

Bridging China's Climate Targets and Mitigation Capacity through Sectoral Policy Implementation

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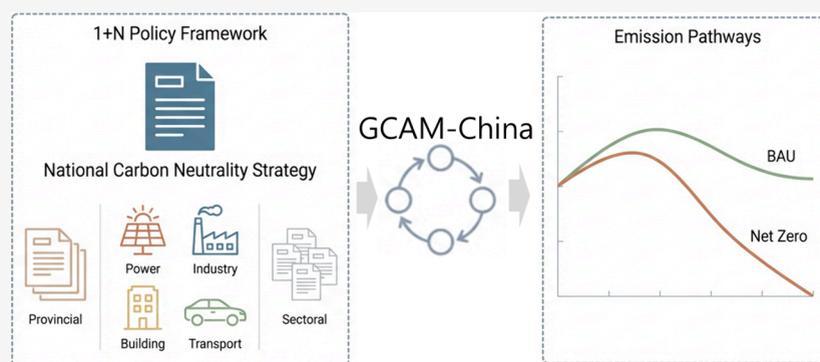
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ABSTRACT: Delivering on climate pledges hinges not only on setting ambitious targets but on translating them into credible, equitable, and regionally feasible action. In China, current policies over the past 30 years have driven a sustained decline in carbon intensity and pushed total installed renewable capacity to 2.16 TW, exceeding 40% of the global total. China's 2060 carbon neutrality goal is supported by a growing suite of detailed energy and climate policies, yet whether near-term actions are already on a pathway that converges with that target remains uncertain. Here, we evaluate how sectoral policy measures adopted between 2019 and 2024, and their plausible near-term extensions, shape China's decarbonization trajectory using a policy-informed integrated assessment model with provincial detail. Our results show that, compared to Current policy, national CO₂ emission intensity falls by 12% to 0.35 kgCO₂ per 2020USD and the nonfossil share of primary energy increases from 33% to 44% by 2035 under Continued policy strengthening. Most near-term reductions are driven by solar and wind expansion as well as industrial and building efficiency gains. However, sustaining such momentum exposes regional disparities: in several western provinces, annual power sector investment requirements are comparable to more than 5% of 2023 provincial GDP. Nationally, cumulative power sector investments exceed \$13 trillion through 2060, concentrated in solar and wind technologies. By linking national targets with disaggregated policy and investment pathways, this study provides an actionable framework for assessing the feasibility and equity of deep decarbonization in heterogeneous economies.

KEYWORDS: Carbon Neutrality Target, Policy Analysis, Integrated Assessment Model, Feasibility, China

1. INTRODUCTION

To achieve its 2060 carbon neutrality goal, China has adopted an integrated framework that combines broad national decarbonization targets with sector-specific energy measures.¹ This framework provides the overarching national guidance while incorporating a suite of sector-specific policies to drive implementation across key areas.² Detailed sectoral energy measures are designed to transform the energy and land sectors through structural changes and efficiency improvements across key sectors, including power, industry, transport, buildings, and emissions associated with AFOLU (Agriculture, Forestry, and Other Land Use),^{3–9} along with actions in methane and other non-CO₂ greenhouse gases. To be effective, achieving net-zero

emissions requires sector-specific mitigation aligned with national targets.

Overall, China's decarbonization strategy relies on a dual approach: structural energy transitions to shift the energy mix away from fossil fuels, and energy efficiency improvements to reduce consumption across sectors.^{10–12} Energy structural

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Table 1. Summary of Key Sectoral Policies Modeled in This Analysis^a

Sector	Category	Subcategory	Policy Documents	Key Policy Measures Modeled	Policy Type
Power	Coal plant eff. improv.	Energy efficiency improvement for coal power	Notice on carrying out nationwide retrofitting and upgrading of coal-fired power units; Benchmarking Levels in Key Fields of Clean and Efficient Coal Utilization (2022 Edition)	By 2025, the national average coal consumption for thermal power supply will be reduced to below 300 gce/kWh.	Efficiency improvement
	Renewable capacity expansion	Wind and solar capacity expansion	14th Five-year plan for renewable energy development Action Plan for Carbon Dioxide Peaking Before 2030; etc. Five policy documents in total	Total installed capacity of wind and solar power reaches more than 1.2 billion kilowatts by 2030; China has already reached this target in 2024. Triple renewable energy capacity globally by 2030.	Structural transition
Nuclear power development	Hydropower capacity expansion	Hydropower capacity expansion	14th Five-Year Plan: Modern Energy System Planning	By 2025, the installed capacity of conventional hydropower will reach about 380 million kilowatts.	Structural transition
			Action Plan for Carbon Dioxide Peaking Before 2030	Add about 40 million kilowatts of installed hydropower capacity during the 14th Five-Year Plan and the 15th Five-Year Plan, respectively.	
	Nuclear power capacity expansion	Nuclear power capacity expansion	14th Five-Year Plan: Modern Energy System Planning Action plan to expedite the green and low-carbon development of electrical equipment China's Nuclear Power Development Plan	By 2025, the operating installed capacity of nuclear power will reach about 70 million kilowatts. Under the baseline scenario, the size of China's nuclear power units reaches 130 million kW, 170 million kW, and 340 million kW by 2030, 2035, and 2050, accounting for 4.5%, 5.1%, and 6.7% of the country's total installed power capacity.	Structural transition
Coal plant phase-out	Phase-out of coal-fired power plants	14th Five-Year Plan: Modern Energy System Planning	Strictly and reasonably control the growth of coal consumption during the 14th Five-Year Plan period and gradually diminish it during the 15th Five-Year Plan period. Strictly control new coal power projects and orderly phase out outdated coal power capacity.	Structural transition	
Industry	Iron and steel eff. improv.	Iron and steel energy efficiency improvement	Benchmarking Levels in Key Fields of Clean and Efficient Coal Utilization (2022 Edition); etc. Six policy documents in total	By 2025, steel energy efficiency reaches international advanced level. Iron and steel industry comprehensive energy consumption of tons of steel reduced by 2%.	Efficiency improvement
			Advanced Level of Energy Efficiency, Saving, and Access of Key Energy-Using Products and Equipment (2024 Edition)	The energy intensity of cement clinker production is targeted to decrease by more than 3% in 2025 compared with 2020.	
Cement	Cement eff. improv.	Cement energy efficiency improvement	Action Plan to Boost Industrial Energy Efficiency, etc. Twelve policy documents in total	The energy intensity of cement clinker production is targeted to decrease by 3.7% in 2025 compared with 2020.	Efficiency improvement
			Advanced Level of Energy Efficiency, Saving, and Access of Key Energy-Using Products and Equipment (2024 Edition); Implementation Plan for Carbon Peaking in the Industrial Sector; etc. Twelve policy documents in total	The energy intensity of cement clinker production is targeted to decrease by 3.7% in 2025 compared with 2020.	
Chemical	Chemical eff. improv.	Chemical industry energy efficiency improvement	Advanced Level of Energy Efficiency, Saving, and Access of Key Energy-Using Products and Equipment (2024 Edition)	By 2025, the energy efficiency of key petrochemical and chemical products reaches the international advanced level.	Efficiency improvement
			Action Plan to Boost Industrial Energy Efficiency, etc. Nine policy documents in total	By 2025, the energy efficiency of key products in the iron and steel, petrochemical and chemical, nonferrous metals, cement and other industries will reach the international advanced level.	
Other industry	Other industry eff. improv.	Other industry energy efficiency improvement	Implementation Plan for Carbon Peaking in the Industrial Sector; Implementation Plan for steady growth of the non-ferrous metal industry; etc. Ten policy documents in total	By 2025, the energy efficiency of key products in the iron and steel, petrochemical and chemical, nonferrous metals, cement and other industries will reach the international advanced level.	Efficiency improvement
			Guideline on promoting the high-quality development of the iron and steel industry; Implementation Plan for Carbon Peaking in the Industrial Sector; Implementation Plan for Synergizing the Reduction of Pollution and Carbon Emission	By 2025, the proportion of electric furnace steel production in total crude steel production is raised to more than 15%.	

Table 1. continued

Sector	Category	Subcategory	Policy Documents	Key Policy Measures Modeled	Policy Type
Building	Residential building eff. improv.	Residential building efficiency improvement	<i>Action Plan to speed up energy conservation and carbon reduction in the construction sector</i> <i>The 14th Five Year Plan for Building Energy Conservation and Green Building Development; etc. Five policy documents in total</i>	The energy efficiency level of newly constructed residential buildings in urban areas increases 30% by 2025.	Efficiency improvement
		Commercial building efficiency improvement	<i>Action Plan to speed up energy conservation and carbon reduction in the construction sector; The 14th Five Year Plan for Building Energy Conservation and Green Building Development; etc. Six policy documents in total</i>	The energy efficiency level of newly constructed public buildings in urban areas increases 20% by 2025.	Efficiency improvement
Transport	Road passenger eff. improv.	Passenger car fuel consumption reduction	<i>Energy-saving and New Energy Vehicle Technology Roadmap 2.0</i> <i>GB 27999–2019 Fuel consumption evaluation methods and targets for passenger cars</i> <i>Notice on Further Enhancing the Upgrade and Application of Energy-saving Standards</i>	In 2035, fuel consumption of internal combustion engine (ICE) passenger vehicles is reduced by 20–25% compared to the average fuel consumption in 2019. This target applies specifically to ICE fuel efficiency improvements and does not include efficiency gains from electrification, which are modeled separately through vehicle technology penetration scenarios.	Efficiency improvement
		Road freight eff. improv.	<i>Energy-saving and New Energy Vehicle Technology Roadmap 2.0; Notice on Further Enhancing the Upgrade and Application of Energy-saving Standards</i>	In 2035, fuel consumption of internal combustion engine (ICE) for freight vehicles is reduced by 15–20% compared to 2019 levels	Efficiency improvement
Civil aviation	eff. improv.	Civil aviation energy efficiency improvement	<i>Civil Aviation Notice on Further Enhancing the Upgrade and Application of Energy-saving Standards</i>	From 2020 to 2025, the fuel consumption of the transport aviation fleet is reduced from 0.316 to 0.293 kg per ton-kilometer.	Efficiency improvement
		Electric vehicle sales growth	<i>The New Energy Vehicle Industry Development Plan (2021–2035); Modern comprehensive transportation system during the 14th Five-Year Plan (2021–25) period; etc. Seven policy documents in total</i>	In 2025, the share of new vehicle sales of new energy vehicles will reach about 20%. By 2035, new energy vehicles will account for more than 50% of total sales, with pure electric vehicles accounting for more than 95% of new energy vehicles.	Structural transition

“Note: This table presents the policy documents reviewed in our analysis and identifies the specific policy measures from these documents that are explicitly modeled in our scenarios. The “Key Policy Measures Modeled” column describes actionable interventions that we simulate as direct model inputs with quantifiable parameters detailed in Table S3.

changes, such as electrification and fuel switching, are central to reducing reliance on fossil fuels, while efficiency improvements are critical for maintaining sustainable growth while optimizing resource use across different sectors.^{11,13–15} Despite the recognized importance of these strategies, conventional top-down modeling approaches often abstract away from policy implementation processes, and overlook the institutional, spatial, and equity dimensions central to sustainable transitions.^{16–18} In this study, we explicitly designate the modeled policies into two corresponding categories: energy structure policies and energy efficiency policies (see [Supplementary Texts 1–2](#) for a detailed literature review and model description).

The simultaneous implementation of structural changes and efficiency improvements involves complex synergies and trade-offs that need to be carefully managed to achieve net-zero emissions. For instance, although electrification reduces emissions, it demands major infrastructure investment and upgrades, and while creating jobs and economic activities in the green industries, may also lead to job losses in traditional energy sectors, posing socioeconomic challenges and risks to energy access.^{19–22} Addressing these challenges requires a bottom-up approach that goes beyond top-down targets, linking national ambition to sector-level policy actions.^{23,24} Moreover, uncertainties regarding the feasibility of these structural and efficiency measures increase at subnational levels, given the substantial variation in regional capacities, local circumstances, and cross-region interactions across China.^{25–27}

Existing literature on China's low-carbon transition has primarily concentrated on national-level pathways toward carbon neutrality,^{28–32} emphasizing the importance of early emission peaking and systemic energy transformation. Other research has focused on sectoral decarbonization and specific energy measures,^{33–36} identifying key strategies such as coal phase-out, renewable capacity expansion, and electrification. While recent assessments have begun to evaluate the effectiveness of China's integrated policy frameworks,^{16,18,27,37,38} they often rely on stylized scenarios or analyze isolated measures, potentially missing cross-sectoral synergies. (see [Supplementary Texts 1–2](#) for a detailed literature review and model description). Therefore, a gap remains between long-term strategic goals and the specific, near-term regulatory measures of China's integrated policy framework. Consequently, it is necessary to bridge top-down national targets with bottom-up, sector-specific policy actions to assess the real-world feasibility of deep decarbonization.

Here, we assess the overall and sectoral outcomes of China's economy-wide decarbonization policies on emissions, energy transition, and investments by quantifying the contributions of sectoral energy policy measures at both national and provincial scales (see [Figure S1](#) for the overall research framework).^{3,39–42} First, we compiled a comprehensive database of the latest 38 policy documents issued by the central government and various ministries from 2019 to 2024, of which 36 could be directly simulated (see [Table S1](#)), and 17 high-level metrics (see [Table S2](#)) were used for validation. We combined quantifiable policies into 15 categories ([Table 1](#)) and simulated these policies using a state-of-the-art, open-source integrated assessment model with improved representation of provincial-level details of China (GCAM-China; see [Figure S2](#) and [Table S3](#)). Key energy activities and CO₂ emissions are harmonized to China's latest inventories (see

[Methods](#)). With different assumptions and interpretations of each policy, we focus on near-term actions across various levels of sectoral policies and uncertainties, ranging from conservative interpretations of the legislated existing policies to more ambitious decarbonization actions that may face implementation challenges. [Table S3](#) provides detailed parameter settings for each policy instrument, illustrating how interpretations vary across scenarios. For instance, renewable capacity targets vary between 1300 and 1800 GW (current) and 1500–3000 GW (continued) across different time horizons, reflecting different assumptions about enforcement stringency and deployment pace. By explicitly linking policy packages to their spatial and sectoral implications, our analysis helps close a persistent gap in sustainability research: the misalignment between top-down decarbonization targets and bottom-up implementation capacity.

Our results show that while national-level decarbonization targets align with trajectories seen in stylized global mitigation pathways, their realization is shaped by underlying regional and sectoral constraints. By 2035, CO₂ emission intensity could fall to 0.35–0.40 kgCO₂ per 2020USD and nonfossil energy could comprise 33%–44% of primary supply, provided current policies are tightened in line with the 2060 net-zero commitment. However, our subnational simulations reveal large disparities in required capacity expansion and investment effort across provinces, with some less-developed western regions facing annual power sector investment needs comparable to more than 5% of their 2023 GDP. Moreover, policy-mechanism decomposition shows that while energy structure policies dominate emissions reductions, efficiency measures are critical for balancing energy intensity and economic productivity.

2. METHODS

Our approach comprises four key steps to comprehensively quantify the outcomes of China's sectoral policies and their effectiveness in reducing emissions, shifting the energy structure, and meeting investment needs. First, we collect and organize policy documents from relevant Chinese government sources to construct a comprehensive policy database. Second, we parametrize and quantify these policies in the Global Change Analysis Model with China details (GCAM-China), ensuring alignment with sectoral targets and carbon neutrality goals. Third, we design and simulate four core scenarios by combining two levels of policy ambition (Current and Continued) with two distinct long-term trajectories (NetZero and BAU) to evaluate the potential outcomes under different policy intensities toward carbon neutrality. Finally, we perform a policy decomposition analysis to isolate and quantify the contributions of individual policies to the overall outcomes, providing a clear understanding of each policy's effectiveness in achieving emission reductions, energy transformation, and technology transition. [Figure S1](#) illustrates the steps of our research, the sections below detail each step. All code and data related to this research are publicly available at public repositories (see [Data Availability](#) and [Code Availability](#)).

2.1. Systematic Collection and Classification of Policy Documents

We collected 38 policy documents issued between 2019 and 2024 by China's central government and ministries, including the National Development and Reform Commission (NDRC), the Ministry of Ecology and Environment (MEE), the State Council, the Ministry of Industry and Information Technology (MIIT), and so on. These documents cover a wide range of sectors, including energy, industry, transportation, buildings, and macroeconomic planning, reflecting the comprehensive scope of China's carbon neutrality and energy transition strategies.

Table 2. Scenarios Explored in This Study

Core Scenarios				
	Policy assumptions through 2025	Policy assumptions between 2025 and 2030	Policy assumptions between 2030 and 2035	Policy assumptions after 2035
Current-BAU	Issued national policy documents	Issued national policy documents and extrapolated to 2030	Extrapolated to 2035	Keep the consistent value as 2035
Continued-BAU	Continued strengthening of current policy efforts			Keep the consistent value as 2035
Current-NetZero	Issued national policy documents	Issued national policy documents and extrapolated to 2030	Extrapolated to 2035	Keep the consistent value as 2035; CO ₂ linear to zero constraint by 2060
Continued-NetZero	Continued strengthening of Current-NetZero efforts			Keep the consistent value as 2035; CO ₂ linear to zero constraint by 2060
Sensitivity scenarios for Supporting Information (all adjustments are based on the Continued-NetZero scenario, key result for sensitivity scenarios can be found in Supplementary Figures 22 to 24)				
RenewableC	The cost of renewable energy is falling rapidly, modeled using lower capital costs for wind, solar, nuclear, and geothermal power. Using the rapid technology advances configuration file (-adv), costs range from 2 to 50% lower than the original scenario for each renewable energy technology.			
NegC	Negative carbon technologies costs are higher, modeled using higher costs for onshore carbon storage and offshore carbon storage. (Costs increased to nearly 50 times the original)			
LucPrice	Change the response factor of land use CO ₂ to price, adjusting it from growing to 1 until 2060 to growing to 1 as soon as 2025.			

We included only legislated, quantifiable and validated policy goals and commitments, including absolute emission limitations, carbon pricing mechanisms, renewable energy targets, energy efficiency improvements, and structural shifts in energy supply, etc. Each policy was broken down into specific measures and targets. For instance, in the electricity sector, the policies included goals for coal power phase-out, increases in renewable energy capacity, and improvements in energy efficiency. Industrial policies focused on energy efficiency improvements in cement and steel production, while building sector policies targeted energy efficiency enhancements in residential and public buildings. We screened and categorized these policies to ensure that only those directly relevant to decarbonization were included in the analysis. Policies were classified into major thematic categories, such as improving energy efficiency and transforming energy structures. We ultimately selected 30 policy entries for energy efficiency improvement and 28 policy entries for structural transition out of 36 quantifiable policy documents (see [Table S1](#)). There are also 17 high-level metrics from 11 policy documents available for validation (see [Table S2](#)). This systematic classification provided a robust basis for parametrizing the policies in the GCAM-China model and analyzing their contributions to emissions reduction and energy transitions.

2.2. Policy Parameterization in GCAM-China

2.2.1. Model Overview. The Global Change Analysis Model (GCAM) is a widely used open-source global integrated assessment model (see detailed model documentation at <http://jgcri.github.io/gcam-doc/>).^{43,44} The model has a detailed market representation of the energy, agriculture, land, and water sectors and their intersectoral connections. The model is calibrated to the base year 2015 and runs in 5-year time steps to 2100, driven by future changes in socioeconomic, technological, or policy conditions. GCAM has been widely used to produce scenarios for international and national assessments, including the Intergovernmental Panel on Climate Change (IPCC) reports,⁴⁵ the Representative Concentration Pathways (RCPs),⁴⁶ and the Shared Socioeconomic Pathways (SSPs).⁴⁷

GCAM-China is developed from GCAM, and includes greater spatial detail in the China region. GCAM-China disaggregates the energy-economic system of the China region into 31 province-level subregions and six electricity grid regions that are also embedded in the global GCAM model. Provincial-level economic activities are driven by exogenous assumptions regarding population, GDP, and labor productivity, which determine energy and service demand for each province. The model has a comprehensive depiction of energy flows, from resources (fossil, uranium, or renewables) to energy carriers (electricity, refined liquids, hydrogen, gas, and district heat) and end-use sectors (building, transportation, and industry). Supply and demand are balanced in each modeling period by solving for a set of equilibrium prices for all agriculture, energy, emission, and policy-related markets. As a result, model solutions represent the most cost-

effective combinations of technologies satisfying the energy and service demands for the current modeling period. The market shares of different fuels/technologies are governed by their relative or absolute cost difference through logit formulations.^{48,49} The share weight parameters in the logit functions are resource-specific and calibrated using historical data. The CO₂ emissions are traced endogenously as their emission factors are linked to activities in the energy, agriculture, and land systems. GCAM-China captures regional variations in energy consumption, industrial processes, and policy implementation, making it well-suited to evaluate the country's decarbonization strategies, and has been widely employed for many China-specific policy analyses,^{50,51} energy transition pathways,^{52–55} environmental and health synergistic benefits,^{56–59} sustainability goal assessments,⁶⁰ etc. More details can be found at: https://umcd-cgs.github.io/metarepo_gcam-china/index.html.

The version of GCAM-China used in this study is the open-source released GCAM-China-v6.0,⁶¹ including important recent technological and socioeconomic trends. First, we calibrated the CO₂ emission factors of the base year using the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC, <http://meicmodel.org.cn>),^{62,63} a widely used bottom-up emission inventory model, and adjusted the capacity factors for each type of power generation using the statistics from the National Bureau of Statistics,⁶⁴ following recent trends and projections. After the calibration, we integrated the existing Chinese policy system to construct China's future development path scenarios, which provided data tailored to China's energy structure, technology paths, and socioeconomic characteristics, thus enabling a robust assessment of China's short- and medium-term development situation. A more detailed description of the model is available in [Supplementary Method 2](#) (see [Figure S2](#) for the model framework, and [Table S4](#) for data sources in the model).

2.2.2. Quantification of Policy Targets. The policy objectives extracted from the selected policy documents were systematically translated into quantitative indicators suitable for integration into the GCAM-China model. This translation process involved converting qualitative goals into measurable metrics, such as capacity expansions, efficiency improvements, and emission reduction targets. For instance, policies aimed at expanding renewable energy capacity were quantified by defining specific additional gigawatts (GW) of wind, solar, and hydropower to be installed by target years. Energy efficiency policies were expressed as percentage reductions in energy intensity across various sectors, including power generation, industry, and transportation. Likewise, emission reduction targets were framed as absolute limits or percentage decreases relative to baseline emissions projections. This quantification ensured that policy measures were not only measurable but also directly aligned with the modeling framework, enabling the GCAM-China model to simulate policy interventions through clear, objective benchmarks. In this study we

modeled the quantifiable policy targets by combining them into 15 categories of policies (Table 1). Table 1 summarizes the key policy documents reviewed and identifies which specific policy measures from these documents we explicitly model in our scenarios (as opposed to outcome targets used for validation in Table S2, with technical specifications provided in Table S3).

2.2.3. Parameterization in the GCAM-China Model. Once quantified, the policy targets were parametrized into the GCAM-China model by aligning them with the appropriate input parameters. This alignment ensured that each policy goal was accurately represented within the model's simulation framework (see Table S3). For example, policies aimed at improving the efficiency of coal plants were reflected in the model through reductions in energy intensity for thermal power generation. Policies to improve transportation fuel economy are achieved by reducing the energy consumption levels of new diesel and gasoline vehicles sold. Similarly, renewable energy targets were incorporated into the model by setting minimum limits on wind, solar, and hydroelectric capacity. Targets for end use electrification are achieved by adjusting the market share weights of technologies to give them an advantage in technological competition to achieve the market penetration rate of policy targets. The parametrized targets were organized into a series of scenarios with intermediate milestones for the years 2025, 2030, and 2035, allowing for the evaluation of both short-term and long-term policy impacts. These scenarios provided a structured timeline for assessing the implications of various policy interventions. This approach enabled the GCAM-China model to simulate the potential effects of energy efficiency enhancements, renewable energy expansions, end-use sector electrification, and emission reduction commitments. By incorporating these parameters, the model generated detailed projections of emissions trajectories, energy system transformations, and economic impacts, serving as the basis for subsequent scenario analyses and policy decompositions.

2.3. Scenario Design and Model Simulation

We designed four core scenarios to analyze the impacts of different policy approaches and carbon neutrality commitments. Each scenario reflects a specific level of policy ambition by 2035 and follows distinct assumptions over time (see Supplementary Text S3 and Table 2).

The *Current-BAU* scenario serves as the baseline, incorporating national policies as stated in government documents through 2025, with these measures extrapolated to 2030. After 2030, no further improvement in policy is assumed. This scenario serves as a reference for evaluating the impacts of incremental policy changes.

The *Continued-BAU* scenario assumes moderate policy advancements beyond the *Current-BAU* scenario. The policy settings are strengthened between 2025 and 2030 in line with the trends in policy goals.

The *Current-NetZero* scenario applies the *Current-BAU* policy pathway (policies adopted through 2025) but imposes a binding linear CO₂ decline constraint, starting from 2035, which reaches carbon neutrality by 2060.

The *Continued-NetZero* scenario applies the *Continued-BAU* policy pathway (strengthened ambition 2025–2030) coupled with a binding linear CO₂ decline constraint, starting from 2035, which reaches carbon neutrality by 2060.

These scenarios reflect differing levels of policy ambition and their impact on achieving carbon neutrality. The two policy strength variations before 2035 (*Current* and *Continued*) provide a spectrum of policy measures, from baseline assumptions to more aggressive decarbonization strategies. For the long-term commitment, the *NetZero* pathway imposes a linear CO₂ decline constraint to reach carbon neutrality by 2060, while the *BAU* pathway continues policy trends without this constraint.

We use GCAM-China-v6 to simulate four scenario pathways through 2060, focusing on key indicators such as energy consumption, emissions changes, technology mix and investment needs (A detailed representation of policies can be found in Supplementary Text S4). We calculate the investment needs by considering the annual capacity and production additions through the year attribute in the model. We

assess the capital required for new installations and capacity expansion (see Supplementary Text S5). By explicitly linking annual investment needs to new capacity installations and incremental output, we capture the dynamic nature of infrastructure development and technological transformation under different policy scenarios. It provides insights into the short- and long-term impacts of different policy intensities and net-zero strategies, leading to a detailed assessment of their implications for China's energy system and decarbonization pathways.

2.4. Policy Decomposition Analysis

We conducted a policy decomposition analysis to evaluate the contribution of individual policies to the outcomes in each scenario. This analysis systematically isolated the effects of specific policies to understand their roles in driving emissions reductions, reshaping energy structures, and influencing technology transitions (see Supplementary Text S6).

The decomposition process involved three key steps:

1. **Full Scenario Simulation:** We simulated each scenario using the complete set of policies to capture the combined impacts of all measures on emissions, energy structures, and technological transitions.
2. **Policy-by-policy Substitution:** We replaced individual ambitious policies in the *Continued-NetZero* scenario with their counterparts from the *Current-NetZero* scenario. For example, policies promoting renewable energy expansion in the *Continued-NetZero* scenario were substituted with the less ambitious policies from the *Current-NetZero* scenario. Replacing one policy at a time, this allows us to isolate the effects of individual policies.
3. **Impact Assessment:** We quantified the changes in emissions, energy structures, and technological adoption resulting from each substitution. This step allows evaluation of the relative effectiveness of each policy in contributing to decarbonization efforts and energy transitions.

In addition to evaluating individual policies, we also assessed the collective impact of policies within specific sectors and policy types by considering the interactions between policies. For instance, when analyzing the effect of energy efficiency improvement policies, we replaced all policies related to energy efficiency improvements from the *Continued-NetZero* scenario with those from the *Current-NetZero* scenario at the same time, rather than simply summing up the individual impacts of each policy. This sector-wide substitution accounted for potential interactions and interdependencies between policies, recognizing that the effects of individual policies are not always independent or additive. By capturing these synergies and overlaps, the analysis provided a more accurate evaluation of sectoral policy impacts.

3. RESULTS

3.1. Emission Reductions and Energy Efficiency Improvement

To reflect uncertainty in future policy implementation, we model four core scenarios to assess the impact of different policy stringencies and carbon neutrality commitments, ranging from conservative interpretations of the legislated existing policies to more ambitious decarbonization actions with potential implementation challenges. In the near term (before 2035), two levels of sectoral policy ambition are explored, the “*Current*” level reflects policies formally adopted by 2025, while the “*Continued*” level assumes strengthened ambition through 2035. These policy pathways are then coupled with two distinct long-term trajectories: a “*NetZero*” pathway imposing a linear emissions decline to net-zero by 2060, starting from 2035, and a “*Business-as-Usual (BAU)*” pathway extending trends without additional emissions

constraints (see [Supplementary Text S3](#) and [Table 2](#) for detailed scenario descriptions).

By 2035, China's key energy and emissions indicators show substantial improvements in both scenarios relative to historical levels, with performance further improving under more stringent policy scenarios. National CO₂ emission intensity declines from 0.77 to 1.5 kgCO₂/\$ during 2010–2020 to a range of 0.40 kgCO₂/\$ under Current-NetZero scenario and 0.35 kgCO₂/\$ under Continued-NetZero scenario in 2035 ([Figure 1a](#)), while primary energy intensity

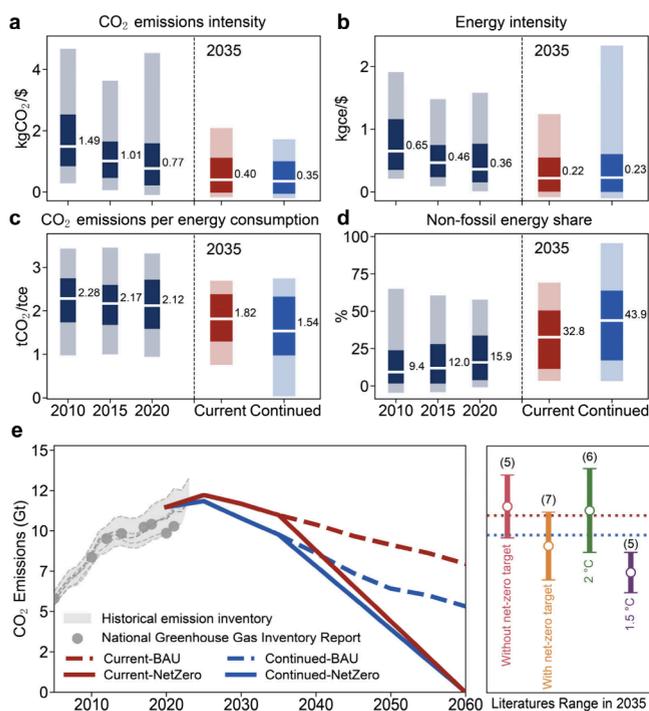


Figure 1. Key emissions and energy indicators in 2035 across policy scenarios and historical context. (a) System-wide CO₂ emissions intensity (kgCO₂ per 2020\$); detailed CO₂ emission data are provided in [Table S5](#). (b) System-wide primary energy intensity (kgce per 2020\$), where primary energy consumption is estimated using the coal consumption method for power generation for comparison with historical data (The results calculated using the electricity heat equivalent method are shown in [Figure S3](#)). (c) Average CO₂ emission per unit of primary energy consumption (tCO₂ per tce). (d) Nonfossil energy shares in primary energy consumption (%). For each bar, labeled values and white lines indicate the national average levels, darker shaded areas represent the first and third provincial quantiles, and lighter shaded areas show the full minimum-maximum provincial ranges. Historical emissions are derived from the MEIC database, and historical GDP and energy consumptions are derived from the National Bureau of Statistics of China.⁶⁴ (e) Left panel shows historical trends and future scenario projections of China's CO₂ emissions from 2005 to 2060. The gray shaded area represents the uncertainty range of historical emission inventories (MEIC,^{62,63} GCP,⁶⁵ CEDS,⁶⁶ CEADs,⁶⁷ EDGAR⁶⁸), and circular markers indicate data from the National Greenhouse Gas Inventory Report.⁶⁹ Right panel displays literature-reported CO₂ emission ranges for 2035, grouped by the scenario classifications commonly used in previous studies (Without net-zero target, With net-zero target, 2 °C, and 1.5 °C) with numbers in parentheses indicating the number of literature sources.^{28,29,32,38,42,70–78} Detailed literature comparison information is provided in [Table S6](#). Horizontal dashed lines denote our modeled 2035 emissions under the Current-NetZero and Continued-NetZero scenarios, shown for comparison.

falls from 0.36 to 0.65 kgce/\$ (kilogram of standard coal equivalent) to 0.22 and 0.23 kgce/\$, respectively ([Figure 1b](#)). These gains reflect advances in both energy efficiency and energy structure, with a shift away from fossil fuels and toward cleaner sources. CO₂ emissions per unit of energy decline from the historical 2.1–2.3 tCO₂/tce to 1.5 tCO₂/tce (Continued-NetZero) and 1.8 tCO₂/tce (Current-NetZero) in 2035 ([Figure 1c](#)), while the nonfossil share of primary energy rises from historical 9.4%–16% to 33% and 44%, respectively ([Figure 1d](#)). The greater emissions reductions in the near term are driven by system-wide ratcheting up of decarbonization actions, particularly in the power and industry sectors. Across policy scenarios, China's CO₂ emissions decline by 10–17% between 2025 and 2035, with reductions ranging from the Current policy to the Continued policy scenario ([Figure 1e](#)). In 2035, our results align with literature across scenarios with and without net-zero targets, consistent with 2 °C but exceeding 1.5 °C-compatible levels ([Figure 1e](#)). While near-term emissions reductions show relatively modest differences across scenarios, these divergences become increasingly pronounced after 2035 in the absence of further policy strengthening. Without additional measures, both the Current and Continued Policy scenarios would require an accelerated post-2035 emissions decline to reach net-zero by 2060 (comparing dashed and solid lines in [Figure 1e](#)). Closing this gap would necessitate a substantial increase in the nonfossil primary energy share, rising from 25% under the Current-BAU scenario to 64% in the Continued-NetZero scenario by 2060 ([Figure S3](#)), alongside deeper structural shifts in energy and industrial systems.

3.2. Energy Structure Change and Investment

Clean energy expansion and electrification enable substantial emissions reductions in all scenarios, but sustaining these rates presents critical challenges. Future capacity additions during 2020–2035 under the Current-NetZero scenario generally align with the 2012–2021 average of 130 GW per year, while the Continued-NetZero scenario projects an expansion rate close to the 10-year average of 200 GW per year ([Figure 2a](#)). In the Current-NetZero scenario, the average annual addition of solar and wind reaches 99.8 GW per year, while the Continued-NetZero scenario projects a significantly higher average annual addition of 179 GW per year for solar and wind. Regarding fossil fuels, limited coal capacity additions persist during the 2025–2035 period, primarily driven by near-term power stability requirements.⁷⁹ The long-term trajectory diverges significantly based on the scenario constraints: the Continued-NetZero pathway implements a strict policy prohibition, resulting in zero new coal capacity built after 2035, while other scenarios allow for continued, albeit declining, market-driven additions. Recent years, particularly 2023 and 2024, have seen record-high levels of new renewable capacity additions around and above 300 GW annually, reaching unprecedented peaks that significantly exceed long-term historical levels. While these achievements demonstrate China's near-term progress, maintaining such exceptional growth rates over the next four decades is uncertain. Increasing challenges, such as market saturation, land-use conflicts, grid integration limits, and the geographic concentration of high-quality wind and solar resources, need to be addressed to maintain continued expansion.^{19,33,80}

On the demand side, electrification remains a critical driver of demand-side decarbonization, supporting deep emissions

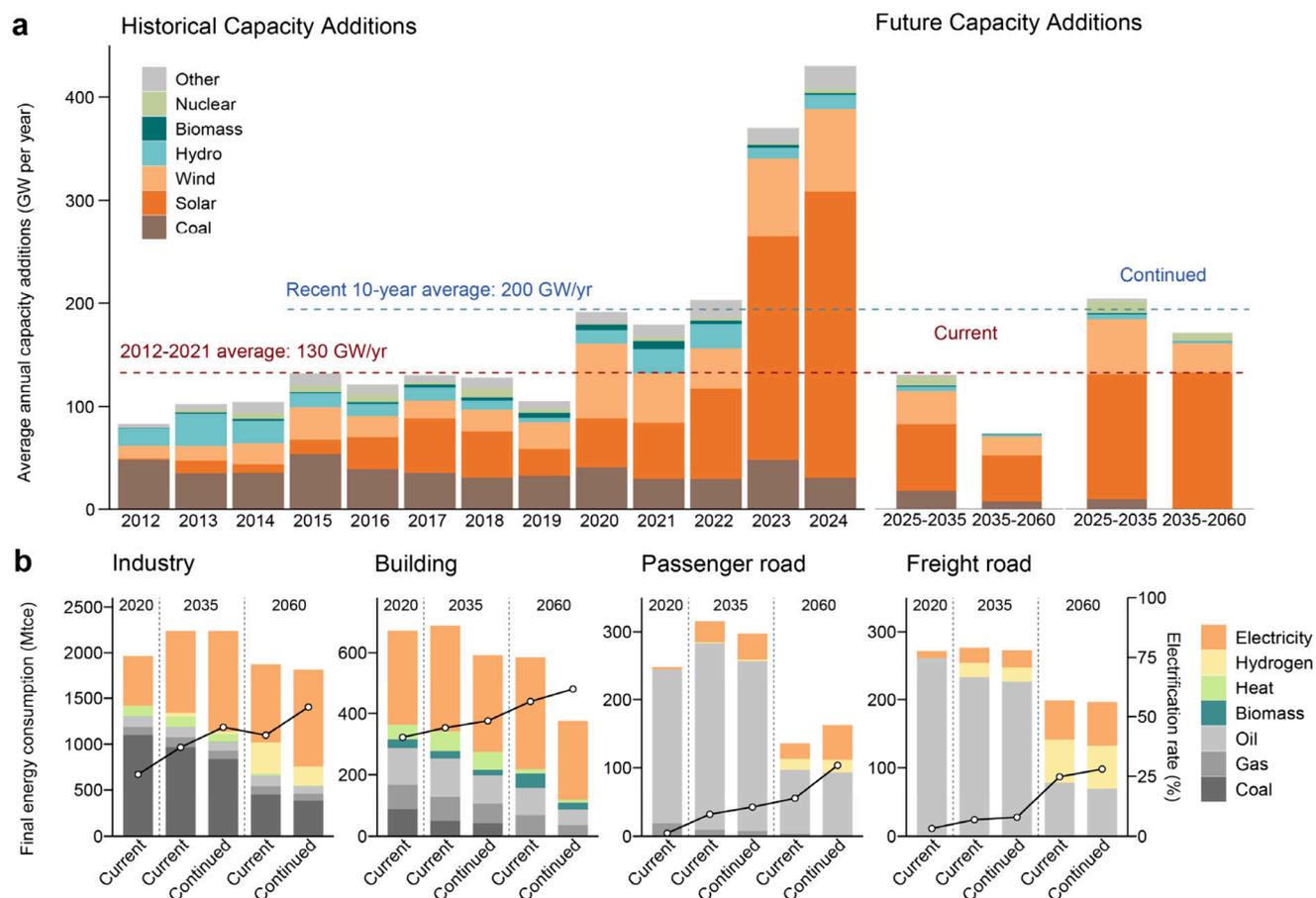


Figure 2. Electric capacity additions and sectoral energy consumption in 2020, 2035, and 2060. (a) Historical and projected electric sector capacity additions. Historical values are from China Statistical Yearbook; the dashed lines represent the average of capacity additions for historical years. Projections show the average annual capacity additions during 2025 to 2035 and 2035 to 2060. The time series electricity capacity and generation can be found in Figure S4 and Figure S5. (b) The four panels on the second row represents energy consumption by fuel (bar chart) and electrification rates (dotted lines) in end-use sectors in 2020, 2035 and 2060: industry, building, on-road passenger transportation, and on-road freight transportation. The corresponding time series can be found in Figures S6 to S9.

reductions across industry, transport, and buildings. By 2035, electricity is projected to account for 40–49% of final energy consumption in industry, nearly doubling from the 2020 level of 28% (Figure 2b). Passenger road electrification's share of transport sector final energy consumption increases from 1% in 2020 to 10–13% by 2035, while freight transport electrification reaches 8–9%, complemented by emerging hydrogen technologies. Beyond 2035, these electrification trends are expected to scale up further, reaching even higher shares in industry and transport toward deeper decarbonization by 2060. The sectoral trajectories imply differentiated policy sequencing, with earlier gains in industry and transport and later responses concentrated in buildings under stronger policies. While higher electrification is critical for deeper decarbonization, sustaining such rapid growth over multiple decades remains challenging.

These large-scale transformations in energy consumption and sectoral transitions are accompanied by substantial increases in clean energy and industrial investments across all scenarios. Under the Continued-NetZero scenario, cumulative power sector investments reach \$13.2 trillion between 2020 and 2060, with solar and wind contributing more than 90%, while coal investments decline sharply (Figure 3a). In heavy industry, cumulative steel and cement sector investments total \$680 billion by 2060, primarily driven by hydrogen-based

processes and electric arc furnaces in the early years, with a growing role for CCS deployment after 2035 to further reduce emissions (Figure 3b).

Investment needs follow distinct sectoral and temporal patterns, with near-term funding concentrated in the power sector and long-term financing shifting toward industrial decarbonization. In the power sector, investment levels remain relatively stable at about \$300 billion per year in the Continued-NetZero scenario for both the near term (2020–2035) and long-term (2040–2060) (Figure 3c). By contrast, heavy industry decarbonization sees a delayed investment surge, with higher capital requirements emerging post-2035. In the steel sector, early investments are concentrated in hydrogen-based processes and electric arc furnaces at around \$10 billion per year during 2020–2035, while later years see a growing reliance on CCS deployment at about \$3 billion per year (Figure 3d). The cement sector, though requiring lower absolute investment scales, follows a similar trajectory, with CCS becoming increasingly necessary after 2035 to address emissions that cannot be mitigated through electrification (Figure 3e). These trends suggest that while the power sector can absorb early investment surges, long-term implementation depends on coordinated policies to mobilize industrial decarbonization and ensure technology readiness post-2035.

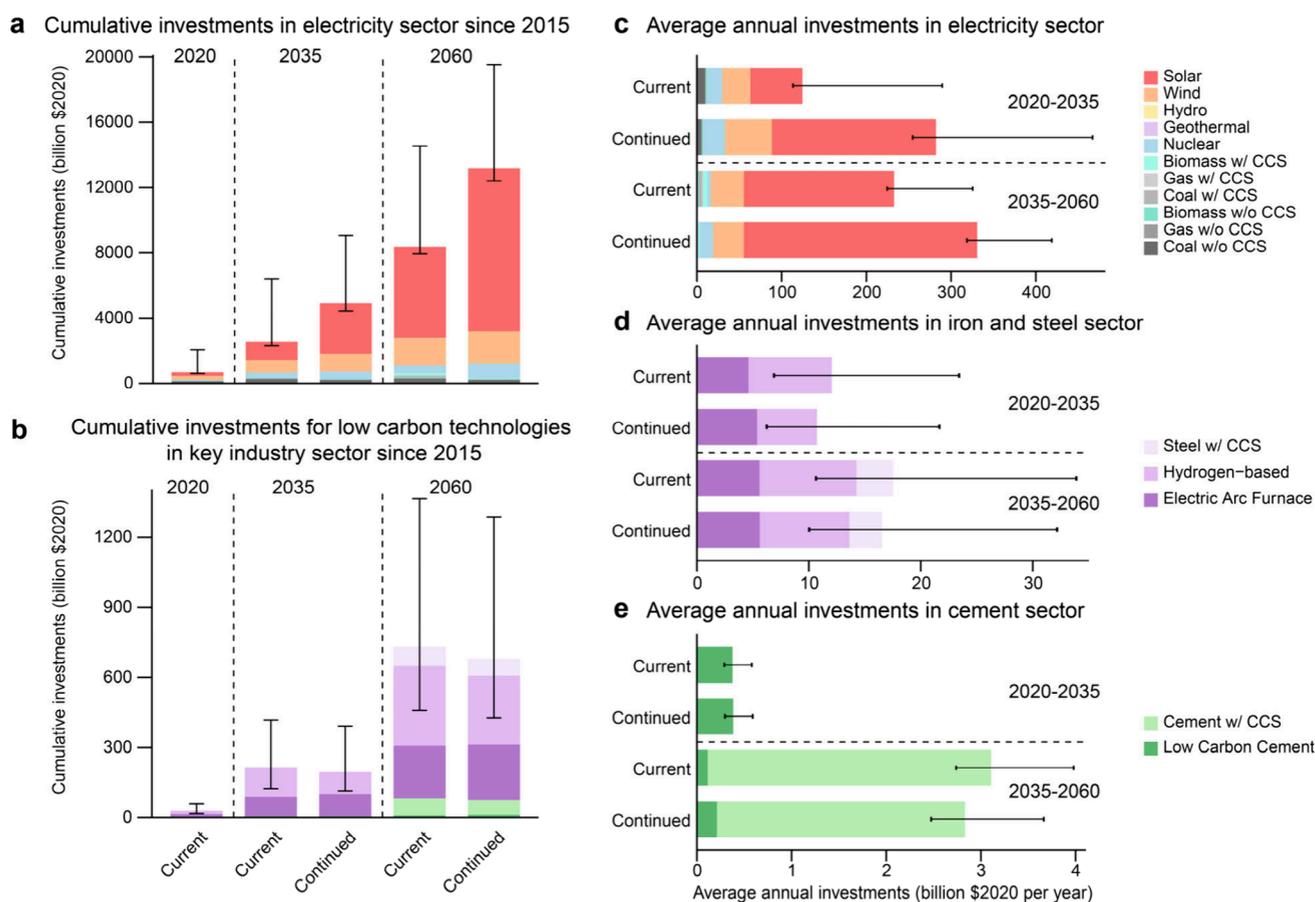


Figure 3. Investments in power and industrial sectors. (a) Cumulative investments in the electricity sector in 2020, 2035, and 2060 since 2015 (billion 2020 USD). (b) Cumulative investments in industry (only steel and cement) sectors in 2020, 2035, and 2060 since 2015 (billion 2020 USD). (c–e) Average annual investments for low carbon technologies in key subsectors (electricity, iron and steel, and cement) during 2020–2035 and 2035–2060 timeframes (billion 2020 USD per year). Uncertainty ranges on each bar reflect the uncertainty associated with the investments with different levels of capital cost assumptions for technologies. Comparison of investments with other studies can be found in Table S7, and capital cost assumptions across different technologies can be found in Table S8.

3.3. Decomposition of Individual Policy Contributions

In addition to assessing overall outcomes, we also examined the policy mechanisms driving these trends, focusing on how specific measures contribute to decarbonization pathways. Decarbonization outcomes depend on the interplay between structural transitions and efficiency improvements, with each policy type driving distinct sectoral transformations. By systematically removing individual measures from the Continued-NetZero scenario and evaluating their effects on key emissions and energy metrics, we find that structural transition policies account for the largest emissions reductions, while efficiency improvement measures primarily reduce energy intensity and enhance overall system performance. Energy structural policies, such as renewable share targets, contribute the most to CO₂ emissions reductions, lowering emissions by 8.3% in 2035 and 33% in 2060, but have limited or even negative impacts on energy intensity (Figure 4a). This arises because structural mandates primarily lower emissions by electrifying end uses, replacing direct fuel combustion with electricity that entails additional conversion losses in generation and transmission, thereby increasing primary energy requirements and dampening energy intensity improvements. In contrast, energy efficiency improvement targets effectively reduce both primary and final energy intensities by 9% and 10% relative to the scenario without these measures,

respectively, by 2060. However, efficiency improvement measures have a smaller contribution on nonfossil energy shares and end-use electrification, as they primarily focus on improving sector-wide energy efficiency across all technologies rather than shifting the energy mix.

The contributions of policy measures also reflect regional differences in resource portfolios and energy structures (Figure 4b and Figure 4c). Northwest China, with its abundant renewable energy potential, sees the highest reduction in regional emission intensity of 18%, driven primarily by energy structural transition measures that enable large-scale deployment of wind and solar power, despite a relatively high emission intensity baseline in 2020 (Figure S10). In contrast, regions with higher industrial energy demand, such as East, Central and South China, exhibit greater intensity reductions due to efficiency improvements. While energy structural policies have a more pronounced impact in regions with substantial renewable resources, efficiency measures contribute relatively evenly across all regions, indicating their broad benefits in improving energy utilization regardless of fuel type.

A more detailed decomposition evaluates individual policy impacts, offering a more granular perspective beyond the aggregated effects of structural transitions and efficiency improvements in Figure 4. Renewable capacity expansion accounts for the largest share of emissions reductions (Figure

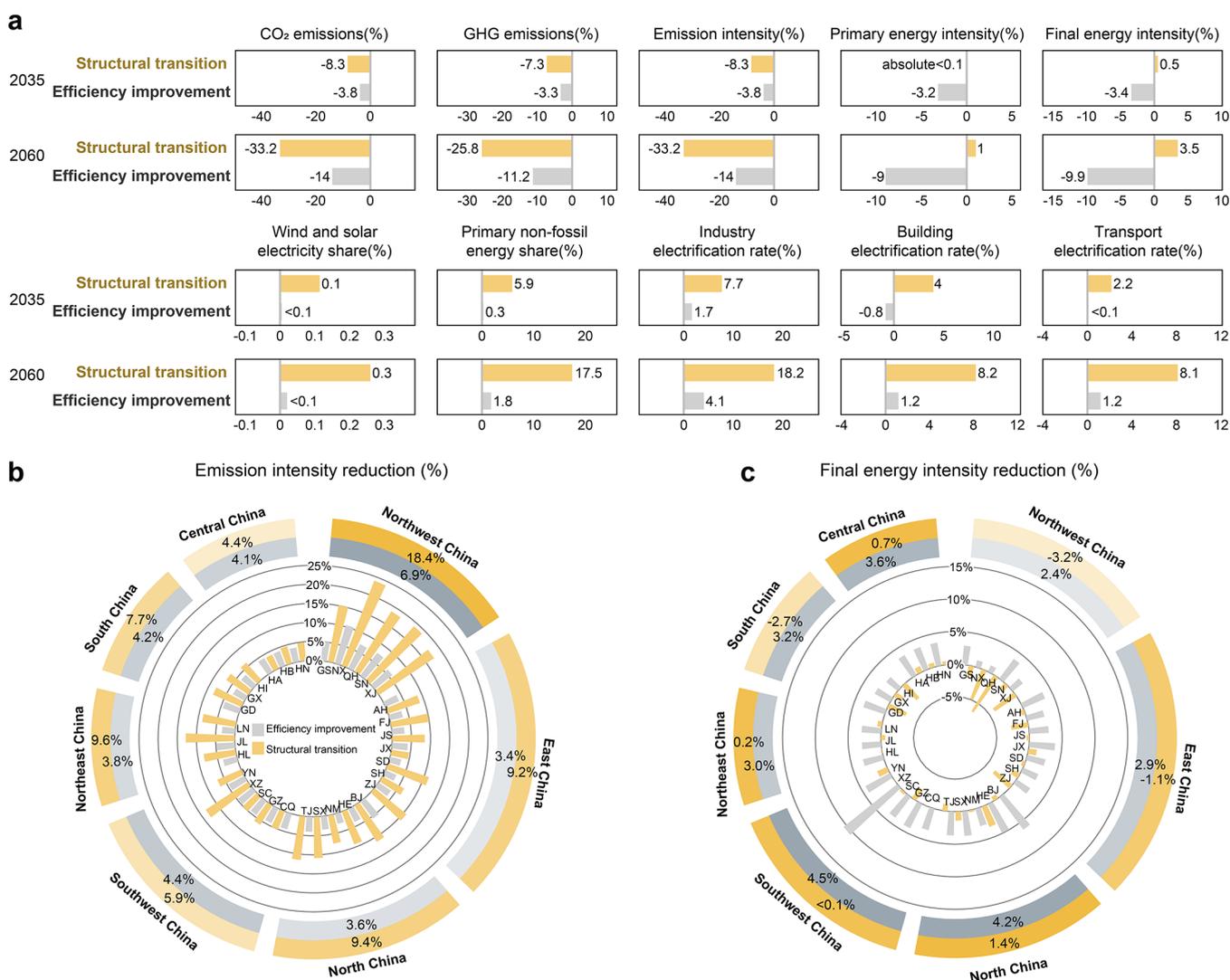


Figure 4. Contributions of aggregated efficiency improvements and energy structural changes measures. (a) Contributions to 10 key metrics in emission and energy systems under the Continued-NetZero Scenario in 2035 (upper) and 2060 (lower). Contributions are represented as the net effect of hypothetically removing all structural transition (yellow) or efficiency improvement (gray) measures on each key metric. The same result for contributions of aggregated sectors measures can be found in Figure S11. Contributions of aggregated policy measures to (b) emission intensity reduction and (c) final energy intensity reduction in each province (inner circle) and aggregate into six broader regions (outer circle) in 2035. The same result for 2060 can be found in Figure S12, and contributions to end-use sectors’ electrification rate across provinces in 2035 and 2060 can be found in Figure S13. Additionally, the contributions of aggregated sector measures to the reduction of CO₂ emissions and emission intensity across provinces in 2035 and 2060 can be found in Figures S14 to S17.

5a), lowering CO₂ emissions by 17% and increasing the nonfossil energy share by 12% in 2060. Other key measures, such as residential building efficiency improvements, also contributes to 6% in reducing CO₂ emissions and 3% in building electrification rate. While coal plant phase-outs further reduce emissions, they slightly reduce electrification rates across all end-use sectors (decreasing by 0.69% in industry, 0.36% in buildings, and 0.26% in transport) due to higher electricity prices resulting from the premature retirement of coal capacity.

The adaptability of implementing structural transitions and efficiency improvements remains uncertain, particularly at subnational scales where regional capacities, economic conditions, and infrastructure readiness vary (Figure 5b and Figure 5c). For example, although renewable expansion underpins national emissions reductions, its effect is not uniform across regions, further depending on regional energy

portfolio and resource availability. Provinces with abundant wind and solar potential in northern and western China, such as Inner Mongolia and Qinghai, see the largest capacity additions, exceeding 150 GW cumulatively from 2020 to 2035 (Figure 5b). In contrast, coastal provinces exhibit more moderate additions, primarily reflecting their higher baseline electricity demand, more diverse historical energy portfolios, and provincial development trajectories that balance multiple generation technologies rather than concentrating on large-scale renewable deployment.

Regional implementation hurdles arise from current economic disparities that are not well aligned with renewable resource availability. While northern and western provinces hold the greatest potential for wind and solar expansion, they also face significantly higher investment requirements relative to their economic scale. For comparison, in some provinces, the average annual power sector investments required during

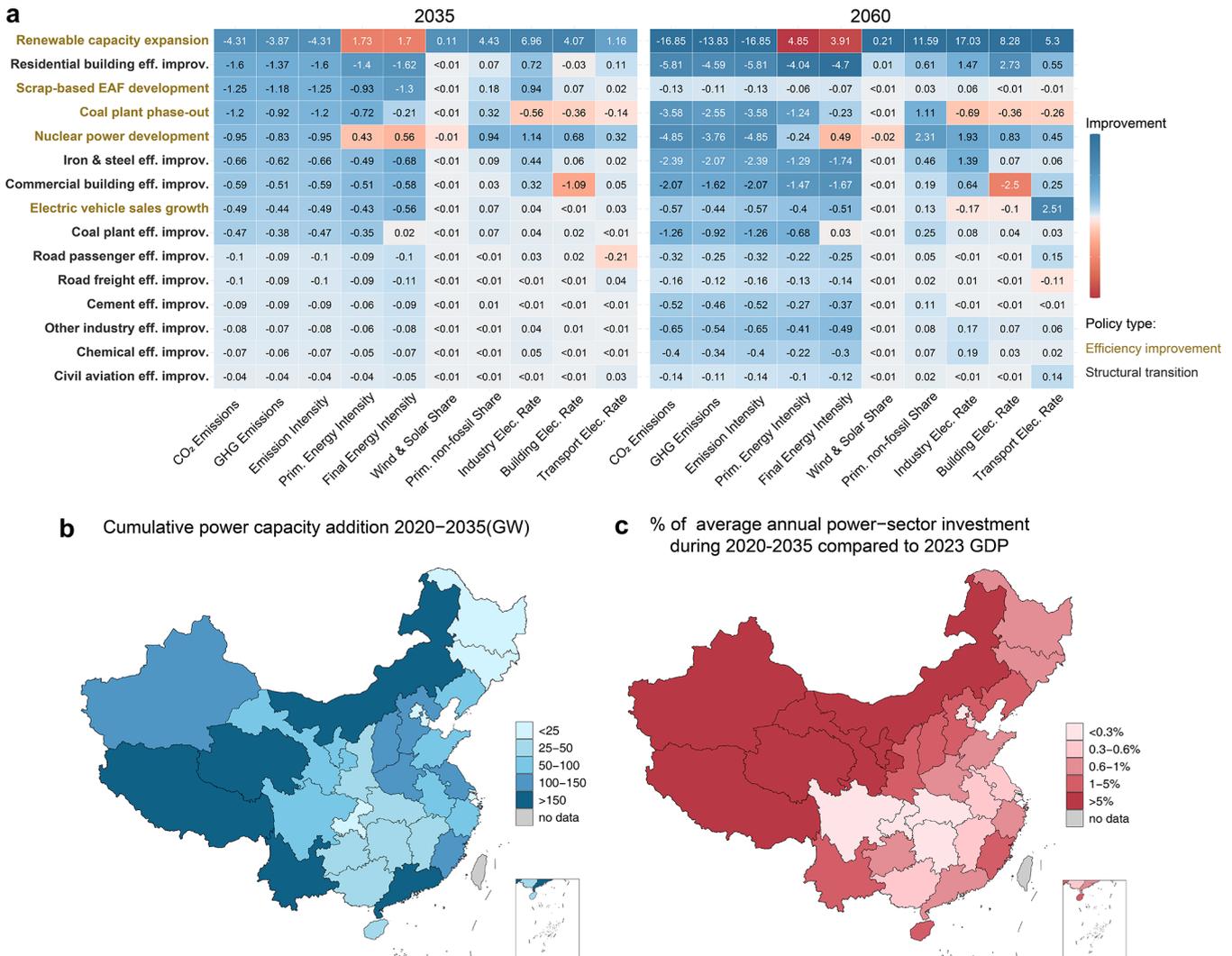


Figure 5. Contributions of individual policy measures and power installation capacity and investment by province. (a) Contribution of 15 key policy measures to 10 key metrics in 2035 (left) and 2060 (right) under the Continued-NetZero scenario. Contributions are represented as the net effect of hypothetically removing each measure on each key metric. Blue shading indicates improvements in the metric, while red shading indicates a negative effect. The correlation among the 10 key metrics can be found in Figure S19. (b) Cumulative power capacity addition and (c) percentage of average annual investment under Continued-NetZero scenarios for the periods 2020–2035. The same result for all scenarios can be found in Figure S20.

2020–2035 under the Continued-NetZero scenario are comparable to more than 5% of their 2023 GDP, as shown in Figure 5c, where northwestern provinces face disproportionately higher burdens. Bridging this mismatch will require flexible investment strategies and regionally adaptive market mechanisms to ensure equitable and sustained decarbonization. In addition to regional differences in capacity expansion, we also report disparities across other key indicators in Figure S18, providing a broader view of regional decarbonization disparity.

4. DISCUSSION

Our analysis of China’s integrated decarbonization framework shows that both energy structural changes and energy efficiency improvements are essential and complementary for achieving emissions reductions and long-term climate goals. Structural transition policies (such as renewable energy expansion and electrification) drive most of the long-term gains, while efficiency improvements play a crucial supporting

role across sectors and regions. Near-term actions, such as continued rapid scaling up of renewable capacity and electrification, are critical for laying the foundation for these long-term outcomes.^{81,82}

More ambitious reductions improve alignment with climate stabilization pathways but also raise critical implementation challenges, ranging from technological and infrastructure demands to fiscal and spatial disparities.^{83,84} Our analysis highlights the scale of the challenge, with a 100 Gt cumulative emissions gap between the Current-BAU and Continued-NetZero scenarios from 2025 to 2060, which represents 10% of the global remaining carbon budget for a 2 °C target (>66% chance) and 51% for a 1.5 °C target (>50% chance) estimated in 2024.⁸¹ Closing this ambition gap would significantly improve alignment with more ambitious climate targets, reducing the risk of exceeding carbon budgets for 1.5 or 2 °C. While our analysis reflects a detailed policy-by-policy modeling effort, the scenarios primarily capture on-the-book regulations and official targets issued to date, which may not

fully capture the depth of transformation required to meet stylized global 1.5 °C-consistent pathways.⁸¹ Echoing the UNEP Emissions Gap Report,⁸² narrowing the gap in the near term is essential not only for climate alignment but also for limiting future socio-economic and ecological risks. However, such ambition raises additional sustainability concerns, including the feasibility of sustaining historically unprecedented deployment rates, integrating emerging technologies, and managing the non-CO₂ components of the emissions portfolio.^{85–87} Although solar, wind, and industrial electrification deliver most near-term reductions, sustaining these gains requires managing uneven deployment capacity and late-stage technological hurdles, including the need to develop more remote and lower-quality renewable resource areas, expand long-distance transmission, and address emerging land-use constraints, which together raise the marginal cost of additional deployment.

Additionally, this study does not fully capture other important sustainability risks, including broader infrastructure investment needs as well as geophysical limitations on land and resource availability,^{88,89} for example, like other integrated assessment model, GCAM does not include the costs of deploying EV charging infrastructure, expanding transmission capacity, or other grid-related physical investments.⁹⁰ These elements are often underemphasized in long-term scenario analysis but are central to the real-world sustainability of decarbonization. It is worth noting that our scenarios apply policy targets at the national level, province-specific policies are not yet represented. As a result, regional differences in the results mainly reflect underlying resources conditions rather than varying provincial targets. Incorporating explicit provincial policies would be a useful next step. A further regional limitation is that the model does not explicitly track revenue flows from cross-regional electricity trade⁹¹ (Figure S21). Consequently, the high investment-to-GDP ratios observed in major electricity-exporting provinces do not reflect the financial returns paid by importing regions. Future research could incorporate interprovincial cost and revenue allocation mechanisms to assess the institutional conditions under which such cross-regional redistribution can be implemented in an equitable manner. Higher ambition needs to be supported by localized, sector-specific implementation strategies that are adaptable to regional capacity, governance environments, and economic contexts.²⁶ China's iterative refinement of sectoral policy under stable institutional guidance¹⁸ offers a potentially useful governance model for other countries navigating complex, multilevel transitions.

Our findings align with the ongoing sustainability discussions on climate action. In the current phase of international climate effort, where the focus is increasingly shifting from target-setting to credible implementation, our policy-integrated, subnational assessment framework provides an operational bridge between ambition and delivery. Recent COPs have emphasized the need for equitable, transparent, and adaptive implementation mechanisms.⁹² As countries worldwide update their national contributions and decarbonization plans, aligning climate ambition with the practical, place-based realities of infrastructure, equity, and institutional capacity will be critical for ensuring durable and inclusive sustainability transitions.

■ ASSOCIATED CONTENT

Data Availability Statement

GCAM is an open-source community model available at <https://github.com/JGCRI/gcam-core/releases>. This study utilizes the GCAM-China-v6.0, a China-specific version of GCAM that is also open-source and available at [10.5281/zenodo.10819115](https://zenodo.org/record/10819115). China's historical emissions are from the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC) and is available at <http://meicmodel.org.cn>. Simulated scenarios are publicly available on Zenodo at <https://doi.org/10.5281/zenodo.19203270>. The code used to process data and generate results will be made available upon request.

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.5c11232>.

Supplementary Text (S1–S6): model validation, GCAM-China structure, scenario details, policy mapping, investment costs, and policy decomposition; Supplementary Figures (S1–S29): research overview, energy/capacity/emission trends, provincial policy contributions, sensitivity tests, spatial net-electricity map, and sectoral outputs; Supplementary Tables (S1–S9): modeled policies, parameter sets, data sources, national/provincial emissions, investment comparisons, and technology costs (PDF)

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Author Contributions

#H.W. and Y.L. contributed equally to this paper. Y.O., R.C., and Q.Z. initiated the study, led the project, and designed the research. H.W., Y.L., and F.W. compiled data, performed the research, and prepared the graphs. N.H., H.M., A.M., S.Y., R.C., Q.Z., and Y.O. contributed to analytical approaches. H. Dai, H. Duan, F.G., X.L., D.T., W.Y., and D.Z. contributed to policy analysis. H.W., Y.L., and Y.O. wrote the first draft of the paper. All authors critically revised successive drafts of the paper and approved the final version.

Notes

The authors declare no competing financial interest.

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