Technology Review for Carbon Neutrality

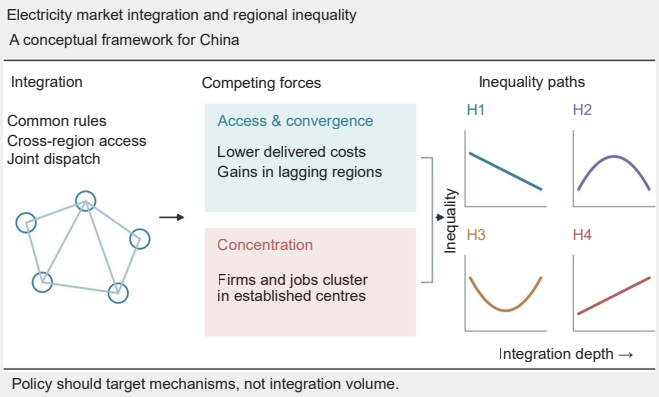
Perspective

Electricity market integration and regional inequality: a research framework for China

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ABSTRACT

Electricity market integration lowers system costs but redistributes economic opportunity across regions. Whether it narrows or widens regional inequality depends on the balance between two opposing forces: broader access to affordable electricity that benefits lagging regions, and the concentration of firms and jobs in already advantaged regions. We develop a conceptual framework that links electricity market integration to regional inequality, and we define integration depth as a measurable institutional index distinct from physical transmission capacity. The framework yields four competing trajectories, i.e., declining, inverted-U, U-shaped, and rising inequality, distinguished by observable differences in delivered electricity costs, firm entry, employment, and migration. We further illustrate how Chinese provinces can be grouped along observable dimensions that distinguish these trajectories. Policy should target the mechanism behind an observed distributional outcome rather than assume that integration alone will reduce regional inequality.



KEYWORDS

Electricity market integration; regional inequality; economic geography; decarbonization; market reform

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1. Introduction

China's carbon neutrality transition requires electricity to move more effectively between regions. Renewable resources and major demand centres are unevenly distributed, while existing operating arrangements can constrain renewable generation[1]. A unified national electricity market seeks to address these barriers through coordinated trading, dispatch and market rules[2]. Integration can lower system costs, reduce curtailment, and lower emissions by reallocating generation and connecting surplus renewable output to demand[3–7]. Broader resource sharing can improve system operation, but its economic benefits may accrue far from the places that supply electricity. The unresolved question is how they are distributed across regions. The central distributional question is therefore who captures the gains from integration and who bears the adjustment costs.

The current research already examines several dimensions of this problem. Dispatch simulations estimate the cost and environmental benefits of broader markets[3]. Economy-wide modelling evaluates the distributional consequences of reforming and integrating China's electricity sector[4]. Evidence from southern China shows that local government preferences can limit efficiency gains[5]. European electricity transition scenarios also reveal regional differences in employment, costs and environmental burdens[6]. What remains unresolved is how the realized integration changes the location of firms and jobs over time, and how those changes translate into household welfare and regional income gaps. This perspective develops a research framework for China that links market rules, delivered electricity costs, firm investment and worker mobility to regional inequality. It identifies four competing distributional trajectories and the conditions under which integration may narrow or widen regional income gaps. It further performs an illustrative classification of Chinese provinces along these trajectories, motivated by the spatial heterogeneity in trading positions, prices and household income.

We define integration as the removal of institutional barriers to electricity exchange and the coordination of trading and dispatch across regions, and we treat integration depth as a multidimensional institutional index distinct from physical transmission capacity. Section 2.2 formalizes this measure.

2. How integration can reshape regional inequality

2.1 Mechanisms linking integration to regional inequality

Electricity market integration can affect regional inequality through three connected mechanisms: changes in delivered electricity costs, adjustment in firm investment and location, and redistribution of employment and population. Cross-border trade can narrow wholesale price differences when transmission constraints allow arbitrage, but wholesale convergence should be distinguished from changes in the bills and reliability experienced by industrial users, because delivered costs include network charges, contractual terms and other regulated components. A fall in delivered electricity costs can make a location more attractive to electricity-intensive production, leading firms to adjust utilisation and investment at existing plants, and subsequently to entry, closure or relocation as capital is renewed. These responses may either attract new investment to disadvantaged regions or allow established economic centres to expand without hosting generation nearby, depending on supplier networks, labour markets, infrastructure, subsidies, land availability and environmental regulation. Employment changes can subsequently affect migration, but mobility is costly and uneven; housing costs, public service access and household registration arrangements may limit adjustment. Evaluation should therefore distinguish the welfare of movers and stayers from the distribution of economic activity across provinces. Existing Chinese firm-level data, including the Annual Survey of Industrial Firms, customs records, and satellite or remote-sensing measures such as night-time lights and thermal anomalies, can help test whether electricity costs affect firm entry, exit, relocation and employment, provided that firm outcomes are matched to actual tariffs, contract exposure and supply reliability rather than to provincial wholesale prices alone[8–12].

2.2 Four competing paths for regional inequality

We use regional inequality to mean dispersion in living standards across provinces, with population-weighted real household disposable income per person as a primary outcome. Real GDP per capita provides a complementary measure of production. Employment, electricity affordability and fiscal capacity reveal other distributional effects. These outcomes can move in different directions. Concentration of GDP does not necessarily imply lower welfare in the regions from which workers leave.

Let I denote the depth of integration, and $D(I)$ denote inequality across provinces. We define integration depth I as a multidimensional index of institutional integration. Its observable components include: (i) coverage of common trading rules across provinces; (ii) access to cross-provincial transactions; (iii) share of electricity settled through continuous spot markets; (iv) scope of coordinated dispatch; and (v) mutual recognition of ancillary services. Each component can be normalized to $[0,1]$ and aggregated into I using equal weights or principal component analysis, with robustness checks for alternative weighting schemes. Physical connectivity should be reported separately using usable transfer capacity.

The net effect of integration on inequality can be expressed as Eq. (1):

$$\frac{\mathrm{d}D}{\mathrm{d}I} = C(I) - A(I) \tag{1}$$

where $A(I)$ is the access and convergence force. It denotes improvements in electricity access and delivered costs that disproportionately benefit lagging regions. $C(I)$ is the concentration and agglomeration force. It denotes advantages to already connected, high-income regions through firm entry, labour pooling and market access.

To discipline empirical work, we specify illustrative functional forms and parameter definitions. Let

$$A(I) = \lambda \cdot a(I), C(I) = \gamma \cdot c(I) \tag{2}$$

where $\lambda \in (0,1]$ is the pass-through rate from wholesale market integration to delivered electricity costs for firms and households; $\gamma \geq 0$ is the agglomeration elasticity, capturing how strongly firm entry and labour pooling reinforce existing spatial concentration; $a(I)$ is an increasing, concave function of integration depth for lagging regions, $a'(I) > 0$, $a''(I) \leq 0$; and $c(I)$ is an increasing, convex function for advantaged regions, $c'(I) > 0$, $c''(I) \geq 0$. Additional parameters include migration elasticity $\mu \geq 0$ and regional adjustment policy strength $\rho \geq 0$. These parameters are not directly observed but can be inferred from reduced-form elasticities of firm entry, employment, and migration with respect to integration depth and delivered electricity costs.

Four conditional trajectories follow:

(1) Declining inequality (H1): Access gains dominate. This is more likely when initial electricity-cost and reliability gaps are large, pass-through is high, lagging regions have usable transmission access, agglomeration is modest, and regional adjustment policy is strong.

(2) Inverted-U inequality (H2): Early gains accrue to already connected, prosperous regions, but network expansion, market deepening or regional policy eventually lowers access barriers elsewhere.

(3) U-shaped inequality (H3): Early integration eases electricity constraints in poorer regions, but later firm and worker agglomeration increasingly favours established centres.

(4) Rising inequality (H4): Integration reinforces existing spatial concentration. This is more likely when high-income regions are better connected, pass-through is weak or asymmetric, agglomeration is high, migration is high, and regional adjustment policy is limited.

These trajectories are not stages that every market must pass through. They are competing

hypotheses. The direction depends on the geography of income and electricity advantages, price transmission to users, mobility and regional policy. Figure 1 presents these four conditional trajectories.

These trajectories do not identify an optimal degree of integration. An inequality minimum along one integration path differs from a Pareto frontier. A frontier contains policy combinations for which efficiency or equity cannot improve without worsening the other objective, given common emissions and reliability requirements. Establishing it requires comparing feasible combinations of market rules, network investment and regional support. Figure 1 contains no such comparison. Its illustrative benchmarks cannot justify slowing integration or selecting a national stopping point.

2.3 An illustrative classification of Chinese provinces

Table 1 provides a descriptive spatial baseline using reported provincial net positions in the interprovincial spot market, medium- and long-term energy trading prices, and nominal household disposable income per person. The four columns correspond to the three dimensions: net spot position, energy-price difference and income/position cue. Positive net positions indicate net sellers and negative values indicate net buyers within the reported market subset. Energy-price differences are energy-only medium- and long-term prices minus the unweighted median of the 31 reported market areas. They exclude network charges and other components of delivered industrial electricity costs. Income is compared with the national mean of CNY 43,377. Values are digitized or directional approximations. The table describes spatial differences rather than causal effects or institutional integration depth.

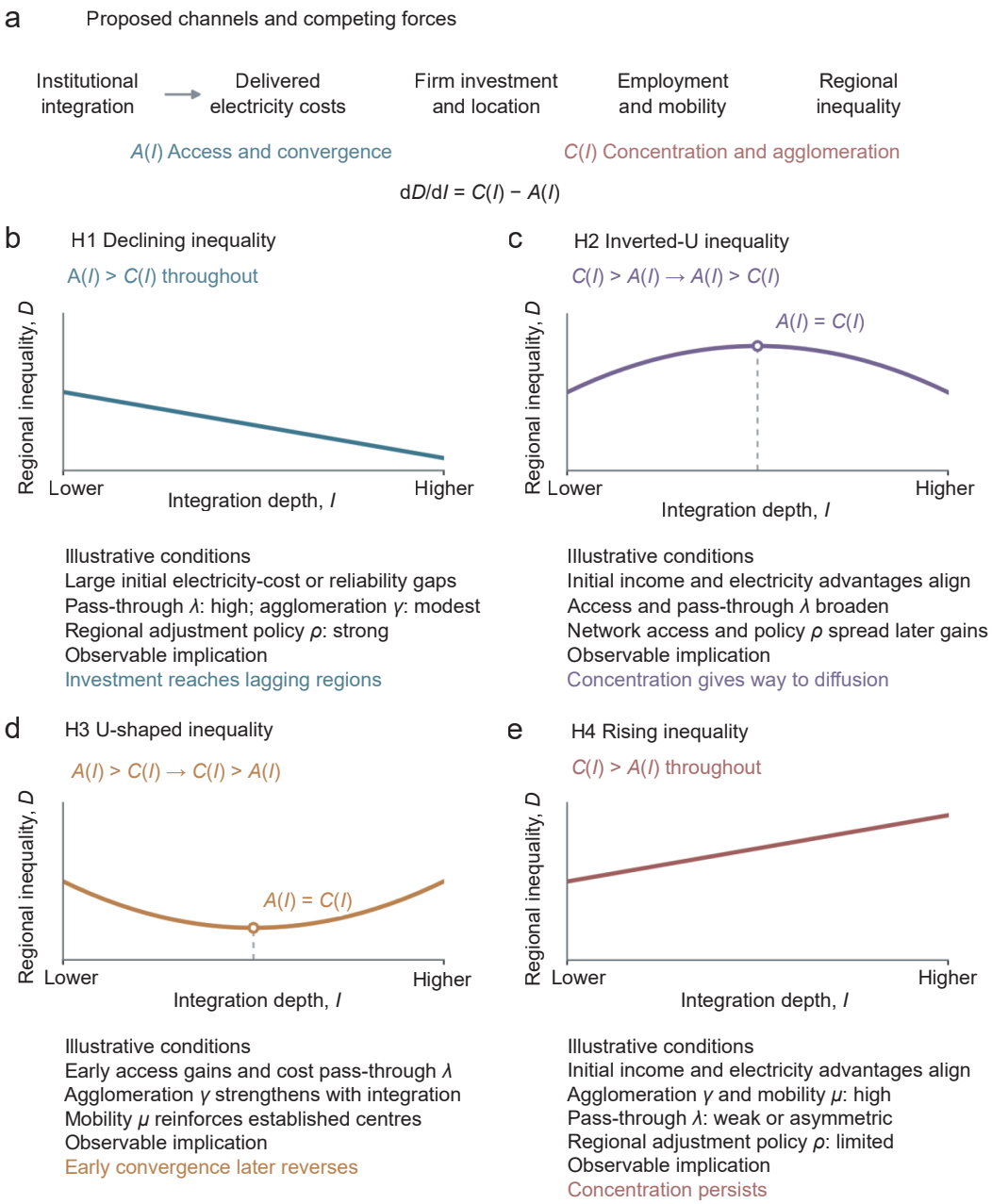


Fig. 1. A conceptual framework linking electricity market integration to regional inequality, with four illustrative trajectories. (a) Proposed channels linking integration to delivered electricity costs, firm location, employment and regional inequality. The change in inequality D with integration depth I reflects the balance between concentration and agglomeration $C(I)$ and access and convergence $A(I)$. (b) H1: inequality declines when access gains dominate throughout. (c) H2: inequality follows an inverted-U trajectory when early concentration gives way to broader access gains. (d) H3: inequality follows a U-shaped trajectory when early convergence is overtaken by agglomeration. (e) H4: inequality rises when concentration dominates throughout. Note: Conditional scenarios, not fitted trajectories. Parameter directions are suggestive, not sufficient conditions.

Table 1. Interprovincial spot trading positions, medium- and long-term electricity prices and household income in selected Chinese provincal regions, 2025.

Provincal regions/market area	Net interprovincial spot position	Energy price relative to the 31-area median	Disposable income per capita and relative position
Shanghai	Net buyer	Above median	CNY 91,987; above national mean
Zhejiang	Net buyer	Above median	CNY 70,240; above national mean
Beijing	Net buyer	Not reported	CNY 89,090; above national mean
Jiangsu	Net buyer	Above median	CNY 57,971; above national mean
Chongqing	Net buyer	Above median	CNY 41,580; below national mean
Jiangxi	Net buyer	Above median	CNY 37,846; below national mean
Hebei	Net buyer	Above median in both Jibei and southern Hebei	CNY 36,439; below national mean
Xizang	Not reliably resolved	Not reported	CNY 33,600; below national mean
Inner Mongolia	Net seller	Below median in both Mengdong and Mengxi	CNY 41,921; below national mean
Shaanxi	Net seller	Below median	CNY 35,790; below national mean
Xinjiang	Net seller	Below median	CNY 32,881; below national mean
Shandong	Net seller	Below median	CNY 44,180; above national mean

The classification below is illustrative and intended to motivate the proposed mechanisms. It does not assign provinces to H1–H4 or locate turning points, which require longitudinal evidence on integration and inequality. To tighten the link between the four hypotheses and provincial positions, we classify provinces along three observable dimensions: (i) net position in interprovincial electricity trade (net importer, net exporter, or balanced); (ii) income level relative to the national average (high, middle, low); and (iii) connectivity is measured by usable transfer capacity and participation in common market rules. Each group is then associated with the hypotheses it can help distinguish.

1) High-income net importers with strong agglomeration. These provinces may gain from lower-cost and cleaner imports, but their access to distant electricity can also allow further industrial concentration. If concentration dominates throughout, they are consistent with H4. If early concentration later gives way to broader access, they are consistent with H2. Observable indicators: firm entry rates, employment concentration, delivered electricity prices, and migration inflows.

2) Middle-income net exporters: Inner Mongolia, Shanxi, Shaanxi, Ningxia, Xinjiang, Sichuan, and parts of western China. These provinces may gain generation revenue and energy investment, but may also lose local cost advantages or bear environmental burdens. Their trajectory is consistent with H1, H2, or H3 depending on revenue sharing and local industrial linkage. Observable indicators: generation revenue retained locally, local industrial value added, employment in electricity-intensive sectors, and environmental burdens.

3) Lower-income importers with weaker connectivity: several central and western provinces. If integration improves access, they are the most likely candidates for H1 or the early phase of H3. If connectivity remains limited, they may be left out of convergence. Observable indicators: usable transfer capacity, cross-provincial trading share, delivered electricity costs, and firm entry.

4) High-income exporters or balanced provinces: provinces with both generation and industry may show mixed outcomes; their position helps distinguish whether integration changes comparative advantage or mainly reallocates rents. Observable indicators: changes in comparative advantage, rent-sharing arrangements, and industrial composition.

This classification identifies contrasting provincial positions that motivate the proposed mechanisms. It can be operationalized with clear rules: for example, classify provinces by terciles of per capita income, net interprovincial electricity flows, and an institutional integration index. However, such classification remains descriptive until linked to longitudinal outcomes.

3. Turning the framework into evidence and policy

3.1 Research questions and identification

A credible assessment should link the timing of rule changes and continuous market operation to provincial and firm-level outcomes. Event studies can compare changes around implementation, but pilot designation alone does not measure effective integration. Staggered adoption methods can accommodate differences in treatment timing[13]. Their application still requires credible comparison groups, assessment of pre-existing trends, and explicit treatment of spillovers. Trading partners may be affected before they adopt the same rules, so neighbouring provinces cannot automatically be treated as unaffected controls.

Reverse causality is a central challenge. Industrial growth can increase demand for transmission and accelerate reform, while local governments may choose market arrangements to protect employment or fiscal revenue. Fuel prices, weather shocks, industrial policy, and network construction can influence both integration and economic outcomes. Mechanism tests should examine delivered electricity costs, plant investment, and employment separately. Estimating the total effect of reform should not condition on these downstream responses. Identifying their individual contributions requires additional assumptions and evidence.

Measurement should distinguish institutional integration from physical interconnection. A consistent measure of cross-border market activity would divide market-traded electricity crossing a provincial boundary by total market-traded electricity over the same period and geographical coverage. Physical transfers should be reported separately because they can include administratively allocated electricity. Price linkage should be assessed after accounting for common fuel costs, weather and demand. It is an outcome of integration as well as other influences, so it should not serve simultaneously as the policy measure and the mechanism used to explain its effects.

Tests of nonlinearity should allow the data to distinguish monotonic, U-shaped, and inverted U-shaped responses. Flexible estimates should be accompanied by uncertainty intervals and adequate observations on both sides of any proposed turning point. Researchers should separate the depth of integration from time since reform and examine differences between exporting and importing regions. Provincial

averages should be complemented by household and firm outcomes to reveal adjustment within regions.

Open research questions include: What is the empirical shape of $A(I)$ and $C(I)$? Which parameters $(\lambda, \gamma, \mu, \rho)$ vary most across provinces? Can policy interventions shift the balance from $C(I)$ to $A(I)$? These questions require longitudinal data linking institutional integration to firm and household outcomes.

3.2 Policy implications tied to hypotheses and observables

Policy should respond to the mechanism behind an observed distributional outcome, not to integration volume per se. If access gains dominate (H1), priority is network access and coordinated dispatch in lagging regions. If inequality follows an inverted U (H2), early policy should extend connectivity to disadvantaged regions and later policy should support diffusion of gains. If it follows a U (H3), early access facilitation must be paired with later retraining, public services and regional diversification. If inequality rises throughout (H4), revenue sharing, compensation for environmental burdens and worker support become central. Table 2 maps each hypothesis to its diagnostic observables, so that policy can be tied to evidence rather than to the level of integration itself.

Maintaining provincial trading barriers cannot be assumed to protect disadvantaged households. The relevant comparison is between feasible policy packages that combine efficient operation with broader access to its gains. Such measures should be evaluated with their fiscal and efficiency costs.

4. Conclusions

China's unified electricity market can improve resource allocation while reshaping regional opportunities. The distributional outcome depends on how electricity access changes, how firms respond and whether workers and communities can benefit from the adjustment. The framework yields competing hypotheses rather than a presumed trajectory.

The next step is to connect observed changes in market institutions to delivered electricity costs, firm investment and household outcomes. This would establish which mechanisms matter, where the gains accrue and how effects evolve. It would also distinguish market reform from physical interconnection and other policies that influence regional development.

Market design should preserve efficient dispatch while addressing the costs of regional adjustment. Transparent access, investment in constrained regions and support for affected workers can help share the benefits of integration. The objective is to build a market whose efficiency gains translate into wider improvements in living standards. Regional equity must be evaluated throughout that process, rather than inferred from national trading volumes or lower system costs.

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Author contribution statement

Yuanxing Xia is responsible for Writing – original draft, Conceptualization, Data curation, Formal analysis. Qi Wang is responsible for Writing – review & editing, Validation, Visualization. Yang Li is responsible for Funding acquisition, Investigation. Alexis Pengfei Zhao is responsible for Methodology, Project administration. Linjun Shi is responsible for Resourcesand Software. Feng Wu is responsible for Supervision, Validation.

Data availability

Not applicable.

Use of AI statement

None.

Table 2. Diagnostic observables for each hypothesis.

Hypothesis	Policy priority	Diagnostic observables
H1: Declining inequality	Network access and coordinated dispatch in lagging regions	Usable transfer capacity; cross-provincial trading share; delivered electricity costs; firm entry in lagging regions
H2: Inverted-U	Early: extend connectivity to disadvantaged regions; Later: support diffusion of gains	Early concentration of firm entry in well-connected provinces; later convergence in delivered electricity costs and employment
H3: U-shaped	Early: facilitate access; Later: retraining, public services, regional diversification	Initial convergence in electricity access; later divergence in employment and population
H4: Rising inequality	Revenue sharing; compensation for environmental burdens; worker support	Local retention of generation revenue; environmental burdens; employment losses; migration outflows

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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