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# *Carbon-Neutral Power Transitions under Constraints: A Comparative Energy-Economic View of China, the United States and the European Union*

**Xinrui Liu**

*Rutgers Business School, New Brunswick, USA*
*xinrui041102@gmail.com*

***Abstract.*** Carbon neutrality is currently accelerating the decarbonization process in the power sector. However, China, the United States, and the European Union are taking significantly different transformation paths. This article uses an energy economics framework to link binding system constraints, policy combinations, and the overall system costs to compare the differences among the three countries. This analysis integrates evidence from international assessments and peer-reviewed studies regarding the value and flexibility of variable renewable energy (VRE). The results show that as the share of renewable energy increases, economic bottlenecks shift from generation costs to flexibility and grid transmission: the marginal market value of wind and solar energy decreases as penetration rates increase, while the value of dispatchable system services increases. The EU's total control and trading system and market integration enhance long-term scarcity expectations, but without appropriate hedging designs, they increase the risk of short-term price fluctuations. The United States relies more on technology-neutral tax credits to reduce capital costs and accelerate deployment in the absence of a national carbon price. China combines large-scale clean infrastructure construction with continuous coal supply guarantees, which makes flexibility compensation, inter-provincial transmission, and reliable emission limits key to achieving cost-effective decarbonization. For China, the policy impact lies in regarding flexibility as a decarbonization asset, strengthening market signals through improved monitoring, reporting, and verification (MRV), and reducing power outages through grid and market reforms.

***Keywords:*** carbon neutrality, power system transition, carbon pricing, clean electricity tax credits, flexibility

## 1. Introduction

Power-sector decarbonization is central to economy-wide net-zero pathways because electrification shifts mitigation to the grid while enabling low-carbon end uses in transport, buildings, and industry [1]. Even with the same global technology frontier, major economies are not converging on a single blueprint. The EU has emphasized carbon pricing and market integration to sharpen long-run scarcity expectations and drive investment away from high-emitting generation [2]. Comparative

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outlooks highlight that inherited fuel mixes and security constraints shape feasible transition choices across regions [3]. The US lacks a federal economy-wide emissions trading system; instead, deployment incentives are strongly shaped by fiscal instruments that lower after-tax capital costs and improve project financeability. China has combined extraordinary deployment rates for wind, solar, and transmission with continued reliance on coal for adequacy, reflecting the priority placed on reliability and regional development objectives [3].

A key reason transition strategies diverge is that the relevant objective is not simply minimizing the levelized cost of electricity. The binding objective is minimizing total system cost under security, network, and institutional constraints. At low penetration, wind and solar can displace higher marginal-cost generation and reduce emissions at relatively low integration cost. At higher penetration, however, the marginal market value of VRE tends to decline because output is correlated across sites, prices fall during high-production periods, and curtailment or congestion increases [4]. The economic consequence is a shift in cost emphasis toward flexible resources and network delivery: storage, demand response, interconnection, and dispatchable low-carbon supply become increasingly important [5]. Financing conditions also matter because many clean technologies are capital-intensive; policy credibility reduces risk premia and lowers total cost even when engineering costs are unchanged [6].

This paper provides a comparative explanation of the transition paths of China, the US, and the EU and draws policy implications for China. The method is comparative synthesis: policy instruments and system constraints are mapped to expected effects on investment incentives, dispatch outcomes, and system cost drivers, using authoritative assessments and peer-reviewed evidence on VRE value and flexibility [1,4-6]. The paper focuses on the power sector because it is both a major direct emitter and the backbone for economy-wide electrification.

## 2. Policy packages and investment signals

### 2.1. Carbon pricing and scarcity expectations

The EU Emissions Trading System (EU ETS) is the longest-running multinational cap-and-trade program and remains the backbone of EU power-sector decarbonization [2]. A tightening cap increases expected allowance scarcity, raising the relative profitability of low-carbon generation and of investments that reduce emissions intensity. Under credible institutions, carbon pricing can reduce policy uncertainty compared with a patchwork of technology mandates because the quantity constraint is clear and compliance is standardized. In electricity markets, a stronger carbon price typically accelerates coal-to-gas switching and increases the competitiveness of renewables and nuclear, while also creating incentives for flexibility resources that reduce high-emission peaking operation [6].

China's national emissions trading system initially covered the power sector with intensity-based allocation, producing a carbon-price signal that is generally weaker than an absolute cap in the short run. Recent reforms have focused on improving monitoring, reporting, and verification (MRV), refining allocation, and expanding coverage to additional industrial sectors, which can strengthen scarcity expectations over time [7]. The design choice matters for power-sector investment because weak or uncertain scarcity expectations reduce the ability of the carbon price to anchor long-run financing decisions. In practice, dispatch and investment remain influenced by planning, administered tariffs, and regional policy objectives, so carbon pricing interacts with non-market controls more strongly than in the EU [7].

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The US does not operate a national cap-and-trade system. Carbon constraints are heterogeneous, with some states participating in regional trading programs and others relying on performance standards and utility regulation. Under a heterogeneous policy, investment incentives often rely on fiscal instruments that operate through the cost of capital rather than through a uniform carbon price [6]. This structure can accelerate deployment but may deliver weaker economy-wide cost minimization if the implicit carbon price varies widely across regions and technologies.

### 2.2. Subsidies, tax credits, and industrial policy

The Inflation Reduction Act (IRA) created technology-neutral clean electricity credits (sections 45Y and 48E) that provide durable investment incentives for low-emission generation and certain storage technologies [8]. By lowering after-tax capital costs and stabilizing expected returns, these credits can accelerate deployment even in regions without strong carbon-price signals. Final rules specifying emissions-rate determination and eligibility conditions reduce regulatory uncertainty and therefore lower financing costs, which is particularly important for capital-intensive technologies [8]. Compared with short-lived subsidy cycles, predictable multi-year credits can reduce boom-bust investment patterns.

EU member states have increasingly used competitive auctions and contracts-for-difference-type mechanisms to expand renewables while limiting consumer exposure to volatile wholesale prices. Market design for a high-renewables European power system emphasizes addressing market failures for system services and ensuring that flexibility and dispatchability are appropriately valued [9]. China has also used industrial policy to support manufacturing scale and deployment, and has expanded grid construction at an exceptional pace. However, fast capacity growth can outpace local network and market design reforms, leading to curtailment and uneven utilization, which reduces the realized emissions benefit per unit of installed capacity [3].

### 2.3. Market design and system-service remuneration

At high VRE shares, market rules for balancing, reserves, and capacity adequacy materially affect total cost because flexibility becomes scarce at critical hours [5]. If ancillary services and capacity are under-remunerated, investment in storage, demand response, and fast-ramping resources may be insufficient, shifting costs into emergency measures, curtailment, or reliability events. EU market integration and cross-border trading can reduce balancing costs by pooling variability across wider regions, but the value of this pooling depends on transmission capacity and coordinated operational rules [9]. Where congestion persists, local scarcity can still produce extreme prices even when aggregate capacity is sufficient.

China's system has moved toward more market-oriented dispatch in some regions, but institutional fragmentation across provinces and the coexistence of planning and market mechanisms complicate efficient sharing of flexibility. Interprovincial transfers can smooth variability, yet they require both physical transmission and market/administrative mechanisms that allow the benefits to be realized. Strengthening remuneration for flexibility and system services, therefore, becomes a core decarbonization policy rather than a secondary market detail.

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## 3. Outcome paths: technology mixes and cost trade-offs

### 3.1. Variable renewables and the economics of flexibility

The declining marginal value of VRE at higher penetration is a robust pattern: as more wind or solar enters, output coincidence depresses market prices during high-production periods, and congestion or curtailment increases [4]. This does not imply that renewables are unattractive. It implies that complementary investments become increasingly important: storage, flexible demand, interconnection, and system services sustain cost-effective decarbonization by shifting energy across time and space and by supporting adequacy during low-renewable periods [5].

In the EU, renewables growth combined with a tightening carbon cap supports coal exit and raises clean shares, but it also increases exposure to weather-driven price volatility and the need for interconnection and balancing resources [5,10]. Where hedging instruments and support schemes are well designed, volatility can be managed; where they are weak, political pressure may arise to intervene in prices, which can reduce investment certainty. In the US, abundant natural gas and existing flexible capacity can reduce integration costs at moderate VRE shares. Yet net-zero alignment requires either a sharp decline in gas utilization, widespread deployment of abatement options, or large-scale firm low-carbon alternatives; otherwise, gas can become a lock-in risk as infrastructure lifetimes exceed the remaining carbon budget [1,4].

China's path features rapid wind and solar build-out alongside a large coal fleet used to ensure adequacy and manage seasonal and regional variability. As VRE shares rise, total system cost increasingly depends on flexibility sources—coal flexibility retrofits, pumped hydro, batteries, demand response, and interprovincial transfers. Where compensation for flexibility and ancillary services is inadequate, additional clean capacity can translate into higher curtailment rather than proportionate clean generation, weakening cost-effectiveness and slowing emissions reduction per unit of investment [3,8].

### 3.2. Firm low-carbon options: nuclear, hydro, and CCS

Firm low-carbon capacity can reduce flexibility requirements because it provides controllable output and valuable system services. Nuclear power offers high-capacity-factor, low-emission generation but is capital intensive and sensitive to regulatory and social constraints. International assessments highlight that in advanced economies, without policy and market design that values dispatchability and system services, nuclear capacity can decline, raising system costs and emissions in high-renewables scenarios [10]. Hydropower can provide both energy and flexibility where geography permits, but it is constrained by resource availability and environmental trade-offs.

Carbon capture and storage (CCS) can allow certain fossil assets to provide dispatchable power with lower emissions, but deployment depends on storage geology, transport infrastructure, and sustained policy support. The IPCC's assessment emphasizes that CCS feasibility and cost are highly context-dependent and require robust regulation, monitoring, and long-run liability frameworks [11]. For the US, IRA-linked incentives may support CCS projects, but power-sector economics remain challenging because CCS increases capital cost and can reduce efficiency. For China, CCS may be more relevant for industrial sources, but the option remains important for firm capacity and for managing residual emissions if deep electrification proceeds.

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### 3.3. Transition fuels and stranded-asset risk

Natural gas and coal can provide reliability services, but long-lived fossil infrastructure risks becoming stranded under tightening constraints. The EU's cap-and-trade signal makes high-emission generation progressively less competitive over time and can anchor expectations for coal exit, although energy-security shocks can influence short-run fuel use and prices [2]. The US may experience lower near-term system costs from gas flexibility, yet net-zero alignment requires either rapid utilization decline or abatement; otherwise, emissions trajectories can diverge from long-run targets [1]. China faces a distinctive trade-off: coal capacity supports adequacy and regional economic objectives, but high utilization conflicts with carbon neutrality. Managing this trade-off economically requires shifting coal's role toward flexibility and reserve provision rather than baseload generation, and ensuring that flexibility is appropriately compensated [3].

### 3.4. System boundary checks and carbon leakage

Evaluating only territorial power-sector emissions can understate system-wide impacts by shifting emissions to upstream supply chains or cross-border trade. Industrial ecology research shows that boundary definitions materially affect carbon footprint estimates and policy comparisons [12]. Wind, solar, storage, and transmission require material inputs whose embodied emissions depend on industrial energy structures. Policies that account for leakage and embodied emissions can influence technology and supply-chain choices; conversely, ignoring boundaries can produce misleading comparisons of "clean" pathways.

## 4. Comparative explanation and policy implications for China

Three drivers explain divergence. First, resource endowments and inherited assets differ. The US benefits from gas availability and existing flexible capacity; China inherits a large coal fleet that provides adequacy; the EU relies more heavily on policy-driven scarcity and cross-border market integration to align investment with decarbonization [5,8]. Second, network and operational constraints differ. Congestion, interconnection limits, and balancing requirements become dominant at high VRE shares, shifting the economic bottleneck from generation cost to flexibility and deliverability [2,3]. Third, institutions and financing conditions differ. Where policy credibility is high, investors apply lower risk premia, reducing the capital cost of clean projects; where uncertainty is high, the same engineering system becomes more expensive in economic terms [6].

Transition policies reallocate costs and benefits across regions, income groups, and industries. Carbon pricing and wholesale volatility can transmit price shocks to consumers unless shielded by policy design, while regions dependent on fossil industries face employment and fiscal pressures. These distributional constraints feed back into policy credibility: if compensation mechanisms are weak, policy reversals become more likely and financing costs rise [6]. The EU has attempted to manage distributional effects through revenue recycling and complementary support schemes, while the US approach embeds distributional goals in tax-credit adders and industrial policy [6,8,13]. China's distributional challenge is closely linked to regional development and coal-dependent provinces; decarbonization design that recognizes these constraints can improve feasibility.

For China, the next-stage challenge is converting rapid capacity additions into reliable, deliverable clean electricity while reducing total system cost. Four directions follow from the comparative analysis. (1) Strengthen carbon-market credibility by improving MRV, allocation rules, and expectations of tightening constraints as coverage expands [7]. Credible scarcity reduces

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uncertainty premia and supports long-lived investment [6]. (2) Expand and standardize ancillary-service and capacity remuneration so that storage, demand response, and flexible generation receive revenue streams consistent with the services they provide [5]. Without this, the system risks paying indirectly through curtailment, emergency measures, or overbuilding. (3) Prioritize transmission and operational reforms that reduce congestion and enable interprovincial sharing of flexibility, converting clean capacity into delivered energy rather than curtailed output [3]. (4) Clarify the long-run role of coal: shifting toward flexibility and reserve provision can maintain reliability while aligning utilization with carbon goals, but it requires retrofits, operational standards, and compensation mechanisms that reward flexibility rather than energy volume [3,8]. Complementary investment in firm low-carbon options, including nuclear and CCS where appropriate, can reduce the burden on flexibility and mitigate extreme weather risk [11,12].

## 5. Conclusion

China, the US, and the EU are pursuing distinct power-sector transition paths because constraints and institutions differ, not because technology rankings are universal. As variable renewable energy (VRE) penetration rises, the economic problem shifts from minimizing generation cost to minimizing total system cost, including balancing, congestion, adequacy, and financing risk premia. Peer-reviewed evidence shows that the market value of VRE tends to decline with penetration, which raises the value of flexibility resources and system services [4,5]. The EU's cap-and-trade institutions can provide a clear long-run scarcity signal, but high-renewables market design requires robust remuneration for system services and tools that manage volatility [2,9]. The US approach relies more on durable, technology-neutral tax credits and associated rules, which can accelerate investment by lowering after-tax capital costs and regulatory uncertainty [13]. China's approach combines rapid clean build-out with coal-based adequacy and expanding emissions constraints, making flexibility remuneration, interprovincial transmission, and credible policy signals decisive for cost-effective decarbonization [3,5,7].

Policy implications for China thus focus on converting capacity additions into reliable, deliverable clean electricity. Strengthening monitoring, reporting, and verification and improving the credibility of the national ETS as coverage expands can reduce uncertainty premia and support more efficient capital allocation [6,7]. A market framework that pays for flexibility and reliability services, including ancillary services, peak adequacy arrangements where needed, and standardized interprovincial trading, can reduce curtailment and lower total system cost as clean shares rise [5]. Maintaining optionality in firm low-carbon technologies, including nuclear and CCS where appropriate, can hedge against weather variability and reduce the cost of deep decarbonization [10,11]. Under these conditions, the transition can move from rapid capacity installation toward a higher-quality phase defined by sustained reliability and lower emissions.

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