Comment

Supplementary information to:

Can China break the 'cost curse' of nuclear power?

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This Supplementary information comprises:

1. Methodology and supplementary figures
2. Raw data (see separate Excel file)

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Supplementary Note S1: Methods and Data sources

Supplementary Figure S1. Overnight construction costs of commercial nuclear power units in the US, France, and China.

Supplementary Figure S2. The effect of indigenization (domestic content rate) on overnight construction costs of Chinese operating nuclear power plants.

Supplementary Figure S3. Equipment domestic content rate of currently operating Chinese nuclear power plants.

Supplementary Figure S4. Construction time of global nuclear power plants.

Supplementary Note S1: Methods and Data sources

Cost data sources:
Collecting nuclear power plant cost data is challenging worldwide, both in terms of availability and reliability. Ideally, such data should be independently audited for accuracy, but audited cost records are rarely publicly available, especially for historical projects. Previous global nuclear cost datasets often rely on various grey literature sources, such as industry reports and news articles. Similarly, we compile a dataset of Chinese nuclear power costs using a wide range of publicly available sources, including peer-reviewed literature, industry reports, environmental impact assessments, project documents, company prospectuses, and news reports. We also track changes in reported costs over time to capture budget revisions for each plant, and we use the most recent reported values as the final costs for analysis.

We collect other relevant data on nuclear power units, such as capacity, model, construction time from the Global Nuclear Power Tracker (https://globalenergymonitor.org/projects/global-nuclear-power-tracker/) and various company reports. Equipment domestic content rates for Chinese nuclear power plants are gathered from news articles and industrial reports (see Figure S3 for details).

Cost data processing:
We process Chinese construction cost data for comparison in three steps. First, we adjust reported total investment costs to overnight costs using a 3.5% annual interest rate. Second, we convert all values to 2020 price levels using Consumer Price Index (CPI) data reported by China's National Bureau of Statistics and the International Monetary Fund. Third, we convert Chinese yuan to U.S. dollars using an exchange rate of 1 USD = 6.9 CNY, based on 2020 values. Total investment costs are often reported as aggregated figures at the project level (often as twin-units), so we assume identical units within a project share the same overnight cost.

Most sources we used report the "total investment" of a nuclear project, including both overnight construction costs and interest during construction. We convert the investment costs (IC) into the overnight construction costs (OCC) using the following equation:

$$OCC = \frac{IC}{\sum_{t=1}^{T} \alpha_t \cdot (1+i)^{T-t}}$$

where α_t represents the fraction of the investment made in year t, i is the interest rate, and T is the construction years. We use typical profiles[1] of construction expenditures to calculate the fraction of the investment made each year. Chinese state-owned nuclear power companies

[1] Source: http://www.cgnp.com.cn/cgnp/c100753/2019-07/18/dd869aefcd494f16beac30e99924fd8f/files/054353180d524349859b5166ffef150b.pdf. Accessed on Dec, 16th, 2024

receive low annual interest rates of 3-4%[2]. Such low interest rates have remained fairly stable over the past two decades. Some earlier plants may have received even lower rates, around 1–2%. Using different interest rates does not affect our conclusions. So, we use an interest rate of 3.5%. This results in interest during construction (IDC) accounting for 11% (ranging from 8-19%) of total investment costs, which is consistent with the typical cost breakdown of Chinese nuclear units.

Two earlier plants, commissioned in 1994 (Qinshan-1 and Daya Bay) while included in the cost data, may not be directly comparable with later units. Qinshan-1 was built during China's market and price reform period (late 1980s to early 1990s), so its cost estimates may be underestimated. Daya Bay's investment data are reported in US dollars, making cost comparisons difficult due to the lack of a market-based exchange rate system in China at that time.

In our analysis, we primarily focus on overnight construction costs because we aim to examine the historical cost escalation trends of these costs. This focus is particularly relevant in the Chinese case, where the trend of overnight construction costs plays a very important role in understanding cost dynamics. However, beyond overnight construction costs, financing costs (interest during construction) are also crucial. For nuclear power plants that take about a decade to build and face higher interest rates, financing costs can account for more than half of the total upfront capital cost of nuclear power plants. Reducing financing costs by shortening construction times, increasing investment return certainty, and improving access to low-cost financing through government-backed loans or guarantees is therefore essential.

Other costs related to nuclear power plants but not included in investment capital costs are: (1) plant operating costs, including fuel, operation and maintenance (O&M), used fuel management, and final waste disposal; (2) system costs for grid operators (balancing, transmission, and backup costs); and (3) external costs, such as health and environmental impacts. These costs are not included in this study's analysis but are also important for understanding the full economics of nuclear power.

US and France cost data:
The nuclear power overnight construction cost data are primarily sourced from Lovering et al. (2016). We adjust their data from 2010 dollars to 2020 dollars using the US inflation rate. However, Lovering et al. (2016)'s dataset does not include the most recently commissioned units in the US and France, namely Watts Bar 2 and Vogtle 3&4 in the US, and Flamanville 3 in France.

Construction of Watts Bar 2 began in 1972, was halted in 1985, and resumed in 2007. Reports indicate that Watts Bar 2 cost approximately $6.1 billion (excluding interest on construction

[2] See https://finance.sina.cn/2024-04-23/detail-inasvmtw7937477.d.html?from=wap, accessed on Dec, 16th, 2024

debt), including $1.7 billion spent before 1985[3]. This results in an overnight construction cost of more than $6/W (in 2020 dollars). Vogtle 3&4 have final overnight costs of $11,000/kW, equivalent to $15/W in 2020 dollars[4]. The overnight costs of Flamanville 3 are estimated to be approximately $4–6/W in 2020 dollars[5].

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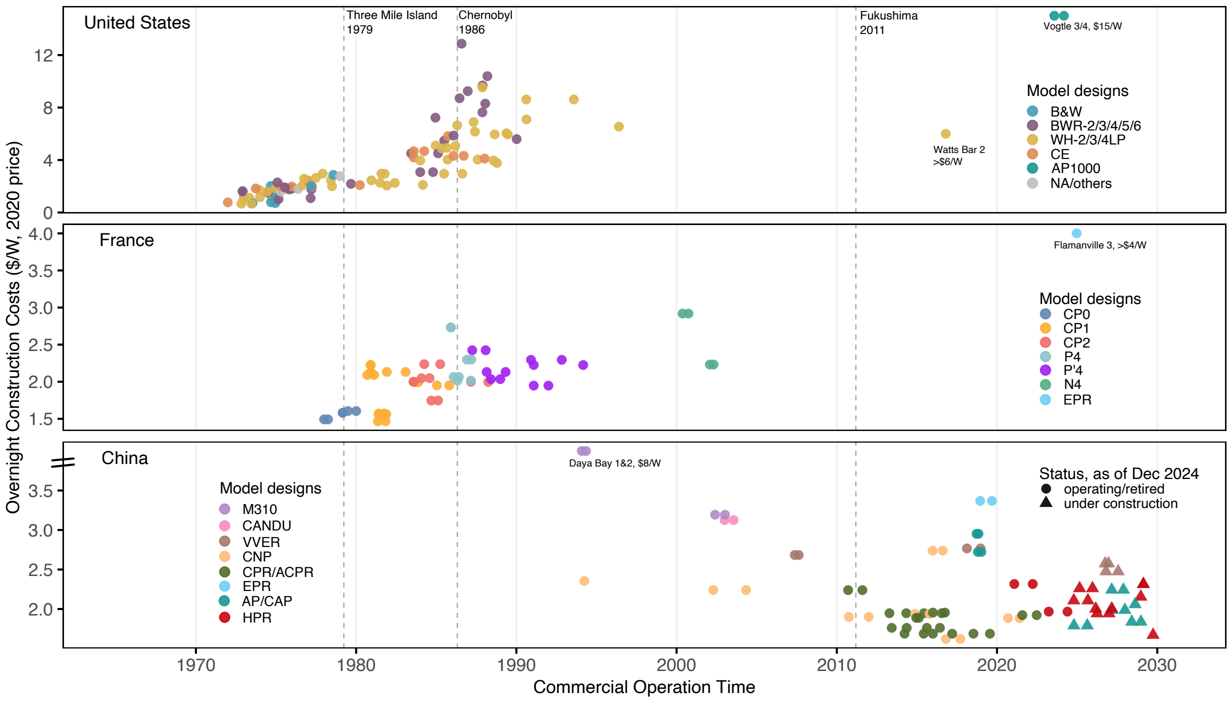
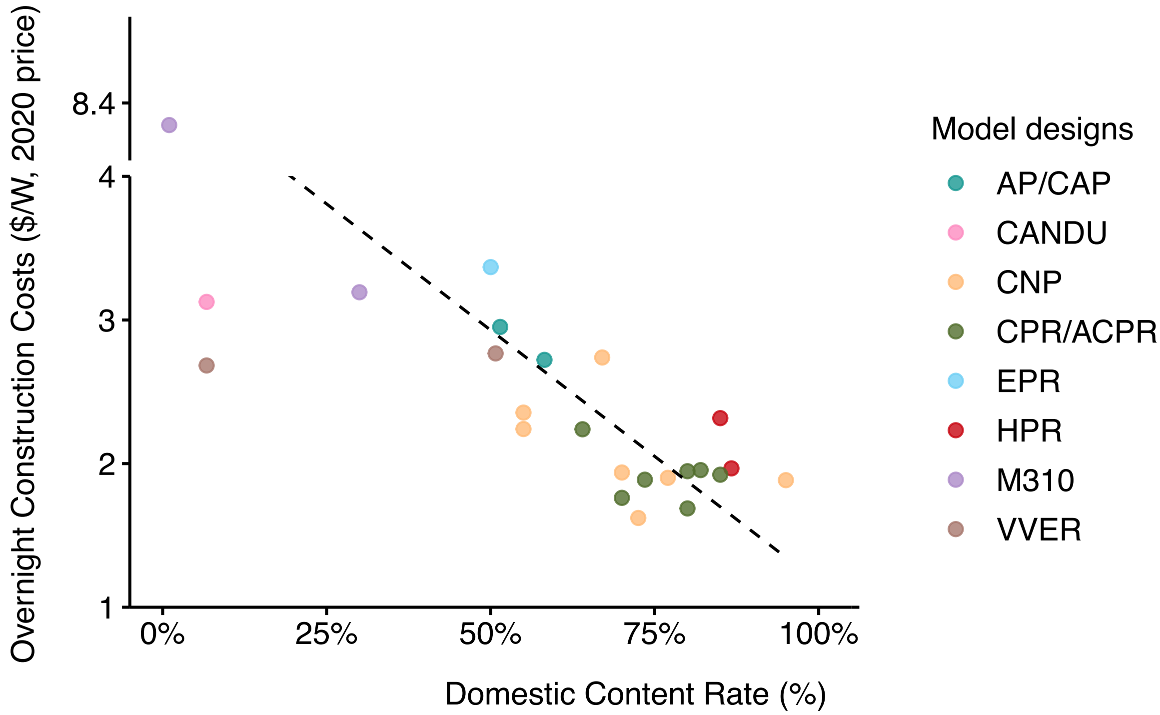
[3] See https://thebulletin.org/2015/10/watts-bar-unit-2-last-old-reactor-of-the-20th-century-a-cautionary-tale/#:~:text=The%20Tennessee%20Valley%20Authority%20now,interest%20on%20the%20construction%20debt., accessed on Dec, 16th, 2024

[4] See https://web.mit.edu/kshirvan/www/research/ANP201%20TR%20CANES.pdf, accessed on Dec, 16th, 2024

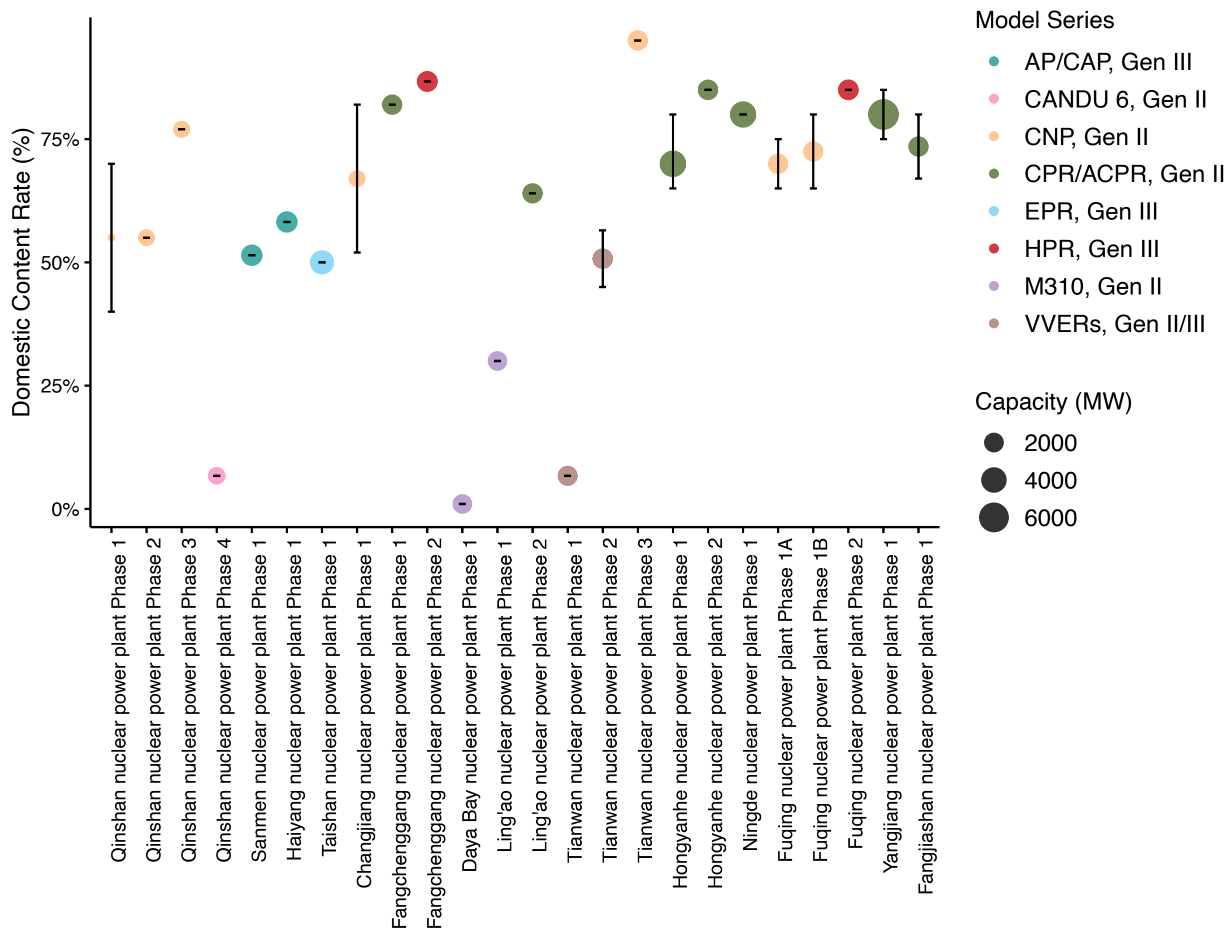
[5] See Rothwell, G. (2022). Projected electricity costs in international nuclear power markets. Energy Policy, 164, 112905.



Supplementary Figure S1 Overnight construction costs of commercial nuclear power units in the US, France, and China. Overnight construction cost refers to the capital cost of building a nuclear power plant, excluding financing charges incurred during the construction period. The y-axes for each country are scaled differently. Dots represent nuclear units that began commercial operation before July 2024 and are currently operating or retired. Triangles indicate units still under construction as of July 2024 in China. For under-construction units, investment costs are based on current estimates and are subject to future budget adjustments; similarly, their commercial operation time are based on expected construction periods and are subject to future adjustments. In the U.S., where nearly every reactor is somehow different, colors represent reactor supply companies, with each color grouping several designs from the same company. Cost data for the United States and France were primarily sourced from Lovering et al. (2016). Cost data for China were collected by the authors. The figure shows cost trends within each country; direct cross-country cost comparisons should be interpreted with caution because of differences in exchange rates and inflation. In the main figure, the trend line is fitted using a linear model for each county.



Supplementary Figure S2. The effect of indigenization (domestic content rate) on unit overnight construction costs of Chinese operating nuclear power plants. Each dot represents a nuclear power plant (including multiple units), as costs and domestic content rates are typically reported at this level. The dashed line represents the fitted linear regression of domestic content rate against unit overnight construction costs.



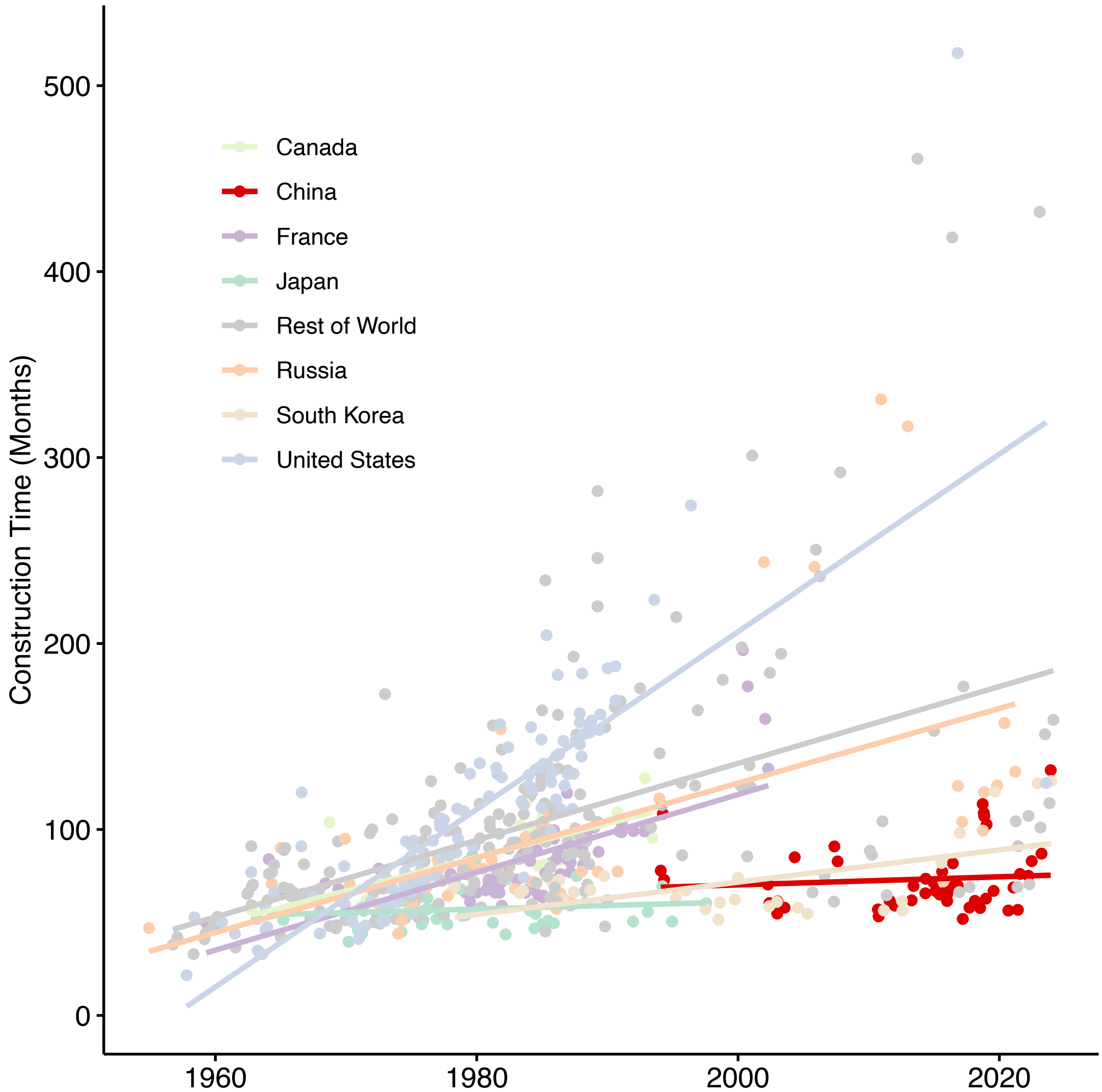
Supplementary Figure S3. Equipment domestic content rate of currently operating Chinese nuclear power plants.

We collected equipment domestic content rates for Chinese nuclear power plants from news articles and industrial reports. For most nuclear plants, these rates are consistent across various sources. However, for earlier plants, the Bluebook for Chinese Nuclear Power (2018) reports lower rates than other sources[6]. Error bars in the figure represent this discrepancy, with higher values from news reports and lower values from the Bluebook. For Qinshan Phase 1, while most sources report an equipment domestic content rate of 70%, an interview with a former director of China's National Energy Administration suggested it could be 40%, which is also represented by error bars. In our main analysis, we use the average when two different values are provided for a plant's equipment domestic content rate. However, using either dataset does not change the conclusion that domestic content rates strongly correlate with investment costs and contribute to huge cost reductions.

In some cases, domestic content rates are reported at the unit level. For example, Sanmen Phase 1 has a 30% domestic content rate for unit-1 and 70% for unit-2; we used the average (50%) to represent the project-level estimates.

No specific domestic content rate is available for Qinshan Phase III, which uses the Canadian CANDU6 reactor model. Reports indicate that most of the equipment (including for the nuclear island, conventional island, and balance of plant) was contracted to companies from Canada, the U.S., and Japan, resulting in a very low domestic content rate. For this analysis, we use the rate from Tianwan Phase 1 (a Russian model) as a proxy for Qinshan Phase III, since both were designed by foreign companies and built around the same time.

[6] See https://www.china-nea.cn/site/term/6490.html, 2018, Page 174, Table 1. Accessed on Dec, 16th, 2024.



Supplementary Figure S4. Construction time of global nuclear power plants. The lines represent linear fitted models, showing changes in construction time over time. Lead times in China are similar to those in other East Asian countries, including Japan (on average 4.8 years) and South Korea (6 years), but are much shorter than in Western countries. Lead times in France grew from about 6 years in the 1960s to 8.3 years in the 1990s, while in the US they increased from 5 years to 12.5 years over the same period. This increase in lead times greatly contributed to cost escalation in both France and the US. Data source: Global Nuclear Power Tracker (2024)