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A Case Study of Decarbonization and the Dual-Carbon Strategy

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Abstract

Global decarbonization efforts form a critical mission in the fight against climate change. This article analyzes the foundational pillars underpinning the Chinese strategy to achieve its ambitious dual-carbon goals—peak emissions by 2030 and carbon neutrality by 2060. We argue that this transition is propelled by a synergistic framework of robust policy mandates, the rapid deployment of energy transition technologies, and the strategic development of a national carbon market. This study presents an analysis of how top-down policies, such as the 14th Five-Year Plan, catalyze an unprecedented shift toward renewable energy sources, primarily wind and solar, while driving innovation in energy storage and smart grid infrastructure. Concurrently, the establishment of the world's largest emissions trading system (ETS) is examined as a crucial market-based mechanism designed to incentivize emission reductions across the power sector, with potential for future expansion. This article synthesizes the significant progress made to date, identifying key achievements and persistent challenges, such as energy security and industrial decarbonization. Finally, it offers a forward-looking perspective on the steps necessary to solidify these pillars, emphasizing the need for technological breakthroughs, deeper market reforms, and a just transition to ensure the long-term viability and global impact of the decarbonization pathway.

Keywords

Carbon Neutrality, Carbon Trade Market, Clean Energy, 14th Five-Year Plan, Climate Change, Carbon Emission Control Limits, Green Industrial Revolution, Energy Mass Conversion

1. Introduction of the Green Transformation Imperative

Confronting the global climate crisis, China has embarked on unprecedented investment and has focused on a national mission toward its dual-carbon goals: achieving peak carbon emissions by 2030 and carbon neutrality by 2060. As the world's largest emitter and renewable energy investor [1] [2], its monumental mission demands a complete overhaul of its very large energy system, driven by strategic state planning, aggressive policy frameworks, and innovative market mechanisms. It has published the Green Energy Pathways document, which provides an exploration of the nation's multifaceted approach to decarbonization, thereby analyzing the synergy between policy goals, technological deployment, and market evolution that defines its energy transition [3].

1.1. Strategic Anchors: The 14th and 15th Five-Year Plans

Chinese transitions are meticulously charted through their Five-Year Plans (FYPs) [4]. The 14th FYP (2021-2025) established binding targets: a 20% proportion of nonfossil energy in primary consumption, 18% carbon intensity reduction, and massive wind/solar capacity expansion. Crucially, it launched the 1 + N policy architecture, providing a top-level decarbonization blueprint. The upcoming 15th FYP (2026-2030) will be decisive for achieving the 2030 emission peak, likely by mandating stricter efficiency standards, deeper coal cuts, and accelerated heavy-industry transitions.

1.2. Policy Drivers and Carbon Markets

A robust policy toolkit enforces progress: stringent efficiency mandates, renewable portfolio standards, green finance incentives, and state-led industrial scaling. Central to this effort is the National Emissions Trading Scheme (ETS), which is the world's largest carbon market in terms of covered emissions. By initially targeting power generation, its expansion to steel, cement, and aluminum will amplify cost-effective abatement. In parallel, environmental, social, and governance (ESG) integration reshapes corporate governance, aligns investments with sustainability and reinforces regulatory efforts.

1.3. Technology Deployment and Global Resonance

China leads globally in solar/wind power deployment and generation, which is enabled by decreasing costs and grid modernization [5]. Energy storage and green hydrogen pilot projects address intermittency and hard-to-abate sectors. This domestic surge has led to a global green industrial revolution, greatly reducing clean-tech costs worldwide and influencing energy strategies across East Asia and emerging economies via initiatives such as the green Belt and Road.

The national pathway offers critical lessons for global climate action that balances growth with sustainability. This article aims to examine its progress, challenges, and implications for sustainable planetary development.

This article aims to examine the complex interplay among these forces, includaing strategic planning, policy drivers, market innovations, technological deployments, and industrial transformations. The above definition defines the monumental national journey and shapes its dual-carbon future. It assesses the remarkable strides made, the substantial challenges that persist, and the profound implications of the chosen pathways for both its own sustainable development and the global pursuit of climate stability.

Carbon emissions are directly related to the warming trend, as shown in Figure 1. Both the 1.5˚C path and the 2˚C path may be considered the control limits for the Paris Agreement. In accordance with the Paris Agreement, international communities strive to achieve net zero emissions via the 2˚C controlled path, as shown in **Figure 1**.

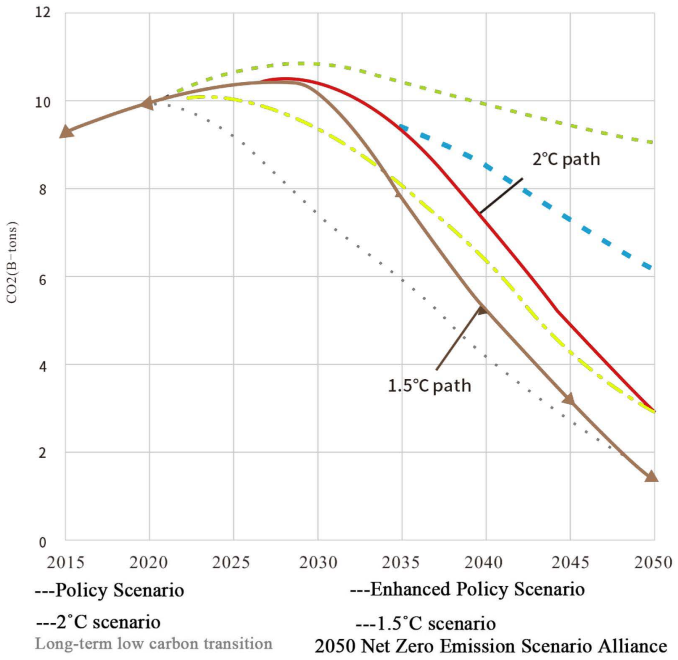

Figure 1. Illustrations of the cases are as follows: 1 policy scenario (blue dash); 2 enhanced policy scenario (yellow dash); 3 red line is the 2˚C path; 4, brown line is the 1.5˚C path; 5, top dashed line is a long-term low-carbon transition; 6, gray dotted line of the Net Zero Emission Scenario Alliance.

2. Decarbonization Policy Is Driving the Green Transition

Its ambitious dual-carbon goals, *i.e.*, achieving peak carbon dioxide emissions before 2030 and carbon neutrality before 2060, represent a fundamental shift for China, the world's largest energy consumer and emitter [6]-[8]. Achieving this transformation necessitates an effective and multifaceted policy engine that is meticulously designed to steer the colossal national economy toward sustainability. The decarbonization policy framework is characterized by its comprehensiveness, state-led coordination, and evolving sophistication, moving from initial subsidies toward a complex blend of regulatory mandates, economic incentives, industrial strategies, and market mechanisms, all of which are orchestrated under the overarching 1 + N system.

2.1. The 1 + N Framework: Strategic Backbone

The cornerstone of the national decarbonization policy architecture is the 1 + N policy framework, formally announced in late 2021 [7]. This structure provides the essential coherence and top-level direction for the entire endeavor.

The "1" denotes the central guiding document, which has the long name "Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy" (working guidance) and was issued by the Chinese Governmental Central Committee and State Council. The Working Guidance group set the overarching principles, main goals, and key tasks for the entire dual-carbon journey, emphasizing systemic planning, a holistic approach, and the embedding of climate action within broader socioeconomic development.

"N" denotes a suite of specific action plans and implementation guidelines tailored to key sectors (e.g., energy, industry, transport, and buildings) and critical enabling areas (e.g., technology, finance, and carbon sinks). These documents translate high-level guidance into concrete targets, timelines, and responsibilities for provinces, ministries, and industries. Examples include the Action Plan for Carbon Dioxide Peaking before 2030 and sector-specific peaking plans for steel, cement, and nonferrous metals. The aforementioned framework ensures alignment and coordinated action across all levels of government and economic sectors, mitigating fragmentation and conflicting priorities [9].

2.1.1. Regulatory Mandates and Standards of Command-and-Control Instruments

The core policy encompasses critical built-in multipronged instruments to achieve dual-carbon goals [10]. China deploys a diverse range of policy tools to drive decarbonization as follows.

Energy and Carbon Intensity Targets:

Binding targets that are set within the Five-Year Plans (FYPs) compel provinces and industries to reduce the energy consumed per unit of gross domestic product (GDP) (energy intensity) and the carbon dioxide emitted per unit of GDP (carbon intensity). The 14th FYP (2021-2025) mandates an 18% reduction in carbon intensity and a 13.5% reduction in energy intensity by 2025.

Renewable Portfolio Standards (RPS)/Guaranteed Consumption Mechanisms:

Grid companies and provinces are obligated to source an increasing minimum percentage of electricity from nonfossil sources (reaching approximately 33% by 2025 and rising further). Penalties for noncompliance create strong pressure for renewable integration.

Strict Energy Efficiency Standards:

Continuously tightened mandatory standards are enacted for appliances, industrial processes, vehicles, and buildings to promote technological improvement and reduce absolute energy demand.

Industrial Restructuring and Capacity Phase-Outs:

Policies actively target the closure of outdated, inefficient, and highly polluting industrial capacity, particularly in coal power, steel, and cement. Supply-side structural reform aims to eliminate excess, dirty capacity while promoting advanced, cleaner production.

Coal Consumption Control:

Provincial coal consumption caps and policies promoting coal substitution (especially in industry and heating) aim to constrain and ultimately reduce absolute coal use, although balancing energy security remains a key challenge. The State Council announced the following: During the 14th FYP period (2021-2025), the increase in coal consumption should be strictly and reasonably controlled, and coal consumption should be gradually reduced during the 15th FYP period (2026-2030).

2.1.2. Instrumentation of Economic Incentives and Financial Leverage

The instrumentation enforces the fund and fundamentals of the economic tasks.

Subsidies and Feed-in Tariffs (FiTs):

Historically, subsidies have been crucial for kickstarting the renewable energy boom (especially for wind and solar PV), providing guaranteed above-market prices for clean electricity. Albeit it is being phased down for mature technologies (transitioning to auctions), targeted subsidies remain for emerging areas such as offshore wind, distributed PV, and green hydrogen.

Tax Incentives:

These incentives provide preferential value-added tax (VAT) rates, corporate income tax reductions, and import duty exemptions for key green technologies and equipment to reduce the cost of deployment and encourage investment.

Green Finance:

This tool provides rapidly expanding ecosystem channel capital for sustainable projects.

Green Bonds:

China's green bond market has become one of the world's largest, with standards evolving to enhance credibility and prevent greenwashing.

Green Loans:

Policy banks (e.g., China Development Bank) and commercial banks are encouraged and guided (e.g., via central bank-relending facilities) to increase lending for green projects, often at preferential rates.

Green Equity Funds:

Government-backed funds and private venture capital increasingly target clean tech innovation and deployment.

Central Bank Guidelines:

The People's Bank of China (PBOC) incorporates climate risk into its financial stability framework and provides targeted support for green lending.

2.1.3. Industrial Policies and Strategic Scaling

The state fulfills a direct and proactive role in fostering world-leading green industries, as described below.

Massive Strategic Investment:

Direct state investment, low-cost financing from state-owned banks, and favorable land/regulatory treatment have propelled their companies to dominate global manufacturing in solar photovoltaic (PV) systems, wind turbines, batteries, and electric vehicles (EVs).

Supply Chain Development:

Policies actively support the development of complete domestic supply chains for critical green technologies and minerals, reducing reliance on imports and enhancing competitiveness.

Economies of Scale and Cost Reduction:

By creating vast domestic markets and supporting manufacturing scale-up, national policies have been instrumental in driving down the global costs of key clean technologies, accelerating their adoption worldwide.

2.1.4. Instrumentation of Market-Based Mechanisms

National Emissions Trading Scheme (ETS):

Launched in July 2021, the national ETS is the centerpiece of the market-based approach (covered in detail in Part 3). The ETS initially covered the power sector (which contributes nearly 40% of national CO_2 emissions). It places a price on carbon, thus incentivizing the most cost-effective emission reductions within the capped sector. Its planned expansion to other high-emitting industries (e.g., steel, cement, and aluminum) is a major policy priority.

Green Electricity Certificates (GECs):

A tradable instrument representing the environmental attributes of 1 MWh of renewable electricity. While still evolving, GECs aim to create a voluntary market for corporations to demonstrate renewable energy use and meet sustainability goals, complementing the mandatory RPS.

2.2. Implementation, Challenges, and Evolution

The sheer scale and complexity of the national decarbonization process pose immense implementation challenges, which can be described as follows.

Balancing Act:

Reconciling rapid decarbonization with energy security (still heavily dependent on coal), economic growth, and regional development disparities requires constant policy calibration.

Local Implementation: Ensuring that provincial and local governments fully embrace and effectively enforce central mandates, thereby avoiding campaign-style compliance or local protectionism that can impede national goals, is key.

Grid Integration:

Accelerating the build-out of grid infrastructure (transmission, flexibility, and storage) to accommodate the massive influx of variable renewables is critical.

Hard-to-Abate Sectors:

The development and scaling of viable decarbonization pathways for heavy industries (e.g., steel, cement, and chemical) and long-haul transport remain significant hurdles and require breakthroughs in technologies such as green hydrogen and carbon capture, utilization, and storage (CCUS).

ETS Effectiveness:

The liquidity, price signal strength, and regulatory robustness of the national ETS should be enhanced to truly drive cost-effective abatement across the economy.

The national decarbonization policy toolkit is not static; it is constantly evolving, along with the targets' progress. The focus is shifting from initial subsidy-driven renewable expansion toward deeper systemic transformation: integrating markets (ETS and GECs), leveraging finance (green bonds, loans), tackling more difficult sectors (industry, transport), and emphasizing technological innovation for the next phase (CCUS and green hydrogen). The effectiveness of this intricate policy engine ultimately determines the pace and success of the national historic green transition, with profound implications for global climate efforts.

3. Carbon Markets: Evolving Market-Based Carbon-Climate Drivers

The establishment of a robust carbon market represents a pivotal shift in the national decarbonization strategy, moving beyond pure command-and-control measures to harnessing market forces for cost-effective emissions reduction. The launch of the national Emissions Trading Scheme (ETS) in July 2021 marked a watershed moment, creating the world's largest carbon market by covering emissions volume. This section examines the structure, progress, challenges, and future trajectory of the carbon market [11]-[13] alongside the synergistic rise of environmental, social, and governance (ESG) principles, which are increasingly shaping corporate behavior and investment flows, reinforcing the carbon pricing signal.

The national ETS includes structure and initial phases. More details are provided in this section.

3.1. Foundational Design and Scope

Sector Focus:

The initial phase targets the power sector, encompassing more than 2000 coal and gas-fired power plants, which are responsible for approximately 40% of national CO_2 emissions (approximately 4.5 billion tons annually). This sector was chosen for its high emissions concentration, relative homogeneity, and robust data monitoring capabilities.

Cap-and-Trade Principle:

The scheme operates on the basis of a cap-and-trade model. A national emission cap is set, which decreases over time to ensure alignment with carbon intensity targets. Emissions allowances are distributed to covered entities, who must surrender enough allowances annually to cover their verified emissions [14].

Allocation Mechanism:

This mechanism largely relies on a benchmarking approach combined with grandfathering. Free allowances are allocated on the basis of the actual outputs (e.g., electricity generated and heat supplied) and predefined emission intensity benchmarks per unit of product. Entities emitting below their benchmark can sell surplus allowances. Notably, those exceeding must buy allowances or face penalties. This incentivizes efficiency improvements within the sector. Grandfathering (based on historical emissions) plays a smaller, transitional role.

Trading Platform:

Centralized trading occurs on the Shanghai Environment and Energy Exchange (SEEE). Trading modalities include listed trading, block trading, and negotiated transfer.

Compliance and Enforcement:

Strict monitoring, reporting, and verification (MRV) protocols are mandated. Noncompliance penalties include fines (up to 30,000 RMB per ton of CO_2 exceeding allowances, although this is considered low), public naming, and potential deduction of future allowances.

3.2. Initial ETS Phase in the Power Sector: Progress and Performance

Market Scale:

The sheer volume of covered emissions makes the ETS globally significant, dwarfing the EU ETS in terms of tons covered.

Price Formation and Liquidity:

Carbon prices generally vary between 50 and 80 RMB per ton (approx. $7 - 11 USD). While providing a signal, liquidity has been lower than anticipated. Trading activity often spikes significantly around compliance deadlines (compliance season), indicating that the market is still driven primarily by regulatory obligations rather than by continuous price discovery for hedging or speculation.

Achieving Compliance:

The first compliance cycles demonstrated high compliance rates (exceeding 99%), thus validating the basic operational framework. Covered entities successfully navigated allowance surrender.

Impact:

The primary impact thus far has been heightened awareness and internal carbon cost accounting within the power sector. While driving some efficiency gains, the relatively low price and free allocation have limited transformative abatement investments triggered solely by the ETS thus far. Its effectiveness is intertwined with complementary policies such as renewable mandates and efficiency standards.

3.3. Expansion and Evolution: The Next Critical Phase

The true potential of the ETS depends on its expansion beyond the power sector. The sectoral expansion includes hard-to-abate sectors that are a top priority under the 14th FYP and that will be crucial for the 15th FYP.

Key targets include the following sectors:

Steel: Major integrated steel mills and electric arc furnaces.

Cement: Large clinker production facilities.

Aluminum: Primary aluminum smelters (significant electricity consumers).

The enhancements in the ETS system include the following.

Tightening the Cap:

Gradually reducing the overall cap to drive meaningful emissions reductions and strengthen the price signal.

Increasing Auctioning:

Gradually shifting from predominantly free allocation toward auctioning a percentage of allowances. This injects a direct cost for emissions, generates revenue for climate initiatives, and enhances market liquidity.

Market Stabilization Mechanisms:

Implementing mechanisms such as a price floor/ceiling or allowance reserves to manage excessive volatility and provide investor certainty.

Financialization:

Exploring the introduction of derivatives (e.g., futures and options) to improve hedging capabilities and attract greater market participation (including financial institutions), deepening liquidity.

Linking:

While politically complex, discussions regarding the potential future linkages with other carbon markets (e.g., regional Asian schemes and the EU ETS) will persist in the long term, promoting global carbon price convergence.

3.4. Synergistic Increase in ESG Integration

The carbon market does not operate in isolation. The parallel surge in ESG adoption in China creates a powerful reinforcing dynamic, as stated below.

Regulatory Push for ESG Disclosure:

Regulators (e.g., the China Securities Regulatory Commission (CSRC) and stock exchanges) are mandating enhanced environmental and climate-related financial disclosures for listed companies, particularly in high-impact sectors. This includes reporting on carbon emissions, climate risks, and mitigation strategies.

ESG Investing Momentum

Institutional investors (domestic and international) are increasingly integrating ESG factors, including carbon footprints and climate performance, into their investment decisions and stewardship activities. Funds explicitly labeled “ESG” or “green” are growing rapidly [15].

Corporate Response:

Companies face growing pressure from investors, regulators, customers, and employees to demonstrate sustainability leadership. Strong ESG ratings enhance reputation, reduce financing costs (via green bonds/loans), and attract investment.

Convergence with Carbon Markets:

This ESG wave directly complements the ETS.

Data Foundation:

ETS MRV systems provide high-quality, verified emissions data, a core component of environmental (E) disclosures within ESGs.

Performance Metric:

A company's carbon intensity, compliance status, and strategy within the ETS become critical ESG performance indicators.

Financial Materiality:

Carbon costs (those currently under the ETS or anticipated future costs with expansion/tightening) and climate transition risks become material financial factors assessed under ESG frameworks.

Capital Allocation

Green finance instruments (e.g., bonds and loans) increasingly link preferential terms to ESG performance, which includes carbon management aligned with the ETS trajectory. Companies that perform well under the ETS and demonstrate strong climate governance attract less expensive capital.

Voluntary action:

Companies seeking higher ESG ratings often go beyond compliance, investing in additional emissions reductions or purchasing green electricity certificates (GECs) or China-certified emissions reductions (CCERs; see below) to offset residual emissions, thereby creating demand in voluntary carbon markets.

3.5. Role of CCERs and Voluntary Markets

In addition to the compliance ETS, China is revitalizing its National/China Certified Emission Reduction (NCCER) program, a domestic voluntary carbon credit mechanism. For details, please refer to the following:

Purpose:

CCERs represent verified emissions reductions from projects in sectors not covered by the ETS (e.g., forestry, renewable energy projects not under FiTs, and methane capture). They can be used by ETS-regulated entities to offset a limited percentage (approximately 5%) of their compliance obligations. CCERs also serve as a voluntary market for corporate carbon neutrality claims.

Revival:

After a pause starting in 2017 due to concerns over credit quality, the program resumed accepting new project applications in 2023/2024 with strict revised methodologies focusing on integrity, additionality, and preventing double counting.

Synergy:

The CCER market provides flexibility for compliance entities, channels financing to emission reduction projects outside the ETS cap, and supports corporate ESG goals through voluntary offsetting.

In summary, the national ETS, coupled with the accelerating integration of ESG principles, represents a fundamental evolution in China's climate policy arsenal.

While the initial phase focused on establishing the operational infrastructure within the power sector, the coming years are critical for its expansion and deepening. Successfully integrating major industrial emitters, tightening the cap, enhancing market liquidity, and strengthening the price signal are paramount. Synergy with ESG principles amplifies the impact, embedding carbon costs and climate considerations into the core of corporate finance and investment decisions. The effective combination of the market and governance approach is a major determinant of its national ability to achieve its dual-carbon goals and solidify its position in the global green economy.

4. Energy Structure in Transition

The ambitious Chinese dual-carbon goals are being propelled forward by an unprecedented deployment of clean and green energy technologies, which are transforming its energy landscape at a scale and speed unmatched globally [16] [17]. This technological leapfrogging is not merely an adjunct to policy but is the physical manifestation of the transition process, enabling tangible progress toward peaking emissions and achieving carbon neutrality [18].

The rapid development of alternative energy technologies propels significant advancements toward its dual-carbon goals. For details, refer to references [19]-[21] and the illustration as follows.

4.1. Energy Storage (ES)

Energy storage technology refers to the process of converting energy into physical or chemical forms for storage and then releasing energy when needed. Storage devices are commonly referred to as accumulators or batteries. Hydropower also constitutes energy storage, although hydropower will be discussed separately.

As long as generation capacity exists, the output can be rapidly increased to compensate for fluctuations. This provides a highly consistent overall power supply with minimal energy loss, reducing the reliance on hydropower. When suitable hydropower (e.g., pumped storage) is unavailable, other forms of grid energy storage—such as compressed air storage and thermal energy storage—can be deployed. These systems store energy that is generated during peak solar/wind periods and release it on demand.

Stored energy enhances the economic value of PV and wind power by displacing higher-cost generation during peak demand. This revenue potential can offset storage costs and efficiency losses.

To achieve carbon neutrality at an early date, China is vigorously developing its new energy industry. Energy storage technology can reduce wind/solar curtailment rates, increase renewable energy utilization, and ensure the secure, stable operation of power systems.

Energy Storage: Enabling the Renewable Era or Sun Era

Recognizing the critical challenge of intermittency, China is investing heavily in energy storage solutions to ensure grid stability and maximize renewable utilization. Utility-scale battery storage deployment is accelerating rapidly, underpinned by its leadership in battery manufacturing (dominating in lithium-ion production) [22]. The application of pumped hydrostorage (PHS), a mature large-scale solution, continues to increase significantly, with numerous large projects under development. The growth trends during the Chinese 14th FYP are shown below in **Figure 2**. Policy mandates and targets increasingly require new renewable projects to incorporate storage capacity. Research and pilot projects have also focused on exploring alternative storage technologies such as compressed air and flow batteries.

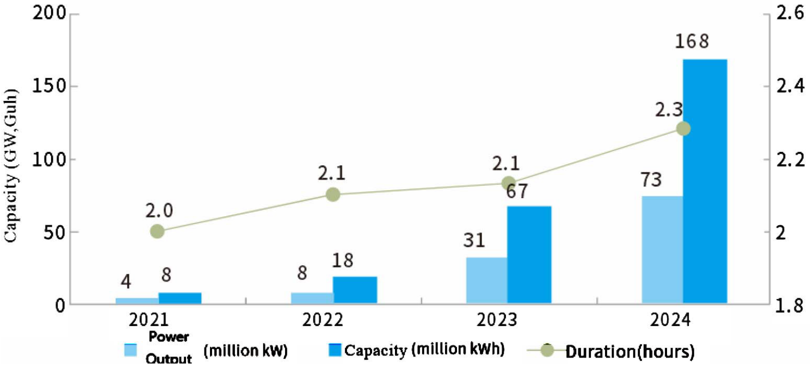

Figure 2. Growth trends in new energy storage installations under the Chinese 14th FYP.

In 2024, the nation added 42.37 GW/1.01 GWh of new energy storage capacity nationwide. The average energy storage duration reached 2.3 hours, which is an increase of approximately 0.2 hours compared with the end of 2023. Since the start of the 14th Five-Year Plan period, the energy storage duration has shown a consistent upward trend. A list of the top provinces with deployment of advanced energy storage over 1 GW by the end of 2024 is shown in **Figure 3**.

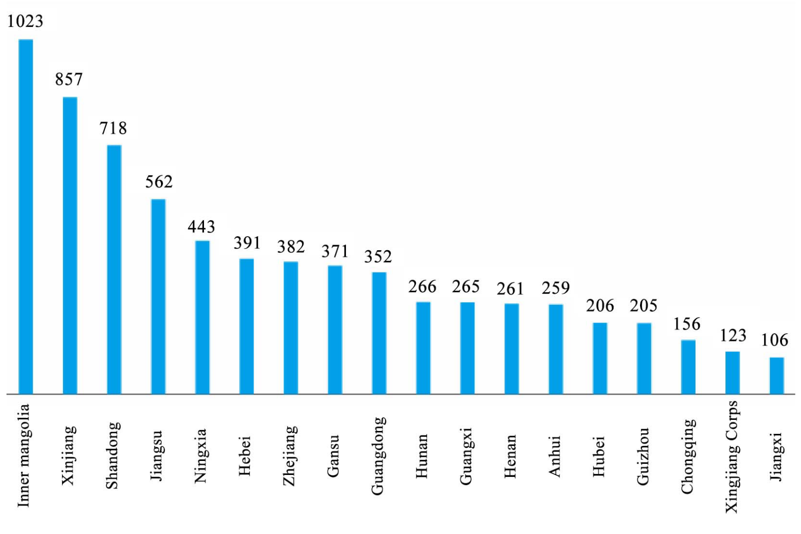

Figure 3. Provincial deployments of advanced energy storage: regions exceeding 1 GW by the end of 2024 (Units: 10 MW).

As shown in **Figure 4**, in 2024, there were eleven provincial-level regions, each of which added more than 1 GW of new energy storage capacity. Notably, Jiangsu, Xinjiang, Zhejiang, and Inner Mongolia experienced particularly robust growth, with newly installed capacity exceeding 3 GW in each region, reaching 4.86 GW, 3.84 GW, 3.53 GW, and 3.05 GW, respectively.

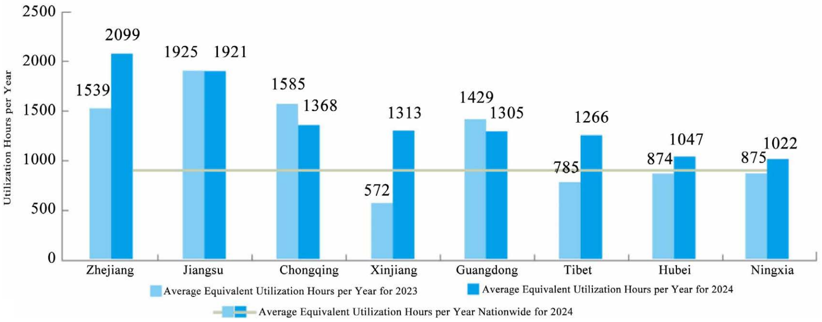

Figure 4. Utilization status of advanced energy storage in key provinces (unit: hours).

In 2024, the use of new energy storage systems significantly increased compared with that in 2023, with an annual average equivalent utilization of 911 hours, an increase of approximately 300 hours over the previous year. The annual average number of equivalent charge-discharge cycles has reached 221, which is approximately 59 times greater than that of 2023. Provinces and autonomous regions such as Zhejiang, Jiangsu, Chongqing, Xinjiang, Guangdong, Xizang, Hubei, and Ningxia all recorded annual equivalent utilization hours exceeding 1000 hours.

4.2. Photovoltaic (PV) Power Generation Systems

PV systems generate electricity via the photovoltaic effect, converting solar energy into electrical power. They consist of PV modules (solar panels), inverters, mounting structures, energy storage devices (e.g., batteries), and monitoring/management systems.

PV systems have broad applications. Residential rooftop installations provide power, reduce grid dependence, and lower electricity costs. Commercial/industrial-scale PV plants deliver stable power while reducing carbon emissions.

Solar and Wind: Scale Dominance

As a major player both domestically and internationally, China has become the world's decarbonization leader because of its major contributions to and dominance in both solar PV and wind power, driven by its massive domestic manufacturing capacity, plummeting costs, and strong policy support. Domestic deployments consistently exceed the FYP targets. Massive utility-scale clean energy bases, particularly in sun-drenched western provinces such as Qinghai and Gansu and in wind-rich regions such as Inner Mongolia, are central to this strategy. The use of distributed solar, especially on commercial and industrial rooftops, is also growing. The above dominance extends to its related global contribution: its firms supply more than 80% of global solar PV components and a major share of wind turbines, continuously driving down costs worldwide through economies of scale and relentless innovation.

A PV power generation system is a technological system that relies on solar energy to generate electricity through the photovoltaic effect and is also known as a PV system. It converts solar energy into electrical energy and primarily consists of PV modules (solar panels), inverters, mounting systems, energy storage devices (such as batteries), and monitoring and management systems.

The applications of PV systems are extensive. In households, rooftop PV systems can provide electricity for residents, reducing their reliance on the traditional power grid and lowering electricity bills. The typical photos of the PV power station elements are shown below in **Figure 5**. In the commercial and industrial sectors, large-scale PV power plants can supply stable electricity to businesses while reducing carbon emissions.

(Note: the photovoltaic effect is retained as a technical term, and PV is used as a standard abbreviation for photovoltaics. The translation maintains clarity while adapting to natural English phrasing.)

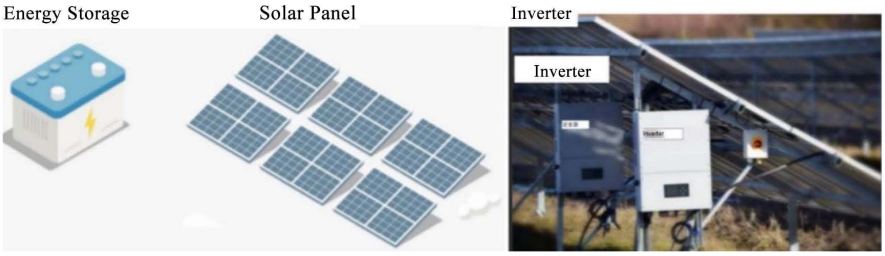

Figure 5. Photos of selected PV power station components.

4.3. Wind Power Generation Technology

Wind power is a widely adopted clean energy source that has emerged as a vital alternative to traditional coal, oil, and gas. It offers significant commercial opportunities. Wind power converts kinetic energy into electricity using turbines. Wind rotates turbine blades, driving generators to produce power. As a clean, green energy source, it consumes no fuel, emits no pollutants, and is environmentally benign. Wind power plays a crucial role in achieving carbon neutrality and has immense potential. Applications include onshore, offshore, and distributed wind power. Key advantages include the following.

1) Renewable energy: Wind is an infinite, sustainable green resource that provides long-term clean energy.

2) Greenhouse gas reduction: Wind power produces near-zero emissions, curbs fossil fuel dependence, and advances low-carbon economies.

3) Cost-effectiveness: Technological advances and economies of scale have progressively reduced costs, enhancing market competitiveness.

4) Wide availability: Wind resources exist globally because of planetary atmospheric dynamics.

4.4. Hydrogen Fuel Cells

The interest in hydrogen fuel cells—a clean, efficient energy conversion technology—is growing. They generate electricity through electrochemical reactions between hydrogen and oxygen, resulting in the emission of only water vapor. With high energy densities, zero emissions, and rapid refueling, they are widely used in transportation, energy storage, and industry.

Fuel cells convert chemical energy from hydrogen and oxygen into electrical energy. Hydrogen is oxidized at the anode, and oxygen is reduced at the cathode, creating electron flow through an external circuit to produce electricity and water.

Green hydrogen (produced via electrolysis using renewable electricity) is identified as a crucial solution for decarbonizing hard-to-abate sectors such as heavy industry (steel and chemicals) and long-haul transport. While this industry is still nascent compared with solar and wind, China is laying the groundwork for a future hydrogen economy. National and numerous provincial hydrogen strategies outline ambitious development pathways. Large-scale pilot projects for green hydrogen production, particularly those with renewable bases in the west, and for industrial use (e.g., hydrogen-based steelmaking) are underway. Significant investment targets the entire value chain, from electrolyzer manufacturing to storage, transportation, and end-use applications.

4.5. Smart Control Systems and Integrated Energy

Smart control systems enable real-time monitoring and management of distributed energy resources (DERs), improving wind power efficiency and reliability. Innovations include AI-based controls and big-data forecasting systems.

4.5.1. AI in Integrated Energy Processes

Artificial intelligence is valuable for achieving optimal energy conversion efficiency in distributed energy resource (DER) systems. The typical flow of the AI APP for decision-making processes is shown below in **Figure 6**. The ability of AI to forecast, optimize, and adapt makes it indispensable for unlocking the full potential of distributed energy resources, driving greater efficiency, resilience, and integration of renewables.

Figure 6. AI application to decision-making processes in integrated energy systems.

4.5.2. Smart Control Systems and Integrated Energy

Smart power systems (equipped with AI) are a new and important technology that drives the electricity/power sector toward carbon neutrality. A smart power system, commonly known as a smart grid, has many applications for carbon neutrality. For example, AI is an enabling and emerging technology with a significant share of the energy market.

The main goal of smart control systems with AI applications is to minimize the carbon emission coefficient of integrated energy [19] [23].

An illustration of a distributed energy resource (DER) system can be used to formulate a mathematical model briefly as follows on the basis of prior works in the literature [23]. **Figure 7** shows a mathematical model known as the EEE model with output solutions of energy consumption (E1), carbon emissions (E2), and economic cost (E3). The input variables of DER include renewable energy (RE), energy storage (ES), and grid power (GP). There is a 3 × 3 square matrix that is characteristic of the DER system and transforms the matrix from the inputs to the outputs.

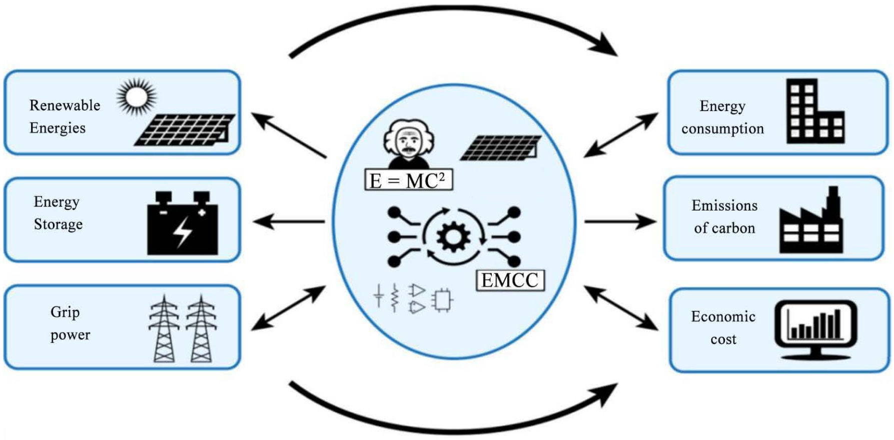

Figure 7. Schematic illustration of multiple energy inputs and three output functions (known as the energy/emission-of-carbon/economic-cost model or EEE model).

The corresponding mathematical equation is as follows:

$$\begin{bmatrix} E1 \\ E2 \\ E3 \end{bmatrix} = \int_{T0}^{T} \begin{bmatrix} K,_{E1,RE} & K,_{E1,ES} & K,_{E1,GP} \\ K,_{E2,RE} & K,_{E2,ES} & K,_{E2,GP} \\ K,_{E3,RE} & K,_{E3,ES} & K,_{E3,GP} \end{bmatrix} \times \begin{bmatrix} RE \\ ES \\ GP \end{bmatrix} \times \frac{dt}{\tau} \tag{1}$$

Equation (1) contains the following 3 × 3 square matrix, which is also known as the power utility matrix [21] in the literature. The time interval ranges from T0 to T where τ is in unit of 1-min.

$$[3\times 3PUM] = \begin{bmatrix} K,_{E1,RE} & K,_{E1,ES} & K,_{E1,GP} \\ K,_{E2,RE} & K,_{E2,ES} & K,_{E2,GP} \\ K,_{E3,RE} & K,_{E3,ES} & K,_{E3,GP} \end{bmatrix} \tag{2}$$

This 3 × 3 square matrix is characteristic of the DER system and has nine coefficients, K, ij, that transform the input variables to the output functions [E1, E2, and E3]. The 3 × 3 matrix is determined by both the hardware design/configuration and the characteristics of the DER system.

Several concepts are related to the reduction in carbon emissions in the text as follows: 1, baseline carbon reduction rate (CRR) in comparison to coal-fired power from traditional grids; 2, net carbon reduction rate (NCRR) in comparison to the system with or without alternative energies versus solely grid power; and 3, optimal carbon reduction rate (OCRR) in comparison to the system with or without algorithm (AI) optimization. These emissions can serve as important metrics for DERs. In particular, the CRR depends on both E_gridlike and E_microgrid, where E_gridlike represents the emissions from grid-purchased electricity and E_microgrid represents the emissions from the internal generation of the microgrid. For example, if the carbon emissions are 0.5777 kg/kWh, one derives the following result for the baseline carbon reduction rate:

$$\text{CRR} = \frac{\text{E}_{\text{gridlike}} - \text{E}_{\text{microgrid}}}{\text{E}_{\text{gridlike}}} = \frac{0.832 - 0.577}{0.832 \times 100\%} = 31\% \tag{3}$$

The result is a 31% CRR, which is a significant reduction. If the current carbon emissions are 0.6205 kg/kWh, the CRR is 25%.

Finally, China has a major advantage in terms of the sheer scale of its investments, and its installations in solar, wind, and energy storage have enabled infrastructure that shapes the global clean energy landscape. Its green transition has advanced energy technology deployment; its strategic focus on emerging solutions such as green hydrogen underscores its national commitment to tackling the NexGen product of decarbonization.

5. The Green Industrial Revolution in East Asia

The green industrial revolution (GIR) [24] is driven both by the imperative of decarbonization and by the need for sustainable power supplies. The GIR signifies fundamental shifts in industrial systems, supply chains, and economic paradigms [25]. By achieving unprecedented economies of scale in clean technology manufacturing and deployment, China has dramatically reshaped global markets, influenced regional strategies across East Asia, and accelerated the dissemination of green technologies and practices worldwide [26] [27]. This section examines the catalytic role of China, regional dynamics in East Asia, and the mechanisms through which the GIR is spreading globally.

5.1. Demonstration

During the Green Industrial Revolution, renewables will become the world's leading overall power source by 2026. For further information, please refer to Figure 1 as illustrated above.

China has achieved strategic state-led scaling, and its success was not accidental. It resulted from decades of concerted industrial policy: massive state investment (often via state-owned banks and enterprises), targeted subsidies (especially in the formative years), R&D support, and favorable regulatory frameworks. The 1 + N policy explicitly identifies strategic emerging industries such as renewables, EVs, and batteries as national priorities.

5.2. Manufacturing Supremacy and Cost Collapse

Solar PV:

Its manufacturers supply more than 80% of global solar PV polysilicon, wafers, cells, and modules. The massive scale, continuous process innovation, and vertical integration have driven down module costs by more than 90% in the past decade, making solar energy the least expensive new-build electricity source worldwide.

Wind Power:

It dominates global wind turbine manufacturing, particularly for onshore turbines, and is rapidly scaling up offshore capabilities. Cost reductions have followed a similar, although less steep, trajectory as solar.

Batteries:

Its firms (e.g., CATL and BYD) lead in global lithium-ion battery production, which is crucial for EVs and energy storage. It controls significant portions of the critical mineral refining and battery component supply chains (e.g., cathodes, anodes and separators).

Electric Vehicles (EVs):

China is the world's largest EV market and producer. Aggressive policy support (purchase subsidies, manufacturing incentives, and ZEV mandates), massive investments in charging infrastructure, and fierce domestic competition have fostered globally competitive automakers and a vast supplier ecosystem.

Economies of Scale as a Global Public Good:

Its manufacturing scale has served as a powerful deflationary force on clean technology prices globally. The China Price Effect has arguably been the single most significant factor in accelerating the global energy transition by making renewables and EVs economically viable far sooner than otherwise possible. It has lowered the entry barrier for countries worldwide.

Beyond Hardware with System Integration and Digitalization:

China's companies are increasingly emerging as leaders in integrated solutions, namely, smart inverters, energy management systems, EV charging networks, and digital platforms for grid management and energy services. This ecosystem approach leverages hardware dominance with digital innovation.

5.3. East Asia Is Marching on: Competition, Collaboration, and Regional Reconfiguration

The GIR surge has notably reshaped the economic and energy landscape of East Asia, forcing adaptations and fostering complex interdependence. A brief analysis is shown below.

Japan and South Korea:

Strategic Responses to the China Challenge: Faced with intense competition in traditional manufacturing strongholds (e.g., batteries, displays, and, increasingly, chips), Japan and South Korea have doubled down on the following.

High-Value Niche Leadership:

Focusing on advanced materials (e.g., battery chemistries such as solid-state, hydrogen fuel cells, and specialized semiconductors for EVs/energy), high-efficiency components, and sophisticated production equipment.

Hydrogen Economy:

Both nations have made hydrogen (particularly green/blue hydrogen) a cornerstone of their decarbonization and industrial strategy, investing heavily in R&D, supply chains, and international partnerships and seeking leadership where China is still scaling up.

Supply Chain Resilience and Derisking:

Actively diversifying supply chains (e.g., battery materials and rare earths) away from excessive or single reliance on China, investing in domestic production and partnerships with other nations (e.g., Australia, Canada, and US allies). This involves significant government support and corporate restructuring.

EV Ambitions:

Korean (Hyundai/Kia) and Japanese (Toyota, Honda, and Nissan) automakers are aggressively accelerating their EV rollouts and battery investments, seeking to counter Chinese EV dominance, particularly in its exports.

Regional Supply Chain Integration (and Friction):

Despite geopolitical tensions, East Asia remains deeply integrated:

Component Dependence:

Chinese manufacturers rely heavily on advanced machinery, components, and specialty chemicals obtained from Japan and South Korea. Conversely, Japanese/Korean battery and EV makers depend on Chinese raw materials and refined products.

Collaborative Ventures:

Joint ventures and technology licensing agreements persist, particularly in complex areas such as battery production and semiconductor manufacturing for green technology.

ASEAN as a Manufacturing Hub & Market:

Southeast Asian nations (e.g., Vietnam, Thailand, Indonesia, and Malaysia) are becoming crucial manufacturing bases for both Chinese firms (diversifying production) and Japanese/Korean firms (seeking lower costs and market access). ASEAN is also a rapidly growing market for EVs, solar panels, and energy storage, attracting investment from all major East Asian players.

Policy Cross-Pollination:

The scale and ambition of Chinese policies have pushed Japan and South Korea to set more aggressive decarbonization targets and increase green industrial support. Competition drives ambition.

How the GIR Is Reshaping the World:

The GIR demonstrates strong global diffusion. The GIR effects described above have accelerated the global energy transition through multiple channels [27].

5.4. Belt and Road Initiative (BRI): The Evolving Green BRI

Infrastructure Exports:

Today, many Chinese firms are dominant in building renewable energy projects (e.g., solar farms, wind parks, and hydropower) globally, particularly in developing countries. This enables China to export its technology, expertise, and financing models.

Technology Transfer and Localization:

Increasingly, BRI projects involve local manufacturing partnerships or technology transfer components, helping develop green industrial capacity in host countries (e.g., EV assembly plants in Southeast Asia and solar panel factories in the Middle East).

Financing:

Its policy banks (e.g., China Development Bank and export-import Bank) and commercial banks provide significant financing for overseas renewable projects, although scrutiny over debt sustainability and environmental/social standards continues. The push for the green BRI aims to address these concerns.

Global Cost Reduction and Market Acceleration:

As noted, China's scale drives down global prices, making solar, wind, batteries, and EVs affordable for virtually all nations. This is the most pervasive impact.

Exporting the EV Revolution:

EV makers are rapidly expanding in international markets (e.g., Europe, Southeast Asia, Latin America, and the Middle East), offering competitively priced, technologically advanced models. This drives legacy automakers globally to accelerate their own electrification plans and invest more heavily.

Supply Chain Diversification and New Geographies:

The drive for supply chain resilience is spurring massive investments in clean tech manufacturing globally.

US and Europe:

Policies such as the US Inflation Reduction Act (IRA) and the EU Green Deal Industrial Plan offer massive subsidies to attract battery gigafactories, EV plants, solar component manufacturing, and clean hydrogen projects. While aimed at reducing their dependence on China, this globalizes their manufacturing capacity, further accelerating the GIR, albeit with potential inefficiencies from duplication.

Resource Nations:

Countries rich in critical minerals (e.g., Australia, Chile, Indonesia, and the DRC) are moving beyond raw material exports to develop domestic refining and midstream processing capabilities, seeking a larger share of the green value chain, often with recent investments and technology from China.

Knowledge and Model Diffusion:

The Chinese experience in rapidly deploying renewables at scale, building integrated supply chains, and implementing large-scale policy frameworks (including ETS pilots) provides valuable lessons (both positive and cautionary) for other developing and emerging economies navigating their own transitions. Its think tanks and companies actively engage in global knowledge exchange.

5.5. Challenges and Contradictions within the GIR

As a critical driver of global decarbonization, the global diffusion of green innovation and infrastructure (in terms of the GIR) faces formidable challenges that hinder its role in advancing energy transition and emission reduction goals.

First, geopolitical friction and protectionism pose major barriers: some countries impose technical barriers and trade restrictions on GIR-related technologies (e.g., advanced renewable energy equipment and carbon capture systems), prioritizing domestic interests over global collaboration and slowing cross-border technology and project deployment.

Second, overcapacity concerns loom large—the rapid expansion of GIR manufacturing (such as solar panels and wind turbines) in some regions has led to potential supply–demand imbalances, threatening the sustainability of the GIR industry and discouraging long-term investment.

Third, environmental and social footprints cannot be ignored: the production of GIR components (e.g., lithium for batteries and rare earths for wind turbines) often involves ecological damage and risks to local communities' livelihoods, undermining the "green" essence of GIR. Fourth, technology access and equity gaps persist: developing countries lack sufficient funds and technical capacity to adopt advanced GIRs, widening the North–South divide in the decarbonization progress.

Finally, and most critically, the risk of carbon leakage undermines genuine global decarbonization. As GIR manufacturing shifts geographically (e.g., to regions with lax emission regulations), emissions may merely be transferred rather than reduced. Addressing this requires robust global carbon accounting standards and strengthened international cooperation that ensure geographic shifts in production to align with a net global decrease in emissions rather than just displacing carbon pollution.

Notably, robust carbon accounting and international cooperation are essential for achieving successful decarbonization through meticulous accounting and total dedication.

5.6. Conclusion

The GIR is currently an irreversible force reshaping the global economy. Commercial green energy surge has launched an irrevocable global green industrial revolution. Its unparalleled manufacturing scale has drastically reduced clean technology costs, making worldwide decarbonization economically feasible. Within East Asia, the GRI has triggered a dynamic mix of fierce competition, strategic adaptations, and deep supply chain interdependence, accelerating the region's collective march toward a greener future. Globally, through exports, BRI projects, and the catalytic effect of its policies on others (such as the US IRA), the GIR is reshaping industrial landscapes, energy systems, and geopolitical dynamics. While the challenges of geopolitics, sustainability, and equity loom large, the direction is clear: the industrial foundation of the global economy is being fundamentally rewired toward sustainability, with China acting as the primary, albeit complex and contested, accelerator. The success of this revolution will depend not only on continued technological innovation and deployment but also on navigating the intricate web of international cooperation, competition, and shared responsibility for a stable climate.

6. Summary

The Chinese energy-structure transition has made significant progress in terms of its global implications [28]. This article is titled "A Case Study of Decarbonization and the Dual Carbon Strategy"; the research presented in this article provides a comprehensive analysis of a multifaceted endeavor toward decarbonization by examining the interplay of policy, market mechanisms, technological innovations, and global influence in its pursuit of dual-carbon goals (carbon peak by 2030 and carbon neutrality by 2060).

Central to China's progress is its hierarchical policy architecture, anchored in the national 14th and 15th Five-Year Plans. These plans integrate binding emission reduction targets, sector-specific action plans, and a mix of regulatory tools, economic incentives, and market mechanisms. The national carbon emissions trading scheme (ETS), which has expanded from regional pilots to cover the power sector and, subsequently, high-emission industries such as steel and cement, has emerged as a key market-driven tool, complemented by ESG disclosure mandates that align corporate behavior with low-carbon goals.

There is a related analysis published by the Centre for Research on Energy and Clean Air (CREA), a think tank in Finland, on May 15, 2025. According to that report, Chinese carbon dioxide emissions are now decreasing. Its emissions have fallen before; in 2022, the carbon emissions dip after the country's strict COVID-19 control initiated economic activities. However, when factories restarted production, these emissions shot back up again. This time, its factories are humming away even as emissions are falling. This occurs because they are becoming less reliant on burning fossil fuels for power. Coal is still the mainstay of its grid. However, the country has also been installing more clean energy than the rest of the world put together. Its carbon dioxide emissions are so large that if decarbonization continues and its carbon emissions are shown to have recently peaked, this could alter the trajectory of global emissions.

Technological innovation has been a linchpin, with China leading global deployment in solar, wind, hydrogen, and energy storage—driving cost reductions and scaling renewable capacity to more than 1.2 terawatts by 2024. These advancements have catalyzed a domestic green industrial revolution (GIR) and have transformed traditional sectors such as automotive and steel while fostering new green tech ecosystems [29].

Regionally, the transition in the Chinese energy structure has positioned East Asia as a hub for green collaboration, with active cross-border initiatives in terms of hydrogen, carbon market linkages, and renewable integration. Globally, the

GIR has spread through technology exports, green infrastructure investments (e.g., via the Belt and Road Initiative), and policy knowledge sharing, enabling developing nations to accelerate their own decarbonization.

While challenges—including regional disparities, critical mineral dependencies, and global policy fragmentation—persist, China's experience demonstrates that strategic policy alignment, technological scale, and market innovation can drive transformative energy transitions. Its pathways offer valuable lessons for global climate governance, emphasizing the need for inclusive, collaborative approaches to balance growth and sustainability (International Energy Agency [IEA], 2025; Tsinghua University Institute of Climate Change and Sustainable Development, 2025).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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