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Towards a green China: energy policy, technological innovation, and green investment as drivers of environmental sustainability

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China's pursuit of environmental sustainability has become one of the defining policy experiments of the twenty-first century, combining an ambitious dual-carbon pledge with the world's largest deployment of clean-energy technology and green capital. This review synthesizes recent scholarship to examine how three interlocking levers, energy and climate policy, technological innovation, and green investment, jointly shape China's transition toward a lower-carbon and more resilient development path. Drawing on a structured reading of peer-reviewed research published predominantly between 2019 and 2025, the article develops an integrated framework in which policy sets direction and incentives, innovation lowers the cost and expands the frontier of abatement, and investment mobilizes the capital required to translate intent into installed capacity. The evidence indicates that target-based governance, embodied in successive Five-Year Plans and the 2030/2060 carbon commitments, has been reinforced by market-based instruments such as the national emissions trading system, and by an expanding architecture of green credit and green bonds. Technological progress in solar photovoltaics, wind power, batteries, and electric mobility has driven steep learning curves, allowing renewable additions to exceed fossil capacity additions by wide margins in recent years. Green finance is shown across numerous provincial and firm-level studies to reduce carbon-emission intensity, chiefly by catalyzing green technological innovation and by reallocating capital away from pollution-intensive activities. Nevertheless, persistent tensions remain, including coal lock-in, energy-security concerns, uneven regional capacity, intensity-based rather than absolute caps, data-quality risks, and the danger of greenwashing. The review argues that the effectiveness of any single lever is conditional on its coherence with the others, and that spatial spillovers and regional heterogeneity mediate outcomes in ways that generic national narratives obscure. Case evidence is integrated throughout to ground the analysis in concrete provincial, sectoral, and corporate experience. The article closes by identifying priorities for policy design and an agenda for future research on the policy–innovation–investment nexus.

KEYWORDS
carbon neutrality, dual-carbon goals, emissions trading, energy policy, environmental sustainability, green China, green finance, green technological innovation

1 Introduction

China occupies a paradoxical position at the center of the global sustainability debate, being simultaneously the largest annual emitter of carbon dioxide and the most consequential builder of clean-energy infrastructure, the world has yet seen. Since the reform era began, rapid industrialization lifted hundreds of millions out of poverty, but it also produced severe air pollution, water stress, soil degradation, and a carbon-intensive energy system anchored in domestically abundant coal (Wang et al., 2022; Wang and Wang, 2020). In September 2020, President Xi Jinping announced that the country would strive to peak carbon emissions before 2030 and achieve carbon neutrality before 2060, a commitment now universally referred to as the "dual-carbon" goal (Du et al., 2025). This pledge reframed environmental policy from a peripheral concern into a central organizing principle of national development, with implications for industrial structure, energy security, fiscal policy, and technological strategy. The dual-carbon framing matters because it converts a diffuse aspiration into a time-bound governance target that can be disaggregated across ministries, provinces, and enterprises. It also signals to markets and innovators that the direction of travel is settled, thereby shaping expectations and investment horizons in ways that a single subsidy or regulation cannot. The scale of the challenge is immense, because coal still supplied the majority of primary energy at the outset of the decade and underpins millions of livelihoods (Zhang et al., 2021). Yet the scale of the response has been equally striking, with wind and solar additions repeatedly setting global records and clean-energy manufacturing becoming a pillar of export competitiveness. Understanding how China is attempting this transformation is therefore not merely a regional question but a global one, since the country's trajectory will substantially determine whether international climate targets remain attainable. This review takes that transformation as its subject and asks how policy, innovation, and investment combine to move the country towards a greener development model.

The transition is best understood as a coordinated mobilization across multiple domains rather than as the product of any single instrument. Energy policy provides the strategic direction, translating high-level pledges into binding intensity targets, renewable-portfolio obligations, and sectoral roadmaps embedded in successive Five-Year Plans (Jin et al., 2021). Technological innovation supplies the means, driving down the cost of solar modules, wind turbines, and batteries to the point where clean generation is frequently cheaper than new coal (Li et al., 2022). Green investment furnishes the fuel, channeling credit, bonds, and equity toward low-carbon projects while progressively restricting finance to pollution-intensive activities (Lee and Lee, 2022). These three levers are deeply interdependent, so that weakness in one can blunt the effectiveness of the others, and strength in one can amplify the returns to the rest. A carbon target without cheap technology risks imposing unacceptable economic costs, while cheap technology without finance cannot be deployed at scale. Similarly, abundant green finance directed by weak policy signals may fund projects that deliver limited additional abatement. The Chinese case is analytically valuable precisely because all three levers have been pulled hard and more or less simultaneously, allowing researchers to study their interactions in a natural experiment of unusual size. This review therefore treats the policy–innovation–investment nexus as its central object, rather than isolating any single element. In doing so it seeks to explain not only what China has achieved but also why the outcomes remain uneven and contested. The conceptual framework developed below (see Figure 1) formalizes these relationships and guides the subsequent synthesize.

Despite a rapidly expanding literature, scholarship on China's green transition remains fragmented across disciplinary silos that rarely speak to one another. Energy economists analyze emissions trajectories and decoupling, innovation scholars study patents and learning curves, and finance researchers examine green credit and bonds, but integrative treatments that connect these strands are comparatively scarce (Jiakui et al., 2023). Prior syntheses have mapped parts of this terrain, bibliometrically for green finance and through reviews of renewable-energy investment in emerging economies, without integrating the three levers (Zeng et al., 2017; Zhang D. et al., 2019). Much empirical work isolates a single mechanism, green finance and emissions, for example, while treating policy and innovation as background conditions rather than as co-determinants of the same outcome (Wang et al., 2023). This partitioning obscure the feedback loops that give the transition its distinctive character, such as the way carbon pricing alters the expected returns to green research and development, which in turn shapes the risk appetite of green lenders. A further limitation is that many studies rely on national aggregates that mask pronounced regional heterogeneity, even though eastern, central, and western provinces differ dramatically in industrial structure, resource endowment, and financial depth (Liu, Lu, et al., 2025). Panel analyzes increasingly reveal spatial spillovers, whereby a province's green-finance development influences emissions in neighboring jurisdictions, complicating any simple attribution of cause and effect. The literature also tends to privilege intensity metrics, which can fall even as absolute emissions rise, producing an over-optimistic picture of progress (Stern, 2004). Methodologically, questions of endogeneity, measurement, and data reliability continue to trouble the field, particularly given documented instances of emissions-data irregularities. There is, in short, a need for synthesis that integrates the three levers, attends to spatial and sectoral heterogeneity, and distinguishes genuine structural change from statistical artefacts. This review responds to that need by assembling recent evidence into a coherent, critical account. It aims to complement rather than replace the specialized empirical work on which it draws.

The primary aim of this article is to provide an integrated, critically synthesized account of how energy policy, technological innovation, and green investment jointly advance environmental sustainability in China. To that end it pursues four objectives: to map the architecture of China's energy and climate policy; to assess the contribution of technological innovation across key clean-energy sectors; to evaluate the role of green finance in mobilizing and steering investment; and to appraise the environmental outcomes and the tensions that condition them. The contribution is threefold and deliberately synthetic rather than narrowly empirical. First, the review offers a unifying framework that positions the three levers as mutually reinforcing components of a single system, thereby making their interactions visible (see Figure 1). Second, it foregrounds regional heterogeneity and spatial spillovers as central features of

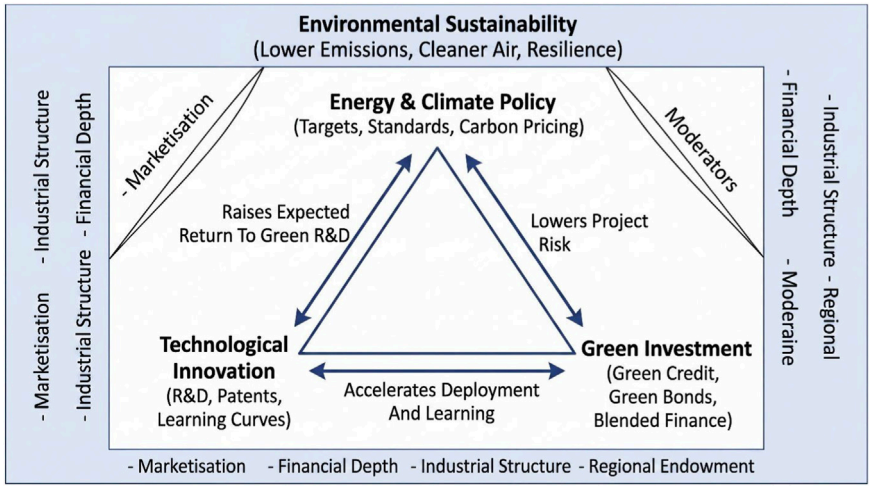


FIGURE 1
The policy–innovation–investment nexus for a green China.

TABLE 1 Representative empirical findings on green finance, innovation, and emissions in China (cited in Sections 2 and 7.1). Illustrative, not exhaustive.

Focus	Typical finding	Representative source
Green finance → emission intensity	Reduces intensity; effect stronger in eastern/central regions	Su et al. (2025)
Green finance → green TFP	Raises green total factor productivity	Lee and Lee (2022)
Green credit → environmental quality	Improves quality; upgrades energy-intensive firms	Zhang et al. (2021)
Green credit → innovation	Promotes low-carbon technology innovation	Chen et al. (2022)
GF + innovation → emissions	Jointly inhibit emissions; regional disparities	ESPR endogenous-growth study (2024)
GF → emissions (spatial)	Reduces intensity in own and neighboring provinces	Frontiers spatial study (2025)
Innovation → energy efficiency	Improves efficiency across cities	Wang and Wang (2020)

the transition rather than as afterthoughts, drawing on the newest provincial-panel evidence. Third, it integrates concrete case material, provincial deployment, sectoral carbon pricing, and corporate innovation, directly into the analytical narrative rather than quarantining it in a separate section. The novelty of the article lies less in new data than in the way it connects strands of scholarship that are usually kept apart, and in its explicit attention to the coherence conditions under which each lever becomes effective. The remainder of the paper is organized as follows. Section 2 describes the review methodology, and Section 3 elaborates the conceptual framework. Sections 4 through 6 examine policy, innovation, and finance in turn, while Section 7 assesses environmental outcomes. Section 8 analyzes synergies and spatial dynamics, Section 9 addresses barriers and governance risks, and Sections 10 and 11 offer policy implications, a research agenda, and conclusions.

2 Methodology of the review

This article is a narrative, integrative review designed to synthesize and interpret a diverse body of recent scholarship rather than to produce new primary estimates. The review was conducted in four stages: scoping, retrieval, appraisal, and synthesize. In the scoping stage, the research question was decomposed into the three thematic pillars of policy, innovation, and investment, and a controlled vocabulary of search terms was constructed for each, including "China," "energy policy," "carbon neutrality," "dual carbon," "green finance," "green credit," "green bonds," "emissions trading," "green technological innovation," "renewable energy," and "environmental sustainability." In the retrieval stage, literature was gathered from major scholarly databases and publishers, with priority given to peer-reviewed research articles in journals such as Energy Policy, Energy Economics, Journal of Cleaner Production, Journal of Environmental Management, Ecological Economics, Renewable Energy, and Environmental Science and Pollution Research, supplemented by authoritative statistical and institutional sources for the most recent capacity and market data (Enerdata, 2025; International Carbon Action Partnership [ICAP], 2025). The temporal focus was placed on work published between 2019 and 2025 to ensure currency, while a small number of foundational theoretical contributions were retained regardless of date because they

anchor the conceptual framework. In the appraisal stage, retrieved items were screened for relevance to the Chinese context and for methodological transparency, with preference given to studies employing panel data, quasi-experimental designs, decomposition analysis, or spatial econometrics. Sources were then organized thematically and cross-checked so that each analytical claim could be triangulated across more than one study wherever possible. In the synthesis stage, findings were integrated within the framework set out in Section 3, and points of convergence, divergence, and unresolved debate were identified. Case material was selected purposively to illustrate mechanisms rather than to constitute a representative sample, and it was woven into the thematic sections instead of being isolated. Because the review is interpretive, it does not claim the exhaustiveness of a formal systematic review, and it acknowledges that publication bias and the predominance of intensity-based metrics may color the available evidence. These design choices privilege breadth of integration and conceptual coherence, which are appropriate to the review's synthetic aim. The summary of representative empirical findings assembled through this process is presented later (see Table 1).

3 Conceptual framework: linking policy, innovation, and investment

The analytical spine of this review is a framework in which environmental sustainability emerges from the interaction of three levers operating on a shared economic and ecological system. The framework draws on the theory of directed technical change, which holds that the direction of innovation responds to relative prices and expected market size, so that credible climate policy can redirect research effort toward clean technologies (Table 2) (Acemoglu et al., 2012). Related work on endogenous technological change and on innovation induced by energy prices provides the economic foundation for this mechanism (Romer, 1990; Popp, 2002). It also incorporates the twin market-failure logic that underpins environmental economics, whereby both the pollution externality and the knowledge externality must be addressed simultaneously if a transition is to be efficient (Jaffe et al., 2005). Within this logic, energy and climate policy performs the function of correcting the pollution externality and setting direction, using targets, standards, and carbon pricing to alter the relative cost of emitting (Wang et al., 2022; Liu et al., 2026). Technological innovation addresses the knowledge externality and expands the abatement frontier, so that each unit of emissions reduction becomes cheaper over time through learning-by-doing and economies of scale (Li et al., 2022). Green investment relaxes the financing constraint that would otherwise prevent capital-intensive low-carbon assets from being built, while simultaneously screening capital away from pollution-intensive uses (Lee and Lee, 2022; Ali et al., 2023). Crucially, the three levers are coupled: carbon pricing raises the expected return to green innovation, successful innovation lowers the risk borne by green financiers, and abundant green finance accelerates the deployment that drives further learning. The Porter hypothesis provides a complementary rationale, suggesting that well-designed environmental regulation can spur innovation that partly or wholly offsets compliance costs (Porter and van der Linde, 1995). Empirical assessments of this hypothesis offer qualified support, finding that well-designed regulation can stimulate innovation under appropriate conditions (Jaffe and Palmer, 1997; Ambec et al., 2013). Outcomes are further shaped by contextual moderators such as marketisation, financial depth, industrial structure, and regional endowment, which determine how strongly each lever transmits to emissions. The framework thus predicts that sustainability gains will be largest where the three levers are coherent and mutually reinforcing, and weakest where they are fragmented or mutually undermining (see Figure 1).

This coupling has important implications for how evidence on any single lever should be interpreted, because the measured effect of one instrument is generally conditional on the state of the others. A study that finds green credit reduces emission intensity is, in framework terms, capturing a composite effect that runs partly through induced innovation and partly through capital reallocation, both of which depend on the prevailing policy signal (Zhang et al., 2021). This is why empirical estimates of the same relationship vary across regions and periods: the transmission channels are differently developed in different settings (Su et al., 2025). The framework also clarifies why intensity-based and absolute metrics can diverge, since innovation and investment may lower the carbon content of each unit of output even as total output, and therefore total emissions, continues to grow (York et al., 2003). It further explains the salience of spatial spillovers, because innovation diffuses and capital flows across provincial boundaries, so that a lever pulled in one jurisdiction can register effects in another. By making these dependencies explicit, the framework guards against the common error of reading a single-mechanism study as though it described the whole system. It also generates testable expectations about complementarity that the subsequent sections evaluate against the evidence. In particular, it predicts that the marginal value of green finance rises where green innovation capacity is already present, and that carbon pricing is most effective where low-cost abatement technologies exist. These conditional relationships recur throughout the empirical literature reviewed below. The framework is deliberately parsimonious, but it is sufficient to organize a large and heterogeneous body of work. It therefore serves as the interpretive lens for the remainder of the article.

4 The architecture of China's energy and climate policy

4.1 Five-year plans and the evolution of energy governance

Energy and environmental governance in China are structured around the Five-Year Plan system, which converts long-horizon ambitions into binding medium-term targets allocated across ministries and provinces. Environmental considerations entered this system incrementally, beginning with energy-intensity targets in the eleventh plan and broadening into carbon-intensity and pollution-control targets in subsequent cycles (Jin et al., 2021; Zhang et al., 2024; Zhang et al., 2025). The fourteenth Five-Year Plan, covering 2021 to 2025, embedded the dual-carbon logic by setting targets for energy intensity, carbon intensity, and the share of

TABLE 2 Key clean-energy technology indicators, 2024 (cited in Section 5.4). Figures are approximate and drawn from national and institutional statistics.

Indicator	Approximate value (2024)	Note
Solar capacity added	~277 GW	Record annual addition
Wind capacity added	~80 GW	Record annual addition
Cumulative solar capacity	~887 GW	Largest in the world
Cumulative wind capacity	~521 GW	Largest in the world
Renewable share of total capacity	~56%	Second year above 50%
Wind + solar target (2030: 1,200 GW)	Met ~2024	Roughly 6 years early
Grid-infrastructure investment	~US$80–85 bn	Includes ultra-high-voltage lines
New coal capacity added	~30 GW	Down year-on-year; permitting slowed

TABLE 3 Selected milestones in China's energy and climate policy (cited in Section 4.1).

Year	Milestone	Significance
2006	Energy-intensity target introduced (11th FYP)	First binding quantitative energy target in the plan system
2013	Regional ETS pilots launched (e.g., Guangdong, Shenzhen)	Institutional learning on monitoring, reporting, verification
2015	Green-credit and green-bond guidelines strengthened	Formalization of the green-finance architecture
2020	Dual-carbon pledge announced (peak <2030; neutral <2060)	Reframes climate as a central development principle
2021	National ETS launched (power sector)	World's largest carbon market by covered emissions
2021–25	14th five-year plan targets (intensity, non-fossil share)	Operationalizes dual-carbon via the plan system
2024	CCER voluntary offset market relaunched	Restores offset finance for additional projects
2025	ETS expanded to steel, cement, aluminum	Coverage rises from ~40% to ~60% of national emissions
2025	Guidance toward absolute cap and auctioning issued	Signals shift from intensity to absolute constraint

non-fossil energy in primary consumption, thereby institutionalizing the 2030 and 2060 pledges. A defining feature of this governance model is the cascading of national targets down to provincial and municipal authorities, whose officials are evaluated in part on their attainment, which creates powerful implementation incentives (Wang and Wang, 2020). This target-responsibility system has proven capable of mobilizing rapid action, as illustrated by the pace at which renewable capacity has been built when central signals were unambiguous. At the same time, the system's reliance on administrative allocation can generate distortions, including episodic curtailment of renewable output and the periodic construction of surplus capacity. The plans also coordinate industrial policy with energy policy, so that support for clean-energy manufacturing is aligned with deployment targets, producing the scale economies that have driven costs down (Li et al., 2022). Over successive cycles the policy mix has shifted from a predominant reliance on quantitative mandates toward a more balanced combination of mandates, subsidies, and market instruments. This evolution reflects a learning process in which the state has adjusted its toolkit as the transition has matured and as the limits of pure command-and-control became apparent. The trajectory of key milestones is summarized below (see Table 3). Understanding this planning architecture is essential, because it is the scaffolding on which every other lever is hung (Figure 2).

The provincial dimension of the planning system is central to explaining the uneven geography of the transition, since sub-national governments enjoy considerable latitude in implementation. Resource-rich western provinces such as Xinjiang, Ningxia, Inner Mongolia, and Qinghai have become the sites of gigawatt-scale renewable bases, exploiting abundant land and solar and wind resources to host the country's largest installations (Enerdata, 2025). The Tenggeli Desert solar base in Ningxia and the vast photovoltaic projects of the Taklamakan region in Xinjiang exemplify how central targets are realized through place-specific deployment that leverages local endowment. Eastern coastal provinces, by contrast, combine distributed generation, offshore wind, and demand-side management with far greater financial and industrial capacity, giving them a different transition profile. This division of labor is productive but also generates a spatial mismatch, because the best renewable resources lie far from the largest demand centers. Resolving that mismatch has required massive investment in ultra-high-voltage transmission to move clean power across the country, a distinctively Chinese infrastructural response (World Economic Forum, 2025). The planning system's ability to coordinate generation siting with transmission build-out is one of its genuine strengths, even as it concentrates certain costs and risks in particular regions. Provincial competition to attract clean-energy manufacturing and to meet assigned targets has further accelerated deployment, though sometimes at the expense of

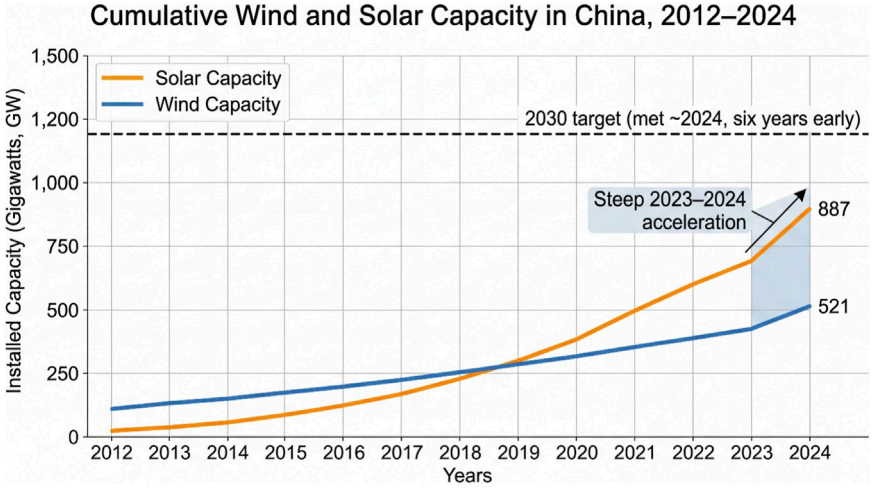


FIGURE 2
Cumulative wind and solar capacity in China, 2012–2024.

overcapacity. The heterogeneity of provincial starting points means that identical national policies produce divergent local outcomes, a theme that recurs throughout this review. The planning architecture, in short, is simultaneously a source of remarkable mobilizing capacity and of persistent spatial imbalance. Both features must be held in view when assessing the transition's progress.

4.2 The dual-carbon pledge and target-based governance

The dual-carbon pledge functions as the apex target from which a widening pyramid of subsidiary commitments descends, giving the transition a clear temporal structure. By committing to peak emissions before 2030 and to neutrality before 2060, the leadership established two anchor dates that discipline planning across sectors and provinces (Du et al., 2025). The thirty-year interval between peaking and neutrality is unusually short by international standards, implying a steep decarbonization gradient once the peak is passed, which raises the stakes for early innovation and investment. To operationalize the pledge, the government has issued a "1 + N″ policy system, in which a guiding document is complemented by numerous sectoral and provincial implementation plans that specify concrete measures. This architecture translates a headline promise into an actionable program, covering power, industry, transport, buildings, and agriculture in differentiated ways. Target-based governance of this kind has demonstrable mobilizing power, as evidenced by China's attainment of its 2030 target of 1,200 GW of wind and solar capacity roughly 6 years ahead of schedule (Renewable Energy Institute, 2025). Yet the pledge also embodies a deliberate ambiguity, because "before 2030"and "before 2060" leave room for the emissions peak to occur at a relatively high level, which would steepen the subsequent decline. The credibility of the commitment rests on the consistency of the signals sent by subsidiary policies, and inconsistency at the margins can dilute its effect on expectations. Analysts have noted that dual-control of energy is gradually shifting toward dual-control of carbon, a refinement intended to sharpen the link between the target and actual emissions rather than energy use alone. The governance system is therefore still evolving, as instruments are recalibrated to bind more tightly to the ultimate objective. The interplay between headline ambition and granular implementation is the crux of China's climate governance, and it shapes the effectiveness of every downstream lever.

4.3 Market-based instruments: the national emissions trading system

Alongside administrative targets, China has constructed the world's largest emissions trading system, marking a decisive move toward market-based climate policy. Launched nationally in 2021 after years of regional pilots, the system initially covered only the power sector but already regulated emissions on a scale unmatched elsewhere (ICAP, 2025). A landmark expansion approved in March 2025 extended coverage to the steel, cement, and aluminum smelting industries, adding roughly 1,500 entities and raising the share of national emissions covered from about forty per cent to around sixty per cent (ICAP, 2025). This expansion brought the system to approximately 3,700 covered entities and some eight billion tonnes of carbon dioxide equivalent, an amount equivalent to a substantial fraction of global emissions. The design, however, remains intensity-based rather than absolute, so that allowances are allocated in proportion to output and efficiency benchmarks rather than under a fixed and declining ceiling. For the first compliance year in the new sectors, entities received free allowances equal to their verified emissions, ensuring a soft landing but limiting the immediate abatement incentive (S&P Global, 2025). Carbon prices have consequently remained modest relative to the European system, dampening the signal transmitted to investment and innovation decisions. Recognizing these limitations, the authorities issued guidance in August 2025 charting a course toward absolute caps, auctioning, and broader sectoral and gas

coverage over time (ICAP, 2025). The regional pilots that preceded the national system, such as those in Guangdong, Beijing, Shanghai, and Shenzhen, generated valuable institutional learning about monitoring, reporting, and verification. The trajectory of the trading system thus illustrates a characteristic sequencing strategy, in which coverage and data integrity are prioritized before price stringency is increased. Whether the system can evolve into a binding constraint on absolute emissions will be a critical determinant of the transition's ultimate success.

The emissions trading system does not operate in isolation but interacts with a suite of complementary market mechanisms that together constitute a maturing carbon-pricing ecosystem. The relaunch of the China Certified Emission Reduction scheme in early 2024, after a multi-year pause, restored a voluntary offset market that channels finance toward projects with additional environmental benefits (ICAP, 2025). Offsets allow covered entities a degree of flexibility while creating revenue streams for renewable, forestry, and methane-abatement projects that might otherwise struggle to attract capital. The prospective introduction of the European carbon border adjustment mechanism has added an external impetus, since exporters of steel and aluminum face the prospect of paying for embedded emissions abroad if they are not priced domestically (IEEFA, 2025). This international pressure strengthens the domestic case for higher carbon prices, because revenue foregone at the border is revenue that could instead be retained at home. The interaction between the domestic trading system and border measures illustrates how climate policy is increasingly shaped by trade as well as by environmental considerations. Data quality remains a live concern, however, following documented cases of falsified emissions reporting that prompted tighter verification rules (Carbon Brief, 2024). The credibility of any carbon market depends on the integrity of the underlying measurements, and the authorities have invested substantially in strengthening monitoring infrastructure. As the system transitions toward performance benchmarks and eventually absolute caps, the demands on data accuracy will only intensify. The gradual maturation of this market ecosystem, encompassing allowances, offsets, and border adjustments, is a significant institutional achievement even where price levels remain low. It provides the price scaffolding on which the innovation and investment responses examined in later sections increasingly depend.

4.4 Governing the coal transition and energy security

No account of China's energy policy is complete without confronting the enduring centrality of coal, which remains both the backbone of the power system and the principal obstacle to decarbonization. Coal has historically supplied the majority of primary energy, reflecting a resource endowment often summarized as coal-rich, oil-poor, and gas-poor (Guan et al., 2018). The policy challenge is therefore not merely to build clean capacity but to manage the orderly decline of an incumbent system on which employment, industrial supply chains, and grid stability depend. Recent signals suggest a tentative turning point, with coal-power permitting reportedly falling sharply in the first half of 2024 relative to the previous year, and net coal additions shrinking even as renewable additions surged (Rystad Energy, 2026). Nonetheless, new coal plants continue to be approved, frequently justified on grounds of energy security and grid flexibility, revealing an unresolved tension at the heart of policy. The official framing increasingly casts coal as a transitional support that will "establish before breaking," providing firm backup while variable renewables scale, rather than as a resource to be abruptly abandoned. This gradualist stance reflects genuine security concerns, sharpened by episodes of power shortage and by geopolitical volatility in fuel markets (Khan et al., 2023). Coal plants are consequently being retrofitted for flexible operation so that they can ramp to accommodate fluctuating wind and solar output rather than run at constant baseload. The just-transition dimension is equally salient, since coal-dependent regions face acute adjustment costs that require deliberate policy attention to employment and regional development. The coexistence of record renewable deployment with continued coal construction is thus not simply a contradiction but a managed hedging strategy under uncertainty. How quickly the balance tips decisively toward clean energy will hinge on grid flexibility, storage, and the credibility of the carbon-pricing signal discussed above. This tension is revisited in the analysis of barriers in Section 9.

5 Technological innovation and the clean-energy transition

5.1 Research intensity, patents, and directed technical change

Technological innovation is the mechanism through which climate ambition is rendered economically feasible, and China has moved from being a follower to a frontier competitor in several clean-energy domains. National research and development intensity has risen steadily, and the country now files a large share of the world's green-technology patents, reflecting a deliberate strategy of building indigenous innovation capacity (Jiakui et al., 2023). Detailed sectoral studies document how this capacity was built in China's wind and solar industries through learning, policy experimentation, and transnational knowledge flows (Lewis, 2013; Gosens et al., 2015; Nahm, 2017). The theory of directed technical change predicts precisely this outcome, because credible and durable policy signals raise the expected return to clean innovation and redirect inventive effort accordingly (Acemoglu et al., 2012). Empirical work on Chinese cities confirms that technological innovation improves energy efficiency and lowers emission intensity, with the magnitude of the effect varying by regional absorptive capacity (Wang and Wang, 2020). Green credit policy has been shown to promote low-carbon technology innovation by easing the financing constraints that bind clean-technology firms and by raising the cost of capital for polluters (Chen et al., 2022). The interaction between policy and innovation is thus bidirectional, since policy induces innovation and successful innovation makes more ambitious policy politically and economically viable. Corporate digital transformation has emerged as a further driver, improving carbon productivity by optimizing processes and enabling more efficient resource use (Feng et al., 2024). The drive to manufacture renewables domestically, together with foreign direct investment, has reinforced both energy security and environmental quality (Mathews and Tan, 2014; Hao et al., 2020). Not all innovation is equal, however, and scholars distinguish between substantive green innovation that genuinely reduces environmental impact and strategic or symbolic

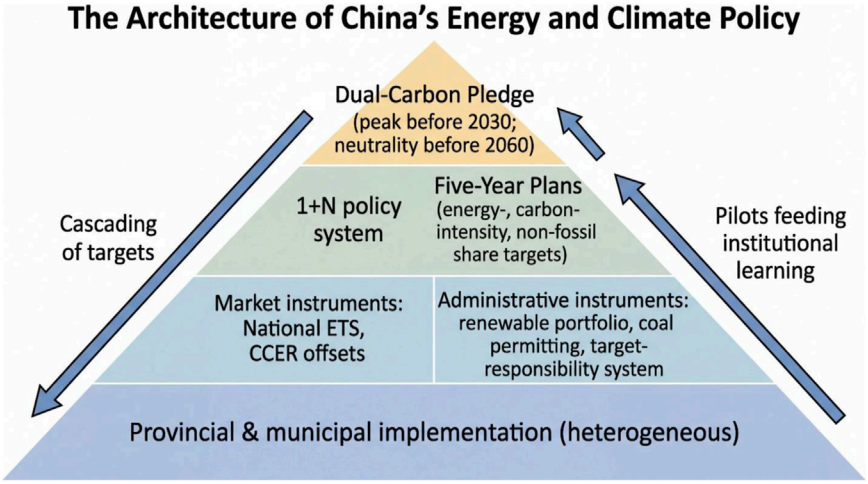


FIGURE 3
The architecture of China's energy and climate policy.

innovation pursued mainly to satisfy regulators or attract subsidies. The risk of subsidy-chasing and low-quality patenting is real, and it underscores the importance of designing incentives that reward genuine abatement rather than mere filing activity. The overall picture is nonetheless one of a rapidly deepening innovation system that has become a decisive competitive advantage. This innovation capacity is the foundation on which the sector-specific achievements described below rest.

5.2 Solar photovoltaics and wind: scale, learning, and deployment

Solar photovoltaics and wind power constitute the most visible and consequential arena of Chinese clean-energy innovation, where manufacturing scale and relentless cost reduction have transformed the global market. In 2024 alone, China added approximately 277 GW of solar and 80 GW of wind capacity, shattering its own records and bringing cumulative solar capacity to around 887 GW and wind to roughly 521 GW (Figure 3) (Enerdata, 2025). These additions meant that renewable sources accounted for the great majority of new capacity, and they enabled the country to meet its 2030 target of 1,200 GW of wind and solar roughly 6 years early (Renewable Energy Institute, 2025). The mechanism behind this achievement is a virtuous circle of scale and learning, in which enormous domestic deployment drives down unit costs, which in turn expands the market and justifies further capacity (Li et al., 2022). Chinese manufacturers such as LONGi, JinkoSolar, and Trina Solar have industrialized the photovoltaic supply chain to the point where module prices have fallen dramatically, reshaping economics worldwide. The distributed segment has also grown rapidly, with commercial and industrial rooftop installations expanding alongside gigawatt-scale desert bases, diversifying the deployment model (International Renewable Energy Agency, 2024). This deployment is not without difficulty, since the concentration of the best resources in remote western regions creates a spatial mismatch with coastal demand that must be bridged by long-distance transmission (World Economic Forum, 2025). Curtailment, whereby available renewable output is wasted because the grid cannot absorb it, has periodically constrained returns, prompting investment in transmission, storage, and market reform. The very success of the manufacturing sector has moreover produced overcapacity and price wars that squeeze producer profitability, illustrating that rapid scaling carries its own risks (International Energy Agency, 2024). Even so, the combination of scale, learning, and policy support has made Chinese solar and wind the cost benchmark against which the rest of the world now measures itself. This achievement anchors the broader claim that innovation has made the transition economically self-reinforcing.

5.3 Electric mobility, batteries, and energy storage

The electrification of transport and the associated battery and storage industries represent a second front on which Chinese innovation has reshaped global markets. The country has become the world's largest market for electric vehicles and the dominant manufacturer of the batteries that power them, with firms such as CATL and BYD achieving global scale and technological leadership (Li et al., 2022). This dominance rests on early and sustained industrial policy that supported the entire value chain, from critical-mineral processing through cell manufacturing to vehicle assembly and charging infrastructure. Battery innovation has driven steep cost declines and improvements in energy density, extending the reach of electric mobility and simultaneously reducing the cost of stationary storage. Stationary storage is pivotal to the wider transition, because it addresses the intermittency of wind and solar by shifting energy from times of surplus to times of scarcity (Wang et al., 2024). The co-evolution of the electric-vehicle and storage industries exemplifies the framework's logic, in which deployment in one application drives learning that benefits adjacent applications. Pumped hydro, new gas peaking plants, and grid-scale batteries are being deployed together to enhance system flexibility as variable renewables grow (World Economic Forum, 2025). The electrification of transport also delivers substantial air-quality co-benefits in cities, where tailpipe emissions have been a major source of harmful pollution (Ali et al.,

2022; Ali et al., 2024; Ding et al., 2024). Challenges remain, including the environmental footprint of battery production, the management of end-of-life recycling, and dependence on particular mineral supply chains. The scale of Chinese battery manufacturing nonetheless confers a strategic advantage that reinforces the country's broader clean-energy position. Together, electric mobility and storage close important gaps in the decarbonization of both transport and power. Their maturation is essential to converting variable generation into reliable, low-carbon energy services.

5.4 Grid modernisation, digitalization, and emerging vectors

Integrating vast quantities of variable renewable generation requires a parallel transformation of the grid, and here too innovation has been central to China's approach. The country has built an extensive network of ultra-high-voltage transmission lines that move clean power thousands of kilometers from resource-rich interiors to coastal load centers, with tens of billions of dollars invested annually in grid infrastructure (World Economic Forum, 2025). Digitalization and artificial intelligence are increasingly deployed to forecast generation, optimize dispatch, and manage demand, enabling the system to absorb fluctuating output while maintaining stability. Corporate and grid-level digital transformation improves carbon productivity by squeezing inefficiency out of operations, complementing the physical build-out of transmission (Feng et al., 2024). Flexibility has become a central policy priority, pursued through the retrofitting of coal plants for ramping, the expansion of pumped storage, and the development of demand-response markets. The emergence of virtual power plants and zero-carbon industrial parks signals a shift toward more decentralized and intelligent system architectures. Green hydrogen represents a further emerging vector, offering a route to decarbonize hard-to-abate sectors such as heavy industry and long-distance transport where direct electrification is difficult (Xie et al., 2023). Although still nascent and costly, electrolytic hydrogen produced from surplus renewable power could eventually absorb curtailed generation and provide seasonal storage. Cross-provincial market reforms aimed at breaking down regional barriers to renewable consumption are being pursued to complement these technical innovations. The combined effect of transmission, Digitalization, storage, and emerging vectors is to raise the ceiling on how much variable renewable energy the system can usefully absorb. These enabling technologies are less visible than solar panels or electric cars but are no less essential to the transition. Their continued development will determine how far the clean-energy build-out can ultimately go.

6 Green finance and the mobilization of investment

6.1 Green credit and the banking channel

Because China's financial system is bank-dominated, green credit is the single most important channel through which capital is steered toward the low-carbon transition (Figure 4). Green credit policy operates by adjusting the availability and cost of bank lending according to the environmental profile of the borrower, tightening finance for high-pollution, high-energy, and high-emission enterprises while easing it for green projects (Wen et al., 2021). This approach built on China's earlier mobilization of banks for environmental cleanup and has since become a central instrument of green industrial policy (Aizawa and Yang, 2010; He et al., 2019). Empirical studies consistently find that green credit policy improves environmental quality and promotes the upgrading of energy-intensive enterprises by raising their cost of capital and constraining their new investment (Zhang et al., 2021). Related studies show that green credit curbs suppliers' pollution, accelerates the green transition of heavily polluting firms, and strengthens firms' environmental performance and debt-financing capacity (Kang et al., 2020; Lu et al., 2025; He and Liu, 2023; Wen and Lee, 2020). The mechanism works partly through direct capital reallocation and partly by signalling to the wider market that polluting activities carry regulatory and reputational risk (Chen et al., 2022). Research also shows that green finance raises green total factor productivity, indicating that the reallocation of capital improves the efficiency with which resources are converted into output (Lee and Lee, 2022). The effect is not uniform, however, and heterogeneity analyzes reveal that green credit bites more sharply in economically developed eastern regions with deeper financial markets than in less developed western ones (Su et al., 2025). Green finance further promotes the transformation and innovation of high-energy-consuming firms, with market-incentivized environmental regulation acting as a partial mediator of the effect (Hou et al., 2022). The banking channel is powerful precisely because of its scale and its centrality to Chinese corporate finance, giving policymakers a potent lever. Firm-level evidence further indicates that demand for green finance relaxes the financing constraints on green innovation and that green credit and high-technology imports support low-carbon upgrading (Yu et al., 2021; Chen et al., 2024; Hassan et al., 2023; Irfan et al., 2022). Yet reliance on banks also concentrates transition risk within the banking system, raising prudential concerns as stranded-asset exposures grow. The design of green-credit standards, and the rigor with which they are enforced, therefore has systemic as well as environmental significance. The weight of evidence nonetheless supports the conclusion that green credit has been a material force in reallocating capital toward cleaner uses.

6.2 Green bonds and capital-market instruments

Beyond bank lending, China has developed one of the world's largest green-bond markets, extending the green-finance architecture into the capital markets. Green bonds allow issuers to raise dedicated funding for environmentally beneficial projects such as renewable generation, clean transport, and pollution control, matching long-dated assets with long-dated finance (Flammer, 2021; Baker et al., 2018). By ring-fencing proceeds for green use, these instruments provide a transparent mechanism for investors seeking environmental impact alongside financial return. Studies of bond pricing identify a modest green premium, whereby investors accept

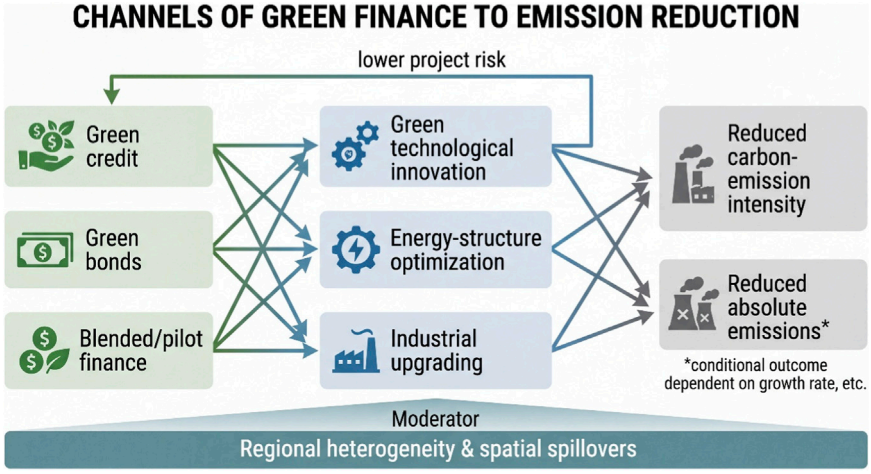


FIGURE 4
Channels of green finance to emission reduction.

TABLE 4 Principal green-finance instruments and their functions (cited in Section 6.3).

Instrument	Primary channel	Function in the transition
Green credit	Banking system	Reallocates bank lending toward green, away from polluting borrowers
Green bonds	Capital markets	Ring-fences long-dated finance for green projects
Green development funds	Blended public–private	Crowds in private capital using public seed funding
Central-bank refinancing facilities	Monetary policy	Lowers cost of qualifying green loans
CCER offsets	Carbon market	Finances additional abatement and sequestration projects
Green-finance pilot zones	Institutional experiment	Tests standards and instruments before national rollout
Fintech-enabled green finance	Digital platforms	Improves identification, monitoring, and pricing of green assets

slightly lower yields for environmental benefit, and point to nationally determined contributions as a driver of market growth (Zerbib, 2019; Tolliver et al., 2020). The market has grown rapidly under supportive regulation and standard-setting, becoming an important complement to the banking channel for large, capital-intensive projects. Research indicates that the growth of the green-finance market, including bonds and environmental-social-governance investment, is associated with measurable improvements in carbon-neutralization capacity over both short and long horizons (Wang and Sun, 2025). Green bonds also interact with the carbon market, and studies of the relationship between the two reveal spillovers that link the pricing of emissions to the pricing of green debt, a coupling that intensified during the COVID-19 period (Ren, Li, et al., 2022; Zhang et al., 2023). The development of the market has been accompanied by efforts to harmonize domestic standards with international norms, improving credibility and broadening the investor base. A persistent concern is the risk of greenwashing, whereby proceeds are labelled green without delivering genuine additional environmental benefit, which threatens the integrity of the market. Robust taxonomies, verification, and disclosure are therefore essential to preserve the informational value of the green label. The maturation of green bonds alongside green credit gives China a diversified financing toolkit that can serve different project types and risk profiles. This diversification is important because the transition requires enormous and sustained capital mobilization over decades. The green-bond market, for all its imperfections, is a significant institutional innovation in service of that goal.

6.3 Blended finance, foreign investment, and pilot zones

The green-finance system is further extended by a range of instruments and institutional experiments that blend public and private capital and mobilize external resources. Green development funds, policy-bank lending, and central-bank facilities that offer low-cost refinancing for qualifying green loans expand the pool of capital available on favorable terms (Wang et al., 2024). Fiscal spending, green development funds, and the broader development of green finance have each been associated with greener economic growth (Lin and Zhu, 2019; Jiang et al., 2020; Falcone, 2020; Wang and Zhi, 2016). Green-finance reform and innovation pilot zones have been established to test new instruments, standards, and coordination mechanisms in

controlled settings before wider rollout, generating institutional learning much as the emissions-trading pilots did (Du et al., 2025). These pilot zones function as policy laboratories, allowing the authorities to refine the design of green finance in response to local conditions and to identify practices worth scaling nationally. A substantial cross-country and China-specific literature finds that green finance and green investment reduce CO2 emissions and raise carbon-emission efficiency, with effects conditioned by financial structure and governance quality (Meo and Abd Karim, 2022; Wu et al., 2024; Yadav et al., 2024; Shen et al., 2021; Ren, Hao, et al., 2022). Foreign direct investment and international capital also play a role, both as sources of finance and as conduits for technology and standards, although geopolitical frictions increasingly complicate cross-border flows. The presence of multinational firms with clean-energy commitments creates additional demand for renewable power and green financing within China, reinforcing domestic momentum. Fintech has emerged as an enabler of green finance, using data and digital platforms to improve the identification, monitoring, and pricing of green assets (Lee, Li, et al., 2022; Lee et al., 2024; Umar and Safi, 2023). The combination of blended public–private finance, pilot experimentation, and international linkage broadens the base of the green-finance system beyond the banking and bond channels. This institutional diversity is a strength, because different instruments suit different stages of the project lifecycle and different risk appetites. It also allows the state to leverage limited public funds to crowd in far larger volumes of private capital. Complementary work examines the roles of foreign investment, financial-development channels, supply-chain financing, and socioeconomic context in shaping these outcomes (Umar et al., 2020; Xu et al., 2021; Cong et al., 2020; Lee and Hussain, 2023; Yi et al., 2023; Zhang and Managi, 2020; Hu et al., 2023; Baloch et al., 2021; Chien et al., 2021). The principal instruments and their functions are summarized below (see Table 4). The overall architecture illustrates a deliberate strategy of building a comprehensive green-finance ecosystem rather than relying on any single instrument.

7 Environmental outcomes and sustainability performance

7.1 Emissions trajectories, decoupling, and intensity

Assessing whether the policy, innovation, and investment levers are delivering environmental results requires careful attention to how progress is measured. The most encouraging evidence concerns carbon intensity, which has fallen substantially as the economy has grown, indicating that each unit of output is becoming less carbon-intensive over time (Wang et al., 2017). Decomposition analyzes attribute this decline to a combination of energy-efficiency improvements, a shift toward less carbon-intensive fuels, and structural change away from heavy industry (Ang, 2005). Index-decomposition and multi-region analyses corroborate these drivers and document the partial decoupling of emissions from output across Chinese regions (Ang and Zhang, 2000; Jiang et al., 2018; Dong et al., 2018; Zheng et al., 2019). Green finance and green innovation have been shown empirically to inhibit carbon emissions across Chinese provinces and cities, with the effect concentrated in eastern and central regions that possess greater financial and technological capacity (Liu, Xu, et al., 2025). However, a fall in intensity does not guarantee a fall in absolute emissions, because rapid output growth can more than offset intensity gains, a distinction that is easy to overlook (Figure 5) (York et al., 2003). This is precisely why the intensity-based design of the emissions trading system attracts criticism, since it permits absolute emissions to rise even as efficiency improves (Stern, 2004). The critical question for the dual-carbon pledge is therefore when absolute emissions will peak, and at what level, rather than merely whether intensity is declining. Recent surges in clean generation have raised the prospect that the power sector could approach peak emissions relatively soon, though continued demand growth and coal construction complicate the picture (Rystad Energy, 2026). Bottom-up estimates of China's emissions and assessments of a possible pre-2030 peak, grounded in the IPAT and Kaya accounting traditions, provide the empirical basis for these judgements (Liu et al., 2015; Guan et al., 2018; Mi et al., 2017; Ehrlich and Holdren, 1971; Kaya and Yokobori, 1997; Poumanyvong and Kaneko, 2010). The distinction between intensity and absolute metrics runs through the entire evaluation of China's progress and must be kept constantly in view. Analysts who conflate the two risk drawing conclusions that are either unduly optimistic or unfairly dismissive. A balanced assessment Recognizes genuine and substantial intensity gains while withholding judgement on the absolute peak until the evidence is clearer. Representative empirical findings on these relationships are collated below (see Table 1).

7.2 Air quality, health co-benefits, and local environment

Beyond carbon, the transition delivers substantial co-benefits for local air quality and public health that are often more immediately salient to citizens than distant climate targets (Hu et al., 2024; Luo et al., 2025; Mihad and Ali, 2026). The severe particulate pollution that afflicted major cities in the early 2010s galvanized public concern and became a powerful political driver of clean-energy policy in its own right. Subsequent campaigns to reduce coal combustion, tighten industrial emissions, and electrify transport have produced measurable improvements in ambient air quality in many urban areas. Analyses of national monitoring data attribute much of the post-2013 decline in fine-particulate pollution to these coordinated controls on coal and industry (Zhang Q. et al., 2019). These improvements illustrate the tight coupling between carbon abatement and pollution control, because measures that cut carbon frequently cut co-pollutants at the same time (Xie et al., 2023; Ali et al., 2026). The health benefits of reduced particulate exposure are large and accrue quickly, providing a near-term justification for policies whose climate benefits are more diffuse and delayed. Collaborative governance of pollution reduction and carbon reduction has accordingly become an explicit policy objective, recognizing the synergies between the two agendas (Huang et al., 2018). Green finance contributes to this collaborative governance by funding the abatement investments that deliver both climate and air-quality gains simultaneously. The local-environmental dimension also encompasses water and soil, where industrial restructuring and cleaner production reduce pollution loads on

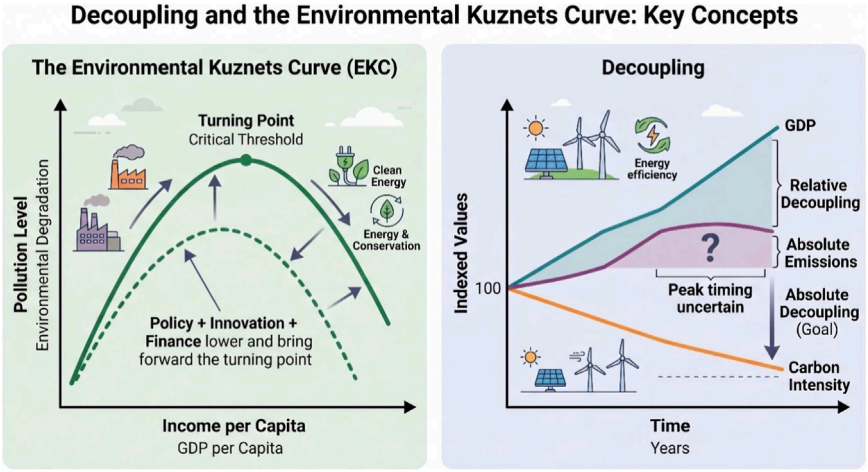


FIGURE 5
Decoupling and the environmental Kuznets curve, stylized.

ecosystems already under stress (Tang et al., 2022; Ma et al., 2024; Dong et al., 2024; Li et al., 2025). Framing the transition in terms of co-benefits helps to build the domestic political coalition needed to sustain it, because clean air is a tangible and widely valued good. The pursuit of these co-benefits demonstrates that environmental sustainability in China is driven by domestic welfare considerations as well as by international climate commitments. This alignment of local and global environmental goals is one of the transition's most durable political assets. It helps explain why the momentum behind clean energy has proven resilient across changing economic circumstances.

7.3 The environmental kuznets curve in the Chinese context

The relationship between economic development and environmental quality in China is frequently interpreted through the lens of the environmental Kuznets curve, which posits an inverted-U relationship between income and pollution. The original hypothesis suggested that environmental degradation rises during early industrialization and falls once incomes are high enough for societies to demand and afford cleaner outcomes (Grossman and Krueger, 1995). Foundational contributions to this debate include early reformulations of the curve as a policy tool and the economics of climate mitigation (Panayotou, 1997; Nordhaus, 1991). Applications to Chinese data have produced mixed results, with some disaggregated analyzes of industrial carbon emissions finding evidence consistent with an inverted-U for particular pollutants or sectors (Wang et al., 2017). Yet the empirical support is far from universal, and critics have long cautioned that the curve is neither a law nor an automatic mechanism, since the downturn depends on deliberate policy rather than income alone (Stern, 2004). Surveys of the literature emphasize that the shape, turning point, and even existence of the curve are highly sensitive to specification, sample, and the pollutant examined (Dinda, 2004). In the Chinese case, the more persuasive interpretation is that policy, innovation, and investment are actively bending the income–emissions relationship rather than waiting for income to do the work. Green finance and green innovation function, in effect, as instruments that can lower the turning point and accelerate the descent, converting a passive hypothesis into an actionable strategy (Xu and Xu, 2024). These reframing matters because it locates agency with policymakers and innovators rather than with the impersonal March of growth. It also cautions against complacency, since nothing guarantees that rising incomes will by themselves deliver decarbonization at the pace the climate requires. The environmental Kuznets curve is therefore best treated as a heuristic to be interrogated rather than a prediction to be trusted. Its chief value lies in focusing attention on the conditions under which growth and environmental improvement can be reconciled. In China those conditions are being actively engineered through the three levers this review examines.

8 Synergies and spatial dynamics of the policy–innovation–investment nexus

The central argument of this review is that the three levers achieve most when they operate in concert, and the empirical literature increasingly bears this out. Studies of the transmission mechanisms linking green finance to lower emissions consistently identify green technological innovation as the principal intermediary, confirming that finance works largely by financing innovation (Jiakui et al., 2023). Multilevel analyzes distinguish several channels, energy-structure change, industrial upgrading, and technological innovation, and show that these channels interact rather than operate independently (Su et al., 2025). This interaction is exactly what the conceptual framework predicts, since carbon pricing raises the return to innovation, innovation reduces the risk borne by financiers, and finance accelerates the deployment that drives further learning. Endogenous-growth models calibrated to Chinese data demonstrate that green finance and green innovation jointly inhibit emissions, with their combined effect moderated by environmental regulation and marketisation (Liu,

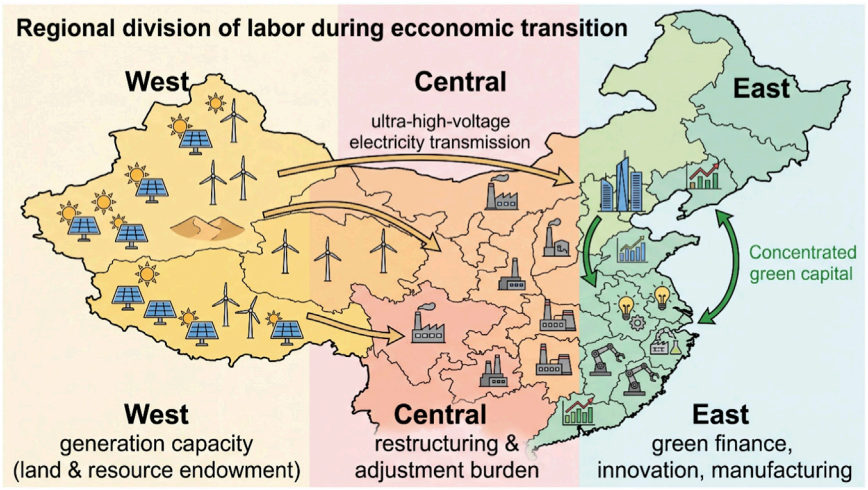


FIGURE 6
Regional division of labor in the transition. A schematic map of China divided into West, Central, and East bands.

Xu, et al., 2025). The complementarity is conditional, however, because the marginal contribution of green finance is greater where green-innovation capacity already exists, and *vice versa*. This conditionality helps explain why identical national policies yield divergent provincial outcomes, since the local configuration of the three levers differs markedly. Spatial econometric studies add a further dimension by showing that green finance reduces emission intensity not only in the implementing province but also in neighboring provinces through spillover effects (Liu, Lu, et al., 2025). These spillovers arise because innovation diffuses across boundaries and because capital and firms are mobile, so that a lever pulled in one place registers effects elsewhere. Regional heterogeneity and spatial interdependence are thus intrinsic features of the nexus rather than nuisances to be controlled away. Recognizing them is essential to designing policies that account for how effects propagate across the national economy. The synergy among the levers, mediated by geography, is the deep structure underlying China's aggregate progress.

The spatial dimension of the transition also reveals a distinctive division of labor that channels each region's comparative advantage toward the common goal (Figure 6). Western provinces contribute vast renewable-generation capacity by exploiting land and resource endowments, hosting the desert solar and wind bases that dominate national capacity statistics (Enerdata, 2025). Eastern provinces contribute financial depth, innovation capacity, and manufacturing prowess, functioning as the engine of green finance and clean-technology development (Su et al., 2025). Central provinces occupy an intermediate position, often bearing the heaviest adjustment burdens as heavy industry restructures under decarbonization pressure. Ultra-high-voltage transmission physically integrates this division of labor by connecting western generation to eastern demand, turning geographic disparity into functional complementarity (World Economic Forum, 2025). Green finance similarly redistributes capital across space, though studies show it flows more readily within developed regions than toward the areas that arguably need it most (Liu, Lu, et al., 2025). This uneven distribution of green capital is a genuine equity concern, because it risks widening rather than narrowing regional disparities in environmental and economic outcomes. Policymakers have accordingly sought to direct additional support toward less developed regions, recognizing that the transition must be inclusive as well as rapid. The interplay of resource endowment, financial depth, and innovation capacity across regions produces a mosaic of transition pathways rather than a single uniform trajectory. Appreciating this mosaic is essential to avoid mistaking national aggregates for a description of any particular place. The spatial structure of the nexus is, in the end, as important as its sectoral structure. Both dimensions must inform the design of a coherent national strategy.

9 Barriers, tensions, and governance risks

For all its achievements, China's green transition is beset by tensions that could slow or distort its progress if left unaddressed. The most fundamental is coal lock-in, whereby continued construction of coal plants, justified by energy-security and grid-stability concerns, entrenches high-carbon assets whose economic lifetimes extend for decades (Rystad Energy, 2026). Energy security itself is a legitimate and pressing consideration, sharpened by episodes of power shortage and by exposure to volatile international fuel markets (Khan et al., 2023). A second tension concerns the design of the emissions trading system, whose intensity-based allocation and abundant free allowances have kept carbon prices too low to drive the deepest abatement (S&P Global, 2025). Until the system transitions to absolute caps and auctioning, its price signal will remain a weak lever relative to its enormous coverage (IEEFA, 2025). A third risk is data quality, since documented cases of falsified emissions reporting undermine the integrity on which any carbon market depends (Carbon Brief, 2024). A fourth is greenwashing in the green-finance system, where assets may be labelled green without delivering genuine additional environmental benefit, eroding the informational value of the

TABLE 5 Principal barriers to the transition and prospective policy responses (cited in Section 9).

Barrier/tension	Underlying driver	Prospective response
Coal lock-in	Energy-security and grid-stability concerns	Flexibility, storage, credible carbon price
Low carbon price	Intensity-based caps; free allowances	Move to absolute caps and auctioning
Data-quality risk	Reporting irregularities	Stronger MRV and verification
Greenwashing	Weak taxonomy/disclosure	Robust standards, verification, disclosure
Regional inequality	Green capital follows existing advantage	Direct finance/support to lagging regions
Just-transition costs	Coal-dependent employment	Active labor-market and regional policy
Overcapacity/price wars	Rapid scaling of manufacturing	Market discipline; international coordination

green label (Bakry et al., 2023). Regional inequality constitutes a fifth tension, as green capital and clean-technology capacity concentrate in developed eastern regions while less developed areas lag (Liu, Lu, et al., 2025). The just-transition challenge in coal-dependent regions represents a sixth, requiring deliberate attention to employment and regional development if the transition is to be socially sustainable. Overcapacity and price wars in the solar and battery industries reveal that even success carries risks, threatening the profitability and therefore the durability of key manufacturers (International Energy Agency, 2024). These tensions are not reasons for pessimism but rather the specific problems that competent policy must solve. The barriers and prospective responses are summarized below (see Table 5).

Confronting these tensions requires Recognizing that they are interconnected rather than isolated, so that progress on one often depends on progress on another. Raising the carbon price, for instance, would simultaneously weaken coal lock-in, strengthen the incentive for genuine green innovation, and improve the economics of the green assets that green finance funds (IEEFA, 2025). Improving data quality is a precondition for tightening the emissions cap, because an absolute cap can only be credible if the underlying measurements are trustworthy (Carbon Brief, 2024). Combating greenwashing through robust taxonomies and disclosure would enhance the integrity of green finance and thereby its capacity to mobilize capital efficiently (Bakry et al., 2023). Addressing regional inequality would require directing green finance and transition support deliberately toward lagging regions rather than allowing capital to follow existing advantage (Su et al., 2025). Managing the just transition demands active labor-market and regional-development policy to cushion the communities most exposed to coal's decline. The overcapacity problem points to the need for market discipline and international coordination to rationalize investment without abandoning the scale that drives learning. Because the tensions are coupled, a piecemeal approach that tackles them one at a time is likely to disappoint, whereas an integrated strategy can exploit their interdependence. This is the practical corollary of the review's central argument that the levers are most effective when coherent. Governance capacity, and the willingness to tighten instruments as the transition matures, will ultimately determine how successfully these tensions are resolved. The trajectory of reform to date suggests a pattern of gradual tightening once foundations are secure, which offers grounds for cautious optimism. Whether that tightening arrives quickly enough to meet the dual-carbon timetable remains the decisive open question.

10 Policy implications and future research directions

The synthesis assembled in this review yields several implications for the design of a more effective and coherent green-transition strategy. The overarching lesson is that the three levers should be designed and adjusted together, since their effectiveness is mutually conditional rather than additive (Jiakui et al., 2023). Strengthening the carbon-price signal by moving decisively toward absolute caps and auctioning would amplify the returns to both innovation and green investment, magnifying the effect of the other levers (IEEFA, 2025). Improving the integrity of environmental data would enhance the credibility of the emissions market and the green-finance system simultaneously, addressing two tensions at once (Carbon Brief, 2024). Directing green finance deliberately toward less developed regions and toward genuinely additional projects would improve both the equity and the efficiency of capital allocation (Su et al., 2025). Sustaining innovation policy that rewards substantive rather than symbolic green technology would guard against the dilution of the innovation effort into subsidy-chasing (Chen et al., 2022). Managing the coal transition through flexibility, storage, and just-transition support would allow the incumbent system to recede without threatening reliability or social stability (Wang et al., 2024). Coordinating deployment with transmission and market reform would reduce curtailment and raise the value of the renewable capacity already built (World Economic Forum, 2025). These implications share a common thread, namely, that coherence across instruments matters more than the aggressive pursuit of any single one. The Chinese experience offers lessons for other developing economies attempting to reconcile growth with decarbonization, particularly regarding the sequencing of coverage before stringency. It also demonstrates the mobilizing power of credible, durable policy signals in redirecting innovation and investment at scale. These lessons are transferable in principle, even if the specific institutional context is not.

Several avenues for future research follow from the gaps identified in the course of this review. First, more work is needed that integrates the three levers within a single empirical framework

rather than examining each in isolation, so that their interactions can be estimated directly (Su et al., 2025). Second, the field would benefit from greater use of quasi-experimental designs that can credibly identify causal effects amid the endogeneity that pervades this literature (Du et al., 2025). Third, research should shift emphasis from intensity metrics toward absolute emissions and toward the timing and level of the emissions peak, which are the variables that ultimately matter for the climate (York et al., 2003). Fourth, the spatial dimension deserves deeper investigation, particularly the mechanisms through which spillovers propagate and the conditions under which they amplify or dampen policy effects (Liu, Lu, et al., 2025). Fifth, more attention should be paid to the distributional and just-transition consequences of decarbonization, which remain comparatively understudied relative to aggregate outcomes. Sixth, the integrity of green finance and carbon markets warrants continued scrutiny, including the development of better methods for detecting greenwashing and data manipulation (Bakry et al., 2023). Seventh, emerging vectors such as green hydrogen and long-duration storage require careful techno-economic assessment as they move from demonstration toward deployment (Xie et al., 2023). Eighth, comparative work situating China's experience alongside that of other major economies would sharpen understanding of what is genuinely distinctive about its approach. These research directions would collectively deepen the evidence base on which sound policy depends. They would also help resolve the interpretive disputes that currently divide the literature. Pursuing them is essential if scholarship is to keep pace with a transition that is evolving with remarkable speed.

11 Conclusion

This review has argued that China's movement toward environmental sustainability is best understood as the coordinated operation of three interdependent levers: energy and climate policy, technological innovation, and green investment. Policy sets direction and price, innovation lowers the cost and widens the frontier of abatement, and investment supplies and steers the capital required to build a low-carbon system (Lee and Lee, 2022). The evidence assembled here indicates that all three levers have been pulled hard and more or less simultaneously, producing achievements without precedent in scale, including record renewable deployment and the early attainment of the 2030 wind-and-solar target (Renewable Energy Institute, 2025). The empirical literature consistently finds that green finance and green innovation reduce carbon-emission intensity, chiefly by financing innovation and by reallocating capital away from pollution-intensive activities (Jiakui et al., 2023). Yet the review has been equally clear that intensity gains do not guarantee absolute reductions, and that the timing and level of the emissions peak remain the decisive uncertainties (Stern, 2004). Persistent tensions, coal lock-in, low carbon prices, data-quality risks, greenwashing, regional inequality, and the just-transition challenge, condition the outcomes and demand competent, integrated governance to resolve (IEEFA, 2025). The central analytical claim is that the levers are most effective when coherent, and that spatial spillovers and regional heterogeneity mediate their effects in ways national aggregates obscure (Liu, Lu, et al., 2025). The Chinese case thus offers both an encouraging demonstration of what credible, durable policy can mobilize and a sobering reminder of how much still depends on tightening instruments as the transition matures. For scholarship, the priority is to study the three levers together and to distinguish genuine structural change from statistical artefact. For policy, the priority is coherence: aligning the price signal, the innovation incentive, and the flow of capital so that each reinforces the others. Whether China can convert its formidable momentum into an early and low absolute emissions peak will shape not only its own future but the trajectory of the global climate. On that question the evidence remains open, and the coming decade will provide the answer.

Author contributions

NN: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

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