Aligning a 1.6°C Pathway with China's 2060 Carbon Neutrality Pledge

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Abstract

Translating global climate targets into national decarbonization roadmaps is profoundly uncertain. To navigate this uncertainty for China, we employ a national-scale energy system model developed in the MESSAGEix framework—calibrated to China's energy balances—that uniquely combines provincial-level resolution for key sectors with a high-granularity representation of intra-annual (48 time slices) power system dynamics. Across three temperature targets (1.5, 1.6, 2.0°C) and six allocation principles, our analysis reveals that wind and solar consistently emerge as "no-regret" pillars, CCS is essential for heavy-industry abatement, and hydrogen's sourcing shifts with budget stringency. A critical systemic co-dependency exists across scenarios with stringent emissions constraints: the power sector must transform into a net carbon sink to enable the decarbonization of heavy industry, creating stark path dependencies across technology choices. The 1.6°C pathway under the Grandfathering principle aligns with China's 2060 neutrality pledge and offers a detailed blueprint for this transition. Our provincial-level analysis distinguishes high-stakes decisions from robust "no-regret" investments, offering a framework to guide China's journey to carbon neutrality.

Keywords: 1.6°C Target, Carbon Budget, Allocation Principles, China, Decarbonization Pathways

***Synopsis**: Pathway analysis shows a power–sector carbon sink balances industry's residual emissions, informing China's climate policy and power–industry interactions on CO_2.*

1 Introduction

Navigating the global response to climate change is an exercise in managing profound uncertainty [1]. This uncertainty is anchored in the concept of the remaining carbon budget (RCB), which fundamentally dictates the stringency and pace of global decarbonization pathways [2]. The Paris Agreement's goal of limiting warming to well below 2°C, while pursuing efforts for 1.5°C, has framed the global ambition [3]. However, the feasibility of the 1.5°C target is increasingly debated, leading some scholars to explore intermediate goals such as 1.6°C as more pragmatic benchmarks [4]. For any individual country, the translation of global targets into concrete action is further complicated by the allocation principles of RCB and the country's economic structure and resource endowments. Recently, Ref [5] systematically quantified how the allocation principles yield vastly different emission allowances for each country, providing a foundational basis for designing national decarbonization pathways under varied temperature targets. This global context frames the central challenge for China's unprecedented journey to carbon neutrality, raising a critical question: How do these layered uncertainties shape the national and sectoral transition pathways for the world's largest emitter?

A substantial body of research has focused on identifying the key sectors and technologies pivotal to China's decarbonization. These studies yield valuable insights into the transition of the power sector by highlighting renewables [6], nuclear [7], BECCS [8], hydropower [9] and CCS [10–12]; the deep decarbonization of heavy industries such as cement [13–15], chemical [16] and steel [17–19]; the role of green hydrogen as a versatile energy carrier and feedstock in hard-to-abate sectors [20]; and the transformation of the building [21], heating [22], and transport [23–25] sectors. However, these analyses mostly adopt a narrow scope, often focusing on a single sector or technology without a holistic perspective on the structural changes inherent in such a transition [26]. This risks underestimating the systemic impact of cross-cutting strategies, for example, demand-side electrification and decarbonization of power supply [27], especially the interplay between them. More critically, this siloed approach precludes a system-wide, cost-optimal allocation of abatement efforts under a unifying carbon budget, which is essential for prioritizing the most economical mitigation options across all sectors. Other studies have employed integrated system models, such as Computable General Equilibrium (CGE) models [28, 29] and Integrated Assessment Models (IAMs) [30, 31], to offer a more comprehensive view. For instance, Ref. [32] explored China's transformations under various global effort-sharing principles for a 2°C target, however, with limited technological details about key sectors and technologies provided. Overall, the explicit transformation roadmaps for key sectors in China, as well as the required spatiotemporal deployment of key abatement technologies remain insufficiently explored, particularly under different climate targets. This research gap limits the availability of actionable insights for effective policy and investment planning.

This paper addresses these gaps by exploring a critical set of questions: How do different global temperature targets and carbon budget allocation principles shape China's national emission pathways? Specifically, what are the transition dynamics of its key industrial sectors, and what is the required spatiotemporal diffusion of key abatement technologies? To answer these questions, we employ a national-scale energy system model for China, developed within the MESSAGEix framework. The model is tailored to capture the core challenges of industrial decarbonization by incorporating the most critical sectors with process-level representations, including power and heat, iron and steel, cement, chemicals, and hydrogen production. To balance this deep sectoral granularity with computational tractability, we adopt a hybrid-resolution approach. This strategy combines provincial-level modeling for these key sectors – along with 48 representative time slices to capture intra-annual power system dynamics – with a more aggregated representation for other end-use sectors. This allows us to elucidate the dynamic, high-resolution transformation pathways for China's key sectors, thereby providing a more actionable roadmap that highlights the critical choices and trade-offs ahead.

The rest of this paper is organized as follows. Section 2 details our modeling framework, while Section 3 explains the design of the scenario matrix used to explore key uncertainties. Section 4 presents the core findings, beginning with an analysis of China's national emission pathways under different climate targets, followed by an examination of the key technology portfolios and their spatiotemporal deployment, and culminating in a deep dive into the 1.6°C pathway aligned with China's neutrality pledge. Finally, Section 4.4 discusses the policy implications of our findings and concludes the paper.

2 Methodology

This study employs a national-scale, bottom-up energy system optimization model for China, developed within the MESSAGEix framework. The framework conceptualizes the energy system – spanning production, conversion, transmission, and end-use – as a network of interconnected technologies and commodities, which can be detailed at the process level. Each technology is characterized by a set of input and output coefficients, defining the flow of different commodities (e.g., energy carriers and materials). To meet the exogenously specified final demands across all sectors, the model is formulated as a linear programming problem with perfect foresight, minimizing the total discounted system cost by optimizing the activity levels and installed capacities of all technologies. The optimization is subject to a series of constraints, including demand-supply balances of all commodities, technology capacity expansion limits, resource availability, and policy-driven constraints like carbon budgets. Refs [33, 34] provide a detailed description of the model framework.

Building upon this framework, our model for China encompasses all sectors of the national energy balance, calibrated to a 2020 base year using official statistics [35], with an optimization horizon spanning from 2025 to 2060 in 5-year intervals. The national energy balance statistics are aggregated into 13 distinct sectors within the model. As summarized in Table 1, the technology portfolio includes 113 backbone and 10 add-on technologies. To represent the energy flows, 14 key energy carriers were selected, each accounting for at least 3% of the final energy consumption in one or more of 13 sectors. These include coal, natural gas, diesel, gasoline, liquefied petroleum gas (LPG), heat, coke, kerosene, fuel oil, electricity, petroleum bitumen, naphtha, petroleum coke, and traditional biomass.

Table 1: Sector and technology coverage

Sectors	**Backbone technology**	**Add-on technology**	
		CHP	**CCS**
trade	23		
afolu	5		
power and heat	26	3	4
oil refining	7		
other upstream	5		
iron and steel	8		2
chemical	9		
non-ferrous metals	4		
cement	3		1
construction	5		
other downstream	4		
building	8		
transport	6		

Finally, to balance representational granularity with computational tractability, a key feature of our model is its hybrid approach to sectoral and spatiotemporal representation, which combines high-resolution detail for sectors critical to decarbonization with a more aggregated representation for others to maintain computational tractability. The sectoral modeling is detailed as follows:

- **Power and Heat:** The power and heat sector is modeled with detailed process-level representation, encompassing a comprehensive portfolio of generation technologies, including conventional thermal power (coal, gas) and various low-carbon options (nuclear, hydro, biomass, wind, and solar). Key abatement measures like carbon capture and storage (CCS) and combined heat and power (CHP) are available as add-on technologies.
- **Iron and Steel:** The iron and steel sector is modeled at the process level, with seven technologies representing three main production routes: the conventional blast furnace-basic oxygen furnace (BF-BOF), the scrap-based electric arc furnace (EAF), and the hydrogen-based direct reduced iron (H2-DRI). CCS is modeled as an add-on technology for key processes. The provincial-level disaggregation accounts for regional heterogeneity in feedstock prices and CCS costs. Key parameters, including techno-economic data for production processes and projections for steel product demand, are adopted from Ref [36].
- **Cement:** The model represents cement production through three sequential processes: material preparation, clinker making, and cement grinding. To address process emissions, CCS is available as an abatement option for the clinker making stage. This sector is modeled at the provincial level to reflect regional variations in CCS costs. The underlying techno-economic parameters and future demand projections for cement are sourced from Ref [36].
- **Chemicals:** The chemical industry is represented at the provincial level with a focus on ammonia and methanol, modeled with distinct process-level technologies. Other chemical products are aggregated, with the total final energy demand of the entire chemical sector calibrated to align with national energy balance statistics. The techno-economic parameters and demand projections are drawn from Ref [36].
- **Other Sectors:** Other energy demand sectors are modeled in a more aggregated manner. This group includes various industries (other upstream, non-ferrous metals, construction), buildings, and transport, which are represented at the national level without process-level detail; their future final energy demands are specified exogenously based on calibrations with national energy balances and projections from the CEEGE model [28] (see Section 3 for details). The land-use sinks of Agriculture, Forestry, and Land Use (AFOLU) sector is incorporated for emissions accounting purposes according to Ref [37]. Finally, the oil

refining sector is also modeled as a single national entity, though it is represented with process-level details based on Ref [36].

Apart from these sector details above, another critical input for the model is the provincial cost of CCS, which is applied across the power, steel, and cement sectors. These costs are derived from a high-resolution source-sink matching optimization model for China. This bottom-up model first compiles a comprehensive database of CO_2 sources (plant-level data for thermal power, steel, cement, and coal chemicals) [38, 39] and sinks (onshore and offshore storage at a 40x40 km^2 grid resolution) [40]. Using detailed cost data for the entire CCS value chain – from capture and compression to transport and storage – a Mixed-Integer Linear Programming (MILP) model is formulated to match sources with sinks at minimum cost. The solution of this model provides plant-level costs of CCS, which are then aggregated to generate the provincial-level, multi-sector input parameters for CCS in the model.

Hydrogen production is modeled at the provincial level, encompassing pathways based on coal, natural gas, and water electrolysis. The techno-economic parameters for these production routes are drawn from Ref [41]. A key model assumption is that hydrogen is consumed locally within the province of its production. In contrast to the "copper-plate" assumption for electricity, inter-provincial transport of hydrogen is precluded – a simplification justified by its high transport costs and designed to manage the scale of the optimization problem. Hydrogen serves multiple end-uses: as a reducing agent for the steel industry, a feedstock for chemical synthesis, and an energy carrier for industrial heat, where it competes directly with coal and natural gas. From an emissions accounting perspective, hydrogen is not treated as an independent sector in the model. Instead, emissions from hydrogen production are attributed to the sectors where hydrogen is consumed: when hydrogen is produced from coal or natural gas, the associated CO_2 emissions are counted in the corresponding end-use sectors (e.g., steel, chemicals, industrial heat).

In summary, the modeling philosophy focuses on representing core decarbonization sectors with high granularity, while other resource inputs or sectors' final energy demands are simplified using "import" or "tube" technologies. The combination of provincial disaggregation for key sectors and the intra-annual temporal resolution (48 time slices) results in a large-scale optimization problem with 1,845,649 variables for activity alone. A single scenario requires 3-4 hours to solve on a MacBook M4 Pro machine, with a peak memory usage of approximately 25 GB. Notably, this version of the model deliberately excludes a suite of 107 energy efficiency add-on technologies for the steel, cement, and oil refining sectors. While a more complex configuration including these options saw its memory footprint reach approximately 280 GB, the optimization results showed minimal deployment of these efficiency measures. This is because they primarily reduce electricity consumption, which has a diminishing impact on carbon abatement in a future power system dominated by renewables. Therefore, to maintain computational tractability and focus on the most critical decarbonization levers, these energy efficiency options were omitted from the final analysis.

3 Scenario Design

To systematically navigate the deep uncertainties inherent in China's decarbonization pathways, this study constructs a comprehensive scenario matrix of 54 plausible futures. These scenarios are designed to explore three key dimensions of uncertainty that fundamentally shape national transition strategies: the stringency of the global climate target, the principle for international carbon budget allocation, and the pace of domestic end-use electrification.

The first dimension considers three long-term global temperature targets. Alongside the Paris Agreement's established 1.5°C and 2.0°C goals, we include a 1.6°C target, which represents a more pragmatic intermediate pathway increasingly discussed in recent scientific literature. The second dimension addresses the contentious issue of equity in global climate action by applying six distinct principles for allocating the remaining global carbon budget, following the framework of Ref [5]. These principles encapsulate a wide spectrum of ethical considerations, ranging from historical responsibility to per capita equality, including: **Grandfathering (GF)**, which preserves current emission fractions; **Per Capita (PC)**, allocating emissions based on population; **Per Capita Convergence (PCC)**, transitioning from GF to PC over time; **Ability to Pay (AP)**, allocating emissions inversely to GDP per capita; **Equal Cumulative Per Capita (ECPC)**, which reconciles historical emissions before converging to a PC basis; and **Greenhouse Development Rights (GDR)**, based on a Responsibility-Capability Index. The combination of these temperature targets and allocation principles defines 18 distinct carbon budget trajectories for China from 2025 to 2060.

The third dimension explores uncertainty in domestic demand-side transformation through three levels of future electrification for sectors where technological change is not endogenously modeled (e.g., buildings, transport). These levels represent different policy and technology adoption narratives: a **High** level assumes rapid technology diffusion (e.g., of electric vehicles and heat pumps) driven by strong policy support; a **Medium** level represents a continuation of current trends; and a **Low** level considers scenarios with slower adoption due to potential barriers. These trajectories are not abstract assumptions but are calibrated against detailed projections from the CEEGE model [28], providing internally consistent pathways of final energy demand by carrier as exogenous inputs to our model.

The resulting 3×6×3 matrix of 54 scenarios provides a robust framework for exploring the solution space. For clarity of visualization in Figures 1-3, results are averaged across the three electrification levels to isolate the impact of carbon budget uncertainty. Sensitivity analyses for these results with respect to the electrification level are provided in the Supplementary Materials. Subsequently, the impact of varying electrification levels is explicitly analyzed in Figures 4-6 for the 1.6°C pathway under the Grandfathering principle, offering a deeper dive into the interplay between supply- and demand-side transformations.

4 Results and Discussion

4.1 China's Emissions Pathways across Global Warming Scenarios

Following Ref [5], we calculated the sectoral decarbonization pathways for China under three temperature targets (1.5°C, 1.6°C, and 2.0°C) and six allocation principles. The carbon budget under different scenarios are downloaded from the CarbonBudgetExplorer[1] for the years from 2025 to 2060.

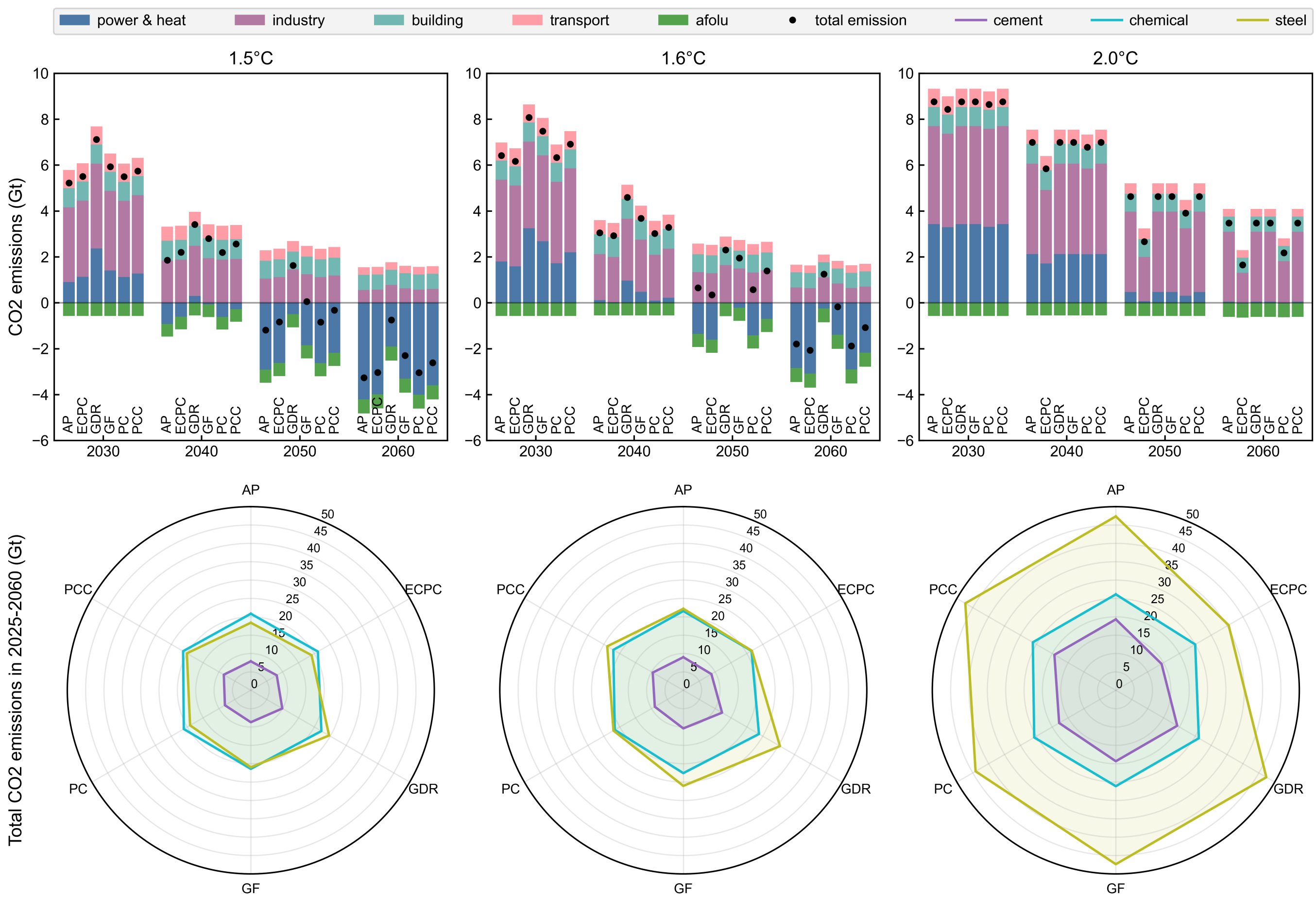

Fig. 1: Sectoral and industrial CO_2 emissions under alternative temperature targets and allocation principles. Top row: Stacked bars show annual CO_2 emissions by sector (power & heat, industry, buildings, transport, afolu) under various target temperatures and allocation principles in 2030, 2040, 2050 and 2060; black dots denote total emissions, and negative values indicate net removals. Bottom row: Radar charts report cumulative CO_2 emissions in 2025–2060 from heavy industry (cement, chemical, steel).

[1] Dekker, M.M. (2023) The Carbon Budget Explorer. [Online]. Available: https://www.carbonbudgetexplorer.eu.

As shown in Figure 1, China's decarbonization pathways are shaped by the stringency of the global temperature target and the choice of allocation principle. A clear pattern emerges across all scenarios: looser temperature targets systematically correspond to larger annual emission allowances and higher cumulative budgets for heavy industry (top and bottom panels, respectively). The 1.5°C pathways, in particular, demand exceptionally deep emission cuts, mandating that the entire economy achieves carbon neutrality no later than 2050. Within a given temperature target, the allocation principle acts as a critical variable, leading to vastly different emission trajectories and sectoral responsibilities. Despite this variability, a common strategy is the pivotal role of the power and heat sector, which must deploy negative emission technologies at scale in later decades to offset residual emissions from hard-to-abate sectors. This underscores the increasing reliance on large-scale CO_2 removal, especially under the more ambitious 1.5°C and 1.6°C targets. Notably, the 1.6°C pathway under the GF principle results in slightly negative emissions by 2060, closely aligning with China's carbon neutrality pledge.

A deeper analysis of Figure 1 reveals a crucial co-dependency between the power sector and heavy industry that defines China's transition. The pathways show the power sector undergoing a radical transformation, shifting from the largest emissions source to the primary engine of carbon removal via technologies like BECCS, particularly after 2040. This pivot is the critical enabler that creates the necessary carbon space for heavy industry to manage its stubborn residual emissions. The radar charts quantify this dependency: the constrained industrial emission budgets under the 1.5°C and 1.6°C targets are only feasible because of the massive carbon sink created by the power sector. This framing shifts the challenge from a simple sum of sectoral cuts to a systemic balancing act, necessitating a specific portfolio of technologies to manage this inter-sectoral carbon offsetting.

4.2 Key Technology Portfolios and Spatiotemporal Deployment

The technological backbone for the ambitious emission pathways outlined above needs to be formed by a strategic portfolio of key technologies. As presented in Figure 2, tighter budgets unequivocally accelerate the adoption of a synergistic suite of low-carbon technologies across key industrial and energy sectors. The role and sourcing of hydrogen, for instance, are highly sensitive to the available budget. Under the most stringent 1.5°C pathways, green hydrogen from electrolysis becomes the dominant production route, accounting for up to 83% of total supply and serving as an essential decarbonization lever for both industrial heat and ironmaking (via H2-DRI). Under the looser 2.0°C scenarios, however, this trend reverses sharply: the share of electrolysis plummets to as low as 6%, while natural gas-based hydrogen expands to supply the nearly 87% remainder. This upstream energy shift is mirrored in the steel industry, where hydrogen-based ironmaking (H2-DRI) is phased out in favor of traditional blast furnaces. This stark trade-off highlights a critical path dependency: near-term investments favoring large-scale electrolysis and renewable capacity under stringent targets lock in a green hydrogen economy, whereas channeling capital into natural gas reforming under looser budgets prolongs the transition away from fossil fuels.

Carbon capture and storage emerges as another key enabling technology, but its role is nuanced and sector-dependent. For cement production, CCS is a robustly essential strategy under 1.5°C and 1.6°C targets, where it is applied to over 70% of clinker production. In ironmaking, CCS applied to traditional blast furnaces is a significant transitional technology, maintaining a share of around 36% in these scenarios, but it is entirely phased out in 2.0°C pathways. Its role in power generation is more limited, primarily serving to extend the lifetime of some coal power plants in pathways with larger carbon allowances. The power sector forms the backbone of the transition, with wind and solar power as the undisputed pillars, collectively constituting between 66% and 75% of total generation across all scenarios. The primary distinction between pathways lies in the composition of the dispatchable, low-carbon fleet. Tighter budgets necessitate a heavy reliance on BECCS, which provides up to 14.5% of electricity generation in 1.5°C scenarios, making it the third-largest contributor. This critical role in providing dispatchable, negative-emission power partially crowds out wind and solar technologies. As the budget loosens, the role of BECCS diminishes, disappearing entirely in 2.0°C pathways, while hydropower and nuclear power provide stable contributions to the grid.

Beyond these broad trends, the boxplots in Figure 2 provide a granular map of the investment uncertainty introduced by allocation principles. As shown, the deployment shares for renewable power – particularly solar and wind – exhibit narrow ranges across all scenarios. This marks them as the unambiguous "no-regret" bedrock of the transition.

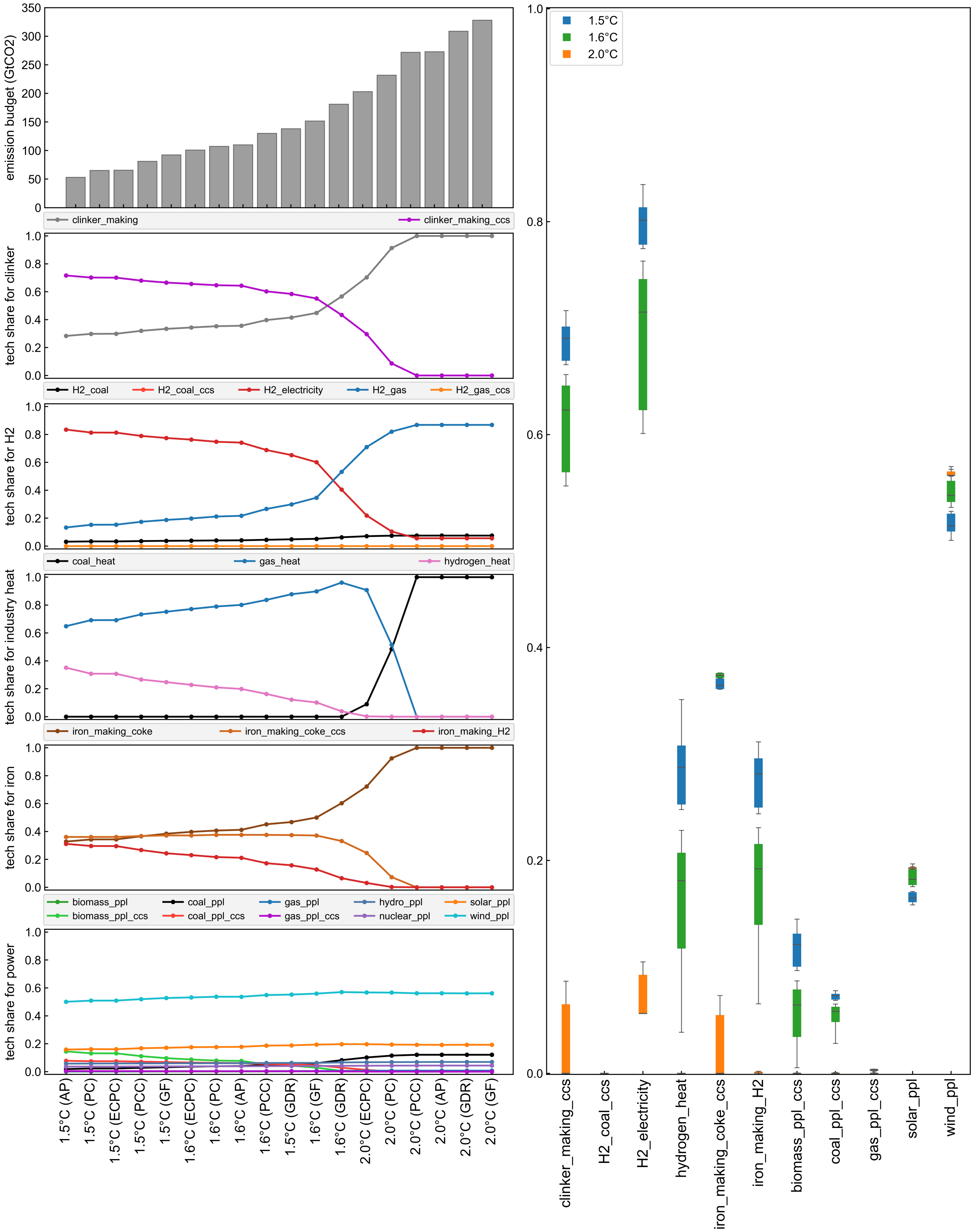

Fig. 2: Technology portfolios under alternative temperature targets and allocation principles. Left: The top panel shows China's cumulative CO_2 budget for 2025–2060 for each scenario, which combines a temperature target and an allocation principle. The subsequent panels report the cumulative technology shares for (i) clinker production, (ii) hydrogen production, (iii) industrial heat, (iv) ironmaking, and (v) power generation. Right: Boxplots summarize the variation in cumulative shares arising from the different allocation principles for each temperature target (blue: 1.5°C, green: 1.6°C, orange: 2.0°C).

In stark contrast, technologies like BECCS in the power sector and green hydrogen production face profound uncertainty. For instance, under the 1.6°C target, the required share of BECCS can vary by over

10-fold (from 0.5% to 8.7%) depending on the allocation principle. Furthermore, another crucial insight is that loosening the climate target can increase planning uncertainty. For cement with CCS, for instance, the planning uncertainty increases as the climate target loosens from 1.5°C to 2.0°C, because the tight budget under the 1.5°C target effectively locks in large-scale CCS as a necessity regardless of the allocation principle, thus reducing uncertainty. In contrast, the looser 2.0°C budget creates more strategic leeway, making the decision to deploy CCS highly contingent on the chosen principle, thereby increasing the planning uncertainty.

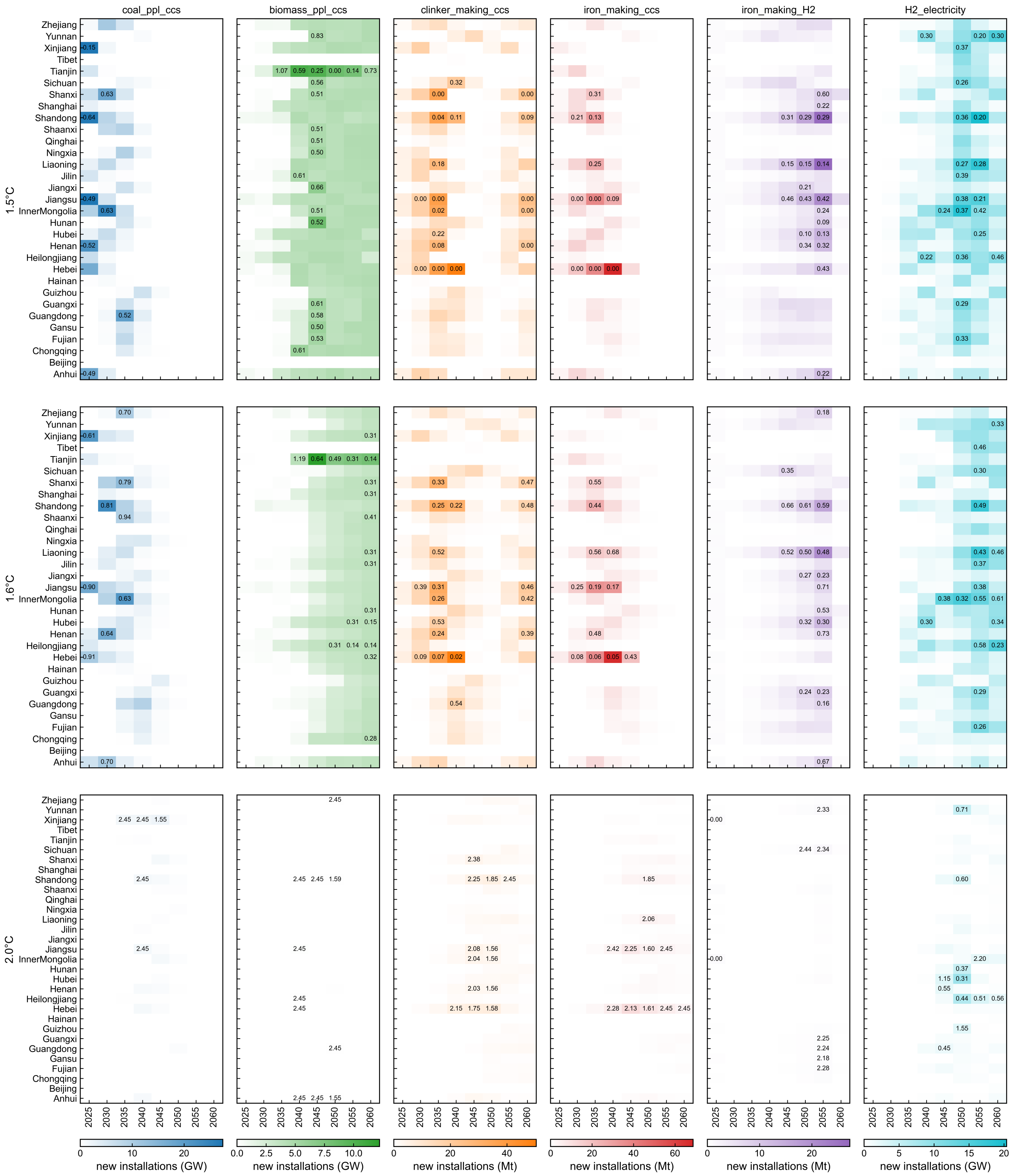

Fig. 3: Spatiotemporal deployment of key technologies under alternative temperature targets. Each column represents one technology (coal power with CCS, biomass power with CCS, clinker with CCS, ironmaking with CCS, H2-DRI ironmaking, electrolytic H2); rows correspond to the 1.5°C, 1.6°C and 2.0°C targets. The heatmaps show the mean annual new capacity installations by province (y-axis) and year (x-axis, 2025–2060). Color intensity denotes the scale of deployment (units indicated below each panel; GW or Mt). Within each panel, cells in the top decile of positive values are annotated with the coefficient of variation (std/mean) across allocation principles, indicating the planning uncertainty for the largest deployments.

Finally, having identified the strategic technology portfolios, Figure 3 maps out their spatiotemporal deployment. A clear, overarching trend is that stricter temperature targets necessitate an earlier, larger-scale, and more widespread deployment across the country. Crucially, the annotated cells in these deployment hotspots also reveal a considerable planning uncertainty, quantified by the coefficient of variation (std/mean). This metric offers a clear guide for investment: intensely colored cells with low variation represent robust, high-priority opportunities, whereas those with high variation highlight high-risk investments whose required build-out pace is highly sensitive to the chosen allocation principle. This planning uncertainty is notably reduced under stricter temperature targets, as the imperative for rapid decarbonization narrows the range of viable options. Furthermore, the strong co-location of electrolytic hydrogen production and H2-DRI iron-making suggests the potential formation of industrial hubs where green hydrogen is produced locally to decarbonize adjacent industrial facilities.

4.3 Aligning China's Carbon Neutrality Pledge with the 1.6°C Global Warming Limit

As shown in Figure 1, China's CO_2 emission in 2060 under the 1.6°C target with the GF allocation principle is −0.169 Gt, close to 0, which is aligned with China's 2060 neutrality pledge.

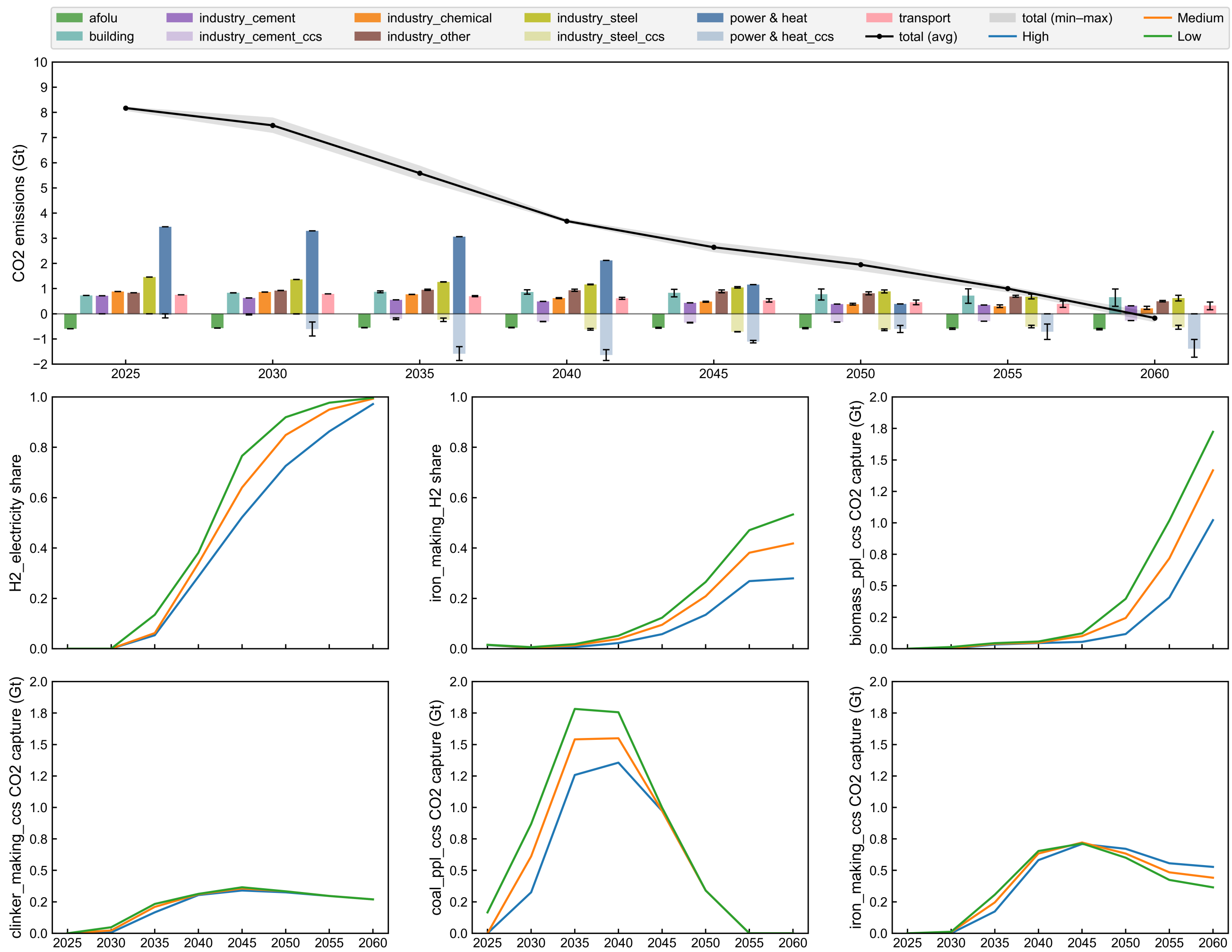

Fig. 4: Emissions pathway and technology responses for China under the 1.6°C target with the GF allocation principle. Top: Stacked bars show annual CO_2 emissions by sector from 2025–2060. The black line denotes total emissions averaged across electrification scenarios, with the grey band indicating the range; negative bars indicate net removals. Bottom: Trajectories of key technology variables by electrification level (green high, orange medium, blue low): share of electrolytic H2 and H2-DRI, and annual CO_2 captured by biomass power CCS, coal power CCS, clinker CCS and ironmaking CCS.

Figure 4 details the 1.6°C–GF pathway and shows the impact of end-use electrification levels. We vary the electrification level because several demand sectors are not modeled at the process level. Their final energy trajectories are specified exogenously based the results from a CGE model, CEEGE [28] (see 3 for details). As shown, across electrification levels, residual emissions from industry and transport must be offset by removals from the power and AFOLU sectors. By 2060, BECCS in the power sector supplies large-scale removals (order of 1–2 Gt CO_2/year across levels). Electrification rebalances the technology mix: higher electrification accelerates and lifts the trajectories of electrolytic hydrogen and H2-DRI, and raises cumulative removals (BECCS). Conversely, lower electrification tightens the residual carbon space within the process-level sectors and induces a stronger pivot toward H2/H2-DRI, while BF-CCS in steel declines as it is displaced. Overall, differences across pathways are expressed mainly as a redistribution of abatement effort between power and industry. A significant finding is the transitional role of CCS on coal-fired power plants: its deployment peaks around 2035–2040 and then declines as the coal fleet is phased out. By contrast, CCS in industrial processes and BECCS are sustained as long-term strategic options; clinker-CCS is indispensable, while ironmaking-CCS gradually gives way to H2-DRI as electrolysis scales.

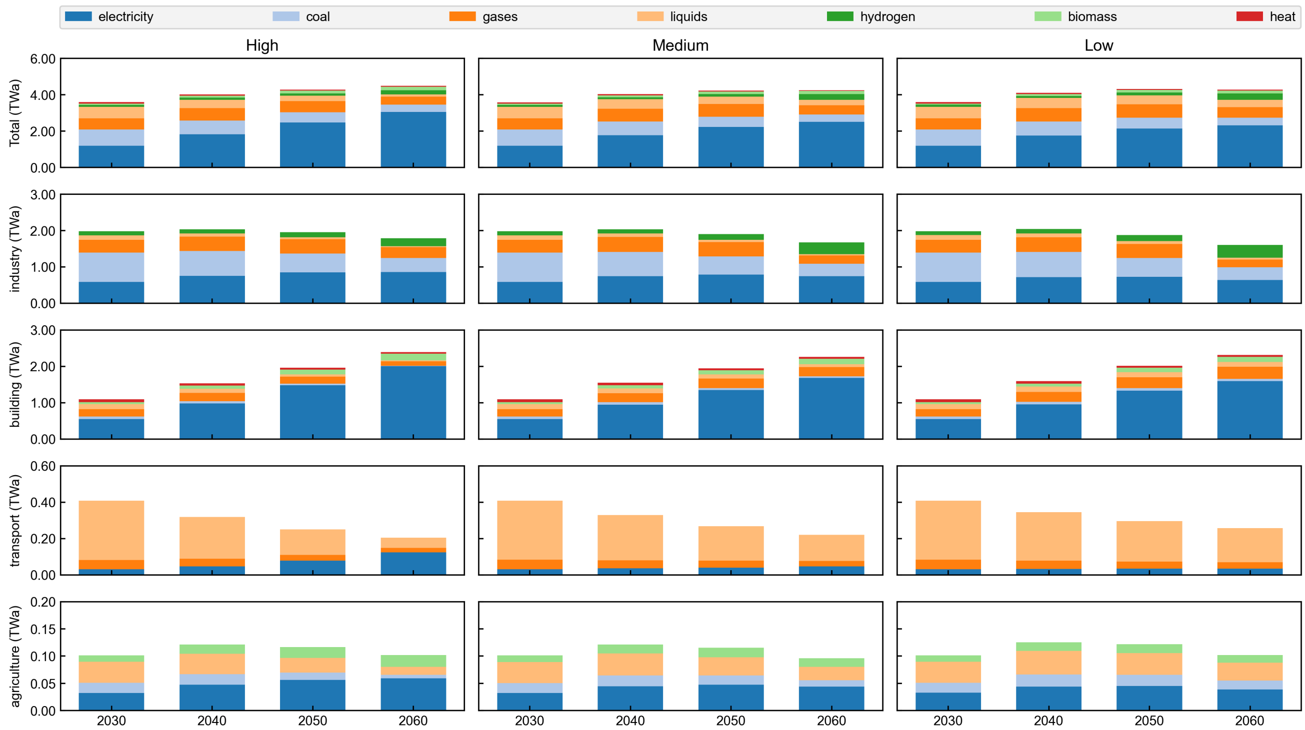

Fig. 5: Final energy demand by sector and carrier under the 1.6°C target with the GF allocation principle. Columns denote electrification levels (High, Medium, Low); rows report Total, Industry, Buildings, Transport and Agriculture. Stacked bars show demand in 2030, 2040, 2050 and 2060 by carrier.

The deep decarbonization of the energy system is contingent upon a profound transformation of final energy demand across all major sectors (Figure 5). A clear and universal trend is the rise of electrification: electricity steadily replaces fossil fuels to become the dominant energy carrier in industry, buildings, and agriculture, with the building sector approaching near-total electrification by 2060. The industrial sector, as the largest energy consumer, acts as the anchor of this transition, exhibiting a complex fuel-switching dynamic where coal is progressively phased out in favor of electricity, natural gas, hydrogen, and biomass. In stark contrast, the transport sector remains heavily reliant on liquid fuels, highlighting the persistent challenge of decarbonizing aviation, shipping, and heavy-duty freight. The level of electrification significantly influences the pace and depth of this transition. A high-electrification scenario accelerates the phase-out of coal, drives higher electricity consumption across the board, and enables an earlier and larger-scale deployment of hydrogen, particularly in industry. Notably, despite continued economic growth, total final energy consumption is projected to plateau and even decline after 2040, underscoring the critical role of system-wide energy efficiency improvements in decoupling economic activity from energy demand.

The evolution of the power system, as the linchpin of the entire energy transition, is detailed in Figure 6. A complete structural shift is projected, with wind and solar power emerging as the undisputed pillars of the future electricity supply. Their contribution grows rapidly from 2025, constituting the vast majority of generation by 2060. Concurrently, the role of coal power diminishes over time, marking an orderly phase-out that culminates in its near-total exit from the generation mix by mid-century. The bottom panels, illustrating the intra-annual dispatch in 2060, depict the operational reality of a system dominated by variable renewables. The distinct daily peaks of solar generation, particularly in spring and summer, create a pronounced "duck curve" that necessitates a portfolio of flexible resources for system balancing. This portfolio includes hydropower, nuclear, and biomass, which provide stable baseload power, thereby ensuring reliability during periods of low wind and solar output. The level of electrification directly determines the scale of the power system; a high-electrification scenario requires a significantly larger generation capacity to meet the increased demand from other sectors. Ultimately, the figure showcases the operational blueprint of a next-generation power system, one that relies on a complementary mix of variable renewables and dispatchable, low-carbon resources to manage seasonal and diurnal variability.

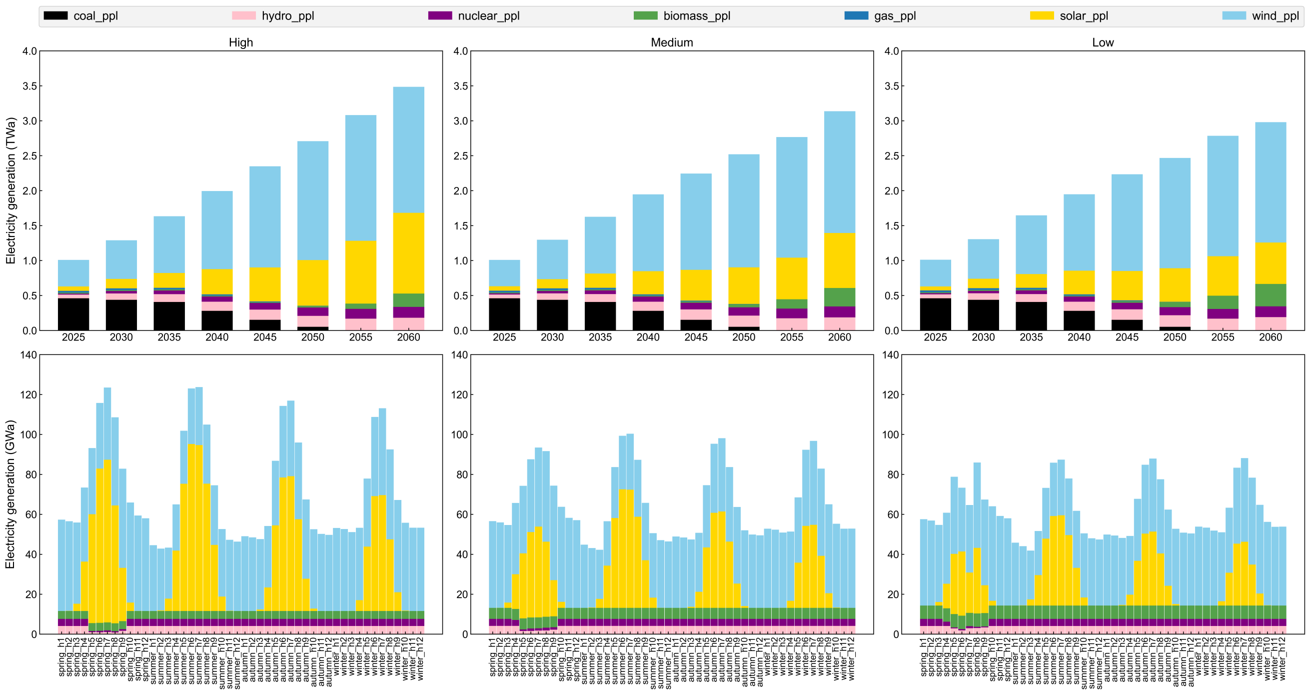

Fig. 6: Power system evolution under the 1.6°C target with the GF allocation principle. Columns denote electrification levels (High, Medium, Low). Top row: annual electricity generation by technology (coal, gas, biomass, hydro, nuclear, solar, wind) from 2025 to 2060 (stacked; units: TWa). Bottom row: intra-annual generation mix in 2060 for four representative days (spring, summer, autumn, winter) at 2-hour resolution (units: GWh), illustrating diurnal/seasonal variability and the complementary roles of variable renewables and flexible resources.

4.4 Discussion

By systematically quantifying China's decarbonization pathways under the dual uncertainties of global climate targets and international equity principles, this study provides critical insights for aligning national strategy with long-term climate goals. Our analysis identifies that wind and solar power are the undisputed "no-regret" pillars of the future energy system, while carbon capture is essential for deep decarbonization of heavy industry. Under the ambitious 1.5°C and 1.6°C targets, this transition further requires the power sector to transform from the largest emitter into a net carbon sink. The 1.6°C pathway under the Grandfathering (GF) principle, which aligns with China's 2060 neutrality pledge, reveals a nuanced technology strategy. It necessitates a complete phase-out of unabated coal power, with CCS on the remaining fleet serving only a transitional role that peaks around 2040. In contrast, CCS on industrial processes is sustained as a long-term solution. Ultimately, neutrality is achieved by deploying BECCS at scale to deliver 1.5 Gt of negative emissions by 2060, compensating for residual emissions from hard-to-abate sectors.

These findings underpin three core insights. First, China's transition is not a simple summation of sectoral efforts but a systemic balancing act, defined by a crucial co-dependency between the power sector and heavy industry. The power sector must undergo a radical transformation – from the largest emitter to the primary engine of carbon removal – to create the necessary carbon space for hard-to-abate industries. Second, this inter-sectoral offsetting is technologically specific and highly sensitive to budget constraints, revealing critical path dependencies. Stricter budgets mandate a pivot to green hydrogen and extensive

CCS, while looser budgets allow for continued reliance on fossil-based routes, highlighting the immense long-term consequences of near-term investment choices. Third, planning uncertainty cascades from the national to the provincial level, but it is not uniformly distributed. Our spatiotemporal analysis pinpoints regional hotspots for technology deployment and, crucially, offers a quantitative metric (the coefficient of variation) to distinguish robust, "no-regret" investments from high-risk ventures that are contingent on specific allocation principles. As a final consideration, while our deterministic optimization framework provides a clear view of cost-optimal pathways, it is important to acknowledge that real-world investment decisions will also need to navigate uncertainties not captured in the model, such as future technological breakthroughs and market dynamics.

Data and code availability

The code of the model used in this study is open-source at https://github.com/iiasa/message_ix. The data can be shared on request.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (grant numbers 72243011, 72325008, 72342002, 72204020, and 72574018).

Author contributions

Songmin Yu and Hongbo Duan conceived the research. Songmin Yu developed the model, based on the industry sectors data collected by Fu Zhao, CGE scenarios created by Lingyu Yang, power sector data collected by Xing Yao, and CCS cost scenarios created by Zezheng Li and Ning Wei. Songmin Yu conducted the analysis, interpreted the results, and wrote the paper with inputs from the other authors.

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