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# A Probabilistic Evaluation of China's Energy-Related Carbon Emission Peak Target

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ABSTRACT

In recent years, China has witnessed a surge in both its total primary energy consumption and its installed renewable energy capacity, which has had a profound impact on the nation's carbon emissions. The future trajectories of energy consumption and renewable energy development are fraught with uncertainties, and these will critically influence the realization of China's climate objectives, especially the goal of reaching a carbon peak. This research employs maximum likelihood estimation (MLE), in conjunction with Monte Carlo simulation and random sampling techniques, to assess the likelihood of China attaining its carbon peak and other climate targets under various scenarios. Additionally, it offers strategic policy recommendations to ensure the fulfillment of these environmental goals. In the baseline scenario, China must either surpass 4000 GW of installed non-fossil energy capacity before 2030 or maintain a total energy consumption below 6500 million tons of coal equivalent (Mtce) to align with its climate commitments. However, should the rate of reduction in energy intensity falter, leading to a total energy consumption exceeding 8250 Mtce before 2030, China may find it challenging to achieve all its climate ambitions.

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## 1. Introduction

Anthropogenic carbon dioxide emissions have emerged as a pivotal global concern toward climate change, which is manifesting in soaring temperatures, severe weather phenomena, and the rapid deterioration of ecosystems. The Paris Agreement, ratified in 2015, set a groundbreaking agenda for climate action beyond 2020, underscoring the critical need to confine global warming to well below 2.0 °C, with an aspiration to limit it to 1.5 °C. As the leading emitter of total carbon emissions in the world, China's efforts to mitigate its carbon output in response to climate change have garnered ongoing scrutiny from the global community. On September 22, 2020, China committed to strengthening its Nationally Determined Contributions (NDCs), implementing more robust policies and measures and aiming to reach a peak in carbon emissions before 2030 and achieve carbon neutrality before 2060 [1]. These objectives, collectively referred to as the "dual-carbon target," have emerged as a pivotal strategy influencing the trajectory of China's socio-economic development. To realize these ambitions, China has outlined its enhanced NDCs, which entail a more than 65% reduction in carbon dioxide emissions per unit of gross domestic product (GDP) before 2030 relative to 2005 levels, as well as an increase in the proportion of non-fossil fuels in China's primary energy consumption to approximately 25%.

As the target yeardraws nearer, China's imperative to reach its carbon peak intensifies. To achieve its dual-carbon target, China has ramped up its development of renewable energy, particularly bolstering its support for wind and solar power initiatives. As depicted in Fig. 1, China's additional installed capacity for wind and solar power reached a staggering 125 GW in 2022. By 2023, this number had surged to 290 GW, accounting for over half of the total renewable energy installed capacity in the world [2]. In 2024, China's expansion in solar and wind power capacity exceeded 350 GW, surpassing the 200-GW goal set forth in the National Energy Work Conference of that year [3].

In recent years, China has seen a stark rise in its total energy consumption. The Energy Production and Consumption Revolution Strategy (2016–2030), formulated by the National Development

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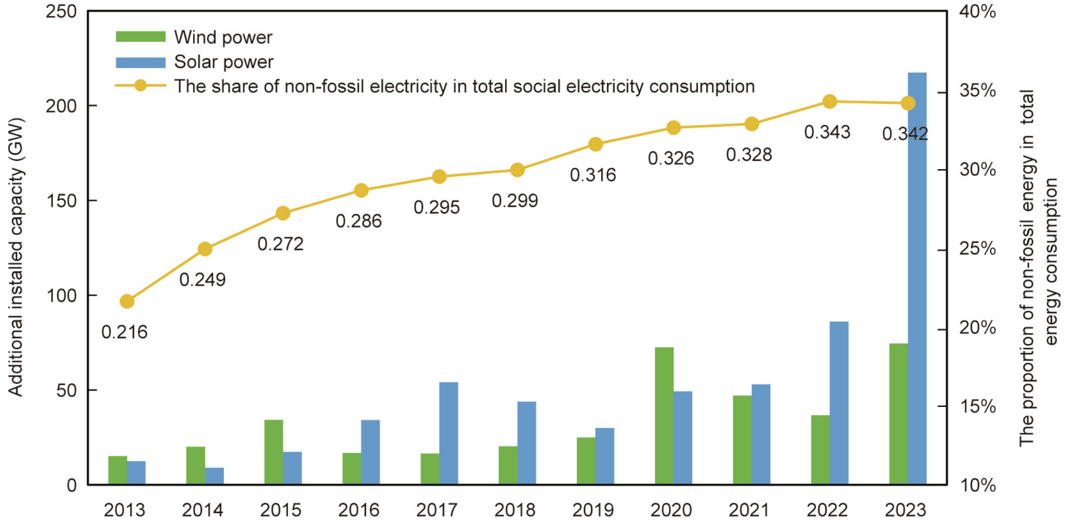

**Fig. 1.** China's additional installed capacity in wind and solar power from 2013 to 2023. Data source: compiled from publicly available data from the National Energy Administration of China.

and Reform Commission in conjunction with the National Energy Administration in 2017, aimed to limit China's total energy consumption to 6000 million tons of coal equivalent (Mtce) by the year 2030 [4]. As depicted in Fig. 2, from 2021 to 2023, China's annual increases in energy consumption stood at 276, 151, and 310 Mtce, respectively, translating to an average annual growth rate of 4.7%. By 2023, the total energy consumption had escalated to 5720 Mtce [5]. Although China has historically experienced a rapid decrease in energy intensity and has made considerable strides in this area, the rate of decline has decelerated, and—in certain instances—has even shown signs of reversing over the past few years. With the challenge of reducing energy intensity becoming more pronounced, it is likely that China's total energy consumption will continue its upward trajectory. Should the current growth rate of 4.7% continue unabated, China's total energy consumption is on track to surpass the initial 2030 target limit of 6000 Mtce as early as in 2025. By 2030, projections estimate that China's total energy consumption could reach around 7900 Mtce, which would present a formidable challenge to China's carbon reduction.

Confronted with the dual pressures of relentless economic growth and escalating energy consumption, China faces a trio of hurdles in its pursuit of its carbon peak targets: Firstly, the nation's annual electricity consumption has been on a steady ascent, increasing by approximately 600 TW·h in recent years, spurred by economic expansion and the growing trend of electrification in various end-use sectors. The expansion of non-fossil electricity generation has struggled to match the rapid increase in societal electricity demand. In 2023, the rise in non-fossil electricity accounted for just 38.4% of the overall growth in social electricity consumption, with non-fossil energy sources making up 34.2% of the total electricity consumed by society. Secondly, the peak load on China's power grids is rising at a rate of 100 GW·a$^{-1}$, demanding a significant boost in flexible power sources, which has inadvertently been largely met by coal power. Thirdly, the seasonal fluctuations in wind and solar power output necessitate an ongoing dependence on coal-fired power to balance China's electricity supply and demand. As a result, even with the rapid expansion of renewable energy capacity in recent years, coal power plants have continued to see an upswing in their electricity production.

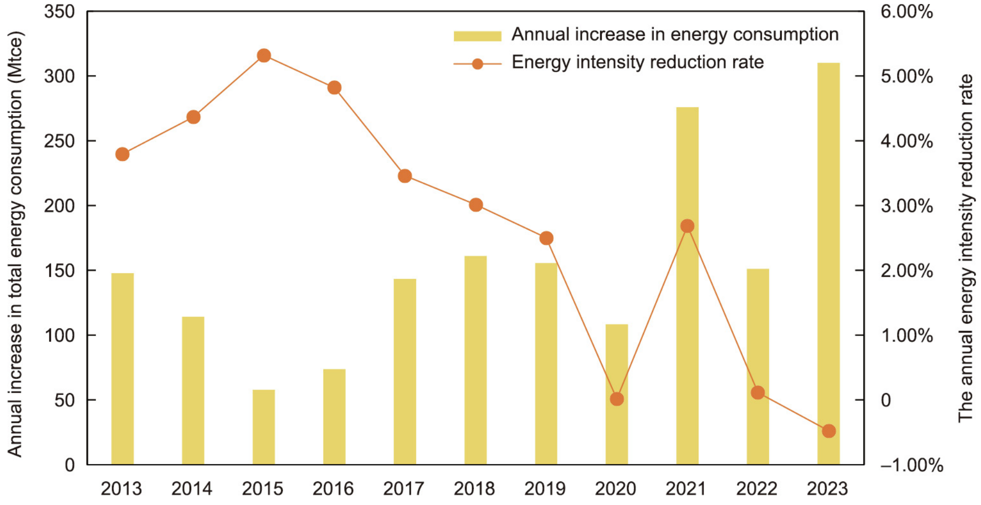

**Fig. 2.** Annual increase in total energy consumption in China from 2013 to 2023. Data source: compiled from publicly available data from the National Bureau of Statistics of China.

Energy-related carbon emissions have consistently made up the predominant share of China's total carbon emissions. According to the *First Biennial Update Report on Climate Change of the People's Republic of China* [6], energy activities accounted for 88.5% of national carbon emissions in 2005, while proportions of 86.2% and 86.8% were observed in 2020 and 2021, respectively. A robust correlation persists between energy consumption levels and carbon emissions from the energy system [7]. As decarbonization progresses within the energy system, the proportion of fossil fuels emerges as the principal determinant of systemic carbon emissions [8]. Renewable energy sources serve a dual function: They not only fulfill terminal energy demand but also displace fossil energy shares, thereby establishing themselves as the most viable strategy for achieving sustainable development [9]. Zheng et al. [10] employed quantile regression and path analysis on provincial data in China and revealed that a 1% increase in renewable energy deployment correlates with a 0.028%–0.043% reduction in carbon emission intensity. Therefore, China must persist in scaling up its installed capacity for non-fossil energy in order to realize its carbon peak objective. However, in the face of the triple challenges outlined above, China's energy consumption is poised to continue its upward trajectory. Looking ahead, China will grapple with two profound yet opposing sources of uncertainty: the potential for overestimated growth in total energy consumption and the swift advancement of renewable energy. The question of whether and how China can attain its carbon peak goal is a matter of significant interest. Total energy consumption is a mirror of China's energy needs for future development, while non-fossil energy consumption signifies the portion of total energy use that is free of carbon emissions, with the remainder being fossil energy consumption that generates carbon emissions. These two primary sources of uncertainty play a critical role in shaping the variability of China's future carbon emissions. This study employs a probabilistic analysis to assess the probability of China reaching its carbon peak and other climate objectives within the context of these dual uncertainties.

Numerous scholars have delved into the subject of China's carbon peak and its accompanying uncertainties. Zhang and Chen [11] mapped out the uncertainty of climate policy by developing four policy scenarios with different carbon peak years. They captured the uncertainty of technological advancement by assigning probability distributions to the costs associated with various technologies. These uncertainties were synthesized using a Monte Carlo method, augmented by Latin hypercube sampling, and incorporated into the China the integrated MARKAL–EFOM system (TIMES) model, which produced a range of potential pathways for China's energy transformation. Ma et al. [12] utilized a flexible chance-constrained programming approach to encapsulate the uncertainty of disrupting the energy supply–demand balance, integrating it as a constraint within a planning model. This approach yielded projections of China's future energy consumption and power installation mix across different levels of optimism. Yang and Qin [13] applied a back-propagation neural network to forecast future carbon emissions in China's civil aviation sector, establishing a parameter decline rate with discrete probabilities and conducting a Monte Carlo simulation to depict the uncertainty in future trends. Wang et al. [14] represented the uncertainty in energy demand with stochastic fuzzy parameters, which were then incorporated into a multi-objective optimization model, resulting in emission pathways for diverse sectors.

The current body of research on uncertainty largely relies on optimization models, producing relatively complex results. Moreover, the applicability of these methods to the specific challenges addressed in this study remains a point of contention. This study concentrates on the uncertainties stemming from overall energy consumption and the installation capacity of wind and solar power. The methodologies used in the literature exhibit limitations when applied to these specific issues, primarily in two critical aspects: Firstly, the uncertainty addressed in prior studies tends to be unidimensional, constrained by the complexity of the models and computational limitations; typically, only a single uncertain factor is represented probabilistically. While these models can yield intricate results by region or sector, such detailed data is not the primary concern from the standpoint of macro-level data and the fulfillment of national policy objectives. Secondly, the installed capacity of wind and solar power is usually an outcome of model optimization rather than a source of uncertainty. Optimization models typically target economic optimality to forecast the future capacities of wind and solar, which may not align with China's recent trends in renewable energy installation. Numerous studies have investigated the transition pathway of China's power system and predicted various capacities for renewable energy, all of which have proven to be more conservative than the actual figures, especially from 2022 onwards [15–19]. Currently, China's wind and solar installations are policy-driven, with the primary goal of meeting climate targets and facilitating energy transition, rather than minimizing total economic cost. To address these uncertainties in two dimensions and mitigate the computational complexity of the model, this study adopts a simplified research framework in lieu of optimization models that meticulously detail technical specifics and regional attributes. This approach enables the calculation of a greater number of sub-scenarios under broader uncertainty ranges. Moreover, the installed capacity of wind and solar power is treated as an input to the model, rather than an output, reflecting the actual national context of China. A probabilistic perspective is utilized to assess the impact of these two primary uncertainties on China's future energy consumption and carbon emissions. This method allows for a thorough evaluation of the probability of achieving a carbon peak and other climate targets under diverse scenarios.

The innovations and contributions of this paper can be summarized as follows: This study utilizes maximum likelihood estimation (MLE) in conjunction with policy-specific scenarios to quantify the uncertainties associated with future total energy consumption and non-fossil energy consumption in China. Probability distributions for each year up to 2035 are meticulously derived. By integrating a Monte Carlo simulation with random sampling techniques, this study computes the probabilities of China meeting all its climate targets before its target year. This probabilistic methodology enables a quantitative evaluation of the challenges in attaining various climate objectives and assesses the effect of different measures in increasing the likelihood of achieving these targets. Finally, drawing on comprehensive sub-scenario analyses that encompass a broad spectrum of uncertainties, this study offers strategic policy recommendations on how China can secure the fulfillment of its climate targets within the bounds of the considered uncertainty.

The structure of this paper is as follows: Section 1 provides the introduction, Section 2 outlines the methodologies employed in the study, Section 3 demonstrates the uncertainty modeling and parameter setting, Section 4 reveals the detailed calculation process, Section 5 presents and interprets the obtained results, and Section 6 draws the conclusions of the research.

## 2. Methodology

### 2.1. Conceptual framework for uncertainty modeling and probability calculation

The research framework is shown in Fig. 3. Uncertainties in total and non-fossil energy consumption can be modeled by a

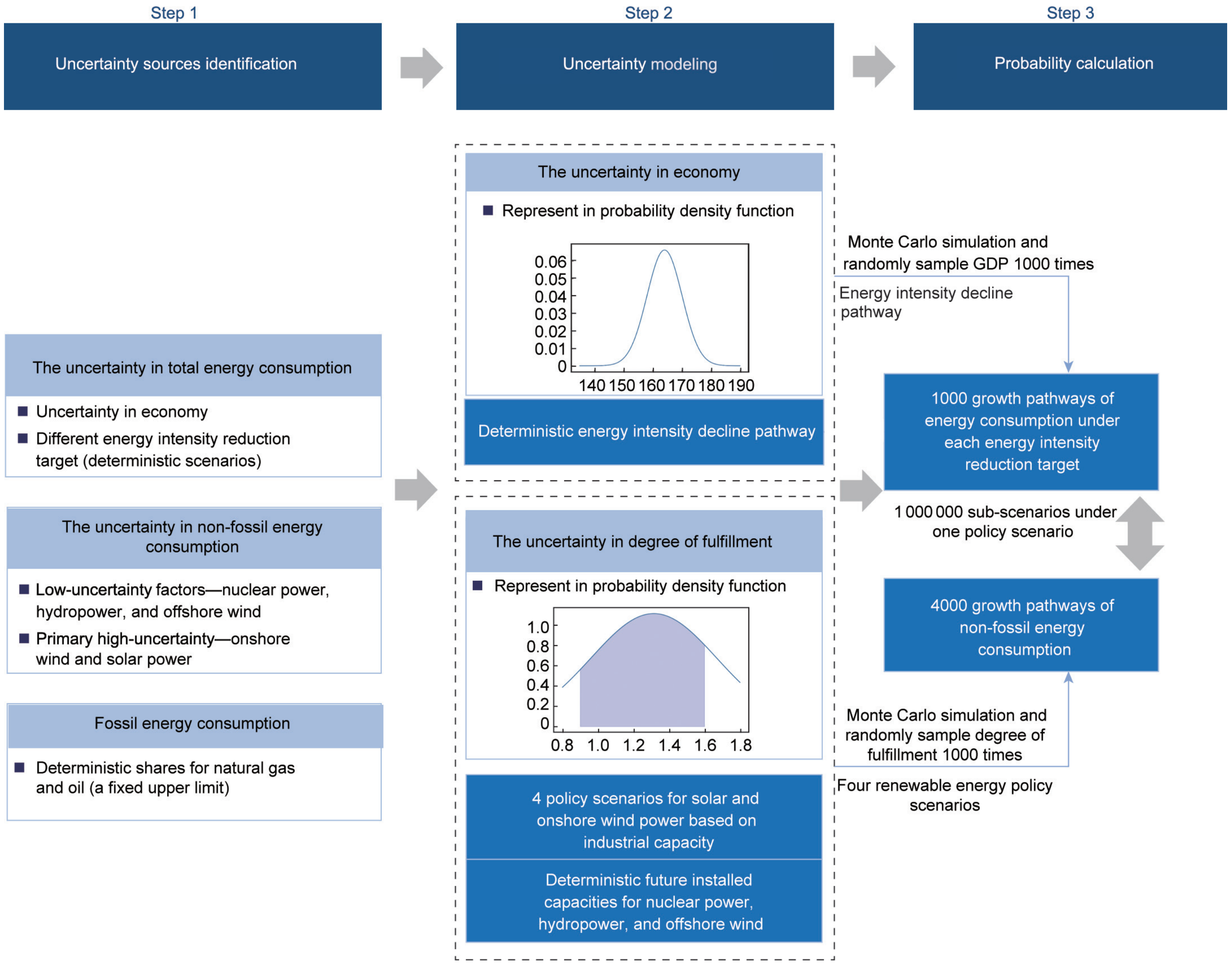

**Fig. 3.** The research diagram for this study.

probability density function combined with different policy scenarios. In this study, total energy consumption is calculated by multiplying GDP by energy intensity, and the annual additional installed capacity is calculated by multiplying policy target values by the degree of fulfillment. GDP value and degree of fulfillment are the main uncertainty sources described by probability density distribution functions. Four different wind and solar power installation policy scenarios with different target values are set, considering the industrial capacity of onshore wind power and solar power. For each sub-scenario, the parameters are determined by sampling from probability density distributions or pre-set values in different scenarios. The probability of achieving a carbon peak can be approximated by the ratio of the number of sub-scenarios that achieve a carbon peak to the total number of sub-scenarios.

Several major assumptions are used in this study: ① China's possible GDP value in 2030 is assumed to follow a normal distribution. ② The average economic growth rate from 2026 to 2030 is assumed to be 0.5% lower than that from 2024 to 2025; similarly, the rate from 2031 to 2035 is assumed to be 0.5% lower than that from 2026 to 2030. ③ The degree of fulfillment of China's renewable energy policy targets is assumed to follow a normal distribution. ④ The generated non-fossil electricity calculated by multiplying the installed capacity by the annual average operating hours is taken as the non-fossil energy consumption.

The mathematical approaches employed in this study are MLE and Monte Carlo simulation. Given the widespread and longstanding use of these methods, a concise overview is provided here, and detailed procedural steps are omitted. Readers seeking a more in-depth understanding are directed to the references cited below. A comprehensive breakdown of the calculation process will be presented in Section 3.4.

### *2.2. Maximum likelihood estimation*

The principle of MLE, initially proposed by Fisher in the 1920s [20], asserts that the optimal probability distribution is the one that makes the observed data as probable as possible. This concept translates to the task of finding the parameter vector that maximizes the likelihood function. The resulting parameter vector, identified through a search across the multi-dimensional parameter space, is referred to as the MLE estimate [21]. MLE is a prevalent technique in statistical inference, celebrated for its favorable statistical attributes, such as consistency and asymptotic normality [22].

In the context of this study, we assume that the distribution of GDP in 2030 and the levels of achievement of policy objectives adhere to normal distributions. These distributions are calculated using the MLE approach. Utilizing MLE enables us to estimate the parameters of these normal distributions that align most closely with the empirical data, thereby establishing a solid basis for further uncertainty assessments and forecasting exercises.

### 2.3. Monte Carlo simulation

A Monte Carlo simulation is a type of simulation that relies on repeated random sampling and statistical analysis to compute the results. This simulation method is closely related to random experiments for which the specific result is not known in advance [23]. It is widely used in the probabilistic analysis of engineering systems. In each experiment, the values of the input random variables are sampled based on their distributions, and the output variables are calculated using the computational model. Several experiments are carried out in this manner, and the results are used to compute the statistics of the output variables [24].

## 3. Uncertainty modeling

### 3.1. Uncertainty in total energy consumption

Multiple factors influence the total energy consumption of a nation, with economic development being widely recognized as the primary driver of growth in energy consumption [25,26]. Extensive research has employed diverse econometric models to examine the relationship between China's economic development and its total energy consumption. Many of these studies—using panel techniques [27], auto-regressive distributed lag [28], a multivariate model [29], or a bidirectional Granger causality using a vector error correction mode [30], panel methods [31], or cointegration tests [32]—suggest that, in the long run, a unidirectional Granger causality exists from economic development to energy consumption. This study quantifies uncertainties in future total energy consumption by integrating economic development uncertainties with energy intensity per unit of GDP.

#### 3.1.1. Uncertainty in economic growth

The dominant uncertainty stems from future economic development, while the energy intensity per unit of GDP can be mitigated through policy interventions and exhibits lower uncertainty. We aggregated GDP forecasts for China (2024–2030) from diverse institutions and studies [33–43]. The projected 2030 GDP value is modeled as a normal distribution, with parameters estimated using MLE. The corresponding probability density function is presented in Fig. 4, and the GDP projections from various institutions are shown in Fig. S1 in Appendix A.

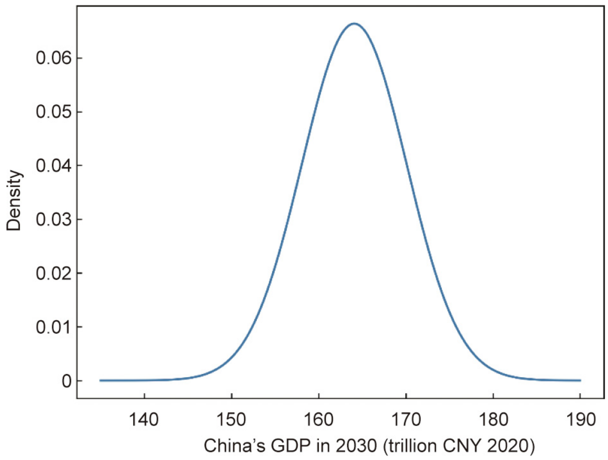

**Fig. 4.** Probability density function for China's GDP in 2030.

#### 3.1.2. The energy intensity decline pathway

Once the uncertainty range for economic growth is quantified, the total energy consumption range can be projected by integrating the economic growth uncertainty with a predefined energy intensity reduction pathway. The Chinese government's 14th Five-Year Plan set the target of reducing energy intensity (i.e., energy consumption per unit of GDP) by 13.5% by 2025 relative to the 2020 level [44]. However, from 2021 to 2023, the energy intensity decreased by only 2.25%. Achieving the energy intensity target in the 14th Five-Year Plan now appears challenging. Empirical studies demonstrate that energy intensity follows an exponential trend, reflecting a consistent decline in energy efficiency across economies. For accurate modeling, the starting point of the trend should align with the onset of the decline [45]. China's energy intensity has exhibited an overall downward trend since 2000, interrupted by a temporary rise between 2000 and 2005. Notably, the decline rate has slowed significantly in recent years compared with the rapid reductions observed around 2010. Consequently, this study adopts an exponential function to model energy intensity trends over the past decade, establishing the fitted trend as the baseline scenario. The fitted trend and historical energy intensity data are shown in Fig. S2 in Appendix A.

### 3.2. Uncertainty in non-fossil energy consumption

Given the variety of non-fossil energy sources, it is necessary to distinguish between low and high uncertainty factors in non-fossil energy consumption when modeling its uncertainty. This study focuses on five categories of non-fossil energy: nuclear power, hydropower, offshore wind power, solar power, and onshore wind power. Nuclear power, hydropower, and offshore wind power are categorized as low-uncertainty sources, with their future installed capacity governed by policy targets, resource availability, and production-capacity limits. Conversely, solar and onshore wind power are identified as the primary high-uncertainty sources due to their resource availability and production-capacity limits.

#### 3.2.1. Non-fossil energy sources with low uncertainty

Owing to constraints arising from resource availability, production-capacity limitations, and policy restrictions, the future growth trajectories of nuclear power, hydropower, and offshore wind power demonstrate limited uncertainty. Consequently, their future capacities are modeled as deterministic projections (Fig. S3 in Appendix A), thereby streamlining the uncertainty assessment of non-fossil energy consumption. Nuclear power expansion in China is strategically constrained by policy frameworks, resulting in a relatively stable annual installation rate compared with other non-fossil energy sources. The 14th Five-Year Plan Modern Energy System Planning emphasizes the "active, safe, and orderly development of nuclear power," prioritizing coastal projects under stringent safety protocols while maintaining a steady construction pace and rational project allocation [46]. By the end of 2023, China was operating 55 nuclear power units with a total installed capacity of 57.03 GW, alongside a further 29.75 GW under construction. Including approved projects, the total nuclear fleet encompasses 93 units, yielding a combined capacity of 101.44 GW. The projections align with current construction and approval trends: Operational installed capacity is expected to reach approximately 70 GW by 2025 [46], escalating to 90 GW before 2030, 130 GW by 2035, and 170 GW by 2040 [47,48]. At the 29th International Nuclear Engineering Conference, Wang Shoujun, the Chairman of the Chinese Nuclear Society, emphasized that China plans to approve 6–8 new nuclear units annually from 2022 to 2025, accelerating its capacity expansion [49]. These targets underscore China's commitment to methodical nuclear development through policy-driven infrastructure scaling.

Hydropower development in China is constrained by geographical resource limitations. According to the China National Energy Administration, the total installed hydropower capacity in 2023 reached 42.2 GW, of which 37.1 GW comprised conventional hydropower. Projections based on existing resource constraints indicate that conventional hydropower capacity will rise to 420 GW before 2030 [50]. China's total exploitable hydropower potential is approximately 687 GW, with the conventional hydropower capacity projected to increase to 530 GW by 2040 under planned development pathways [47,51].

Offshore wind power development in China faces constraints due to production capacity limitations. According to the *Global Wind Energy Report 2023* by the Global Wind Energy Association, China's annual offshore wind power production capacity is capped at about 16 GW, which is significantly lower than that of other non-fossil energy sources [52]. Consequently, uncertainties in deployment remain minimal. As of 2024, the offshore wind power projects slated for grid connection or construction amount to 16.65 GW. Provincial targets under China's 14th Five-Year Plan collectively aim for a cumulative offshore wind capacity exceeding 80 GW, with a national long-term target of 200 GW. The Global Wind Energy Association further forecasts a 72-GW increase in China's offshore wind capacity between 2024 and 2028 [53].

#### 3.2.2. Non-fossil energy sources with high uncertainty

This study identifies three key reasons for categorizing onshore wind and solar power as highly uncertain non-fossil energy sources, distinct from nuclear, hydropower, and offshore wind. First, unlike hydropower in China, which is constrained by the upper limits of resource availability, and nuclear power, which is restricted by site-selection limitations, wind and photovoltaic (PV) resources are abundant. The potential installed capacity for wind power can reach up to 2300 GW [54], while that for solar power ranges from 4700 to 39 300 GW [55]. In 2024, China's total installed wind power capacity was 521 GW and its total installed capacity of solar power was 887 GW, indicating substantial remaining development potential.

Second, unlike offshore wind, the manufacturing capacity of onshore wind and PV power in China is relatively high. Currently, the newly added wind installations in the domestic market approximately equal the production capacity, which will be elaborated in subsequent sections. China's PV production capacity far exceeds its installed capacity, with silicon wafer production reaching 753 GW, PV cell production 654 GW, and module production 588 GW in 2024 [56], far exceeding the annual domestic solar installations of 278 GW. This production capability ensures sufficient capacity to support rapid deployment increases.

Third, Chinese government policies strongly encourage the rapid development of wind and solar power. In contrast to the steady and orderly development required for nuclear power, the Chinese government has vigorously supported wind and solar expansion in recent years, although it may implement policies in the future to curtail installation rates in order to maintain stability and order. This combination of abundant resources, strong manufacturing capacity, and evolving policy frameworks creates inherent uncertainty in China's wind and solar power development trajectory.

Within this framework, uncertainty in solar and wind capacity projections is decomposed into two key dimensions: policy support level and policy target fulfillment. The policy support level reflects the anticipated capacity under existing policies and serves as a proxy for the government's commitment. The degree of fulfillment quantifies the divergence between actual installations and policy targets, assessing the extent to which objectives are exceeded or underachieved.

#### 3.2.3. Uncertainty in degrees of fulfillment

Historically, China's annual wind and solar power capacity additions have consistently exceeded policy targets. For example, in 2023, the national target for wind and solar installations was established at 160 GW; however, the actual installed capacity surpassed this target by 83%, reaching approximately 293 GW. This persistent discrepancy highlights the degree of fulfillment—defined as the ratio of actual to target capacity—as a critical source of uncertainty under predetermined installation targets. Table 1 documents China's renewable energy policy targets and their corresponding degrees of fulfillment from 2016 to 2023. Under the assumption that the historical degree of fulfillment follows a normal distribution, MLE is employed to estimate its parameters. The derived bounds for the degree of fulfillment range from 0.9 to 1.6 (Fig. 5) in this study.

#### 3.2.4. Uncertainty in policy levels

Uncertainty in non-fossil energy consumption, driven by policy support levels, is characterized through four distinct policy scenarios. These scenarios establish capacity targets for wind and solar power based on the projected growth potential of China's onshore wind and PV industries:

(1) **Aggressive development scenario (ADS)**. Driven by steep declines in wind and solar power generation costs and transformative breakthroughs in energy technologies, encompassing advanced system integration and large-scale storage solutions, the legacy energy infrastructure is rapidly phased out, while cutting-edge production capacity is deployed at an accelerated pace. The proliferation of artificial intelligence (AI) in the energy sector, coupled with systemic digital transformation, further facilitates the prioritized development of large-scale wind and solar power bases. AI-driven energy-intensive computing workloads exhibit nonlinear escalation, with electricity demand emerging as the dominant contributor to growth in energy consumption. This dynamic interplay between technological innovation and surging power demands propels the rapid expansion of China's wind and solar capacity deployment, establishing renewable energy as a critical enabler of both digital economy advancement and carbon mitigation objectives.

(2) **Business-as-usual scenario (BAU)**. Underpinned by moderate cost reductions in renewable electricity generation and incremental technological refinements in energy storage and grid adaptability, legacy energy systems experience gradual replacement, with next-generation capacity deployment progressing through a linear trajectory. Annual capacity additions grow at a reduced pace compared with ADS, reflecting limited adoption of cutting-edge innovations and slower optimization of supply chains. The selective adoption of AI in energy management, paired with partial digitalization initiatives, supports the steady but constrained development of regional wind and solar clusters. Concurrently, AI-induced growth in energy-intensive computing workloads gradually escalates, contributing to a proportional rise

**Table 1**
Degree of fulfillment for policy targets from 2016 to 2023.

| Year | Installed capacity of non-fossil energy | Wind and solar power share of electricity generation | Non-fossil share of energy consumption |
|---|---|---|---|
| 2016 | – | – | 1.023 |
| 2017 | – | – | 0.965 |
| 2018 | 1.245 | – | 1.000 |
| 2019 | – | – | – |
| 2020 | 1.702 | – | – |
| 2021 | 0.864 | 1.075 | – |
| 2022 | – | 1.129 | 1.006 |
| 2023 | 1.825 | 1.042 | – |

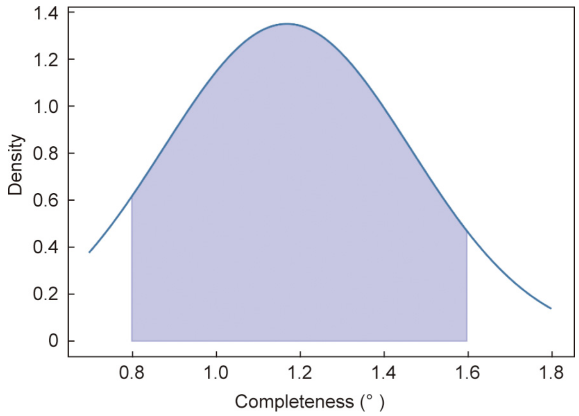

**Fig. 5.** Probability density function of the degree of fulfillment.

in electricity demand relative to broader energy consumption. This equilibrium between incremental innovation and demand-side evolution sustains renewable capacity expansion at a pace aligned with conventional grid modernization.

(3) **Below-expectation scenario (BES)**. Hampered by relatively low reductions in the cost of renewable energy technologies and fragmented advancements in storage technoeconomic viability, legacy energy systems persist due to suboptimal grid infrastructure investment, with next-generation capacity deployment constrained to relatively low growth rates. Inadequate grid infrastructure investment results in systemic renewable energy integration barriers, restricting annual wind and solar capacity expansion. The constrained integration of AI-driven optimization, combined with the technoeconomic immaturity of large-scale storage solutions, fails to address escalating challenges in intermittent renewable power absorption. This systemic inadequacy compels operators to rely disproportionately on fossil-fuel-based power plants, resulting in stagnation in renewable penetration rates and lower annual additional installed capacity targets.

(4) **Lower-bound scenario (LBS)**. This scenario is designed to illustrate China's carbon peak situation under particularly extreme conditions. Constrained by the stagnation in cost reductions for wind and solar power and a systemic lack of next-generation energy technology innovation, the annual installation capacity of wind and solar power remains at a persistently low level. As a result, there is a risk of delays in achieving China's carbon peak and carbon neutrality targets.

China's solar power production capacity has undergone rapid expansion in recent years, facilitating the unprecedented deployment of solar infrastructure. According to data from the Ministry of Industry and Information Technology, China's 2023 manufacturing outputs reached 622 GW for silicon wafers, 545 GW for solar cells, and 499 GW for PV modules [56], capturing over 85% of the global market share. This capacity suffices to support annual solar installations approaching 500 GW, with potential for further scale-up. Previous studies have systematically underestimated China's solar power growth trajectory, rendering their projections inadequate for guiding future installation targets. Notably, the International Energy Agency (IEA) has revised its forecasts upward annually since 2021. Its latest report projects China's annual solar power additions from 2024 to 2030 to range between 260 and 420 GW under a conservative baseline and between 340 and 470 GW in an accelerated deployment scenario [57]. Aligning with these projections and historical trends, this study establishes solar installation targets under the four policy scenarios outlined above.

Onshore wind power in China has exhibited steady growth in installed capacity in recent years, characterized by utility-scale project deployment and extended project cycles, which have collectively avoided significant overcapacity. As of 2022, China's domestic onshore wind supply chain had a total production capacity of approximately 70 GW. The market is projected to sustain annual installations of 70 GW in the near term (2024–2026), rising to 75 GW in 2027 and 2028 [53]. The IEA projects China's annual wind power additions from 2024 to 2030 to range between 70 and 80 GW (main case) or between 80 and 100 GW (accelerated case) [57]. Consequently, annual onshore wind capacity additions are anticipated to stabilize within 50–80 GW through 2030, marking a more conservative growth trajectory compared with the rapid expansion seen in solar power.

Fig. 6 shows the annual additional installed capacity targets for solar power and onshore wind power under the four policy scenarios from 2024 to 2035.

### *3.3. Other parameters without considering their uncertainty*

#### *3.3.1. Annual operating hours*

To estimate the annual electricity generation from non-fossil energy sources, the installed capacity of each technology is multiplied by its corresponding annual operating hours. Yearly operating hours for power generation technologies exhibit minimal interannual variability, with negligible impact on total annual electricity generation. Therefore, this study uses the 2023 annual average operating hours for each technology (Table S1 in Appendix A) to project future non-fossil electricity generation. For offshore wind power, the average operating hours are calculated from data for nine typical Chinese sea areas [58]. Here, annual non-fossil electricity generation is equated to annual non-fossil energy consumption—a common simplification in energy system modeling.

#### *3.3.2. Shares of oil and natural gas in total energy consumption*

After obtaining the annual energy consumption and non-fossil energy consumption, the proportion of each fossil energy consumption and its emission factor must be determined to calculate the yearly carbon emissions. The shares of oil and natural gas in the total energy consumption are determined according to reports by authoritative energy institutions and previous research, as shown in Table 2 [47,59–65]. The proportions of oil and gas used in this study are shown in Fig. S4 in Appendix A.

Table 2 reveals two perspectives in current studies regarding the future shares of oil and natural gas in China's total energy consumption. The first perspective suggests that the share of oil and natural gas will hover around 30% before 2030. By 2040, the share of oil is expected to decline while that of natural gas is expected to rise, making the combined share stable. The second perspective posits that the combined share of oil and natural gas will be approximately 25% before 2030, with a slight overall decline by 2040. The present study adopts a median trajectory, assigning combined oil and gas shares of 27% (2030) and 24% (2040). To mitigate uncertainties in total energy consumption arising from economic variability, upper bounds are imposed on oil and natural gas consumption. Fixed ratios in extreme scenarios may produce implausibly high levels, surpassing China's infrastructural capacities and reserve thresholds. Consequently, projected consumption exceeding 1.2 Gtce (oil) or 0.931 Gtce (natural gas; 700 billion $m^3$) is truncated to these ceilings to maintain realistic projections. The emission factors used in Eq. (1) are detailed in Table S2 in Appendix A [62].

## 4. Probability calculation

The probability calculation process is provided in this section. The calculation formula for total energy consumption is as follows:

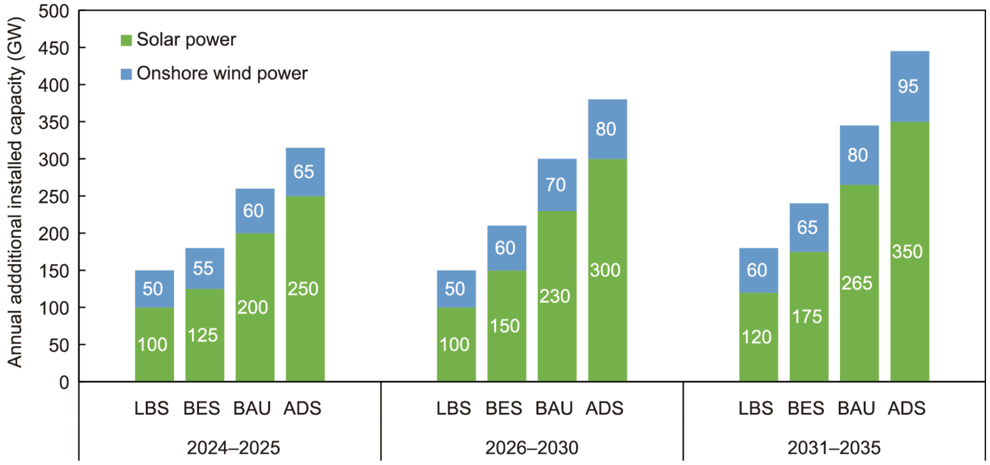

**Fig. 6.** Annual additional installed capacity targets under the four policy scenarios.

**Table 2**
Shares of oil and natural gas in China's total energy consumption in different studies.

| Reference | Oil in 2030 | Natural gas in 2030 | Oil in 2035 | Natural gas in 2035 |
|---|---|---|---|---|
| [59] | 18.2% | 12.0% | 16.2% | 13.5% |
| [60] | 17.0% | 11.0% | 15.5% | 12.0% |
| [49] | 15.7% | 10.6% | 14.0% | 11.4% |
| [61] | 20.9% | 10.8% | – | – |
| [62] | 19.0% | 11.0% | 16.5% | 13.5% |
| [63] | 14.6% | 10.3% | 13.0% | 11.0% |
| [64] | 17.3% | 13.0% | 17.2% | 12.9% |
| [65] | 20.0% | 10.0% | – | – |

$$E_t = \mathrm{GDP}_t \times \mathrm{EI}_t \tag{1}$$

where $E_t$ represents the total energy consumption in year $t$, $\mathrm{GDP}_t$ represents the GDP in year $t$, and $\mathrm{EI}_t$ represents the energy intensity per unit of GDP in year $t$. The GDP value in 2030 can be sampled from the distribution in Fig. 4.

The growth rate $a$ can be solved from this equation:

$$\mathrm{GDP}_{2021} \times (1 + a)^5 \times (1 + a - 0.005)^5 = \mathrm{GDP}_{2030} \tag{2}$$

For each 2030 GDP value sampled from the distribution, the annual GDP from 2024 to 2035 can be calculated, and the total yearly energy consumption from 2024 to 2030 can be obtained by combining the annual decline rate of the energy intensity decline pathway. The GDP in 2035 can be calculated by applying the $a$ value obtained through Eq. (3).

$$\begin{aligned}\mathrm{GDP}_{2035} = \mathrm{GDP}_{2021} \times (1 + a)^5 \times (1 + a - 0.005)^5 \\ \times (1 + a - 0.01)^5\end{aligned} \tag{3}$$

The GDP value in 2030 will be sampled 1000 times, and 1000 economic growth pathways will be derived. The uncertainty range of the total energy consumption can be calculated by combining the 1000 economic growth pathways with the energy intensity decline pathway described in Section 3.1.2.

The calculation formula for the installed capacity of solar power and onshore wind power is shown in Eq. (4):

$$\mathrm{IC}_{i,t} = \mathrm{IC}_{i,2023} + \sum_{i=2024}^{t} S_{i,t} \times \alpha_{i,t} \tag{4}$$

where $i$ represents the technology (solar power, onshore wind power); $\mathrm{IC}_{i,t}$ is the installed capacity of technology $i$ in year $t$; $S_{i,t}$ is the additional installed capacity target of technology $i$ in year $t$; and $\alpha_{i,t}$ is the target degree of technology fulfillment in year $t$. The main uncertainty in China's wind and solar installed capacity comes from the choice of additional installed capacity targets and the degree of fulfillment.

$S_{i,t}$ is set in Fig. 6, and the degree of fulfillment $\alpha_{i,t}$ is sampled from the distribution in Fig. 5. Each $\alpha_{i,t}$ is sampled 1000 times. By combining $\alpha_{i,t}$ with the four renewable energy scenarios, 4000 pathways of future solar power and onshore wind power are derived.

China's non-fossil energy consumption can be calculated by summing all the electricity generated by non-fossil energy sources, as shown in Eq. (5):

$$E_{\text{non-fossil},t} = \sum_{s} \mathrm{IC}_{s,t} \times H_s \tag{5}$$

where $E_{\text{non-fossil},t}$ represents the non-fossil energy consumption in year $t$; $s$ represents the non-fossil energy sources (solar power, onshore wind power, offshore wind power, nuclear power, or hydropower); and $H_s$ represents the annual average operating hours for non-fossil energy sources $s$, as shown in Table 2.

By combining the energy intensity baseline scenario with one renewable energy scenario, 1000 energy growth pathways with 1000 non-fossil energy consumption growths lead to the derivation of 1 000 000 sub-scenarios. For each sub-scenario, the oil and nature gas consumption can be calculated by the ratios in Fig. S4, and the coal consumption can be calculated by Eq. (6).

$$E_{\text{coal},t} = E_{\text{total},t} \times (1 - r_{\text{oil},t} - r_{\text{gas},t}) - E_{\text{non-fossil},t} \tag{6}$$

For each sub-scenario, the carbon emissions in each year can be calculated by Eq. (7).

$$C_t = \sum_{f=\text{coal,oil,gas}} E_{f,t} \times F_f \tag{7}$$

where $C_t$ represents the carbon emissions in year $t$; $f$ represents the three fossil-fuel energy sources (coal, oil, and natural gas); and $F_f$ is the carbon emission factor for the fossil-fuel energy sources $f$.

The electricity consumption can be calculated using Eq. (8).

$$P_t = E_{\text{non-fossil},t} + E_{\text{coal},t} \times K_t \times c \tag{8}$$

where $P_t$ represents the total electricity consumption in year $t$, $K_t$ represents the proportion of coal used for power generation, and $c$ is a conversion factor for coal to electricity (300 g of standard coal per kilowatt-hour).

For each sub-scenario, all carbon emission and energy consumption values from 2024 to 2035 can be calculated. Therefore, it can be determined whether a sub-scenario can achieve specific climate targets, such as reaching a carbon peak before the target year. The probability of achieving a carbon peak is quantified as the proportion of sub-scenarios that meet this target relative to the total number analyzed. This ratio provides a probabilistic evaluation of China's trajectory toward reaching a carbon peak.

## 5. Results and analysis

### 5.1. The uncertainty range considered in this study

The uncertainty ranges for future economic growth and the corresponding energy consumption under the energy intensity baseline scenario are illustrated in Figs. 7 and 8, respectively. After sampling from the distribution in Fig. 5, 1000 times and combining these with the different renewable energy policy levels in Fig. 6, the uncertainty range for the capacities of solar power and onshore wind power can be derived. Taking the other non-fossil energy sources into consideration, the uncertainty ranges for non-fossil energy consumption under the four policy scenarios can be calculated, as shown in Fig. 9. The specific values of the four uncertainty ranges are shown in Table S3 in Appendix A.

Within the uncertainty range considered in this study, the 2030 uncertainty ranges under the four policy scenarios for the installed solar power capacity are 2500–3600, 2000–3000, 1500–2100, and 1200–1700 GW, respectively. Those for the installed capacity of onshore wind are 850–1200, 800–1100, 750–1000, and 700–900 GW, respectively, and those for the non-fossil energy consumption are 2400–2900, 2200–2550, 1950–2250, and 1750–2000 Mtce, respectively. Minor fluctuations in uncertainty boundaries (generally below 50 GW or below 50 Mtce) are addressed by rounding values to appropriate significant figures, thereby preserving analytical rigor while reflecting inherent variability.

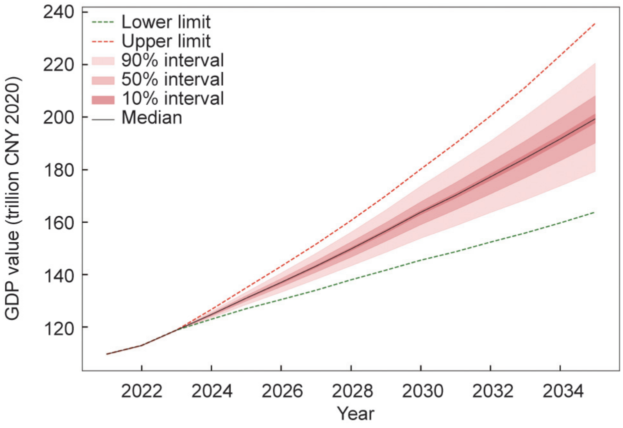

**Fig. 7.** Uncertainty range for economic development in China from 2024 to 2035.

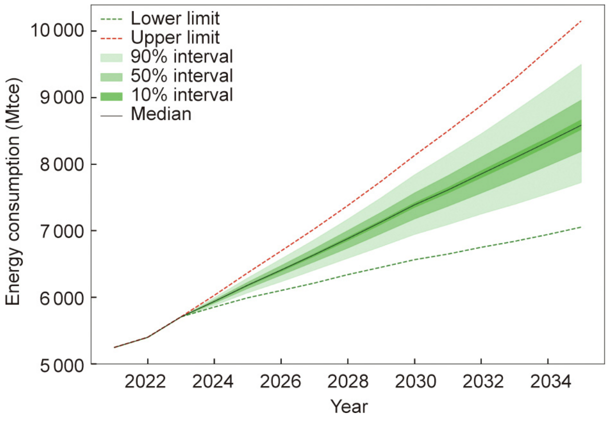

**Fig. 8.** Uncertainty range for total energy consumption in China from 2024 to 2035.

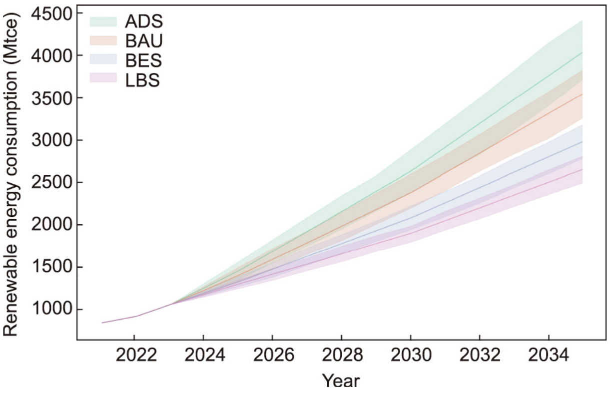

**Fig. 9.** Uncertainty ranges for non-fossil energy consumption under the four policy scenarios.

### 5.2. Impact of renewable policy on the probability of achieving a carbon peak

The carbon emission ranges for the four renewable energy scenarios are depicted in Fig. 10. Each plot illustrates the probabilistic distributions of carbon emissions, with color gradients distinguishing the 90%, 50%, and 10% probability intervals for sub-scenario emissions. As demonstrated in Fig. 10, the 90% probability ranges for peak emissions vary significantly across scenarios, at 12.21–12.61 Gt (ADS), 12.29–12.74 Gt (BAU), 12.41–13.46 Gt (BES), and 12.45–14.35 Gt (LBS). These results reveal a consistent trend: Scenarios implementing stricter renewable energy policies (e.g., ADS) demonstrate narrower and lower peak emission ranges than those with more lenient targets (e.g., LBS). This result underscores the necessity of prioritizing aggressive renewable energy adoption in order to mitigate carbon emission levels effectively.

Fig. 11 depicts the probabilities of achieving a carbon peak across different time periods under the four policy scenarios. The probability of meeting the 2030 target can be calculated by adding the probabilities of "2025 and before" to those of "2026–2030." Under the LBS, the probability of reaching a carbon peak before the target year is 0.776, signifying that 77.6% of the 1 000 000 simulated pathways would attain this milestone if China adheres to LBS-defined solar and onshore wind deployment levels. This probability escalates to 0.905 for the BES, 0.991 for the BAU, and 0.999 for the ADS, exhibiting a positive correlation between policy support level and the probability value. However, the probability result identifies diminishing marginal returns: Increasing policy ambition beyond BAU (e.g., transitioning to ADS) produces a

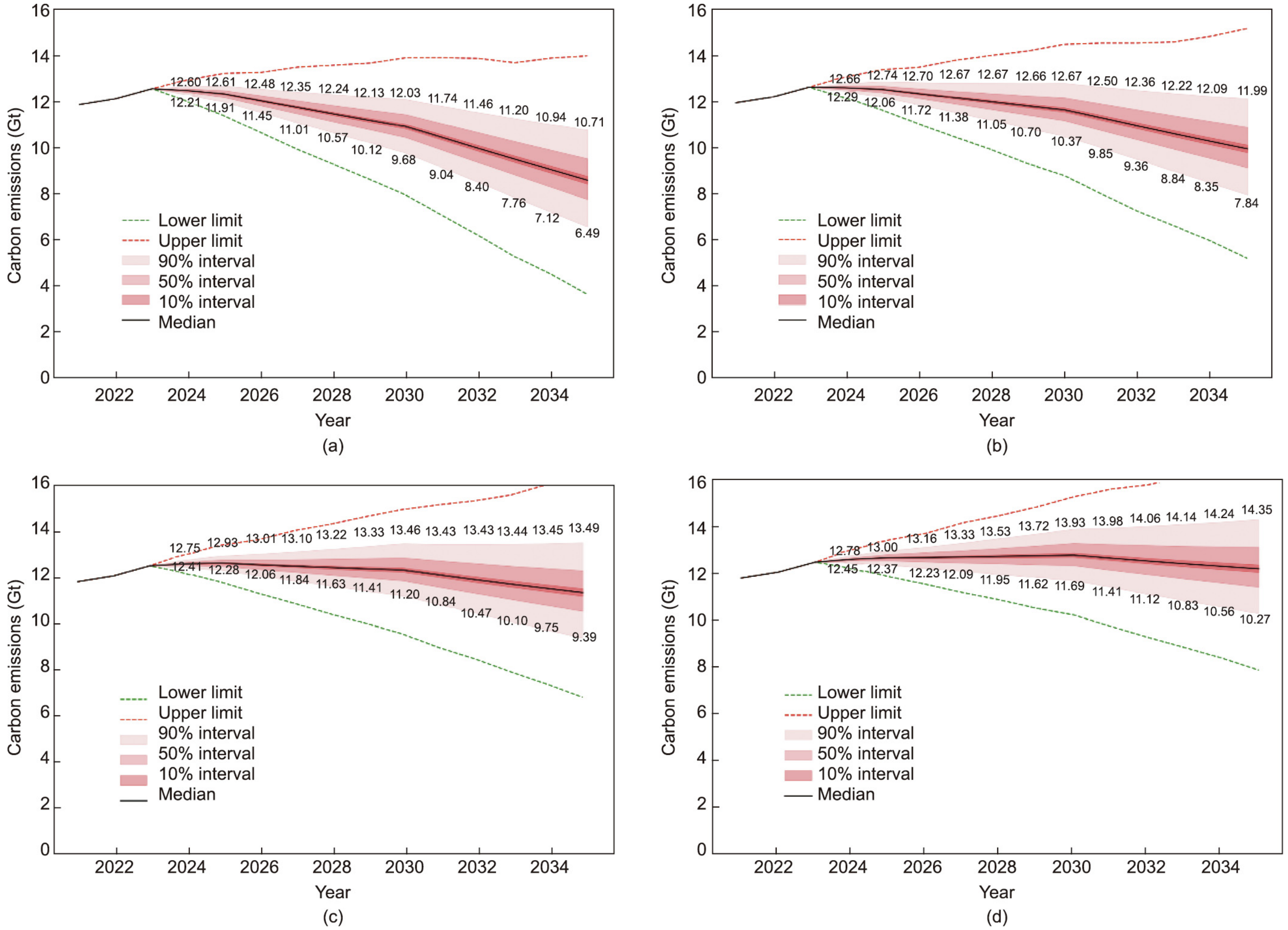

**Fig. 10.** Probability ranges of achieving a carbon peak during different periods under the four policy scenarios: (a) ADS; (b) BAU; (c) BES; and (d) LBS.

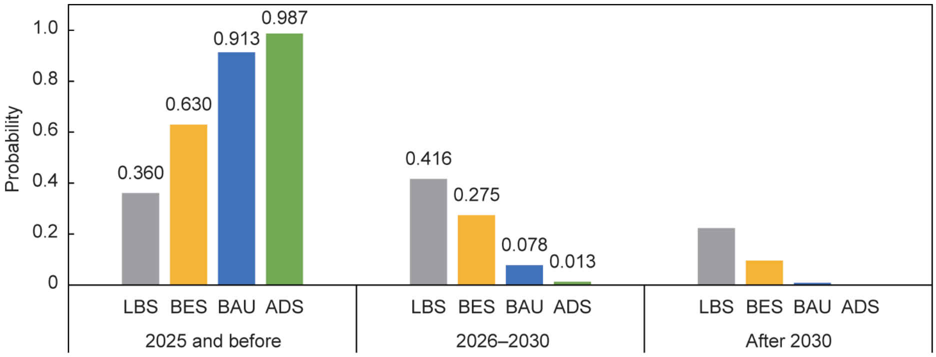

**Fig. 11.** Probabilities of achieving a carbon peak during different periods under the four policy scenarios.

negligible 0.008 increase in probability, implying that substantial renewable energy investments for incremental gains may represent economically suboptimal pathways.

Fig. 11 further demonstrates that stricter renewable energy policies are associated with earlier carbon peak timelines. For example, the probability of reaching a carbon peak by 2025 rises from 0.360 under LBS to 0.987 under ADS, highlighting the temporal benefit of rapid renewable energy adoption.

Fig. 12 plots the 2030 installed capacity of non-fossil energy (GW, *x*-axis) against the 2030 total energy consumption (Mtce, *y*-axis) to depict the carbon peak outcomes. Each data point corresponds to a sub-scenario, with a color scale indicating the associated carbon peak year.

The uncertainty range for China's total energy consumption in 2030 is 6300–8100 Mtce under the energy intensity decline pathway described in Section 3.1.2. Under the ADS, almost all the sub-scenarios with a total energy consumption in 2030 below 8000 Mtce lead to the achievement of a carbon peaktarget. The carbon peak results of the ADS indicate that, within the considered uncertainty range of total energy consumption uncertainty, achieving an installed capacity of non-fossil energy of over 4000 GW before 2030 and maintaining the support level in the ADS after

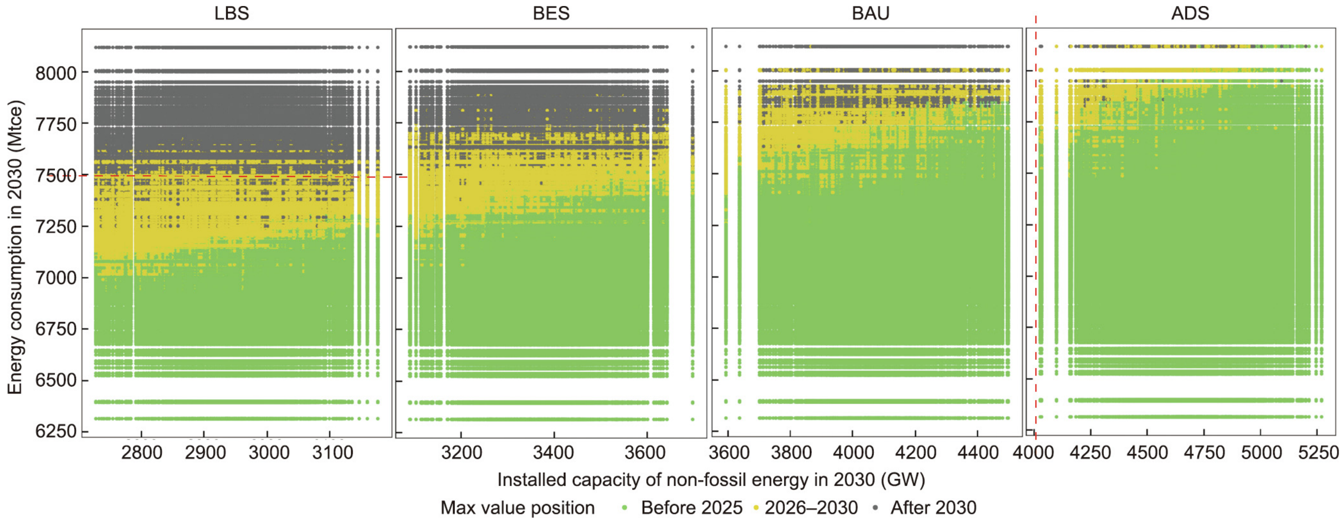

**Fig. 12.** Carbon peak results for all sub-scenarios under the four scenarios.

2030 ensures that China will achieve the peak target. For the LBS scenario, which presumes limited non-fossil energy deployment, achieving a carbon peak with no less than 2700 GW of installed capacity of non-fossil energy before 2030 requires keeping the total energy consumption below 7500 Mtce before 2030. As of 2024, China's installed capacity of non-fossil energy was 1904 GW, and the nation's total energy consumption in 2024 was about 5970 Mtce.

### *5.3. The probability of achieving other climate targets for 2030*

China has set other climate targets for 2030 (NDCs), which include reducing the nation's carbon emission intensity per unit of GDP by over 65% from 2005 levels and increasing the non-fossil energy share of China's total energy consumption to exceed 25%. This study assesses the attainability of these targets under dual uncertainties in energy demand and policy execution. Fig. 13 quantifies the probabilities of achieving both targets, while Fig. 14 delineates scenario-specific fulfillment outcomes.

As evidenced in Fig. 13, the carbon intensity and non-fossil energy share targets are consistently met under the ADS and BAU. Conversely, the LBS exhibits a probability of only 0.334 of achieving both targets simultaneously. Crucially, no sub-scenarios within the four policy frameworks satisfy the carbon intensity target without concurrently meeting the non-fossil energy share requirement. This result emphasizes that the carbon intensity target imposes a stricter constraint than the non-fossil energy share target. When carbon intensity reductions are achieved, the non-fossil energy share target is inherently fulfilled. Thus, prioritizing carbon intensity mitigation emerges as a strategic imperative for China to ensure compliance with both objectives.

Fig. 14 shows details of the climate target results under the four policy scenarios. Each point in this plot represents a sub-scenario, and the color of each point represents the fulfillment of different targets.

Fig. 14 demonstrates that achieving China's 2030 carbon emission intensity and non-fossil energy share targets within the modeled uncertainty range of its total energy consumption necessitates a non-fossil energy installed capacity of over 3900 GW before 2030. Notably, this capacity threshold is lower than that required to guarantee reaching a carbon peak. If such a high capacity proves infeasible, the scenario with a minimum non-fossil energy installed capacity of 2700 GW before 2030 requires the total energy consumption to remain below 6500 Mtce in order to meet both targets—a more stringent constraint than that for reaching a carbon peak. Under the BES, limiting China's total energy consumption below 7000 Mtce while deploying more than 3100 GW

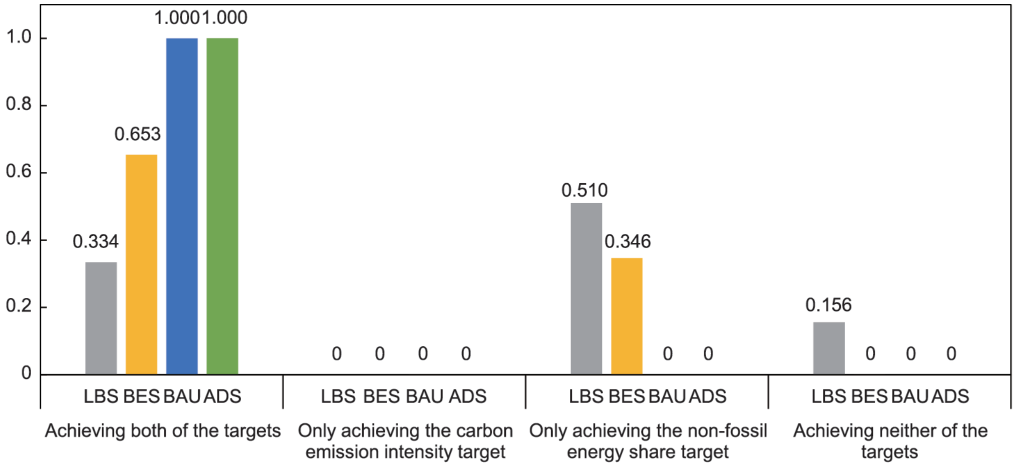

**Fig. 13.** Probabilities of achieving two targets under the four policy scenarios.

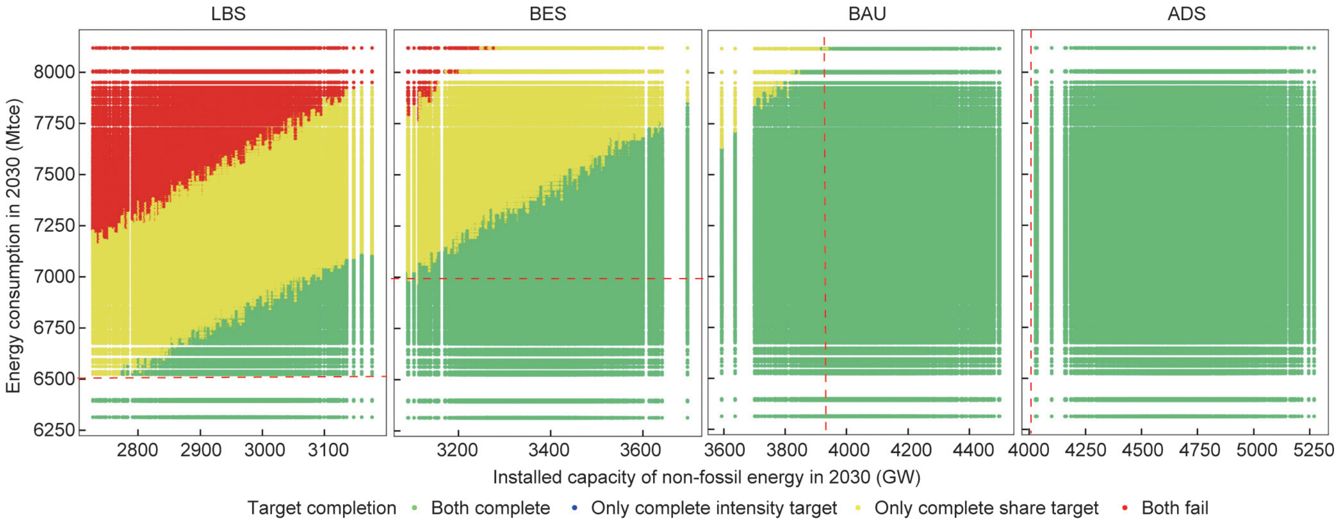

**Fig. 14.** Target fulfillment results for all sub-scenarios under the four scenarios.

of non-fossil energy before 2030 also ensures compliance with both targets.

In conclusion, in order to achieve all climate targets—including a carbon peak—within the uncertainty range considered in this study, it is necessary for China to exceed a total installed capacity of 4000 GW of non-fossil energy before 2030, if there are no restrictions on total energy consumption. For alternative policy pathways, to achieve all targets, the BES requires keeping the nation's total energy consumption below 7000 Mtce and installing more than 3100 GW of non-fossil energy before 2030, while the LBS requires keeping the total energy consumption below 6500 Mtce and installing more than 2700 GW of non-fossil energy before 2030. All three recommendations ensure that China achieves all of its climate targets.

### *5.4. How will electricity consumption change in the future?*

This section analyzes the growth of China's future electricity consumption under four different renewable energy policy scenarios. Future electricity consumption is determined by the sum of non-fossil fuel electricity and coal-fired electricity. This study assumes that the proportion of coal used for electricity generation will increase linearly from 56% in 2023 to 65% in 2035. Consequently, coal-fired electricity generation can be calculated. The resulting growth in future electricity consumption, the ratio of the increase in non-fossil electricity to the increase in electricity consumption, and the proportion of non-fossil energy in the total energy consumption under the ADS are depicted in Fig. 15. The 90% probability interval for these three values in 2030 under the four renewable energy scenarios are listed in Table 3.

As Table 3 clearly illustrates, as the support for renewable energy policies increases, both the proportion of non-fossil energy and the ratio of the ratio of the increase in non-fossil electricity to the increase in electricity consumption rise significantly. In the LBS, the total installed capacity of non-fossil energy in 2030 is projected to range from 2700 to 3200 GW. In contrast, this range is estimated to be from 4000 to 5300 GW under the ADS. The median value in the ADS is approximately 1.5 times greater than that in the LBS. However, the 90% probability interval for electricity consumption in 2030 is 13.60–15.61 PW·h under the ADS, compared with 12.7–14.27 PW·h under the LBS, with the median ratio being around 1.08. This relatively minor impact on total electricity consumption suggests that, under the same uncertainty range in total energy consumption, different renewable energy policy scenarios significantly influence the installed capacity of non-fossil energy but have a comparatively smaller effect on the total electricity consumption. This finding affirms the methodological rigor of the study's scenario framework and parameterization, reinforcing the validity of its analytical approach.

### *5.5. How does energy intensity affect China's likelihood of achieving its climate targets?*

Recent trends highlight a pronounced deceleration in China's energy intensity reduction. From 2021 to 2023, the annual decline in energy intensity plummeted from 3.3% to 0.1%, culminating in a 0.5% year-on-year increase by 2023. This trajectory implies that maintaining the historically rapid pace of energy intensity reduction observed in earlier decades will be increasingly untenable. The energy intensity pathway used in this study, which extrapolates energy intensity trends from the past decade, forecasts a 15% reduction before 2030 relative to 2023 levels. However, current progress deviates markedly from this pathway, rendering this target unlikely without substantial intervention. To quantify the implications of this divergence, we assessed the sensitivity of climate goal attainment to varying energy intensity reduction rates between 2023 and 2030. Sixteen scenarios were formulated, spanning cumulative reductions from 0 (status quo) to 15% (model-projected target), to systematically evaluate the feasibility of policy-driven pathways under uncertainty.

Assuming that the four renewable energy scenarios occur with equal probability, each subplot in Fig. 16 systematically illustrates policy target fulfillment outcomes across distinct energy intensity reduction pathways. The horizontal axis represents the projected range of non-fossil energy installed capacity in 2030, derived from the integrated results of the four scenarios. Each subplot contains 4 million sub-scenario data points, produced via Monte Carlo simulations. Green data points denote sub-scenarios in which China achieves all three climate targets simultaneously: a carbon peak, carbon intensity reduction, and the non-fossil energy share target. Conversely, sub-scenarios failing to meet one or more targets are marked in red.

As demonstrated in Fig. 16, the probability of China achieving its climate targets demonstrates a strong positive correlation with the stringency of the nation's energy intensity reduction goals. Leveraging projected 2030 energy consumption ranges, this section delineates minimum thresholds for the 2030 energy intensity reduction target and total non-fossil energy installed capacity

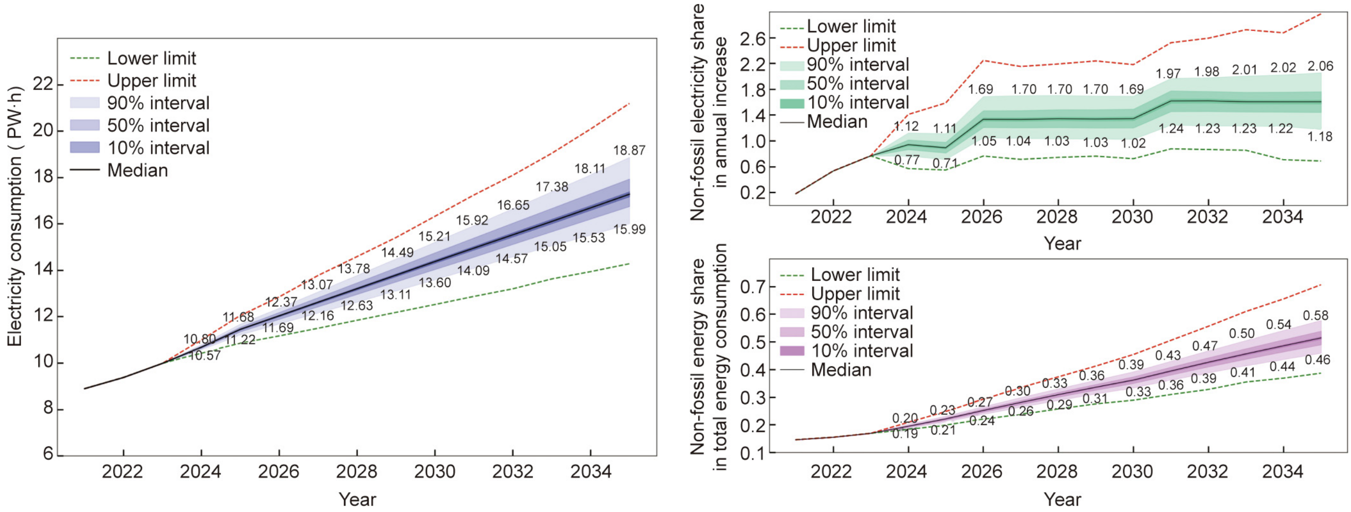

**Fig. 15.** Electricity consumption growth range, ratio of new non-fossil electricity to new electricity consumption, and share of non-fossil energy in total energy consumption under the ADS.

**Table 3**
The 90% probability intervals for three values in 2030 under the four renewable energy scenarios.

| Scenario | 90% interval for total electricity consumption in 2030 (PW·h) | 90% interval for the increase in the ratio of non-fossil electricity to electricity consumption by 2030 | 90% interval for the proportion of non-fossil energy in total energy consumption |
|---|---|---|---|
| ADS | 13.60–15.21 | 11.02–1.69 | 0.33–0.39 |
| BAU | 13.30–14.69 | 0.91–1.56 | 0.30–0.35 |
| BES | 12.92–14.50 | 0.76–1.37 | 0.27–0.31 |
| LBS | 12.70–14.27 | 0.65–1.21 | 0.24–0.28 |

necessary to concurrently meet China's carbon peak, carbon intensity reduction, and non-fossil energy share commitments. Given the anticipated challenges in curbing energy intensity growth under current economic and technological constraints, policy prioritization favors scenarios with lower energy intensity reduction targets. These scenarios pragmatically reconcile feasibility with climate ambition, mitigating a reliance on unrealistically steep declines in energy intensity while still attaining the non-fossil energy capacity thresholds required to achieve all three targets.

Recommendations for achieving all of China's climate targets by 2030 under varying total energy consumption levels are provided below:

- **Total energy consumption in 2030 is below 6500 Mtce.** The energy intensity in 2030 must be reduced by 12% or more compared with that in 2023, and the installed capacity of non-fossil energy in 2030 should be higher than 3100 GW.
- **Total energy consumption in 2030 is below 7000 Mtce.** The energy intensity in 2030 must be reduced by 5% or more compared with that in 2023, and the installed capacity of non-fossil energy in 2030 should be higher than 4200 GW.
- **Total energy consumption in 2030 is below 7500 Mtce.** The energy intensity in 2030 must be reduced by 0 or more compared with that in 2023, and the installed capacity of non-fossil energy in 2030 should be higher than 5200 GW.
- **Total energy consumption in 2030 is below 8000 Mtce.** The energy intensity in 2030 must be reduced by 4% or more compared with that in 2023, and the installed capacity of non-fossil energy in 2030 should be higher than 5200 GW.

If China's total energy consumption in 2030 is higher than 8250 Mtce, it will be impossible to ensure that the nation can achieve all of its climate targets under the certainty ranges considered in this study. Therefore, China's total energy consumption in 2030 must be controlled at below 8250 Mtce.

## 6. Conclusions

This study addresses the uncertainties surrounding China's future energy consumption growth and the expansion of the nation's installed capacities for wind and solar power. By employing MLE in conjunction with a Monte Carlo simulation and random sampling, this study evaluated the probability of China achieving its 2030 climate targets. This analysis aimed to ascertain whether and how China can meet all its climate goals, including reaching a carbon peak. In response to these uncertainties, this study offered several policy recommendations to ensure China successfully meets its climate objectives.

First, the study established probability distributions for both total and non-fossil energy consumption for future years. In the baseline scenario for reducing energy intensity, the projected uncertainty range for total energy consumption in 2030 is between 6300 and 8100 Mtce, and the uncertainty range for the installed capacity of non-fossil energy is between 2700 and 5250 GW. Despite the significant influence of various renewable energy policies on China's installed capacity for non-fossil energy, the 90% probability ranges for total electricity consumption across the four renewable energy scenarios show minimal variance.

Second, the study evaluated the probability of achieving a carbon peak and other climate targets under four different renewable energy installation policy scenarios. In the baseline scenario, to meet all climate targets within the considered uncertainty range of this study (where total energy consumption is maintained within 6250–8100 Mtce in 2030), it is crucial to exceed a total installed capacity for non-fossil energy of 4000 GW before 2030. Conversely, if the installed capacity for renewable energy is maintained within the uncertainty range considered in the baseline scenario (2700–5250 GW in 2030), China's total energy consumption must remain below 6500 Mtce before 2030 to ensure the realization of all climate targets.

Third, this study examined the probability of China achieving its climate targets under more stringent and extreme reductions in energy intensity. The study considered different levels of total

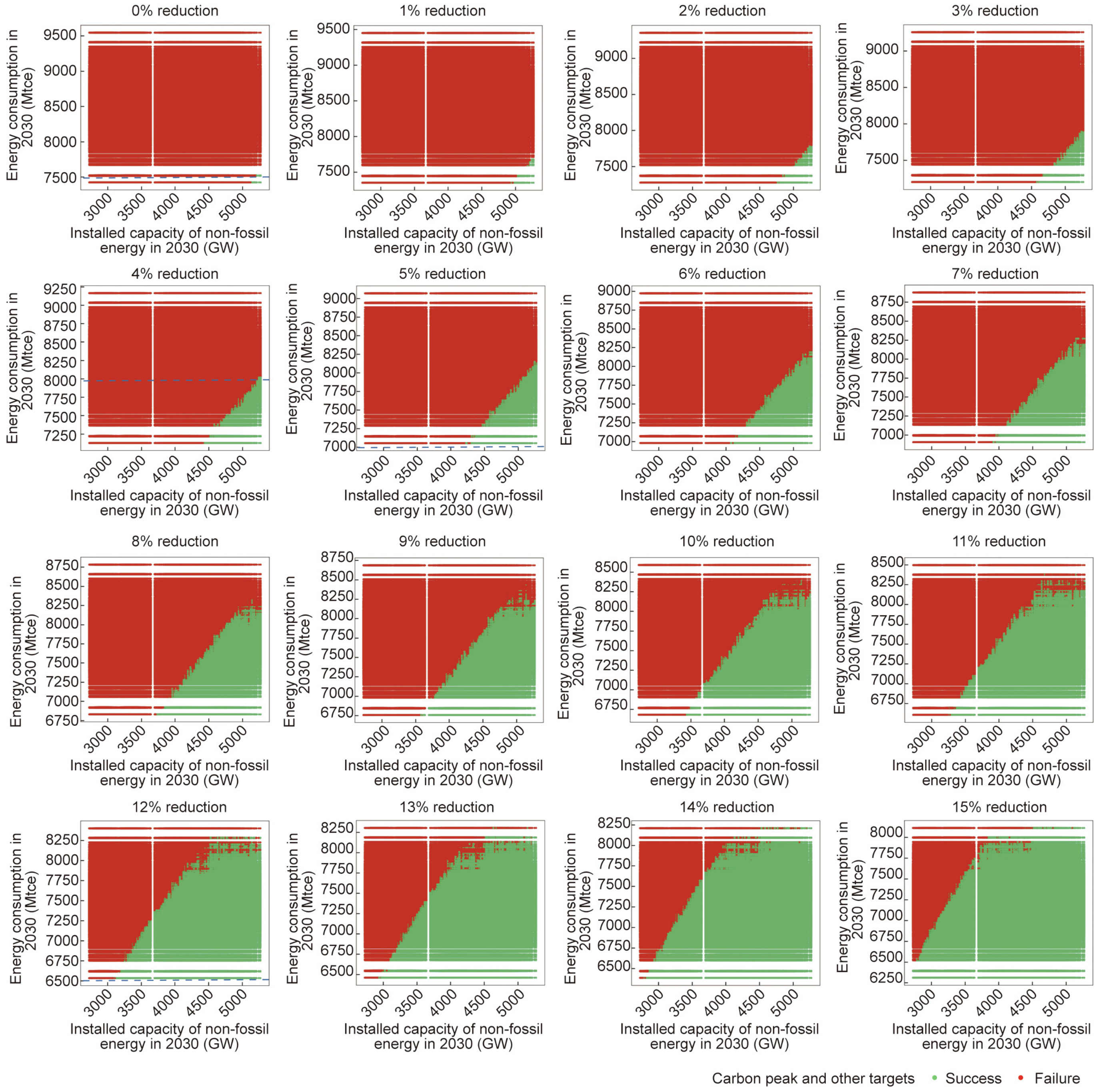

**Fig. 16.** Fulfillment of all of China's climate targets under different energy intensity reduction scenarios.

energy consumption for that year and offered corresponding policy recommendations to ensure the fulfillment of China's climate objectives. To meet all targets, China's total energy consumption in 2030 should be kept below 8250 Mtce; exceeding this level would make it impossible to guarantee the achievement of all targets within the considered range of non-fossil energy installed capacity.

Fourth, the framework developed here can serve as a quantitative tool for policy evaluation. By incorporating probability calculations, it facilitates the assessment of the viability of policy targets and the impact of various measures. For instance, the probability calculations suggest that achieving a 65% reduction in carbon emission intensity per unit of GDP before 2030, compared with the 2005 level, is more difficult than reaching a 25% share of non-fossil energy consumption. The probability assessments of achieving a carbon peak under the four renewable energy policy scenarios can be used to gauge the effectiveness of different wind and solar support policies in aiding the realization of a carbon peak.

Based on the policy objectives established in this study, three main policy recommendations are proposed:

- First, it is necessary to develop a systematic, phased national plan to expand China's non-fossil energy capacity by setting clear milestone targets for 2025, 2030, and beyond. These non-fossil energy targets should be further disaggregated to the provincial level, with particular emphasis on regions with abundant renewable resources. During the medium-term phase (2025 targets), priority should be given to scaling up wind/solar base construction and energy storage demonstrations. Provinces must formulate annual growth targets and spatial allocation plans, prioritizing resource-abundant regions for megaproject development. As the timeline progresses toward 2030, dynamic equilibrium mechanisms should be established through policy targets such as provincial renewable utilization rates and interregional green power trading quotas. Moreover, it is recommended that a dynamic monitoring and performance-evaluation mechanism be established that can regularly assess the progress of wind, solar, and storage projects and ensure that the capacity consistently approaches or exceeds the target value (e.g., 4000 GW by 2030). This renewable development evaluation mechanism can be integrated into governmental performance evaluations to ensure baseline capacity targets are met.

- Second, region-specific differentiated technological innovation pathways are needed to address critical bottlenecks in long-duration storage, high-voltage direct-current transmission, and virtual power plant integration. National research and development initiatives should advance integrated wind/solar/storage/hydrogen demonstration projects alongside modern grid dispatch frameworks. Concurrent infrastructure strategies must align with regional characteristics: Northwest China should focus on ultra-high voltage corridors and green power/hydrogen/chemical industrial clusters, while Eastern load centers should develop intelligent microgrid systems incorporating rooftop PVs. These technological and infrastructural advancements will collectively underpin China’s carbon peak objectives.
- Third, a coordinated governance mechanism that can harmonize energy consumption management with socioeconomic development is required. Guided by a three-pronged policy framework (i.e., total control, structural optimization, and livelihood protection), supply-side reforms should implement dynamic evaluation mechanisms to phase out obsolete capacities in energy-intensive sectors such as steel and cement. Institutional drivers—including green certificate trading, renewable quotas, and mandatory green power ratios for new capacities—must reinforce renewable energy penetration. Management paradigms should transition from consumption caps to efficiency-driven production transformations, fostering a virtuous cycle of obsolete capacity retirement, advanced production expansion, and green power integration. This systemic approach will effectively synchronize energy structure optimization with the transition of economic growth momentum.

In conclusion, this study provided several policy recommendations to ensure China can successfully navigate uncertainties to meet its climate objectives. These findings are intended to guide policymakers in formulating and implementing effective strategies to achieve China’s ambitious climate targets.

## CRediT authorship contribution statement

**Zheng Li:** Supervision, Project administration, Conceptualization. **Chenpeng Li:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Yujuan Fang:** Writing – review & editing, Visualization, Supervision, Funding acquisition. **Pei Liu:** Supervision. **Ershun Du:** Visualization, Validation. **Linwei Ma:** Supervision, Project administration. **Xiu Yang:** Supervision.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2025.07.018.

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