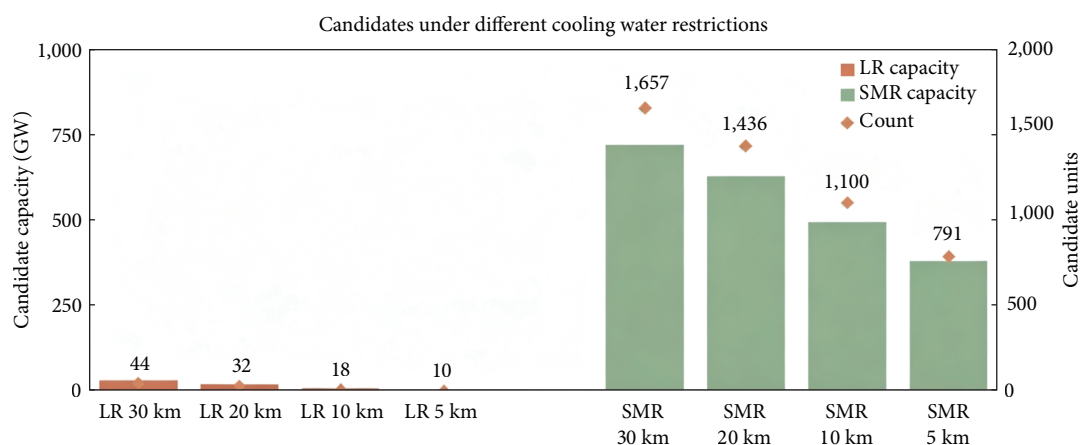


Fig. 7 C2N geospatial screening potential under alternative cooling-water distance thresholds. (30 km / 20 km / 10 km / 5 km: maximum permitted distance from qualifying water source)

3.4 Limitations

Several limitations should be considered when interpreting the results. First, cooling-water availability is represented using river-flow thresholds and distance to qualifying freshwater or marine water sources; this national-scale screening does not explicitly capture seasonal hydrological variability, extreme droughts, ecological-flow requirements, competing water uses, or reactor-specific cooling configurations. Second, this study focuses on physical siting potential and does not conduct project-level economic assessment, including reactor and licensing costs, construction time, learning effects, leveled cost, coal-site remediation costs, or detailed power-system integration value. Third, nuclear fuel-cycle and waste-management considerations, including fuel supply, spent-fuel management, and radioactive-waste disposal, are outside the present site-screening framework. Finally, a substantial share of the identified candidate capacity is

located in inland provinces, while future inland nuclear deployment in China remains subject to policy and regulatory uncertainty. Accordingly, the identified inland sites should be interpreted as conditional geospatial potential rather than currently deployable nuclear capacity.

4 Conclusions

This study develops a unit-level C2N siting model for China by integrating multi-source geospatial constraint layers at 1-km resolution with a comprehensive database of 4,440 coal-fired units. A four-dimensional framework encompassing geological stability, cooling water availability, population distribution, and unit capacity is applied to evaluate national C2N preliminary geospatial screening potential for both LRs and SMRs. The main conclusions are as follows: First, China possesses substantial C2N geospatial potential, with SMRs offering markedly broader siting

compatibility than LR. Screening identifies 44 coal-fired units totaling 30.80 GW passing the geospatial screening criteria for LR and 1,657 units totaling 718.36 GW for SMR. In spatial terms, more than 70% of LR candidate capacity and approximately 60% of SMR candidate capacity are located in inland provinces, implying that the ultimate scale of C2N implementation will depend critically on future inland nuclear power policies. Second, population is identified as the dominant constraint on C2N siting, accounting for approximately 50% of site exclusions nationwide by Shapley-value decomposition, followed by cooling-water availability and geological stability, while unit-capacity constraints primarily limit LR screening outcomes. The main limiting factors and their relative importance differ across regions. Third, sensitivity analyses show that SMR siting advantages in the screening results persist under all population and cooling-water standards considered, while changes in these standards are shown to substantially reshape the regional technology mix and spatial distribution of C2N candidate sites, underscoring the policy significance of regulatory choices for the trajectory of C2N transitions in China.

These results highlight the broader geospatial compatibility of SMRs under the modeled siting constraints. Based on these findings, four implications for C2N planning are offered.

1. Consider SMRs as a potentially suitable option across a broader range of coal sites. Given their broader siting compatibility under the geospatial constraints considered in this study, SMRs may represent a potentially suitable C2N option for a wider range of existing coal sites than LR. However, the identified siting advantage does not imply overall economic or deployment superiority. Further project-level assessments of economics, licensing, construction requirements, site remediation, and power-system integration are needed before deployment decisions can be made.

2. Implement a three-stage phased assessment strategy. A regionally differentiated rollout is proposed based on the siting results: (1) coastal provinces with existing NPPs, where mature regulatory frameworks and established public familiarity with nuclear energy provide favorable conditions to pioneer C2L and C2S projects; (2) coastal provinces without existing NPPs, focusing on C2S demonstrations aligned with local load growth and coal retirement schedules to incrementally build social acceptance; and (3) inland regions, where sites with optimal seismic stability and water availability should be cautiously prioritized, contingent on the evolution of inland nuclear power policy. This phased approach supports nationally coordinated C2N assessment and possible implementation while managing systemic transition risks at each stage.

3. Refine population standards and strengthen public engagement. As population distribution is the most binding constraint on C2N siting in China, continued advances in severe-accident prevention and consequence mitigation should provide the technical basis for dynamically updating exclusion-zone requirements. Risk communication and sustained public engagement are needed to address concerns about nuclear proximity. For SMRs in particular, introducing differentiated emergency planning requirements commensurate with their enhanced inherent safety characteristics would shift regulatory criteria from uniform thresholds toward technology-specific standards, thereby expanding the available siting space.

4. Integrate cooling-water planning with reactor technology selection. Nuclear cooling water demand should be incorporated into national water-energy nexus planning, particularly in water-

stressed inland regions. Differentiated water intake standards should be developed based on regional hydrological conditions and seasonal flow variability. Incentivizing water-efficient cooling technologies, including air cooling and hybrid cooling systems, through pricing instruments and targeted subsidies would reduce dependence on large surface water bodies. Establishing cross-sectoral monitoring mechanisms spanning water resources and energy authorities would provide dynamic, evidence-based constraint boundaries for inland C2N siting and help prevent cumulative regional water stress.

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Author contribution statement

Boqun Lyu is responsible for writing – original draft, investigation, methodology, formal analysis, data curation, visualization. Zihan Zhen is responsible for writing – original draft, methodology, formal analysis. Ying Zhou is responsible for methodology. Xiliang Zhang is responsible for conceptualization, methodology. Sheng Zhou is responsible for writing – review & editing, conceptualization, methodology, validation, supervision. All the authors have approved the final manuscript.

Data availability

Data will be made available on request.

Use of AI statement

During the preparation of this work, Boqun Lyu used ChatGPT in order to assist with language polishing and clarification of academic expressions. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. The author Xiliang Zhang is the Editor-in-Chief of this journal.

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