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Article

Keywords: energy transition, decarbonization, capital investment, project finance

Posted Date: October 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11067354/v1>

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Additional Declarations: There is **NO** Competing Interest.

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Abstract

Decarbonizing the power sector is central to global climate mitigation, but the deployment of low carbon technologies highly depends on their cost of capital. Existing estimates of the risk-adjusted weighted average cost of capital (WACC) commonly base on country, market and technology conditions without resolving how risks accumulated during project development result in technology-specific financing premiums. Here we combine a multi-stage project development model with expert elicitation to translate stage-specific failure rates and development durations into equivalent risk-adjusted WACCs for 13 power generation technologies in China. We find that short-cycle technologies, including solar photovoltaics and onshore wind, have lower risk-adjusted WACCs of 6.2~6.6%. By contrast, the WACCs of large-scale high-risk technologies, including nuclear and thermal generation with carbon capture and storage, could reach 7.0~9.6%. The early-stage development success rate dominates such financing premiums. Applying the risk-adjusted WACC to 120 power transition pathways in China, we find project developers provide more than 90% of pre-construction investment and bear most of the risk exposure to development failure. These findings identify high-risk pre-construction capital as critical constraint for timely kicking-off of low-carbon technologies.

Key words: energy transition, decarbonization, capital investment, project finance

Main

By 2026, anthropogenic carbon emissions were nearing the upper limits of the Paris Agreement's 1.5°C carbon budget¹. China, as the world's largest CO₂ emitter, must take urgent action to reduce emissions, particularly in the power sector, which accounts for around 40% of the country's total emissions^{2, 3}. Decarbonizing China's power system necessitates a rapid expansion of clean power generators as well as retirements of high-emitting fossil fuel power plants^{4, 5}. Various modeling tools and scenarios suggest that China must scale its solar and wind generation multiple times to deliver a reliable and low-carbon power generation mix by 2060^{6, 7}. They also find that achieving net-zero power generation needs complementary clean-firm power resources to provide dispatchable emissions-free power during low solar and wind generation hours of the year^{8, 9}. These modeled pathways delineate the technological possibilities for power-sector decarbonization¹⁰, but their real-world implementation ultimately depends not only on construction and operating costs, but also on the cost of capital^{11, 12}.

The weighted average cost of capital (WACC) determines how upfront investment is converted into annualized costs and can materially affect the overall cost of transition pathway¹³. Previous studies have documented substantial variation in WACC across countries, regions and technologies (Table S1), reflecting differences in macroeconomic conditions, sovereign and policy risks, market maturity, financing structures and access to low-cost debt¹⁴. However, these estimates commonly summarize observed market and technology conditions in an aggregate parameter, which thereby provide limited insight into how technology-specific financing premiums arise¹⁵.

One potential interpretation of these premiums is through the lens of capital discipline of project development¹⁶. In reality, project developers have to undertake a multi-year, structured decision-making process to mitigate the potential risks for substantial future investments (also known as capital discipline¹⁶). For example, China's power generation project development typically involves four stages: site selection, feasibility study, financing and permitting, and construction (Figure 1 and Table S2). Each stage demands capital and time to demonstrate that the risks are manageable, benefits are acceptable, thus feasibility outcomes align with expectations for related stakeholders (developers, government, and investors). Projects only commence operation

after all decision gates are successfully passed; otherwise, potentially abandoned, suspended, or repeated until all these requirements are met.

Notably, project suspension and cancellation during the development process is not rare in real world. Over 70%~90% of renewable power projects fail due to early-stage development risk^{17, 18}. For example, nuclear power plant developments have been canceled in China after years of feasibility study¹⁹, and offshore wind projects were canceled in U.S. due to economic and regulatory changes after significant pre-construction work²⁰. At the enterprise portfolio level, revenues from successfully commissioned projects must be sufficient to recover investments incurred across both successful projects and failed development attempts²¹. Stage-specific success rates and development durations may therefore increase the expected investment required to commission a project and contribute to a technology-specific financing premium²². This premium can be expressed as an equivalent risk-adjusted WACC, providing a potential connection between observable development conditions and the financing costs used in system model and analysis.

Existing WACC calculations can approximate aggregated financing costs, yet they do not capture several key features of capital mobilization, namely the timing of investment, the accumulation of capital during development, and the extent of capital tied up in unsuccessful projects²³. It is also unclear how project-level financing premiums accumulate across transition pathways with different technology portfolios²⁴. Hence, useful insights are missing to identify where financing constraints arise and which interventions could reduce them for smoothing the power transition.

To support an iterative dialogue between energy system modelers and project development practitioners, this study strives to investigate how project-level capital discipline could shape the risk-adjusted WACC across technologies and thereby impact the national-level transition capital. To achieve this objective, we first develop a project-level model to mimic the real-world multi-stage decision making process in power plant development (see Methods for details). This project-level model determines an equivalent risk-adjusted WACC based on multi-stage project finance process, and thereby identify where financing premiums arises. Upon this model, we downscale selected IPCC's AR6 power transition pathways²⁵ into annualized lists of newly started, commissioned, or failed development attempts in China. We further conduct national-level transition feasibility assessment based on project finance insights, which discloses: how long capital remains tied up,

what share becomes stranded, and which stakeholders bear these risks along the prolonged power transition process.

Risk Adjustment in WACC from Project Finance

Lower development success rates and longer development durations increase the equivalent risk-adjusted WACC across the 13 power technologies examined (Figure 2). Using project-level model and expert-elicited parameters, we convert the multi-stage investment into an equivalent risk-adjusted WACC for power project development. The resulting estimates broadly overlap with technology-specific WACC ranges reported in previous studies.

Our results show that, widely deployed technologies generally exhibit higher development success rates and smaller financing premiums. Solar photovoltaics, onshore wind, energy storage and thermal power without carbon capture and storage (CCS) have overall development success rates of 20%~35% and development durations of 1~3 years. Their risk-adjusted WACCs range from 6.2% to 6.6%, corresponding to a risk premium of approximately 0.2%~0.6% above the baseline. On contrast, large-scale and high-risk technologies exhibit higher financing premiums. Concentrated solar power (CSP) and offshore wind have the overall development success rates of 10%~15% and mean development durations of 3.5~5 years. Their risk-adjusted WACCs reached 6.7~7.5%, approximately 1.0%~1.5% of risk adjustment. Hydropower, nuclear power and thermal power with CCS show the highest risk-adjusted WACCs, ranging from 7.0% to 9.6%. Under an assumed long-term debt cost of 3.5% in China, the baseline WACC for nuclear is approximately 5%, indicating that development risks add a further 2.0%~4.6% in cost of capital. ^{26, 27, 28, 29, 30, 31, 32}

Further sensitivity analysis shows that changes in stage-specific success rates produce larger variations in risk-adjusted WACC than changes in development duration (Figure 3). For hydropower and nuclear power, reducing the site-selection success rate from 10% to 5% would increase the risk-adjusted WACCs by 2.1%~2.5%, and thereby result in an increasement in the investment cost by 12%. Conversely, increasing their site-selection success rate towards 30%, a level comparable to that of mature and widely deployed technologies, would reduce their risk-adjusted WACCs by up to 1.9% and lower the investment cost by 10%.

Capital Mobilization across Different Pathways

To examine how project development risks impact the economic feasibility of transition

pathways, we categorize the 120 modeled transition scenarios into four groups, namely Business as Usual (BAU), high solar/wind, high nuclear, and high CCS pathways (Figure 4a). Pathways are classified as “high” when the corresponding technology’s capacity share in 2050 exceeds the 90th percentile threshold across all scenarios (SI section S3).

Our results show that, the transition capital needs clearly differ across pathway groups (Figure 4b). High solar/wind pathways (solar and wind capacity ratio larger than 70% in 2050) exhibit the lowest overall capital need, 4.3~6.6 and 4.2~5.1 trillion USD for 1.5°C and 2°C scenarios, respectively. These values are comparable to these of the BAU pathway. By contrast, high nuclear and high CCS pathways show much larger deviations from overnight-based estimates. High nuclear pathways require 6.1~7.3 and 6.7~7.4 trillion USD in overall capital need for 1.5°C and 2°C scenarios, respectively; whereas high CCS pathways require 5.9~6.5 and 5.9~7.3 trillion USD for 1.5°C and 2°C scenarios, respectively.

Capital needs across the pathway groups are distributed unevenly among technologies and development stages (Figure 4c). Solar and wind contribute substantially across all pathway groups, and most of their investments are concentrated in the construction stage. Nuclear and hydro account for some of the largest stage-specific capital need across pathway groups, especially in site selection and construction. This pattern indicates that the development challenges for them lie not only in large-scale investment need, but also in the need to commit substantial capital to lengthy and uncertain development before the final investment decision. Thermal power with CCS shows a more pathway-specific pattern. Its contribution is mainly concentrated in high CCS pathways, with relatively larger shares arising during stages of feasibility study and finance and permit. It indicates that CCS-related capital needs are shaped not only by high capital intensity, but also by repeated technical, commercial, and permitting assessments before projects reach final investment decisions. The contrast across technologies reveals that higher cost of capital premiums could adjust the overall capital needs, whereas separating investment from technology and development stage further identifies where financial exposure arises within a specific pathway.

Large-scale Project Development during the Coming Decade

The lead time of project development also affects the national-level transition feasibility. To deliver the projected capacity on schedule, project development has to begin at least five years

before the modeled commissioning year (Figure 5a). Since development of a power plant spans several years or even decades under the real-world capital discipline, the project development model provides a direct estimate of how much project capacity must enter the development pipeline in advance for achieving the transition ambition. The annual capacity of newly initiated project indicates that a large pipeline of power projects must be initiated during the coming decade to keep China's clean power transition on schedule (Figure 5b).

For high solar/wind pathways, annual solar and wind project commencements exceed 100 GW per year throughout 2020~2050. With annual solar and wind capacity additions exceeding 105 GW over the past five years³³, China is relatively well-positioned to sustain such pace if current momentum continues. Since China has committed 3600 GW solar and wind in its 2035 NDC³⁴, our results indicate that an equivalent amount of solar and wind will need to be commenced by 2030 as early-stage development activities. Yet, high solar/wind pathways also require timely expansion of energy storage and other clean-firm flexibility sources³⁵. If such flexibility lags, reliability requirement of power system might reinforce a continued reliance on fossil fuel power³⁶.

For high nuclear pathways, annual nuclear plant commencements must reach 16~22 GW per year during 2020~2050. In the years following the Fukushima incident, China slowed down and even temporarily halted the approval of new nuclear plant development³⁷. In China's ongoing 15th Five-Year energy planning process, the government has, for the first time, outlined the orderly advancement of nuclear power projects. Notably, in 2024 the State Council approved five new nuclear power projects comprising 11 reactor units of 13 GW, a historical high record. However, this still falls short of the annual capacity addition required for high nuclear pathway, underscoring the substantial challenge for such pathway.

For high CCS pathways, under the 1.5°C scenario, large-scale CCS deployment via retrofitting existing thermal plants is expected to reach 65 GW by 2025. Yet China's current installed capacity of thermal power with CCS is only 10 GW, with an additional 10 GW in commitments, far below the anticipated development rates³⁸. For 2°C scenario, while the annual project development rate appears feasible, the total investment of 6~8 trillion USD required from 2020 to 2050 presents significant financial challenges. Moreover, these pathways require developing about 400~700 GW non-CCS fossil fuel power plants during 2020 and 2035, harboring potential lock-in effect of fossil fuel infrastructure³⁹. Overall, the capacity development timeline of high nuclear and high CCS

pathways seems relatively behind of the needed development rate.

High-risk Capital Allocation Could Hold Back Clean Power Transition

In terms of capital mobilization, it is important to acknowledge how financing risks are distributed across stakeholders¹⁵. We therefore further separate project-finance-based capital needs between developers and investors, with particular attention to exposure to development failure (Extended Data Fig.1 and Figure 6). It is found that across transition pathways, most construction-stage capital is financed by investors, whereas developers bear a much larger share of pre-construction investment and the associated failure risk (Figure 6a).

For high solar/wind pathways, the investor bears over half of the capital need, which are directed to the construction stage. In contrast, 18%~25% of capital needs arise in pre-construction stages, and are thus borne by developers. In high nuclear and high CCS pathways, such developer-borne capital for pre-construction development rises further to 29%~34%. Such pre-construction capital is more likely stranded at site selection where failure rates are highest, making developers' financing burden substantially higher than that of investors (Figure 6b). The largest amount of stranded capital occurs in the high nuclear pathways, averaging 1.9 and 1.7 trillion USD for the 2°C and 1.5°C scenarios, respectively. The large stranded estimates partly reflect the assumption that all site-selection investment is written off when a project is abandoned. In an alternative scenario, nuclear and hydro projects that initially fail at site selection receive a second development attempt. This additional attempt would increase the mean site-selection success rate from 7.5% to 14.4% and thereby reduces stranded capital to 1.1 and 1.3 trillion USD under the 2 °C and 1.5 °C scenarios, respectively.

Power projects typically have long development and payback periods, so capital committed to unsuccessful projects remain tied up for years before recovery or write-off. Even if losses are eventually recovered through successful projects, this capital must first be mobilized during early development⁴⁰. Such funding commonly takes the form of scarce developer equity, which carries a higher required return⁴¹. Constrained corporate cash flows could therefore discourage developers from initiating long-cycle projects with high early-stage failure risks⁴². This dynamic would reduce the attractiveness of clean-firm technologies, redirecting investment towards mature solar and wind projects. Pathways retaining substantial clean-firm capacity therefore require targeted early-stage

financing and risk-sharing arrangements to initiate projects at the scale and pace assumed in modelled pathways.

Enhancing Transition Feasibility through Targeted Investment

Early-stage development success emerges as a key lever to smooth the high-risk clean-firm technology investment and thereby to enhance transition feasibility. Our sensitivity analysis proves that site-selection success rate has strong impact on the overall capital needs of power transition (Figure 7). Herein, a baseline scenario is defined in which all technologies retain their current site-selection success rates. In alternative scenarios, new success rate thresholds are gradually increased until 25%~30%, which is the observed upper range for mature technologies under established market conditions²⁸. In each scenario, technologies with lower success rates are raised to a specified threshold, while technologies already above it retain their own higher rates. It can be seen that as success rates improve, capital needs decline across all pathway types, though the magnitude varies. In high solar/wind pathways, raising success rates to 25~30% reduces capital needs by 8~13%. The reductions are larger in high nuclear and high CCS pathways, reaching 20~22% and 13~14%, respectively. Since these high-risk technologies characterized by long cycles, high uncertainty, and costly repeated failures (Figure S1), making site-selection stranded capital a significant burden in these pathways. Improving early-stage success rates for these technologies therefore offers a meaningful pathway to reducing overall transition costs.

Our results suggest that the capital mobilization challenge is not only to lower the average cost of capital, but also to strategically target the early-development risks within the project development timeline. Many project financing tools (green credit, green bonds, development funds, insurances among others listed in Table S3) are suitable for projects that have already become sufficiently de-risked and bankable. The gap identified here calls for more financing tools specifically designed to address early-development and developer-borne risk⁴³. Among existing practices, the Green Climate Fund's Project Preparation Facility, for example, has already directly supported 116 projects by funding feasibility studies, environmental studies, and risk assessments before projects become bankable⁴⁴. In the future, tools of this kind still need to be expanded in scale and diversified in form to support a smoother clean power transition.

In addition, stronger front-end project preparation is also critical. Improving developers' pre-

development capacity can reduce the number of failed projects, thus making better use of the scarce early-stage capital^{45, 46}. Meanwhile, public coordination also supports the development process by simplifying procedures and shifting part of the initial screening and survey burden away from developers. In Denmark, preliminary offshore-wind investigations are conducted and published before tendering⁴⁷, while in Japan public bodies such as JOGMEC carry out initial site surveys and provide the results to developers⁴⁸. Similar approaches have also been adopted in China, including competitive allocation arrangements that combine public coordination with developer participation⁴⁹.

Discussion & Conclusion

Our study has several limitations. First, our analysis is a one-way post-processing of IPCC AR6's energy transition pathways²⁵. It does not account for how project-level capital discipline may in turn alter the cost-optimal energy transition pathway. Secondly, we use exogenous success rates derived from survey data. We do not consider the endogenous interactions among development success rates, policies, markets, and power system structure. Thirdly, our study focuses on supply side and we do not include the grid infrastructure and the demand side. Addressing such issues in future studies will further enhance understanding of project-level capital discipline in clean power transition. It is also underlined that a naïve integration of our analysis and modelling analysis could be technology-specific risk-adjusted WACC ranges. Based on the project-finance-based estimates, specific risk-adjusted WACC ranges are recommended, yet they should be dynamically adjusted as well.

For policymakers, our results clearly indicate that reaching a net-zero power sector by 2050 requires accelerated capital mobilization and improved project bank-ability⁵⁰. Investment hesitation is likely to remain pronounced if the early-stage financial risks of clean power project development are solely borne by developers, particular for technologies with higher early-stage failure risk, like CCS and nuclear power⁵¹. Given the indispensable role of such technologies as sources of clean-firm power in future generation mix, establishing a risk-sharing or insurance mechanism to protect high-risk pre-construction capital becomes critical for timely kicking-off of such technologies.

From a global perspective, considering capital discipline would also shift the scale, speed, and difficulty of overall capital needs for clean power transition. In regions where project financing costs

are already high, the effects of capital discipline will be even more pronounced. It is already evident that renewable energy growth in global south has already fallen behind the global average^{52, 53} due to insufficient investment^{54, 55}, it is crucial to further analyze how project finance will bring additional impact to the cost of capital for such regions. In summary, incorporating project-level capital discipline provides penetrative lens to better navigate the scale, timing, and distribution of capital required for clean power transition, therefore better informing targeted policy for accelerating clean power transition^{14, 56}.

Method

Modelling the Real-World Development Process of Power Plant Project

In this study, a project-level power project development model is proposed to replicate the real-world decision-making sequence of power generation project development (Extended Data Fig.1). This model includes three main parts: technology-specific power project development workflows, stage-specific development success rates and time requirements, and stage-specific development investments. The parameters used for this model are introduced in section S5 of SI file. This project-level model strives to mimic the real-world power plant development process as follows:

(1) Project-level Development Process

We model China's power project development process as a standardized four-step process based on both literature insights and expert elicitation. We first synthesize official government documents⁵⁷, policy guidelines⁵⁸, research reports^{18, 38, 59, 60, 61, 62, 63, 64, 65} to outline a generalized development process applicable to all power technologies. Then structured interviews are conducted to refine such development process. Finally, iterative expert consultations are performed to ensure that the proposed process align with the engineering practices in China. For the present, more than 40 experts from 17 organizations provide estimates based on their practice experience (Table S4~S6). More details on expert interview are provided in section S5 of SI file.

(2) Multi-Stage Development Model

To reflect the success rate and duration time of each development stage for specific power plant, we developed a multi-stage development model based on the power plant project's development decision-making sequence. The model first generates a representative nameplate capacity, sampled from the probability distribution of real-world clean power project database, Global Energy

Monitor⁶⁶. Next, the model simulates the multi-stage development process for power plant project. At each decision gate between two adjacent stages, Bayesian probability is deployed to determine whether the project will proceed to the next stage, or return to the previous stage, or terminated. If the project passes through all decision gates, the power plant will be commissioned. If the project fails at any decision gates during feasibility study or finance and permit stage, the development will re-enter the same stage until the Bayesian probability exceeds the predefined threshold (Table S7). Based on expert's experience, if the project fails three times during feasibility study or finance and permit, or fails once at site selection, the project development is terminated. Moreover, the model simulates the time spent in each development stage according to the information gathered from expert interviews (Table S8 and Figure S2~S3). The total time spent in that stage is the sum of multiple development attempts.

(3) Multi-Stage Investment Model

A multi-stage investment model is developed to calculate the multi-stage capital need for power plant project development. Two forecasting methods are used to estimate future overnight construction cost for an individual power project, i.e., Wright's Law (WL) model^{67, 68} and First-order Auto-regressive (AR(1)) model⁶⁹. Both models are widely used and empirically validated for cost forecasts. The WL model, Eq. (1), is used for technologies such as solar and wind whose historical cost has shown clear reductions as cumulative capacity increases. In contrast, the AR(1) model, Eq. (2), is applied to hydro, nuclear, coal, gas, and biomass power projects, whose historical cost has either increased or fluctuated over time.

$$\ln C_t - \ln C_{t-1} = -\omega \cdot (\ln X_t - \ln X_{t-1}) + u_t + \rho u_{t-1} \quad (1)$$

$$\ln C_t = \ln C_{t-1} + \beta \cdot (\mu - \ln C_{t-1}) + \varepsilon \quad (2)$$

where C represents the overnight construction cost (\$/kW); X is the cumulative installed capacity (kW); ω characterizes the rate at which costs decrease as a function of experience; β is the rate of mean reversion; u and ε are the noise variance which draw from normal distributions; ρ is an auto-correlation parameter; and the subscript t and $t-1$ indicate the respective years.

In addition, the stage-specific financing cost and investment cost for an individual power plant project is calculated based on cost of capital parameters, multi-stage development timelines, and multi-stage overnight cost, Eq. (3). The parameters used for this model include investment cost,

overnight construction cost, return of equity, cost of debt, etc. The data collection method is introduced in section S3 of SI file and the employed parameters are listed in Table S9~S15.

$$TIC = [C_1 \cdot (1+ROE \cdot t_1) + C_2 \cdot (1+ROE \cdot t_2) + C_3 \cdot (1+ROE \cdot t_3) + C_4 \cdot (1+r \cdot t_4)] \cdot Cap \quad (3)$$

where TIC represents the total investment cost for developing an individual power plant (\$); $C_1 \sim C_4$ are overnight cost for multi-stage development (\$/kW); $t_1 \sim t_4$ are development time for different stages (yr); ROE and r are return on equity (%) and weighted average cost of capital (%); and Cap is the capacity of the power plant (kW).

Modelling the risk-adjusted WACC from project finance

We developed a project finance model to translate the multi-stage development risks into an equivalent risk-adjusted WACC. The model comprised three steps. First, we estimated the expected number of development attempts and the effective success probability at each stage. Second, we calculated the expected investment required to deliver one commissioned project, including investments on both successful and unsuccessful projects. Third, we converted this additional expected investment into an equivalent risk-adjusted WACC using capital recovery factors.

(1) Stage-specific development success rates

For stage i , let p_i denote the probability that one development attempt succeeds, and let $N_{i,max}$ denote the maximum number of permitted attempts. Assuming independent attempts within a stage, g_i is the probability of completing stage i within the permitted attempts, calculated by Eq. (4).

$$g'_i = 1 - (1 - p_i)^{N_{i,max}} \quad (4)$$

Let m_i be the expected number of attempts at stage i . An attempt k is made only when the preceding $k-1$ attempts fail. Therefore, m_i could be determined by Eq. (5).

$$m_i = \sum_{k=1}^{N_{i,max}} (1 - p_i)^{k-1} = \frac{1 - (1 - p_i)^{N_{i,max}}}{p_i} = \frac{g'_i}{p_i} \quad (5)$$

The probability that a candidate project reaches stage i is R_i , calculated by Eq. (6).

$$R_i = \prod_{j=1}^{i-1} [1 - (1 - p_j)^{m_j}] \quad (6)$$

The probability that it completes every stage is P , calculated by Eq. (7).

$$P = \prod_i [1 - (1 - p_i)^{m_i}] \quad (7)$$

(2) Expected investment per commissioned project

We next estimated the investment required to deliver one successfully commissioned project while accounting for investments on unsuccessful developments. Let C_i be the investment required for one attempt at stage i . For reference, IC_0 is the direct investment in a commissioned project, calculated by Eq. (8). It provides a no-failure investment benchmark used to isolate the financing effect of development risk.

$$IC_0 = \sum_{i=1}^4 C_i \quad (8)$$

Across a portfolio of candidate projects, the expected investment $E[IC]$, required to deliver a commissioned project is calculated by Eq. (9).

The investment required for a project that proceeds through all four development stages is calculated by Eq. (9).

$$IC_0 = \sum_{i=1}^4 C_i \quad (9)$$

Where IC_0 is the total investment for a commissioned project, C_i denotes the investment committed at stage i .

Hence, the expected investment $E[IC]$ required to deliver one successfully commissioned project while also accounting for investments on failed developments is calculated by Eq. (10).

$$E[IC] = \frac{\sum_{i=1}^4 R_i C_i}{P} \quad (10)$$

(3) Equivalent risk-adjusted WACC from project finance perspective

Finally, we translated the additional expected investment arising from development failure into an equivalent risk-adjusted WACC. We assumed that investments on unsuccessful developments are fully recovered through the operating revenues of successfully commissioned projects over an operational lifetime of L years.

Let r_0 be the baseline WACC and r_{ad} the equivalent risk-adjusted WACC. Define the capital recovery factor (CRF) for discount rate r and lifetime L as Eq. (11). It converts a present investment into an equal annual capital-recovery requirement over L years.

$$CRF(r, L) = \frac{r(1+r)^L}{(1+r)^L - 1} \quad (11)$$

We assume that the development losses embedded in $E[IC]$ are recovered through the operating revenues of commissioned projects. The equivalent rate r_{ad} is therefore defined by the break-even condition of Eq. (12)

$$IC_0 \cdot CRF(r_{ad}, L) = E[IC] \cdot CRF(r_0, L) \quad (12)$$

Finally, Eq. (13) solves the break-even condition to calculate the r_{ad} , an equivalent financing metric representing the capital-recovery burden caused by both successful and unsuccessful development, rather than an observed market WACC.

$$r_{ad} = CRF^{-1} \left[\frac{E[IC]}{IC_0} CRF(r_0, L), L \right] \quad (13)$$

Downscaling National Transition Pathway to Project-level

In our study, we develop a downscaling method centered on the project-level multi-stage power project development model, to downscale national-level clean power transition scenarios into power plant development lists and national power transition capital mobilization schedules. Extended Data Fig.2 illustrates the procedure for developing such downscaling method framework. This downscaling method consists of three main steps: identifying the annual capacity requirements of newly commissioned power projects to achieve the national-level clean power transition scenario; determining the annually started project developments to meet this project commissioned target; and estimating project-finance-based capital allocation schedules based on the annually started project development list.

(1) Annually Commissioned Power Project

In the first step, this downscaling method back casts the deployments of power technologies by tracing their projected future capacity back to the current state, thus determining the annual capacity addition requirements of newly commissioned projects. In this study, the initial input comes from 120 scenarios derived from IPCC's scenarios²⁵ (SI section S2). These scenarios include the installed capacity data of various power technologies with 5-year time granularity. Considering the lifetime of different types of power plants (e.g., PV and onshore wind plants with 25 years and nuclear plant with 60 years), we calculate the annual requirements for newly commissioned capacity, accounting for the retirement of aging plants.

(2) Annually Started Power Project

In the second step, we use the project-level multi-stage power project development model to estimate when a new project development should start. First, we repeatedly simulate the development process of individual power projects using this project-level model until the cumulative capacity of successfully developed projects exceeds the annual commissioned

requirement. Second, based on the multi-stage development time and commissioned year of each project, we determine the start year of different development stages for each project, and thus obtain a project development list under the national-level power transition scenario. Finally, given that the capacity, stage-specific success rate, and development time of each project randomly fluctuate within a defined range, this step is repeated multiple times, and the average result is used to determine the final annual project development list (Figure S4).

(3) Project-finance based Capital Needs of Power Transition

In the third step, we calculate the project-finance-based capital mobilization schedule for achieving a clean power transition considering the multi-stage project development characteristics. First, we use the WL and AR(1) models to predict the future overnight cost and investment cost for stage-specific power plant development. Second, we calculate the annual project-finance-based capital needs across power projects and development stages, based on the foregoing annual project development list (Figures S5 and S6). Finally, considering the cost fluctuation noise and learning rate for each project also vary within a certain range, the above steps are repeated multiple times, and the average result is used to determine the capital mobilization schedule. To validate the developed downscaling approach, we compare our forecasts with China's historical annual capital need in power sector (Extended Data Fig.3 and Figures S7~S10). The correspondence between historical data and predictions indicates the robustness of this method.

Data availability

The power transition pathways data are available from the IPCC AR6 Scenarios Database, hosted at <https://data.ece.iiasa.ac.at/ar6/> (ref.²⁵). The source data for technology-specific power project development workflows, stage-specific development success rates and time requirements, and stage-specific development investments are provided in Methods and Supplementary Information.

Code availability

The code of the developed model is developed using Windows-based MATLAB 2022b software, through execution of the main file “project_level_CAPEX.m”. The code for the developed model is available via Code Ocean. Software Origin 2022 is used to visualize the results.

References

1. *WMO Global Annual to Decadal Climate Update*. (WMO, 2026).
<https://wmo.int/publication-series/wmo-global-annual-decadal-climate-update-2026-2028>
2. *World Energy Outlook 2024* (IEA, 2024).
<https://www.iea.org/reports/world-energy-outlook-2024>
3. *Energy system of China* (IEA, 2024). <https://www.iea.org/countries/china>
4. Sepulveda, N.A. et al. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule*. **2**, 2403-2420 (2018).
<https://doi.org/10.1016/j.joule.2018.08.006>
5. Klaaßen, L., & Steffen, B. Meta-analysis on necessary investment shifts to reach net zero pathways in Europe. *Nat. Clim. Change*. **13**, 58-66 (2023).
<https://doi.org/10.1038/s41558-022-01549-5>
6. Wang, Y. et al. Accelerating the Energy Transition towards Photovoltaic and Wind in China. *Nature*. **619**, 761-767 (2023). <https://doi.org/10.1038/s41586-023-06180-8>
7. Zhang, S., & Chen, W. Assessing the Energy Transition in China towards Carbon Neutrality with a Probabilistic Framework. *Nat. Commun.* **13**, 87 (2022).
<https://doi.org/10.1038/s41467-021-27671-0>
8. Tong, D. et al. Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5°C climate target. *Nature*. **572**, 373-377 (2019). <https://doi.org/10.1038/s41586-019-1364-3>
9. Liu, S. et al. China Reins in the Spiralling Construction Costs of Nuclear Power - What can Other Countries Learn? *Nature*. **643**, 1186-1188 (2025).
<https://doi.org/10.1038/d41586-025-02341-z>
10. Hu, P. et al. Comparative Analysis of Economic Feasibility in China's Power Transition Pathways. *Energy Conv. and Manag.* **344**, 120256 (2025).
<https://doi.org/10.1016/j.enconman.2025.120256>
11. Egli, F., Steffen, B., & Schmidt, T.S. A dynamic analysis of financing conditions for renewable energy technologies. *Nat. Energy*. **3**, 1084-1092 (2018).
<https://doi.org/10.1038/s41560-018-0277-y>
12. Battiston, S. et al. Accounting for finance is key for climate mitigation pathways. *Science*. **372**, 918-920 (2021). <https://doi.org/10.1126/science.abf3877>.
13. Ameli, N. et al. Higher cost of finance exacerbates a climate investment trap in developing economies. *Nat. Commun.* **12**, 4046 (2021). <https://doi.org/10.1038/s41467-021-24305-3>
14. Calcaterra, M. et al. Reducing the cost of capital to finance the energy transition in developing countries. *Nat. Energy*. **9**, 1241-1251 (2024). <https://doi.org/10.1038/s41560-024-01606-7>.
15. Lonergan, K.E. et al. Improving the Representation of Cost of Capital in Energy System Models. *Joule*. **7**, 469-483 (2023). <https://doi.org/10.1016/j.joule.2023.02.00425>.
16. Uden, S., Socolow, R., & Greig, C. Bridging Capital Discipline and Energy Scenarios. *Environ. Sci.* **15**, 3114-3118 (2022). <https://doi.org/10.1039/D2EE01244H>.
17. Pre-Development at Scale: Modeling Risk in Early-Stage Solar Development (PACES, 2025).
<https://www.paces.com/white-papers/pre-development-at-scale-modeling-risk-in-early-stage-solar-development>.
18. Greig, C., & Jenkins, J. *Princeton's Net-Zero America study - Annex M: Mobilizing Capital for the Transition* Princeton (Princeton University, 2021).

19. Jiangmen city government (Guangdong) announces suspension of the Heshan nuclear fuel project (People's Daily Online, 2013)
<http://politics.people.com.cn/n/2013/0715/c14562-22194186.html>
20. 2.4 GW New Jersey offshore wind project canceled by developer (Utilitydive, 2025).
<https://www.utilitydive.com/news/invenenergy-offshore-wind-energy-leading-light-wind/805451/>
21. Drews, M.C. et al. Assessment criteria and risk mitigation of hydrogeothermal energy portfolios for district heating. *Commun. Eng.* **4**, 138 (2025). [10.1038/s44172-025-00478-3](https://doi.org/10.1038/s44172-025-00478-3).
22. Schmidt, T.S. Low-carbon investment risks and de-risking. *Nat. Clim. Change.* **4**, 237-239 (2014). <https://doi.org/10.1016/10.1038/nclimate2112>.
23. Frilingou, N. et al. Regional impacts on decarbonisation under evolving financing conditions for energy technologies. *Nat. Commun.* **17**, 6611 (2026). [10.1038/s41467-026-73522-1](https://doi.org/10.1038/s41467-026-73522-1).
24. Fisch-Romito V. et al. Multi-country evidence on societal factors to include in energy transition modelling. *Nat Energy.* **10**, 460-469 (2025). [10.1038/s41560-025-01719-7](https://doi.org/10.1038/s41560-025-01719-7).
25. Byers, E. et al. AR6 Scenarios Database (IIASA, 2022). [2022. 10.5281/zenodo.5886911](https://zenodo.org/record/5886911)
26. Hatton, L. et al. Historical and future projected costs of capital for ten energy technologies across 176 countries. *Sci Data.* **12**, 1912 (2025). [10.1038/s41597-025-06177-0](https://doi.org/10.1038/s41597-025-06177-0).
27. *Coal transitions in China's power sector: A plant-level assessment of stranded assets and retirement pathways* (IDDRI, 2017)
28. *The Cost of Capital in Clean Energy Transitions* (IEA, 2021).
29. Rong, Y., Sun, X. Discount Rate of China's New Energy Power Industry. *Energy Eng.* **119**, 315-329 (2022). <https://doi.org/10.32604/EE.2022.015485>.
30. Steffen, B. Estimating the cost of capital for renewable energy projects. *Energy Econ.* **88**, 104783 (2020). [10.1016/j.eneco.2020.104783](https://doi.org/10.1016/j.eneco.2020.104783).
31. Wilson, C., Shrimali, G., & Caldecott, B. Financing costs and the competitiveness of renewable power. *iScience.* **28**, 113777 (2025). [10.1016/j.isci.2025.113777](https://doi.org/10.1016/j.isci.2025.113777).
32. Steffen, B. et al. A global dataset of the cost of capital for renewable energy projects. *Sci Data.* **12**, 1624 (2025). [10.1038/s41597-025-05912-x](https://doi.org/10.1038/s41597-025-05912-x).
33. *National Electricity Industry Statistics 2023* (National Energy Administration, 2024).
https://www.gov.cn/lianbo/bumen/202401/content_6928723.htm
34. *China's 2035 National Determined Contributions* (UNFCCC, 2025).
<https://unfccc.int/documents/497392>
35. Zheng, D. et al. Strategies for Climate-Resilient Global Wind and Solar Power Systems. *Nature.* **643**, 1263-1270 (2025). <https://doi.org/10.1038/s41586-025-09266-7>
36. Schill, W.P., Pahle, M., & Gambardella, C. Start-Up Costs of Thermal Power Plants in Markets with Increasing Shares of Variable Renewable Generation. *Nat. Energy.* **2**, 17050 (2017). <https://doi.org/10.1038/nenergy.2017.50>
37. Zhou, Y. Why is China going nuclear? *Energ. Policy.* **38**, 3755-3762 (2010).
<https://doi.org/10.1016/j.enpol.2010.02.053>
38. *China's Annual Report on CO₂ Capture, Utilization and Storage* (The administrative Center for China's Agenda 21, Global CCS Institute, and Tsinghua University, 2023).
39. Vergragt P.J., Markusson N., & Karlsson H. Carbon Capture and Storage, Bio-Energy with Carbon Capture and Storage, and the Escape from the Fossil-Fuel Lock-In. *Global Environ. Chang.* **21**, 282-292 (2011). <https://doi.org/10.1016/j.gloenvcha.2011.01.020>

40. Greig, C. et al. Speeding Up Risk Capital Allocation to Deliver Net-Zero Ambitions. *Joule*. **7**, 239-243 (2023). <https://doi.org/10.1016/j.joule.2023.01.003>
41. Schmidt, T.S. et al. Adverse effects of rising interest rates on sustainable energy transitions. *Nat. Sustain.* **2**, 879-885 (2019). [10.1038/s41893-019-0375-2](https://doi.org/10.1038/s41893-019-0375-2).
42. Lane, J., Greig, C., & Garnett, A. Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nat. Clim. Change*. **11**, 925-936 (2021). [10.1038/s41558-021-01175-7](https://doi.org/10.1038/s41558-021-01175-7).
43. *The Success of Global Energy Transitions Starts with Early-Stage Project Financing* (IRENA, 2025). <https://www.irena.org/News/articles/2025/Apr/The-Success-of-Global-Energy-Transitions-Starts-with-Early-Stage-Project-Financing>
44. *Project Preparation Facility* (GCF, 2026). <https://www.greenclimate.fund/projects/ppf>
45. *How to Unlock Pipelines of Bankable Renewable Energy Projects in Emerging Markets and Developing Countries?* (World Bank Group, 2024). <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099120623171525006>
46. *Developing Robust Project Pipelines for Low-Carbon Infrastructure* (OECD, 2018) https://www.oecd.org/en/publications/developing-robust-project-pipelines-for-low-carbon-infrastructure_9789264307827-en.html
47. *Preliminary investigations for ongoing offshore wind farm tenders in Denmark* (Energinet, 2025). <https://ens.dk/en/energy-sources/ongoing-offshore-wind-tenders/preliminary-investigations-ongoing-offshore-wind-farm>
48. *JOGMEC and ClassNK sign a Memorandum of Cooperation for accelerating Japan's Offshore Wind Development* (JOGMEC, 2023). https://www.jogmec.go.jp/english/news/release/release_00245.html
49. *The 2024 Annual Competitive Allocation Plan for Offshore Wind Power Projects in Shanghai* (Shanghai Development and Reform Commission, 2024). https://fgw.sh.gov.cn/fgw_gsgg/20240320/e032bebe7bfa45b09cae3ecd7fee36.html
50. Pye, S. et al. Technology Interdependency in the United Kingdom's Low Carbon Energy Transition. *Energy Strateg. Rev.* **24**, 314-330 (2019). <https://doi.org/10.1016/j.esr.2019.04.002>
51. Christensen, P. et al. How to Spend one Trillion Dollars: the US Decarbonization Conundrum. *Nature*. **634**, 1050-1052 (2024). <https://doi.org/10.1038/d41586-024-03474-3>
52. *Africa Energy Outlook 2022* (IEA, 2022). <https://www.iea.org/reports/africa-energy-outlook-2022>
53. *Financing Clean Energy in Africa* (IEA, 2023). <https://www.iea.org/reports/financing-clean-energy-in-africa>
54. *Renewable Energy Market Analysis: Africa and Its Regions* (International Renewable Energy Agency and African Development Bank, 2022). <https://www.irena.org/publications/2022/Jan/Renewable-Energy-Market-Analysis-Africa>
55. *Who is Financing Fossil Fuel Expansion in Africa?* (StopEACOP, 2022). <https://inis.iaea.org/records/rhtyp-cfh68>
56. Steffen, B. The Importance of Project Finance for Renewable Energy Projects. *Energy Econ.* **69**, 280-294 (2018). <https://doi.org/10.1016/j.eneco.2017.11.006>.
57. *Regulations on the Approval Procedures for Preliminary Work on Nuclear Power Plant Construction Projects* (National Energy Administration, 2012).

- https://www.nea.gov.cn/2012-01/04/c_131262765.htm
58. *Engineering Survey and Design Fee Schedule* (China Price Press, 2002).
 59. *Big Hydropower Development Approval and Stakeholder Analysis - A Case Study of the Nu River* (International Rivers, 2016).
<https://www.internationalrivers.org/wp-content/uploads/sites/86/2021/01/approval-process-for-large-hydropower-projects-and-analysis-of-their-stakeholders-compressed.pdf>
 60. *Land-Based Wind Market Report: 2023 Edition* (U.S. Department of Energy, 2023).
<https://www.energy.gov/eere/wind/articles/land-based-wind-market-report-2023-edition>
 61. *What Gets Measured Gets Financed: Climate Finance Funding Flows and Opportunities* (The Rockefeller Foundation, 2022).
<https://www.rockefellerfoundation.org/reports/what-gets-measured-gets-financed-climate-finance-funding-flows-and-opportunities/>
 62. *China's New Growth Pathway: From the 14th Five-Year Plan to Carbon Neutrality* (Energy Foundation China, 2020).
https://www.efchina.org/Attachments/Report/report-lceg-20201210/SPM_Synthesis-Report-2020-on-Chinas-CarbonNeutrality.pdf
 63. *China's Climate Transition: Outlook 2023* (CREA, 2023).
<https://energyandcleanair.org/publication/chinas-climate-transition-outlook-2023/>
 64. *Carbon Capture and Storage Policy in China* (Columbia University, 2013).
<https://doi.org/10.7916/D8DZ07H1>
 65. *Nuclear Power in China: its Role in National Energy Policy* (Oxford Institute for Energy Studies, 2023).
<https://www.oxfordenergy.org/publications/nuclear-power-in-china-its-role-in-national-energy-policy/>
 66. *Global Energy Monitor* (GEM, 2024). <https://globalenergymonitor.org/>
 67. Trancik, J.E. Testing and Improving Technology Forecasts for Better Climate Policy. *Proc. Nat. Acad. Sci. U.S.A.* **118**, e2109417118 (2021).
<https://doi.org/10.1073/pnas.2109417118>
 68. Meng, J. et al. Comparing Expert Elicitation and Model-Based Probabilistic Technology Cost Forecasts for the Energy Transition. *Proc. Nat. Acad. Sci. U.S.A.* **118**, e1917165118 (2021).
<https://doi.org/10.1073/pnas.1917165118>
 69. Way, R. et al. Empirically Grounded Technology Forecasts and the Energy Transition. *Joule*. **6**, 2057-2082 (2022). <https://doi.org/10.1016/j.joule.2022.08.009>

Acknowledgements

This research was supported by the National Key R&D Program of China (2023YFF0613900) (C.Z.), the National Natural Science Foundation of China (72571005, 72243012, T2600623) (C.Z., P.Z., P.H.), China National Petroleum Corporation-Peking University Strategic Cooperation Project of Fundamental Research (2024-2027), and High-performance Computing Platform of Peking University (C.Z.).

Author contributions

C.Z., C.G. and J.M. conceived the concept of this work. J.L., H.W. and Y.L. conducted the expert interviews to collect data. P.H. Y.J., and D.T. developed project-level development model and downscaling method. J. L., B.T. and P.Z. conducted the analyses. P.H. drafted the paper. C.Z. supervised and guided the project.

Competing interests

The authors declare no competing interests.

Additional information

Supplemental information includes sections S1~S7, Tables S1~S15 and Figures S1~S10. Extended data is available for this paper.

Figures in main text:

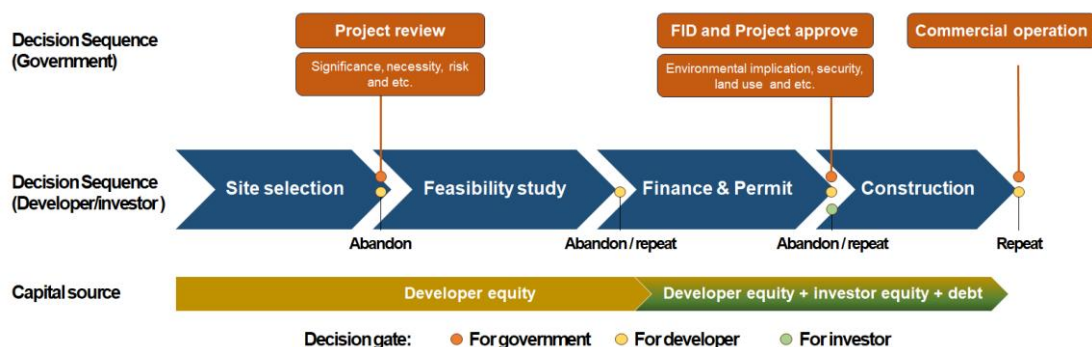


Figure 1 An illustrative decision-making sequence for real-world power plant project development. The dot between two stages indicates a decision gate, the color indicates the stakeholders (yellow representing the developer, green representing the investor, and orange representing the government). FID indicates the final investment decision. Modified versions of such investment decision sequence for different clean power plant projects are listed in Supplementary Information Note S2.

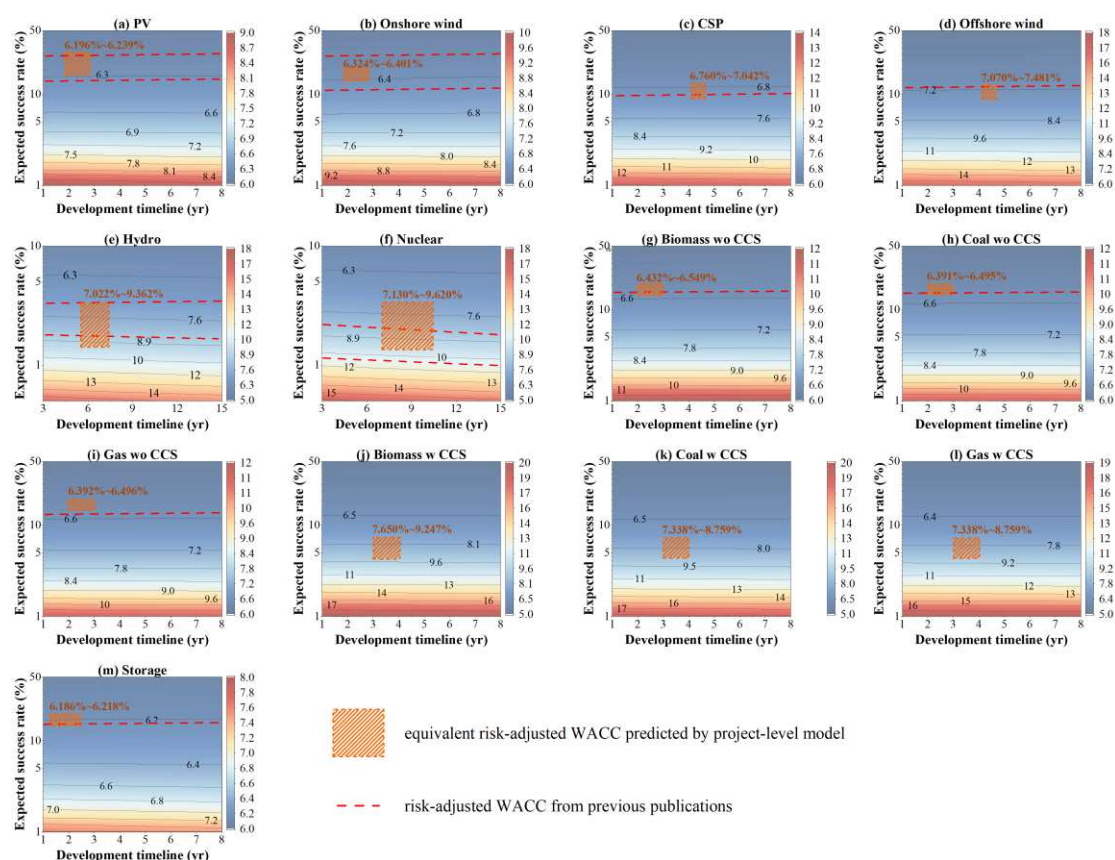


Figure 2 Function of risk-adjusted WACCs as the expected success rate and timeline for power project development. The equivalent risk-adjusted WACCs calculated from the project-level model (red shadowed block) are compared with the risk-adjusted WACC reported in previous publications

26-32 (yellow dotted line).

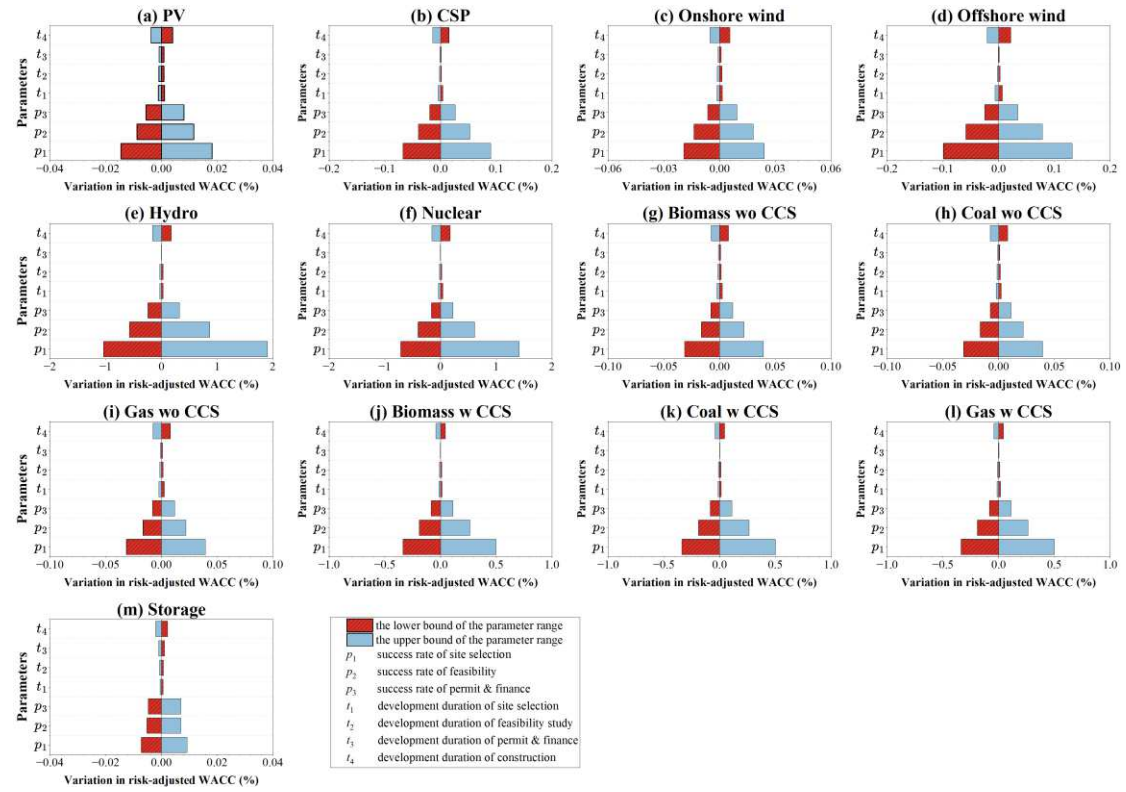


Figure 3 Impacts of multi-stage success rate and development duration on equivalent risk-adjusted WACCs of various power generation technologies. The baseline parameters are based on the mean values obtained from expert elicitation.

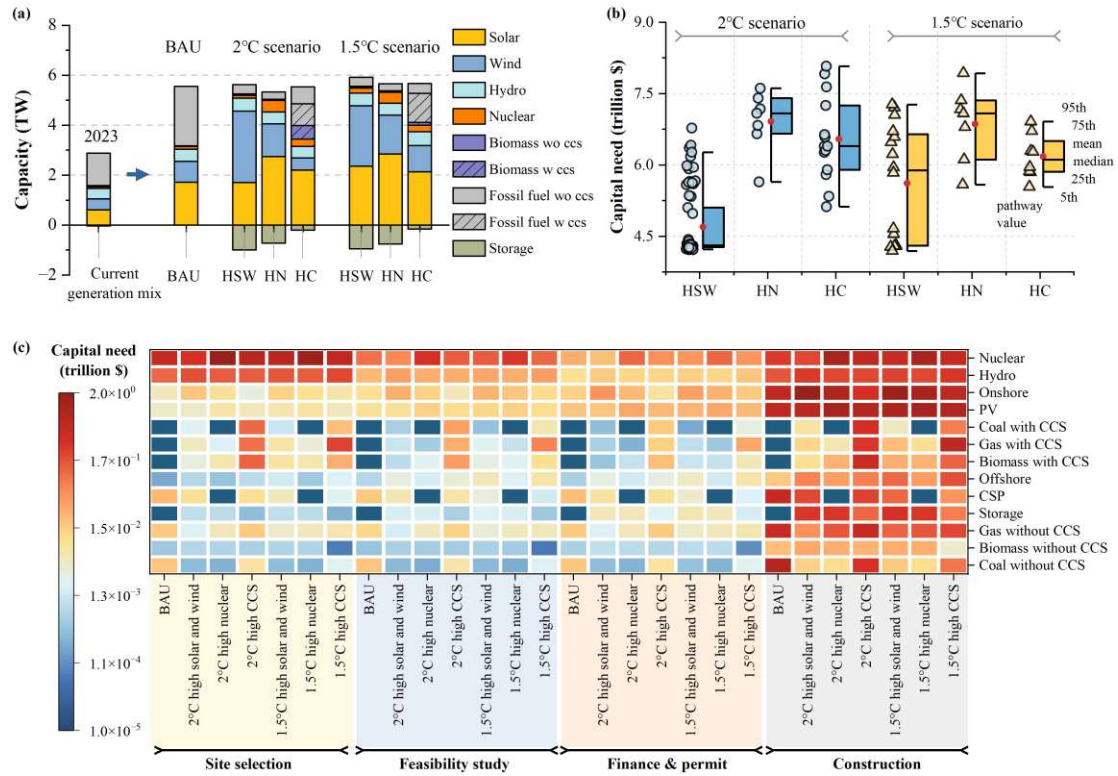


Figure 4 Financial consequences of project development risks scale from individual projects to transition pathways. (a) shows the future power generation mix of different power transition pathways under 2°C scenario and 1.5°C scenario extracted from 120 scenarios in the AR6 Scenarios Database²⁵. These scenarios are classified into four categories, namely BAU, high solar/wind, high nuclear, and high CCS. **(b)** compares the project-finance-based capital needs for the 120 transition scenarios. **(c)** breakdown the project-finance-based capital need by development stages, transition pathways and power technologies.

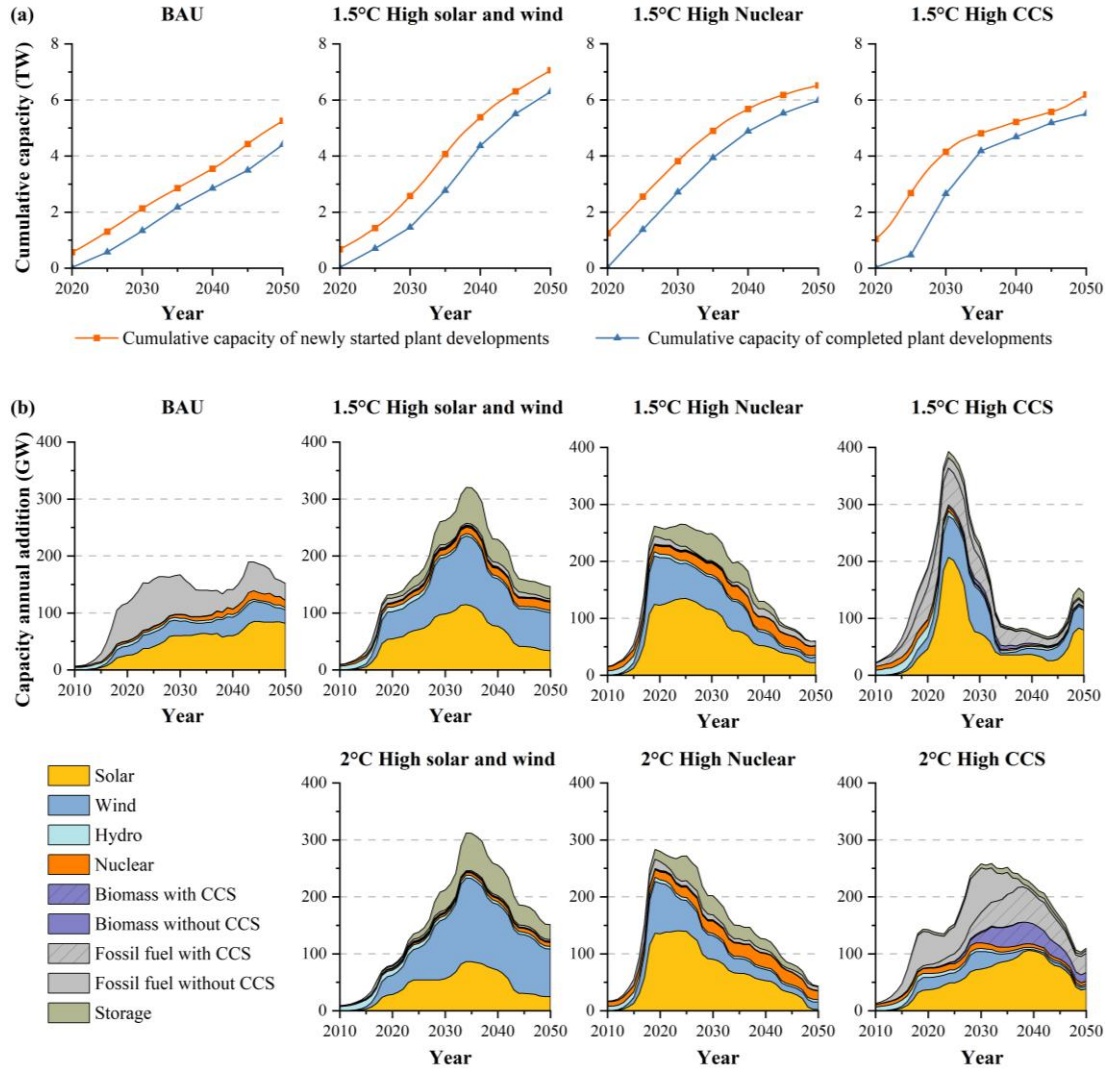


Figure 5 Cumulative and annual capacity addition of power plant projects initialization till 2050 in China. (a) Comparison of cumulative capacity for power projects at development starting years (orange cycle scatter line) and that at completed years (blue triangle scatter line). **(b)** Annual capacity addition and generation mixes for newly initialized power project development across various transition pathways.

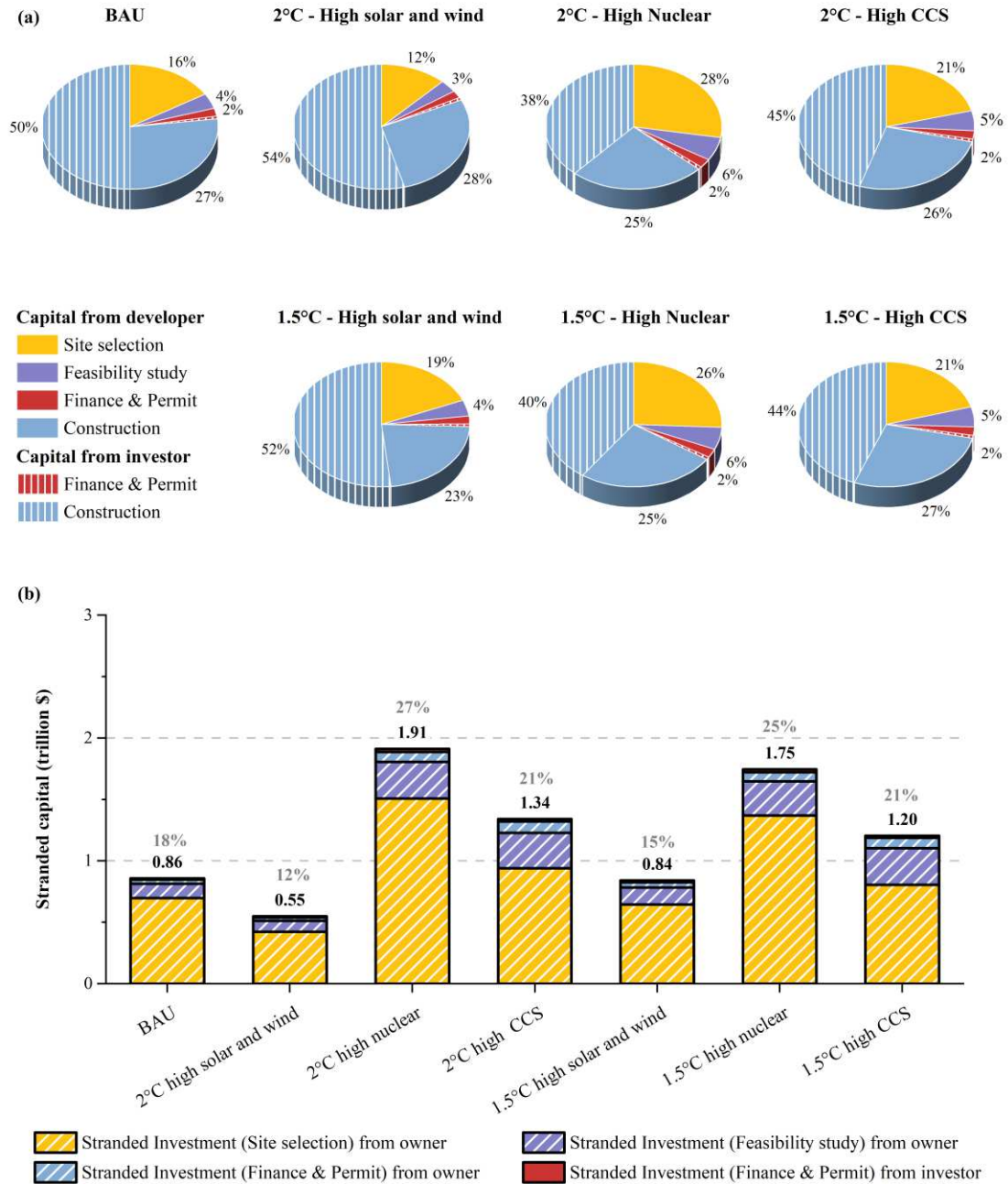


Figure 6 Decomposition of China's clean power transition capital needs by stage and stakeholder. (a) Distribution of developers' (solid fill) and investors' capital (hatched fill) within the overall capital needs across different stages of project development. (b) Stranded capital from developer (hatched fill) and from investor (solid fill) across various transition pathways.

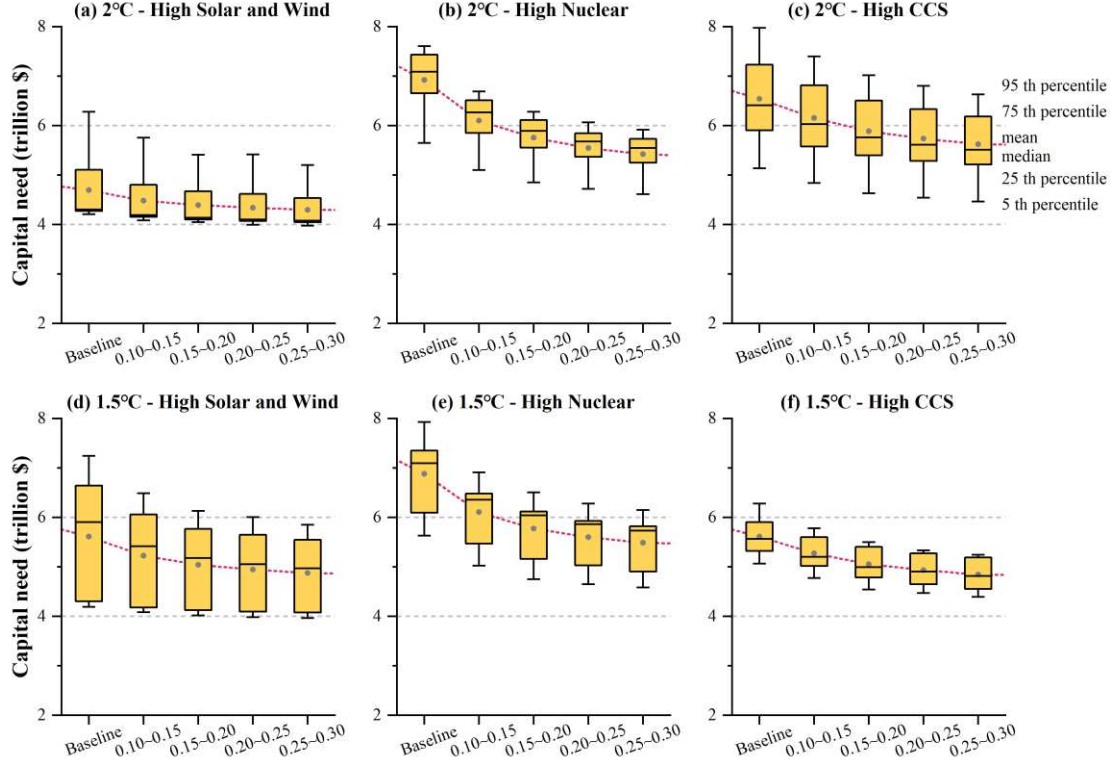
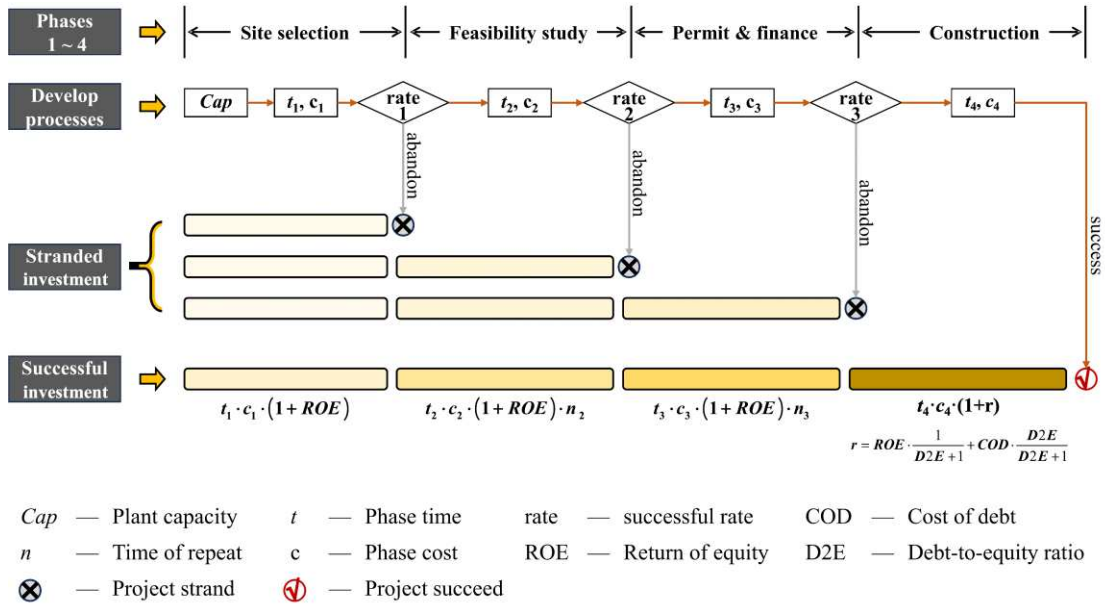
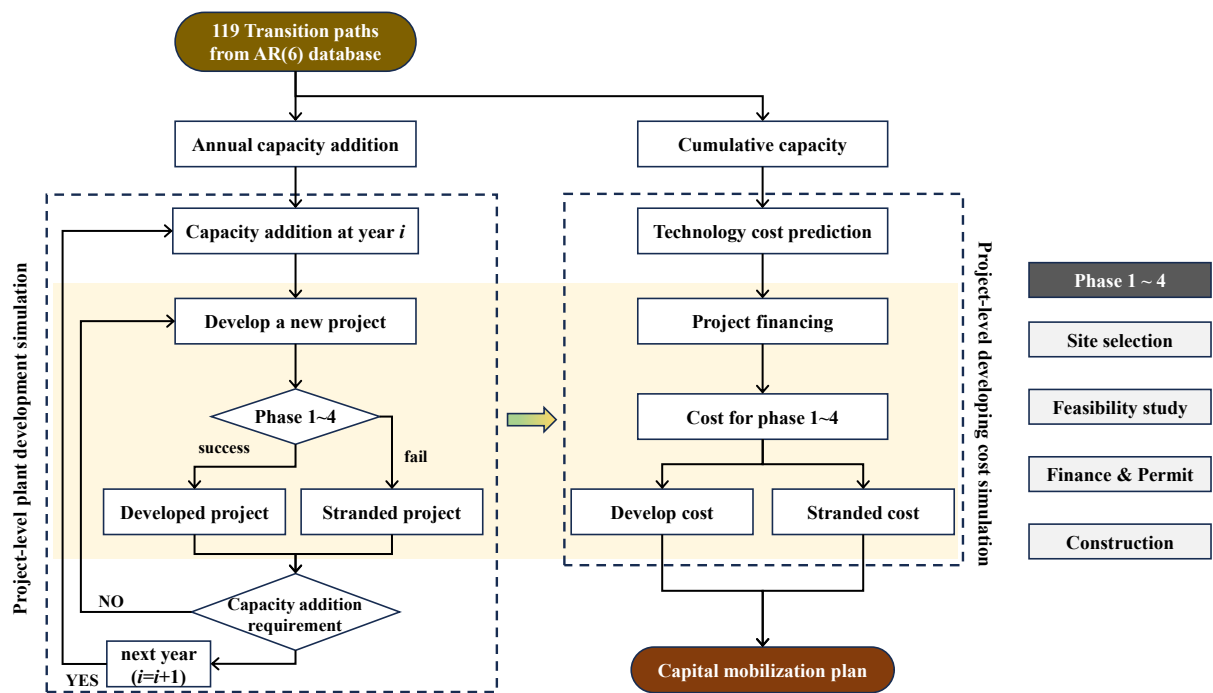


Figure 7 Impact of site-selection success rate on China's clean power transition capital need across different pathways. For baseline scenario, all technologies retain their current site-selection success rates; and for alternative scenario, technologies with lower success rates are raised to the threshold, while other technologies retain their higher rates.

Extended Data:



Extended Data Fig. 1 | Schematic of the proposed multi-stage power plant project development and capital investment model.



Extended Data Fig. 2 | Schematic of the clean power transition pathway downscaling framework. The framework starts from the model produced transition pathway, which contains the annual installed capacity for different power generation technologies. The dotted curve box shows the calculation method of the project-level multi-stage development model, which simulates development time, success, and multi-stage capital requirements for each project.

Supplementary Files

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