

Electricity Market Imbalance, Cross-regional Trade and Transmission in China¹

25 February 2025

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Abstract

Persistent mismatches between electricity demand and domestic generation should not be viewed solely as an “operational-problem-driven imbalance,” but rather as part of striking balancing that accounts for both short-term operational fluctuations and long-term structural differences in generation availability and costs. This paper examines how structural imbalance shapes cross-regional electricity trade and transmission demand, using theoretical analysis and provincial data from China for 2018–2023. We show that structural imbalance can improve supply efficiency by enabling the substitution of low-cost electricity for high-cost generation through interconnectors and by signalling investment needs. China’s sustained West-to-East electricity flows illustrate this strategy, generating substantial economic value. Empirically, the imbalance-related demand accounts for roughly half of total inter-provincial and inter-regional transmission. We also find pronounced asymmetry in transmission infrastructure: cross-regional interconnectors operate well below capacity, whereas demand for cross-provincial transmission substantially exceeds available capacity. These findings highlight the importance of structural imbalance in electricity market design, transmission planning, and the development of a unified national electricity market for deeper renewable integration.

Keywords: Imbalance of Electricity Market, Electricity Generation, Efficient Supply of Electricity, Power Transmission, Cross-regional Electricity Trade, Cross-border Power Trade, Interconnectors.

JEL Classification: L94

¹ We are grateful to Jing Chaoxia and Ji Tianyao of the School of Electric Power at South China University of Technology, and Guo Bowei of Remin University for their comments, and to Wing T. Woo of UC Davis and two anonymous referees for their valuable comments on the paper. The views expressed in this paper, and any remaining errors, are those of the authors. The authors have received no external funding for this research.

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1. Introduction

Electricity market in China is configured as a multi-zonal system, consisting of 30 provincial zones grouped into 6 geographical regions. Each provincial zone organizes its electricity trading independently, forming a price or market equilibrium that is separate from other zones.

In such a multi-zonal system, when provincial zones are interconnected with free electricity flow between them, surplus electricity in one zone can be transferred to zones experiencing shortages. Conversely, zones with insufficient local generation can balance their needs through imports from other zones with surplus capacity. As a result, transmission between provincial zones emerges endogenously as a response to imbalance. This implies that the power balance of a provincial zone can be separate from the local gap between production and consumption, since part of the gap can be anticipated and addressed through planned imports or exports of power via interconnective transmission.

We define this gap as market disequilibrium, referring to mismatches between electricity supply and demand within a zonal market over a given period. Eicke et al. (2021) use the term imbalance to describe such disequilibrium as a general state of market condition, while Chen et al. (2024) define imbalance operationally as the difference between the metered volume of consumed power and contracted volume that must be resolved by the dispatch system. Building on these interpretations, imbalance shall be distinguished between first, structural imbalance or tradable imbalance, referring to persistent local-market disequilibrium that requires inter-market trade to balancing local demand and supply, and second, system imbalance, which arises from short-term and unpredictable shocks affecting real-time power flows. This decomposition provides a useful framework for analysing the respective roles of markets and dispatch in maintaining system balance.

Since the start of EU electricity market integration, cross-border power trade has increased significantly (Bahar & Sauvage, 2013). The extension of single market to intraday trade generated around 50% of total flows across borders from low to high price areas (Pollitt, 2019). Such trade helps offset both imbalance or structural mismatch within national markets across wholesale, day-ahead, and intraday markets, while local dispatchable capacity continues to respond to real time system imbalance. Two main factors explain this expansion. First, cross-border trading improves efficiency and reduces renewable curtailment (Newbery et al., 2016; Gisse, 2019). Second, market liberalisation and integration have facilitated electricity trade and significantly increased cross-border flows (Bahar & Sauvage, 2013; Batalla-Bejerano et al., 2019).

A similar development has occurred in China. Following the establishment of intra-provincial trading pilots and the creation of inter-provincial trading platforms, including the Guangzhou Power Exchange Centre for the Southern Grid region and the Beijing Power Exchange Centre for the State Grid region in 2016 (Yang, 2016), China has increasingly relied on cross-regional power trade to address disequilibrium across provincial markets. The total volume of inter-provincial and

inter-regional transmission increased by approximately 52% over 6 years from 1775 TWh in 2018 to 2700 TWh in 2023². Of the total in 2023, 38% (1015.9 TWh) was traded through the Beijing Power Exchange Centre, illustrating the growing role of market-based cross-provincial and cross-regional trading³. These developments indicate market liberalization has significantly facilitated inter-regional power trade.

Cross-border and cross-regional electricity trade has also been widely shown to improve the cost efficiency of power supply. Empirical and modelling studies find that market integration and interregional trading reduce generation costs and improve welfare in various systems, including Europe (Newbery et al., 2016; Abrell and Rausch, 2016), Chile (Gonzales et al., 2023), Southern Africa (Bowen et al, 1999; Valickova & Nicholas, 2021), and China (Chen et al., 2022; Cai et al., 2024). Antweiler (2016) further demonstrates theoretically that electricity trade arises naturally from differences in marginal costs and demand conditions across regions.

Because efficiency improvement can be achieved by transmitting electricity from lower-cost production regions to higher-cost areas, structural imbalance in local markets may not only be inevitable but also be strategically intended and sustained. China's West-to-East power development strategy provides a clear example. Electricity generation costs in western regions are substantially lower than in East, and in 2023 approximately 359 TWh of electricity was transmitted from West to East, accounting roughly 10% of power consumption in East⁴, and generating an estimated RMB 190 billion annually in economic value⁵. This process contributes to narrowing regional disparities and while increasing overall social welfare.

Competition for efficient supply therefore generates local tradable imbalances and induces cross-zonal trade, which is argued by this paper. Studying structural imbalance as a dynamic phenomenon arising from market competition and interregional trade is the central focus of our discussion. Our aim is to provide both theoretical analysis and empirical evidence from China's electricity sector to support this argument.

Existing studies tend to treat imbalance primarily as a short-run operational deviation rather than as a dynamic outcome of market competition. They emphasise the role of inter-regional trading and transmission in optimizing power flows, improving efficiency, facilitating renewable integration (Brown et al, 2018), and alleviating spatial mismatches between energy resources and electricity demand (Wang et al., 2021).

However, two gaps remain in literature. First, relatively few studies measure and analyse regional imbalance as an economic variable influenced by market structure, economic development, and spatial competition. Second, the literature rarely

² Economic Operation Report of China's Electric Power Industry 2018 -2023

³ China Electricity Council - Briefing Electricity Market Trading of China (2020-2023),

⁴ See Beijing Power Exchange Centre 2023 Annual Report, East means East China and Central China regions.

⁵ See Table (5) of this paper

distinguishes between different drivers of inter-regional electricity trade, such as imbalance correction, cost arbitrage, and renewable integration.

This paper therefore seeks to address these gaps by analysing China, the world's largest electricity market, as a case study of how their provinces and regions are integrated and managed structurally and systematically in supply of electricity efficiently and securely in relation to imbalance and its role in shaping cross-provincial trade and demand for transmission infrastructure.

In an open electricity market, real-time equilibrium in a local or provincial zonal market is achieved, on the one hand, by offsetting the predicted gap between local demand and supply. This predicted gap reflects demand for cross-market trade and constitutes the trade- or structurally driven imbalance of the local market. On the other hand, equilibrium is maintained by deploying dispatchable capacity to offset unpredicted system imbalances arising from short-term stochastic shocks.

As decarbonisation increases renewable penetration, total demand for inter-market trade can be decomposed into two components: (i) an imbalance-driven component arising from local supply–demand gaps, and (ii) a non-imbalance component associated with renewable integration. This distinction is demonstrated empirically in our study.

Using provincial and regional data for China over 2018 to 2023 from various sources of government institutions, we quantify large and persistent imbalance-related demand for cross-zonal trade, which accounts for roughly half of total inter-provincial and inter-regional transmission. We also show that transmission capacity exhibits structural asymmetry: cross-regional interconnectors operate well below capacity, whereas cross-provincial transmission demand substantially exceeds available capacity. Finally, we demonstrate that the strategically sustained West–East imbalance generates significant efficiency gains.

Our contribution is threefold. First, we conceptualise electricity market imbalance as comprising two analytical components: a tradable, or structural, imbalance and a system imbalance. The structural imbalance refers to a situation in which local supply and demand cannot achieve equilibrium. The system imbalance reflects operational fluctuations or deviation from scheduled contract plan, caused by stochastic shocks, and therefore relies on the dispatch system for real-time correction. Second, we introduce an empirical decomposition of transmission demand into imbalance-related and non-imbalance-related components. Third, we show that sustained regional imbalance can improve cost efficiency while simultaneously creating structural pressure on transmission infrastructure and balancing capacity.

These findings have important implications for electricity market design. They provide lessons not only for China's ongoing reform toward a unified electricity market but also for other systems considering zonal market design, including the United Kingdom and the European Union. In particular, transmission planning should account not only for congestion management and renewable integration but also for the structural imbalance generated by market competition.

The paper recommends that China shall develop a unified power market with a two-tier structure, centralised inter-regional trade while remains intra-provincial market trade in each provincial zone. Further expansion of cross-regional trade requires improved market access, transaction efficiency, and transmission capacity, particularly, significant investment in cross-provincial transmission capacity.

The remainder of the paper is organised as follows. Section 2 discusses application of equilibrium framework linking imbalance to cross-regional trade. Section 3 examines market trading and dispatching as mechanisms for managing imbalance. Section 4 documents regional imbalance and transmission flows. Section 5 analyses strategic West-to-East imbalance and estimates its economic gains. Section 6 decomposes imbalance-related and non-imbalance-related trade. Section 7 evaluates transmission capacity constraints. Section 8 concludes.

Table 1 Structural Imbalance of Each Provincial Zone between Production and Consumption 2023

		Power Consumption of each Provincial zone TWh	Power Generation of Each Provincial Zone TWh	Structural Imbalance TWh	Structural Imbalance as % of Consumption
北京市	Beijing	135.8	45.5	90.31	66.50%
天津市	Tianjin	105.1	80.8	24.29	23.11%
河北省	Hebei	475.7	373.6	102.09	21.46%
山西省	Shanxi	288.5	437.6	-149.11	-51.68%
内蒙	Inner Mongolia	482.3	745.1	-262.75	-54.48%
辽宁省	Liaoning	266.3	220.3	46.05	17.29%
吉林省	Jilin	92.8	109.8	-16.98	-18.30%
黑龙江	Heilongjiang	118.4	123.4	-4.98	-4.21%
上海市	Shanghai	184.9	95.5	89.41	48.36%
江苏省	Jiangsu	783.3	610.6	172.67	22.04%
浙江省	Zhejiang	619.2	435.3	183.89	29.70%
安徽省	Anhui	321.4	333.6	-12.16	-3.78%
福建省	Fujian	309	307.4	1.64	0.53%
江西省	Jiangxi	202.6	166.9	35.7	17.62%
山东省	Shandong	796.6	591.6	205.03	25.74%
河南省	Henan	409	317.2	91.82	22.45%
湖北省	Hubei	270.6	301.3	-30.66	-11.33%
湖南省	Hunan	227.7	170.0	57.66	25.32%
广东省	Guangdong	850.2	671.9	178.34	20.98%
广西	Guangxi	244.9	228.7	16.17	6.60%
海南省	Hainan	48.2	44.8	3.4	7.05%
重庆市	Chongqing	145.3	105.4	39.87	27.44%
四川省	Sichuan	371.1	471.3	-100.16	-26.99%
贵州省	Guizhou	178.3	227.1	-48.84	-27.39%
云南省	Yunnan	251.3	390.5	-139.21	-55.40%
西藏	Tibet	13.5	13.7	-0.24	-1.78%
陕西省	Shaanxi	245	294.6	-49.58	-20.24%
甘肃省	Gansu	164.5	192.5	-28.04	-17.05%
青海省	Qinghai	101.8	87.4	14.42	14.17%
宁夏	Ningxia	138.7	224.6	-85.93	-61.95%
新疆	Xinjiang	382.1	491.2	-109.11	-28.56%
Total		9224.1	8909.1	315.01	

Source: Compiled from China Electricity Statistical Yearbook 2023, 2022, 2021 and 2020 (National Bureau of Statistics of China).

2. Demand for Interregional Power Transmission

2.1 Zonal market structure and the imbalance

An electricity market can be configured as a single market zone where the electricity generated and consumed must not only be in real-time balance but also achieve equilibrium between demand and supply if it operates as a closed zonal system. Within this system, electricity can flow freely from where it is generated to where it is consumed.

Alternatively, the market can be configured as a multi-zonal system, consisting of multiple zones or geographical regions. Each zone organizes its electricity trade independently, forming a price or market equilibrium separate from other zones.

In a multi-zonal system, when a zone is open and connected to other zones with free electricity flow between them, we can expect that surplus electricity in one zone will be absorbed by or transferred to zones experiencing a shortage of power. Conversely, zones with insufficient electricity generation relative to consumption can balance their needs through power from other zones with surplus capacity. Thus, in an open zone, the balance of electricity can be separate from the local gap between production and consumption.

This local gap is defined as imbalance of electricity between production and consumption in a zonal market. Zonal imbalance implies that the market equilibrium cannot be achieved by local supply and demand alone when the two do not match. Imbalance pertains to real-time fluctuations in electricity flow, implying the aggregated mismatch between demand and supply in a region or zonal area over a defined period. It reflects disequilibrium of a local or zonal market.

Different zones may exhibit varying structures of imbalance between electricity generation and consumption. Some zones generate more electricity than they consume, while others generate less than their demand. The former is referred to as a zonal imbalance with surplus, and the latter as a zonal imbalance with shortage. The imbalance of zone i at time t is denoted as d_{it} below:

$$d_{it} = q_{it} - y_{it} \quad \dots\dots\dots (1)$$

Let q_{it} denote the total amount of electricity consumed by a region or zone i at time t , and y_{it} the total amount of electricity produced for local consumption by the region or zone i at time t . If $d_{it}=0$, then demand and supply are balanced locally in zone i . When $d_{it} < 0$, the imbalance is caused by local supply exceeding demand in the zone. Conversely, if $d_{it} > 0$, the imbalance indicates that local supply (y_{it}) is less than demand (q_{it}) in the zone.

For zones with shortage of power, $d_{it} > 0$, they rely 'imports' of electricity to balance the shortage. For these zones, in addition to imports, they may also export power to other zones at same time, e.g. export renewable electricity needed by other regions, or export flexible power to where needs to cover intermittent supply. This implies that, in the shortage zones, their power production y_{it} can be split to two

parts: production for local or zonal uses denoted by y_{it}^d , and production for exports denoted by y_{it}^x , which means

$$d_{it} = q_{it} - y_{it} = q_{it} - (y_{it}^d + y_{it}^x) \quad \dots\dots\dots (2)$$

where $y_{it}^d + y_{it}^x = y_{it}$, where y_{it} is total output generated by all domestic generators in the zone, y_{it}^d is consumed in the zone, and y_{it}^x is exported outside the zone. The equation (2) can also be applied to regions or zones with surplus $d_{it} < 0$.

Summation of both sides of Equation (2) gives

$$\sum_{i=1}^n d_{it} = \sum_{i=1}^n q_{it} - \sum_{i=1}^n y_{it}^d - \sum_{i=1}^n y_{it}^x \quad \dots\dots\dots (3)$$

By rearranging Equation (3), it gets

$$\sum_{i=1}^n y_{it}^x + \sum_{i=1}^n d_{it} = \sum_{i=1}^n q_{it} - \sum_{i=1}^n y_{it}^d \quad \dots\dots\dots (4)$$

Since $y_{it}^d = y_{it} - y_{it}^x$, then Equation (4) can be rewritten as

$$\sum_{i=1}^n y_{it}^x + \sum_{i=1}^n d_{it} = \sum_{i=1}^n y_{it}^x + (\sum_{i=1}^n q_{it} - \sum_{i=1}^n y_{it}) \quad \dots\dots\dots (5)$$

Clearly, the (5) indicates

$$\sum_{i=1}^n d_{it} = \sum_{i=1}^n q_{it} - \sum_{i=1}^n y_{it} \quad \dots\dots\dots (6)$$

where the (6) implies that $\sum_{i=1}^n d_{it}$ captures the aggregate imbalance of the system, which is required to be bridged for balance by deploying transmission of power from other zones or regions. It indicates the aggregate demand for transmission, which is driven by the aggregate power shortages across regions or zones.

In contrast, in Equation (5), $\sum_{i=1}^n y_{it}^x$ is the exports not attributable to imbalance in total generation.

Therefore, the total demand for transmission in the whole system, denoted by Y_t^S , is

$$Y_t^S = \sum_{i=1}^n d_{it} + \sum_{i=1}^n y_{it}^x \quad \dots\dots\dots (7)$$

Clearly, the (7) explains that the total demand for transmission or cross-zonal power trade consists of two elements: the imbalance-related demand ($\sum_{i=1}^n d_{it}$) and non-imbalance-related demand ($\sum_{i=1}^n y_{it}^x$).

2.2 Economics of structural Imbalance and Cross-Zonal Power Trade

Regarding what determines imbalance itself, it is argued for the cost of power production that matters for an open market. In an open zonal market i , electricity can

be sourced from local generation at a marginal cost of c_{it}^Z , or transmitted from outside the zone or the system at a marginal cost of c_{it}^T , which includes both generation and transmission (grid) costs. To minimize the cost of electricity usage, a consumer's choice between locally generated electricity y_{it}^Z or transmitted electricity y_{it}^T depends on the cost scenario described below.

Scenario One: if $c_{it}^Z > c_{it}^T$,

then y_{it}^T as power transmitted from other zones is preferred, subject to the capacity of transmission. This implies that $y_{it}^Z < y_{it}^T$, meaning supply from local generation in zone i is lower than supply transmitted from other zones or other systems. As a result, given q_{it} as the demand of the zone, we have $q_{it} - y_{it}^Z > 0$, indicating a shortfall state of the zonal imbalance due to local power generation cost higher than the 'import' power cost. This shortage is chosen by market that will find the low-cost supply of y_{it}^T from other zones to balance the gap between local supply and demand.

Scenario Two: if $c_{it}^Z < c_{it}^T$,

then y_{it}^Z as local generated power is preferred, subject to the capacity of local generation in the zone. This implies that $y_{it}^Z > y_{it}^T$, meaning supply from local generation in zone i is higher than supply transmitted from other zones or systems. As a result, given q_{it} as the demand of the zone, we have $q_{it} - y_{it}^Z < 0$, indicating a surplus state of the zonal imbalance due to local power generation cost lower than the 'import' power cost. This surplus is determined by the market, which will allocate the excess y_{it}^Z beyond q_{it} for export to other zones or systems, or for energy storages.

Scenario Three: if $c_{it}^Z = c_{it}^T$,

then the choice between y_{it}^Z and y_{it}^T becomes neutral, depending on the capacity of zonal generation and transmission. This implies that either $y_{it}^Z > y_{it}^T$ or $y_{it}^Z \leq y_{it}^T$, allowing a higher supply from either source. As a result, given q_{it} as the demand of the zone, we may have either $q_{it} - y_{it}^Z < 0$, or $q_{it} - y_{it}^Z \geq 0$. This resulting state of imbalance is influenced or determined by other factors, such as capacity constraints.

The analysis of the three scenarios shows that, in an open zone with a competitive market, the cost of supply is a key determinant of zonal imbalance and its state, given the demand of the zone. When the costs are known, the capacity of supply becomes a constraint in determining the state of imbalance, particularly in Scenario Three.

The implications of these three scenarios are clear: market competition will inevitably drive price equilibrium to align with supply costs. Without capacity constraints, the cost of supply alone determines the state of imbalance. This, in turn, indicates where investment is needed: generation or transmission, to improve cost efficiency for the zone.

Based on the analysis above, we can assert the following Claim:

Competition for efficient supply in liberalised electricity markets generates tradable imbalances between local supply and demand, giving rise to two equilibrium states: shortfall and surplus. A shortfall state signifies relatively inefficient local supply and incentivises investment in interconnectors to facilitate more imports from other lower-cost markets. In contrast, a surplus state signifies comparative efficiency of supply and incentivises investment in local generation assets to expand exports to shortfall regions. Consequently, shortfall markets invest in transmission while surplus markets invest in generation, allowing both to enhance efficiency and create additional economic value through inter-market trade.

3. Bridging the Gap of Imbalance

3.1 Inter-zonal Market as the Tradable Balancing Mechanism

Empirical consistency with Equation (2) is reported in Table 2, which documents inter-provincial power trading through the State Grid transmission network covering 26 provincial zones in China. Inter-provincial trade corresponds to y_{it}^x in Equation (2). Column (1) reports total traded volumes in inter-provincial market, while column (2) reports total intra-provincial market transactions, equivalent to $\sum y_{it}^d$ in Equation (3).

Table 2 indicates that inter-provincial trading functions primarily as a mechanism for resolving anticipated supply–demand imbalances that remain after local market clearing. When local producers and consumers cannot fully match supply and demand within provincial markets, cross-provincial transactions provide an adjustment margin. In the State Grid system, the scale of this adjustment was substantial: inter-provincial trade accounted for roughly 50% of total market trade in 2020, declining to about 30% by 2024. This trend suggests that local market depth and internal balancing capacity have increased over time, reducing reliance on cross-provincial adjustment.

Table 2 Inter- and Intra-Provincial Power Trade across Zonal Markets of the State Grid Network, 2020 - 2024

	Total Power Trade of Inter-provincial Zones TWh	Total Power Trade of Intra-provincial Zones TWh	Total Market Power Trade TWh
	(1)	(2)	(3)
2024	1,507	3,513	5,020
2023	1,399	3,259	4,658
2022	1,312	2,820	4,131
2021	1,239	1,630	2,870
2020	1,157	1,158	2,315

Source: Beijing Power Exchange Centre Annual Report, 2020 -2024

Inter-provincial trading therefore reflects the anticipated component of imbalance—that is, mismatches between expected supply and expected demand that can be reasonably forecast and addressed through scheduled transactions.

Data from the Beijing Power Exchange Centre show that inter-provincial trading reached 1,399 TWh in 2023, a magnitude closely aligned with the 1,353 TWh aggregate provincial shortages calculated in Table 3 for provinces where annual consumption exceeded local production. The close correspondence between these figures suggests that a large share of cross-provincial trading is directly associated with provinces importing electricity to offset expected structural shortfalls.

In Table 3, aggregate provincial shortages are constructed by summing the positive differences between annual provincial consumption and production. Both variables are reported annually by the National Bureau of Statistics of China (NBS) in the National Data database website <https://data.stats.gov.cn/english>.

However, even after accounting for scheduled inter-provincial trade, a residual imbalance remains at the national level. As reported in column (5) of Table 3, this residual is defined using Equation (6) as aggregate consumption minus aggregate production, equivalently aggregate shortages minus aggregate surpluses. This residual represents the unanticipated component of imbalance, arising from forecasting errors, unexpected demand fluctuations, outages, or stochastic variation in renewable generation due to weather conditions. By definition, this component cannot be fully resolved through pre-determined market transactions.

Maintaining system balance in the presence of such real-time uncertainty requires administrative and operational mechanisms beyond market scheduling. Power dispatch centres perform this function by deploying generation and transmission resources in real time to maintain frequency stability and ensure the security of the system. In this sense, dispatch operations complement market trading: while markets address predictable imbalances ex ante, dispatch mechanisms resolve stochastic imbalances ex post.

Table 3 Aggregate Imbalance between Power Demand and Supply across Provinces in China

	Aggregate shortages of provinces with $d > 0$ TWh	Aggregate surpluses of provinces with $d < 0$ TWh	Total electricity consumed by all provinces TWh	Total electricity generated by all provinces TWh	Aggregate imbalance of all provinces TWh	Overall provincial disbalance as % of power generated
	(1)	(2)	(3)	(4)	(5)	(6)
2023	1352.8	-1037.8	9224.1	8909.1	315.0	3.5%
2022	1257.1	-997.9	8647.9	8388.7	259.3	3.1%
2021	1183.4	-963.9	8331.6	8112.2	219.5	2.7%
2020	1081.1	-976.7	7521.4	7417.0	104.4	1.4%
2019	984.4	-878.1	7248.4	7142.2	106.2	1.5%
2018	902.1	-777.3	6916.3	6791.4	124.8	1.8%
2017	802.0	-715.3	6362.5	6275.8	86.7	1.4%
2016	730.4	-666.8	5974.7	5911.1	63.6	1.1%
2015	698.0	-623.0	5693.3	5618.4	74.9	1.3%
2014	713.6	-613.7	5563.7	5463.8	99.9	1.8%
2013	619.6	-522.4	5342.4	5245.1	97.2	1.9%
2012	594.5	-447.5	4965.7	4818.8	146.9	3.0%
2011	510.8	-411.8	4702.6	4603.7	98.9	2.1%
2010	462.9	-404.5	4199.7	4141.3	58.4	1.4%

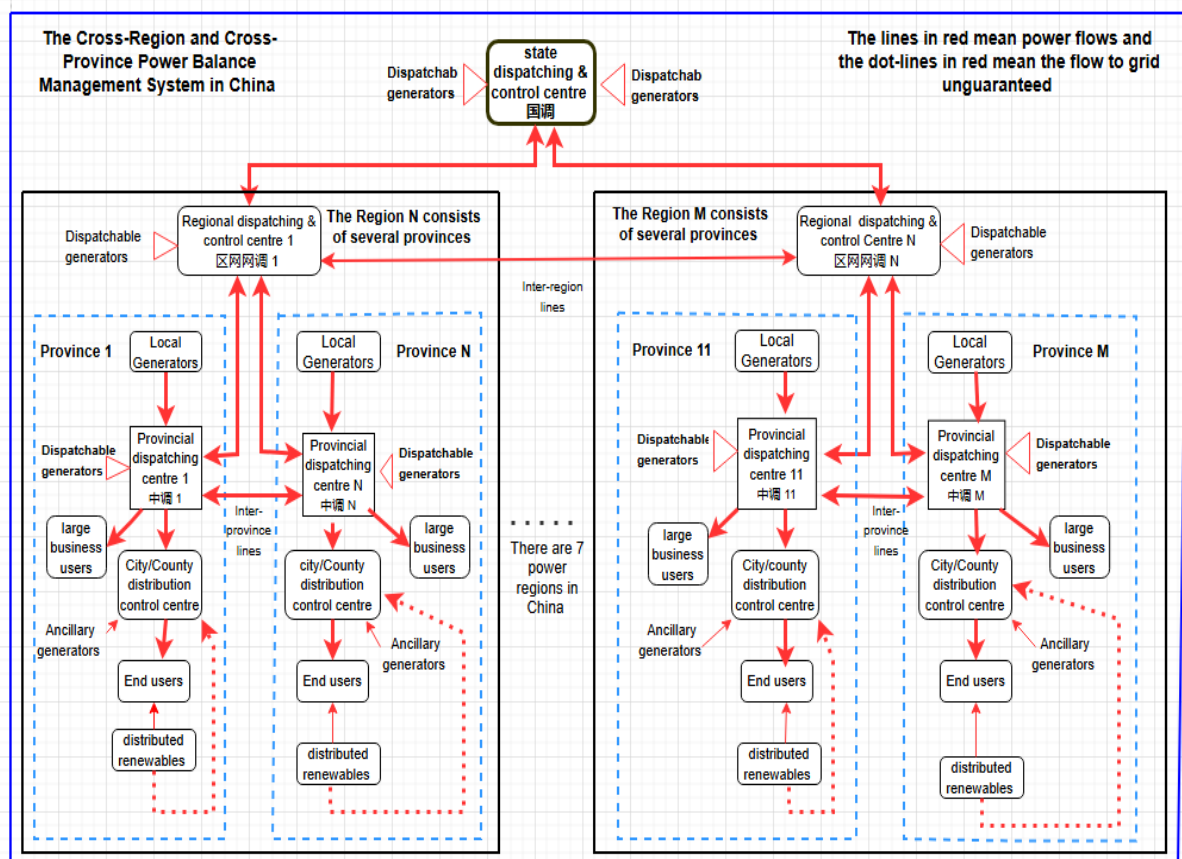
Source: China Statistical Yearbook 2010 – 2023 at <https://data.stats.gov.cn/english/> for column (3) and (4). (4) includes all of utility-scale power firms. For Column (5), it is calculated by (3) – (4), which is identical to (1) – (2). For Column (6), it is from (5) / (4). Columns (1) and (2) report the aggregate demand–supply imbalances for surplus and shortfall provinces, respectively, based on the data in Table 1.

3.2 Dispatch as the Non-Tradable Balancing Mechanism

China operates a largely closed electricity system comprising 30 provincial zones, each with its own market to establish prices and determine the state of zonal imbalance independently of other zones. Each provincial zone has a dispatching centre responsible for maintaining supply security and grid balance within the zone. Provincial zones are further grouped into regional zones, each governed by a regional dispatching centre that oversees regional balancing and system security. These regional centres coordinate directly with, and are supervised by, the national dispatching centre, which is responsible for maintaining the overall security of the country's electricity system (see Figure 1).

The role of China's national dispatching centre is broadly comparable to that of the UK Electricity System Operator (ESO), now the National Energy System Operator (NESO), both of which are responsible for ensuring supply security and real-time system balance at the national level.

Figure 1. Structure of the Centralized Three-Tier Electricity Balance and Security Management System in China under a Multi-Zonal Framework



Note: There is one state dispatch centre, six regional dispatch centres, 30 provincial dispatch centres, approximately 310 city-level dispatch centres, and around 2,000 county-level distribution centres.

As illustrated in Figure 1, the system forms a centralized three-tier balancing structure embedded within a five-level operational hierarchy. The national dispatch centre oversees system-wide balancing, regional dispatch centres coordinate balancing within regional zones, and provincial dispatch centres maintain grid stability within provincial networks. City- and county-level centres provide localized operational support and distribution-level control. This hierarchical structure enables real-time coordination of electricity flows across multiple geographic scales.

Within this framework, as stated by Grubb (2014), two categories of generation assets can be distinguished in electricity market: generation assets and dispatchable assets. In China, generation assets are deployed for serving local provincial demand and participating in market trading, and dispatchable generation assets are dedicated to balancing and system security at provincial, regional, or national levels. Regardless of ownership, the operation of dispatchable assets is coordinated by dispatch centres in accordance with *National Grid Dispatch Regulation (2023)*. Most dispatching centres and major transmission infrastructure are invested in or controlled by the State Grid Corporation, creating a vertically coordinated system capable of reallocating power across large geographic areas in real time.

When a supply shortfall is anticipated within a provincial zone, the provincial dispatch centre first deploys available local dispatchable resources. If this is insufficient, it coordinates through the regional dispatch centre to obtain additional supply from neighbouring provinces or regions. Should shortages persist, the national dispatch centre may intervene by reallocating generation from surplus regions or deploying centrally controlled backup capacity. This hierarchical escalation mechanism enables imbalances to be resolved progressively across spatial scales and time horizons.

Dispatchable generation assets under the control of dispatching centres are geographically distributed across China and include large-scale hydropower, thermal generation, and inter-regional transmission infrastructure. Both national and regional dispatch centres control substantial balancing capacity, allowing rapid responses to unexpected demand fluctuations, supply disruptions, or variability in renewable generation. Electricity generated for balancing purposes is accounted for as system output rather than local provincial production, ensuring that balancing resources remain available for security rather than being absorbed into local market clearing.

The institutional structure described above provides the operational counterpart to the analytical decomposition developed in Section 3.1. Market trading primarily resolves the *anticipated (tradable) component of imbalance*, which can be forecast and scheduled through intra- and inter-provincial transactions. By contrast, the dispatching system addresses the *unanticipated (non-tradable) component of imbalance*, arising from real-time uncertainty in demand, supply outages, and stochastic renewable generation.

This distinction highlights a structural boundary of electricity markets. Even in systems with extensive market trading, a residual imbalance remains that cannot be eliminated through price-mediated exchange alone because it arises from uncertainty realized after-market clearing.

Renewable integration increases stochastic imbalances that emerge after spot-market clearing. In response, China's current reform allows coal-fired power plants to participate in capacity services alongside existing dispatchable resources. Coal-fired plants receive state-set capacity payments, while selected units are dispatched by system operators to meet grid balancing needs. Neither capacity payments nor participation is determined through competitive capacity auctions, as in the UK. Instead, dispatch centres decide when these plants operate as flexible capacity to offset system imbalances. Payments for electricity generation are based on day-ahead spot market prices. China therefore does not operate a formal capacity market; rather, it relies on spot-market pricing to cover variable cost of generation while capacity remuneration remains administratively determined. Whether this dual dispatch system — combining state-set payment and market pricing — represents a transitional stage toward full marketisation or a deliberate long-term design remains an open question.

The coexistence of market trading and centralized dispatch in China illustrates a general principle of electricity system design: *markets allocate planned energy, while system operators allocate security*. Recognizing this dual structure clarifies the respective roles of market mechanisms and operational control in large and interconnected power systems and provides a framework for analysing balancing arrangements, capacity mechanisms, and the integration of intermittent renewable generation in both China and other electricity markets.

4. The Regional Imbalance and Interconnectors

Table 4 reports aggregate imbalances at both regional and national levels. The data show that some regions experienced persistent shortages while others recorded surpluses during 2021–2023.

The region with the largest shortage was East China (EC), with shortfall of 435 TWh in 2023, 397 TWh in 2022, and 343 TWh in 2021. North China, which includes Beijing and Tianjin, followed with shortages of 272 TWh in 2023, 236 TWh in 2022, and 243 TWh in 2021. In both regions, the shortfall increased over the period. Among the four shortfall regions, the Southern Grid recorded the smallest imbalance, at 9.8 TWh in 2023. Notably, the Southern Grid operates largely independently from the State Grid system.

In total, the aggregate shortfall across the four shortfall regions reached 872 TWh in 2023, representing approximately 9% of China's national electricity consumption of about 9,200 TWh. The volume of shortfall was very close to the volume of power transmitted by the regional interconnectors (849.7 TWh), accounted 53% of the inter-regional transmission capacity (see Table 8).

Conversely, three regions—Northeast, Southwest, and Northwest China—recorded surpluses. If the combined surplus of 557 TWh from these regions were fully transmitted or exported through interconnectors, the national net shortfall would decline from 872 TWh to 315 TWh in 2023⁶ (see Table 4). The remaining shortfall

⁶ The figure of net shortfall of the nation excludes non-metered power consumption, e.g. transmission losses.

was balanced through generation dispatched by national and regional dispatching centres, as discussed in the previous section.

This evidence demonstrates that when the aggregate imbalance across regions remains a net shortage—indicating that exports from surplus regions are insufficient to meet the import requirements of shortfall regions—dispatchable generation and transmission capacity controlled by dispatching centres must be deployed to maintain supply security. Output from dispatching centres operates independently of local provincial production and serves primarily as balancing power.

As shown in Figure 1, regions and provinces are interconnected through cross-regional and cross-provincial transmission lines that enable electricity flows across geographic areas. These physical interconnections support market trading conducted through the Beijing Power Exchange Centre, which provides a platform for bilateral and listed transactions between generators and large users located in different provincial zones (see Figure 2).

Figure 2 yields three observations.

First, interconnectors between Northeast China and North China allow surplus electricity in the Northeast to be exported to deficit areas in North China. In 2023, Northeast China recorded a surplus of 238 TWh, while North China faced a shortfall of 272 TWh, indicating substantial potential for regional balancing through existing transmission corridors.

Second, East China—the region with the largest shortfall and home to major industrial provinces such as Shanghai, Jiangsu, and Zhejiang—required approximately 435 TWh of imports in 2023. Potential sources include Northwest China, which recorded a surplus of 258 TWh, either through direct interconnectors or through indirect transmission routes via North China. Southwest China also has the capacity to export surplus power to East China through existing transmission channels.

Third, although the Southern Grid region includes Guangdong, China's largest provincial economy and a shortfall region with a shortfall of 178 TWh in 2023, it relies primarily on internal balancing within its own grid system. Cross-provincial transmission within the Southern Grid allows electricity to flow from surplus provinces such as Yunnan to deficit provinces such as Guangdong, reducing reliance on cross-regional exchanges with the State Grid system.

These observations highlight three structurally important transmission corridors in China's power system. First, *west-to-east interconnectors* play a critical role in enabling Central and East China to import electricity from resource-rich western regions through both market transactions and dispatch arrangements. Second, *interconnectors linking Northeast and North China* facilitate relatively low-cost regional balancing by transferring surplus generation to nearby deficit regions. Third, *the Southern Grid* demonstrates a largely self-balancing regional system based on internal cross-provincial transmission.

Table 4 Regional and Provincial Imbalance between Consumption and Production 2021-23

Regions with Shortages		2023	2022	2021	Regions with Surplus		2023	2022	2021
华北	北京 Beijing	90.31	83.11	77.4	东北	内蒙古 Inner Mongolia	-262.71	-224.03	-199.56
Nothern	天津 Tianjing	24.29	25.12	20.68	North	辽宁 Liaoning	46.05	43.13	42.9
China	河北 Hebei	102.09	88.57	100.84	East	吉林 Jieling	-16.98	-14.09	-11.66
	山西 Shanxi	-149.11	-143.73	-112.64		黑龙江 Heilongjiang	-4.98	-1.04	-5.59
	山东 Shandong	205.03	183.64	157.5	NE Regional Imbalance		-238.62	-196.03	-173.91
NC Regional Imbalance		272.61	236.71	243.78	西南	重庆 Chongqing	39.87	44.83	41.01
华东	上海 Shanghai	89.41	84.48	79.32	South	四川 Sichuan	-100.16	-118.67	-105.45
East	江苏 Jiangsu	172.67	156.87	131.86	West	西藏 Xizang	-0.24	0.47	1.67
China	浙江 Zhejiang	183.89	168.36	149.57	SW Regional Imbalance		-60.53	-73.37	-62.77
	安徽 Anhui	-12.16	-14.2	-19.69	西北	陕西 Shanxi	-49.58	-35	-39.88
	福建 Fujian	1.64	1.73	2.88	North	甘肃 Gansu	-28.04	-31.56	-22.96
EC Regional Imbalance		435.45	397.24	343.94	West	青海 QingHai	14.42	6.24	-80.06
华中	江西 Jiangxi	35.7	41.44	43.78		宁夏 Ningxia	-85.93	-92.63	-84.94
Central	河南 Henan	91.82	71.76	83.39		新疆 Xinjiang	-109.11	-120.3	-111.81
China	湖北 Hubei	-30.66	-33.84	-67.72	NW Regional Imbalance		-258.24	-273.25	-339.65
	湖南 Hunan	57.66	57.7	49.64	Summary				
CC Regional Imbalance		154.52	137.06	109.09	Summary of two groups of regions		2023	2022	2021
南网	广东 Guangdong	178.34	176.78	175.18	Aggregate Imbalance of all Regions with Shortages		872.44	806.4	736.93
Southern	广西 Guangxi	16.17	34.82	21.88	Aggregate Imbalance of all Regions with Surplus		-557.39	-542.65	-576.33
Grid	海南 Hainan	3.4	3.59	4.19	Aggregate Net Imbalance of All Regions of Country		315.05	263.75	160.6
	贵州 Guizhou	-48.84	-44.01	-49.6					
	云南 Yunnan	-139.21	-135.79	-111.53					
SG Regional Imbalance		9.86	35.39	40.12					

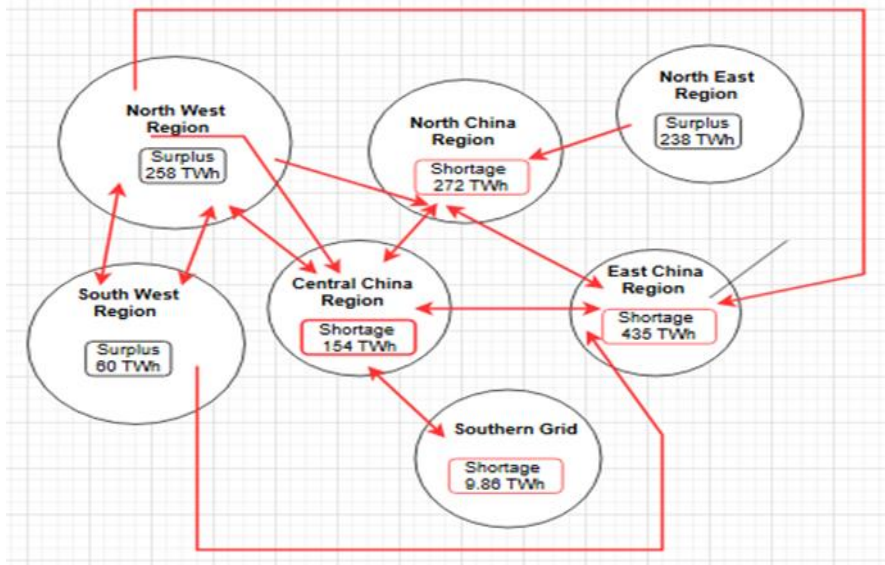
Notice: 1. According to equation (6), when $\sum_{i=1}^n d_{it} = \sum_{i=1}^n q_{it} - \sum_{it} y_{it} > 0$, the system exhibits a shortage.

Otherwise the imbalance is a surplus (negative value).

2. Aggregate shortage at the regional level is lower than that reported in Table 1 due to regional aggregation. In 2023, the system shortfall is 872.44 TWh in Table 4, compared with 1,352 TWh in Table 1. The difference (approximately 480 TWh) reflects internal balancing through intra-regional transfers, implying that 872 TWh represents the net shortage requiring additional balancing resources.

Sources: Compiled by the author from China Electricity Statistical Yearbook (2020–2023), National Bureau of Statistics of China.

Figure 2 Cross-region Transmission Channels Opened for Bilateral and Listed Inter-Provincial Electricity Market Trade at Beijing Power Exchange Centre



Source: edited by the author based on BPX, 2023 May 15 at www.bjx.com/mnews

Ultimately, the persistent shortages in Central and East China represent the most significant structural constraint in the system. Imports of surplus power from western regions can partially mitigate these shortfalls, but interregional transfers alone are insufficient to eliminate the imbalance. As illustrated in Figure 2, dispatchable generation and centrally coordinated balancing remain necessary to maintain system stability. This underscores the complementary roles of interregional trade and centralized dispatch in offsetting both regional and system-wide imbalances and ensuring secured operation of China's electricity system.

The regional evidence presented in this section clarifies the distinct but complementary roles of interconnectors and dispatch in managing electricity-system imbalance. Interconnectors primarily address structural (spatial) imbalance by enabling surplus regions to export electricity to deficit regions through market trading and scheduled transfers. However, because regional surpluses are insufficient to fully offset national shortages and because demand and supply conditions vary in real time, a residual imbalance remains even after interregional exchanges. This residual represents the stochastic (temporal) component of imbalance, which must be resolved through dispatchable generation and centralized system operation.

5. A Case of Value Creation through Inter-Market Trade: Strategic Imbalance between West and East

The severe power shortages in Central and East China are further evidenced by the large number of interconnectors constructed specifically to link western regions with these demand centres. This pattern suggests that China's strategy for addressing regional imbalance has emphasized investment in interconnectors and power generation in the West rather than expanding supply capacity or demand-side adjustments within shortfall zones in the East and Central regions.

Prioritizing large-scale power transfers from the West to the East and Central regions, rather than boosting local supply in shortfall areas, is consistent with China's broader regional development strategy for western provinces. Supported by this policy framework, China has developed an extensive network of cross-regional and cross-provincial interconnectors, particularly along west-to-east transmission corridors. This infrastructure facilitates geographical coordination in electricity supply and improves system-wide cost efficiency. The western regions, endowed with abundant coal, hydropower, and renewable resources, provide the resource base for this strategy.

This cross-regional development approach reflects a deliberate tendency to maintain a persistent imbalance in electricity production and consumption between western surplus regions and eastern deficit regions. Such a **strategic imbalance** has widened in recent years. As shown in Table 4, the gap between electricity shortages in East China and the surplus in Northwest China expanded from 4 TWh in 2021 to 124 TWh in 2022 and further to 177 TWh in 2023.

Beyond supporting regional development objectives, this strategic imbalance generates measurable economic value by enabling lower-cost electricity produced in the West to replace higher-cost supply in the East. Price signals play a central role in

cross-location electricity trade (Cartea et al., 2019). Table 5 reports grid electricity prices in selected provinces in East China and Northwest China for 2021 and 2023. These prices—applicable to industrial and commercial users at voltage levels of 1–10 kV—include generation costs, regional transmission charges, and government levies, as reported by provincial grid companies.

Risk-averse commercial users who do not participate in wholesale markets typically pay these regulated grid prices. In 2023, approximately 879.4 TWh of electricity was purchased under such pricing arrangements (China Electricity Council, 2023). Moreover, grid prices often serve as an anchor in bilateral contract negotiations. For example, in Jiangsu's provincial market, the average bilateral contract price in 2023 was RMB 0.4667/kWh, close to the average grid price of RMB 0.4606/kWh (Wu Weinan, 2024).

Using grid prices as a benchmark and deducting an estimated high-voltage transmission cost of RMB 0.03/kWh, the average provincial electricity price in Northwest China was approximately 34% lower than in East China in 2021 and 35% lower in 2023. Under Scenario One, this cost differential enabled the Northwest to export substantial electricity surpluses—258 TWh in 2023 and 339 TWh in 2021—to East China, generating export revenues roughly ranged from RMB 134 billion to RMB 183 billion in 2023, depending on the applicable regional sale prices.

In 2023, electricity purchased at RMB 0.548/kWh in the Northwest was resold in East China at RMB 0.736/kWh, yielding trade profits of approximately RMB 49 billion. Comparable trade profits in 2021 were about RMB 55 billion. Averaged over 2021–2023, annual trade profits were approximately RMB 52 billion, totalling around RMB 156 billion over three years.

In addition to trade profits, electricity exports transferred financial resources from higher-income regions in the East to lower-income regions in the West. These transfers amounted to approximately RMB 151 billion in 2021, RMB 140 billion in 2022, and RMB 134 billion in 2023, see Table 5, summing to about RMB 425 billion over three years. Combining trade profits with export revenues, the strategic imbalance generated roughly RMB 575 billion in economic value between 2021 and 2023, or about RMB 190 billion annually.

Furthermore, consumers in East China benefited from increased consumer surplus due to access to lower-cost imported electricity, which exerted competitive pressure on market prices in periods of high demand, see Figure 3.

Despite substantial imports, East China still faced residual shortages of 4.29 TWh in 2021 and 177 TWh in 2023 (see Table 5). These remaining deficits were balanced through generation dispatched by central and regional dispatching centres, at an estimated cost of RMB 2 billion in 2021 and RMB 88 billion in 2023, excluding transmission costs. The sharp increase in payments to dispatching centres reflects strong incentives for these institutions to control or invest in dispatchable generation assets, since larger regional imbalances increase demand for balancing services.

Table 5 Estimate Economic Values Created by Strategic Imbalance between East and West

State Grid Sale Price: RMB/kwh		2021	2023
华东	上海 Shanghai	0.5861	0.8529
East	江苏 Jiangsu	0.6414	0.6941
China	浙江 Zhejiang	0.8656	0.8041
(EC)	安徽 Anhui	0.5048	0.7123
	福建 Fujian	0.5759	0.6205
	Average EC sales price (1)	0.63476	0.73678
西北	陕西 Shanxi	0.5607	0.6721
North	甘肃 Gansu	0.5943	0.6831
West	青海 QingHai	0.3694	0.4421
(NW)	宁夏 Ningxia	0.4683	0.5018
	新疆 Xinjiang	0.3782	0.4409
	Average NW sales price (2)	0.47418	0.548
Sales Revenues of Export Surplus by North West to East China			
High-Voltage Transmission Charge RMB/kwh (3)		0.03	0.03
Power Surplus of NW for exports TWh (4)		339.65	258.24
Expt Value of Surplus at NW price RMB Billion (5) = (4)X((2)-(3))		151	134
Expt Value of Surplus at EC price RMB Billion (6) = (4)X[(1)-(3)]		205	183
Trade Profits between NW and EC at RMB Billion (7) = (6)-(5)		55	49
Revenues for Output produced by State & Regional Dispatch Centres			
Total shortage of power at EC TWh (8)		343.94	435.24
Remaining shortage at EC net Import of NW surplus TWh (9) = (8)-(4)		4.29	177
Average costs of transmission and distribution of EC RMB/KWh (10)		0.208	0.208
Value of output made by dispatch centres at EC price RMB Billion (11) = (9)X[(1)-(10)-(3)]		2	88

Sources: Compiled by the author based on provincial electricity price announcements reported at www.news.bjx.com.cn (4 January 2025) for row (1) and (2); NDRC Price Bureau Document No. 1508 (2020) on transmission and distribution tariffs for row (3) and (10); and imbalance data reported in Table 4 for row (4) and (8).

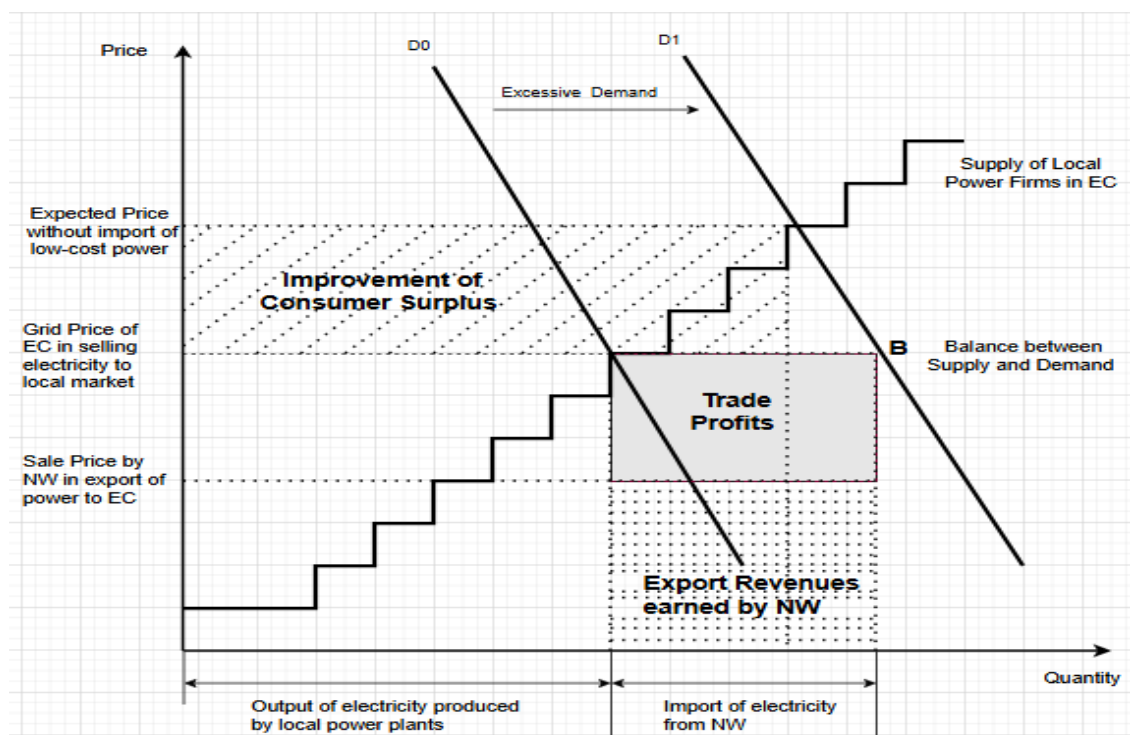
Overall, the analysis highlights the economic role of persistent regional imbalance in creating demand for long-distance electricity transmission from low-cost to high-cost regions. This imbalance supports China's regional development policy by transferring income to western provinces while improving overall system efficiency and social welfare. At the same time, the economic value generated by cross-regional trade provides incentives for grid operators and dispatching centres to expand interconnectors and balancing capacity. Mehling (2024) characterizes such outcomes as positive spillovers of China's industrial policy for energy development in western regions. Under Scenario One, the imbalance between western surplus regions and eastern shortfall regions is likely to persist, and potentially widen, as additional interconnectors are constructed and market integration deepens.

The evidence in this section suggests that regional imbalance in China's electricity system can be interpreted as a strategically sustained system equilibrium shaped by regional development policy and three interacting institutions: markets that identify lower-cost suppliers, large-scale investment in interconnectors that enables long-distance transmission at relatively low marginal cost, and a centralized

dispatch system that ensures security of supply when interregional trade alone cannot eliminate shortfalls.

Within this framework, imbalance performs an economic function. Persistent differences in regional production costs enable welfare-enhancing trade and income transfers that support regional convergence. At the same time, residual imbalance creates demand for dispatchable capacity and balancing services. When markets reveal cost differentials, transmission enables trade, and dispatch maintains security, a positive level of regional imbalance can constitute a stable and welfare-enhancing cross-regional trade.

Figure 3 Modelling Economic Values of Importing Low-cost Electricity from North West to East China



6. Structural imbalance and Demand for Cross-provincial Trade

The strategic imbalance creates economic value for the market and drives demand for cross-regional transmission of low-cost electricity. However, demand for such interconnective transmission is not always motivated by cost efficiency. For instance, in 2023, the Northeast region exported its power surplus of 238 TWh through direct interconnectors to its neighbouring region, North China, which faced a power shortage of 272 TWh (see Figure 2). North China required these imports to balance its shortages and ensure security of supply, despite the North East's wholesale electricity price being less competitive compared to local market prices in North China. This situation reflects Scenario Three discussed in Section 1 (see Table 5).

Table 6. Wholesale Electricity Prices and Transmission Charges in North China and Northeast China

2023 Price RMB/KWh		State Grid Whole Sale Price	Price on Transmission & Distribution	Ex-factory Price of Power Firms
		(1)	(2)	(3) = (1) - (2)
华北	北京 Beijing	0.6482	0.3891	0.2591
North	天津 Tiangjiang	0.6639	0.2577	0.4062
China (NC)	河北 Hebei	0.5494	0.1659	0.3835
	山东 Shandong	0.6089	0.1885	0.4204
	山西 Shanxi	0.5104	0.1256	0.3848
	Average price	0.59616	0.22536	0.3708
东北	内蒙 Inner Mongolia	0.5813	0.2494	0.3319
North	辽宁 LiaoNin	0.6262	0.2384	0.3878
East	吉林 JiLing	0.7072	0.2891	0.4181
(NE)	黑龙江 Heilongjinag	0.7065	0.3061	0.4004
	Average price	0.6553	0.27075	0.38455

Source: Compiled by the author using Column (1) from provincial electricity price announcements reported at www.news.bjx.com.cn (4 January 2025), and Column (2) from NDRC Price Bureau Document No. 1508 (2020) on provincial transmission and distribution tariffs (2020–2022).

This example illustrates that cross-regional electricity trade can be driven either by the need to balance supply and demand, as in Scenario Three, or by efficiency and profitability considerations—such as cost differentials and arbitrage opportunities—as in Scenario One. When local supply capacity is constrained, cross-regional imports become necessary to meet demand regardless of price competitiveness. Conversely, surplus regions may seek exports to absorb excess generation. From a system perspective, interprovincial trade therefore frequently reflects the need to bridge regional imbalances.

Beyond balancing and cost efficiency, cross-regional trade may also be motivated by renewable-energy objectives. Even when local supply and demand are broadly balanced, provinces may import renewable electricity to meet mandated renewable-energy targets or increase renewable integration, or export flexible generation to complement intermittent renewable output elsewhere. Similarly, provinces with large renewable capacity but limited flexible generation may import dispatchable electricity to manage intermittency. These cases represent non-imbalance-driven motivations for interzonal trade.

The Chinese government sets renewable-energy consumption targets at the provincial level. Guangdong, for instance, is required to achieve a renewable penetration rate of 29.5% by 2024 (NDRC and NEA, 2024). If local renewable supply is insufficient, Guangdong may import hydropower from Yunnan while exporting flexible generation in exchange. Likewise, provinces with surplus daytime solar generation may export electricity and import flexible power during evening peak periods. Such exchanges increase interprovincial trade without directly reflecting local supply–demand imbalances.

When power is swapped between provinces to increase renewable penetration through leveraging each other's production advantages, the swap does not directly affect local market supply and demand but does lead to greater interprovincial trade. This trade is driven by non-balance-related needs, contributing to the strategic deployment of renewables and grid optimization.

Our Equation (2) and (3) reflects the context above, and define two types of demand for inter-zonal trading: the *imbalance-driven demand* ($\sum_{i=1}^n d_{it}$), representing imports required to offset shortfalls; and the *non-imbalance-driven demand for supply of power* ($\sum_{i=1}^n y_{it}^x$), reflecting trade motivated by factors such as renewable integration or operational optimization. This leads to the total demand for inter-zonal trading or transmission as defined by Equation (7): $Y_t^S = \sum_{i=1}^n d_{it} + \sum_{i=1}^n y_{it}^x$.

Table 7 reports empirical estimates of these components. Column (1) presents imbalance-driven demand ($d_{it} > 0$), while Column (9) shows its share in total transmission. Column (10) reports the share of non-imbalance-driven transmission, including renewable and flexibility exchanges. Each component accounts for roughly half of total transmission over the sample period.

In 2023, the combined volume of interprovincial and interregional transmission reached approximately 2,700 TWh, representing about 30% of national electricity consumption (9,220 TWh). On average, for every 3 kWh of electricity consumed nationally, approximately 1 kWh is associated with inter-provincial or inter-regional power transmission. Of this transmitted power, roughly a half is driven by demand for correcting imbalance. Over the past six years, the share of the imbalance-driven transmission has remained relatively stable (see Column (9) of Table 7).

With respect to market-based transactions, cross-regional and cross-provincial trade conducted through the Beijing Power Exchange Centre reached 1,015 TWh in 2023, accounting for about 38% of total transmission and roughly 11% of national electricity consumption (see Column (7) of Table 7). This highlights the growing role of market mechanisms in facilitating interprovincial and interregional electricity trade in China.

Table 7 Imbalance and Non-imbalance-related demand for Transmission across Provinces and Regions

	Total power shortages of all provinces TWh	Total power surpluses of all provinces TWh	Total electricity generated by all provinces TWh	Total Power trasmitted across regions TWh	Total Power trasmitted across provinces TWh	Total cross-region and cross-provinces transmission TWh	Inter-region & province power traded by market TWh	Total power transmitted across zones as % of total production of all provinces	Imbalance related trade	Non-imbalance related trade
	(1)	(2)	(3)	(4)	(5)	(6) =(4)+(5)	(7)	(8) = (6)/(3)	(9) = (1)/(5)	(10) = 1-(9)
2023	1352.8	-1037.8	9224.1	849.7	1850	2700	1015.9	29.3%	50.1%	49.9%
2022	1257.1	-997.9	8647.9	767.4	1770	2537	899.9	29.3%	49.5%	50.5%
2021	1183.4	-963.9	8331.6	687.6	1600	2288	503.8	27.5%	51.7%	48.3%
2020	1081.1	-976.7	7521.4	613.0	1536	2149	395.1	28.6%	50.3%	49.7%
2019	984.4	-878.1	7248.4	540.5	1444	1985		27.4%	49.6%	50.4%
2018	902.1	-777.3	6916.3	480.7	1294	1775		25.7%	50.8%	49.2%

Source: Column (1), (2) and (3) are cited from Table 3; Column (4) and (5) are cited from *Economic Operation Report of China's Electric Power Industry (2018 -2023)* for the respectively years. Column (7) is from *China Electricity Council - Briefing Electricity Market Trading of China (2020-2023)*, and (8) is calculated by author; (9) is calculated as (1)/(5) corresponding to $\sum_{i=1}^n d_{it} / Y_t^S$, where Y_t^S is total amount of all electricity transmitted across regions and provinces, and $\sum_{i=1}^n d_{it}$ is imbalance between demand and supply, as defined in Equation (1). Column (10) is calculated as 1- (9), i.e. $[1 - (\sum_{i=1}^n d_{it} / Y_t^S)] = \sum_{i=1}^n y_{it}^x / Y_t^S$ and y_{it}^x is defined in Equation (5) as exports not attributable to imbalance in power generation.

The evidence in this section suggests that interzonal transmission is driven by three analytically distinct forces. First, imbalance-driven trade occurs when regions import electricity to offset structural shortfalls in local supply. Second, efficiency-driven trade reflects persistent differences in regional production costs, enabling welfare gains through arbitrage and large-scale transfers from low-cost to high-cost regions. Third, integration-driven trade arises from the need to accommodate renewable generation, including exchanges of renewable and flexible power to manage intermittency and meet policy targets.

Together, these drivers determine the scale and pattern of interregional electricity flows. Transmission demand in large interconnected systems therefore reflects not only temporary disequilibria but also structural cost heterogeneity and policy-driven changes in generation portfolios, helping explain the sustained growth of interprovincial transmission in China and other systems undergoing energy transition.

7. Transmission Capacity and Utilization Rate

China publishes annual statistics on interprovincial and interregional electricity transmission. Transmission across regions is closely related to the aggregate imbalance of provinces experiencing shortages, as shown in Columns (1) and (2) of Table 8. This relationship indicates that larger imbalances require greater interconnective transmission to reconcile mismatches. Table 8 also provides evidence on whether existing interconnector capacity is sufficient to meet this demand.

For cross-regional interconnectors, utilization rates range from 44% to 53% of total installed capacity. Spare capacity in these lines has partly been used, or effectively “borrowed,” to accommodate provincial transmission (Columns (10), (11) and (12), Table 8), suggesting that cross-regional interconnectors currently have adequate capacity relative to demand. In contrast, demand for cross-provincial transmission significantly exceeds available capacity. In 2023, approximately 1,850 TWh of electricity required cross-provincial transmission, compared with a maximum infrastructure capacity of about 1,081 TWh (Columns (3), (9), and (11), Table 8). This imbalance indicates the need to pool cross-regional and cross-provincial transmission resources to balance supply and demand effectively.

These patterns point to a structural asymmetry in transmission investment. Cross-regional interconnectors appear relatively overbuilt, while cross-provincial interconnectors remain capacity-constrained. Moreover, near-full utilization of maximum transmission capacity (Column (12), Table 8) suggests limited headroom for future growth. Such constraints are likely to intensify as distributed renewable generation expands, since higher penetration of solar and wind tends to increase, rather than reduce, in demand for network capacity (Astier et al., 2021).

With continued growth in East–West imbalances and renewable deployment, demand for interconnective transmission is expected to rise further, placing increasing pressure on existing infrastructure. Capacity constraints may therefore limit the expansion of cross-regional and cross-provincial electricity trade, despite

strong policy support for a unified national electricity market and greater renewable integration.

The high proportion of electricity consumption supported by interconnectors emphasises the critical role of China’s transmission infrastructure in enabling cross-region and cross-province trade, and in advancing the development of a unified electricity market in China. Transmission infrastructure is an important determinant of cross-regional power trade (Abrell and Rausch,2016). Expanding transmission capacity and market coordination support cost reductions (Bowen et al., 1999), At the same time, the viability of such a market depends on sustained demand for cross-region and cross-province trade. This trade is characterised as ‘trade of imbalance across provinces’ by study of IEA (2024).

The evidence presented here points to a structural mismatch between the composition of transmission demand and the allocation of transmission capacity. Demand for interprovincial transmission—largely driven by imbalance correction and renewable integration—has grown faster than the capacity of provincial interconnectors, while cross-regional lines retain spare capacity. This suggests that transmission constraints in large interconnected systems are not determined solely by total capacity, but also by how capacity is distributed across network layers and geographic scales.

More broadly, transmission infrastructure performs a dual function: it enables spatial arbitrage and regional development while simultaneously providing balancing flexibility and facilitating renewable integration. Where capacity expansion is uneven across network segments, bottlenecks may emerge that limit market integration even when aggregate transmission capacity appears sufficient. Recognizing this structural dimension is important for understanding the evolution of China’s electricity market and for designing transmission investment and market reforms.

Table 8 Transmission Capacity & their Utilizations Rates: Region VS Province

	Aggregate Disbalance of all regions with shortages TWh	Total Power transmitted across regions TWh	Total Power Transmitted across provinces TWh	Total Power Transmitted across-region and across-provinces TWh	Capacity of Transmission across regions GW	Capacity of Transmission across province GW	Total Capacity of corss-region and corss-province transmission GW	Maximal capacity of transmission aross regioins TWh	Maximal capacity of transmission across Provinces TWh	Utilization Rate of Cross-Region Capacity as % of (8)	Utilization Rate of Cross-Province Capacity as % of (9)	Utilization rate of residual max regional capacity & max province capacity as % of (3)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
2023	872.4	849.7	1850	2700	188.15	126	314	1618.09	1081.61	53%	171%	100%
2022	806.4	767.4	1770	2537	188.15	107	295	1618.09	919.31	47%	193%	100%
2021	736.9	687.6	1600	2288	172.15	94	266	1480.49	807.11	46%	198%	100%
2020		613.0	1536	2149	156.15	94	250	1342.89	806.11	46%	191%	100%
2019		540.5	1444	1985	144.4	86	231	1241.84	742.66	44%	194%	100%

Source: Column (1) is cited from Table 4. Columns (2) and (3) are taken from the *China Electricity Council, Economic Operation Report of China’s Electric Power Industry (2018–2023)* for the respective years. Column (4) is the sum of Columns (2) and (3). Column (5) is from the *China Electricity Council, China Electric Power Industry Annual Development Report (2020–2024)* for the respective years. Columns (6) and (7) are calculated assuming 8,600 annual operating hours for interconnectors: Column (7) = (4) × 1000 / 8600, and Column (6) = (7) – (5). Column (8) = (5) × 8600 / 1000, and Column (9) = (6) × 8600 / 1000. Column (10) = (2) / (8), and Column (11) = (3) / (9). Column (12) = {(1 – (10)) × (8)} + (9) / (3),

representing the sum of residual regional transmission capacity and provincial transmission capacity, divided by the total power transmitted across provinces in each year.

8. Conclusions and Policy Implications

8.1 Arguments and Findings

In this study, we conceptualise electricity market imbalance as comprising two analytical components. The first is a tradable, or structural, imbalance that refers to a situation in which local supply and demand cannot achieve equilibrium. Correction of this disequilibrium relies on inter-market trading and transmission-based reallocation, as the imbalance is anticipated. The second is a system imbalance that reflects operational fluctuations or deviation from scheduled contract plan, caused by stochastic shocks, and therefore relies on the dispatch system for real-time correction. This distinction implies a dual-equilibrium structure of the electricity system, and the interaction between these two equilibrium processes forms the institutional foundation of modern electricity market design.

Empirically, China has structural imbalance in its power market every year. In 2023 China exhibited an aggregate provincial power shortfall of 1,352 TWh and an aggregate surplus of 1,037 TWh. Shortfall provinces can therefore offset predictable imbalances through inter-market trade to import from surplus provinces, while dispatching centres address unpredictable imbalances (estimated at 315 TWh in 2023). These findings support our conceptual decomposition of imbalance into tradable and non-tradable components.

Our theoretical framework further suggests that, in liberalised electricity markets, competition for efficient supply generates local imbalances and thus induces cross-market trade. This theory predicts that the structural imbalance can be intended or sustained strategically, as illustrated by China's West-to-East power development policy. Because average electricity prices in West are around 35% lower than in East, inter-regional transmission generates roughly RMB 190 billion annually in economic value, narrowing regional disparities and increasing overall welfare, while strengthening incentives for further investment in transmission and generation.

Inter-regional trade is driven both by imbalance correction and by non-imbalance motives, particularly renewable energy integration. Each accounts for roughly 50% of total transmission over the sample period. In 2023, inter-provincial and inter-regional transmission reached 2,700 TWh, about 30% of national electricity consumption (9,220 TWh), implying that one-third of electricity consumption depends on interconnectors.

Transmission statistics also reveal a structural asymmetry. Cross-regional interconnectors operate at 44–53% of capacity, whereas demand for cross-provincial transmission exceeds capacity by 171% in 2023 and 193% in 2022. This indicates over-investment in cross-regional transmission lines and under-investment in cross-provincial ones. Even when combined, overall utilisation remains tight, limiting the scope for further growth in demand for transmission.

Finally, imbalance poses risks to system security, especially in its unpredictable part. China controls these risks through a centralised three-tier dispatching structure (national, regional, and provincial). These centres control substantial balancing resources: for example, the East China Dispatching Centre manages directly around 30 GW of generation capacity⁷, compared with 5.3 GW for EDF in the UK. Nationally, dispatching centres generated approximately 3.8% of national output (9,224 TWh) in offsetting an approximate 315 TWh shortfall in 2023.

8.2 Policy Implications

The empirical results highlight the importance of understanding imbalance for improving system efficiency and guiding investment in generation and transmission assets. They also provide insights into how imbalance can be managed to mitigate risks to system security. Four main policy implications follow.

A Two-Tier Structure for a Unified Electricity Market

As China moves toward a unified electricity market from a multi-zonal system, a two-tier structure is recommended: (i) intra-provincial trade to address supply efficiency in local market, and (ii) inter-provincial and inter-regional trade to offset the structural imbalance resulted from intra market competition. The scale of trade imbalance has already stimulated development of inter-provincial markets in Beijing (State Grid region) and Guangzhou (Southern Grid region). These national markets should complement, rather than replace, provincial markets, enhancing efficiency, renewable integration, and security of supply through open access and competition.

Reform of Dispatchable System for Deeper Renewable Integration

China's dispatch centres function as a de facto capacity mechanism by managing system imbalances and safeguarding security of supply. As renewable penetration expands rapidly in the country, existing dispatchable resources are increasingly insufficient to absorb the growing stochastic variability introduced by weather-dependent generation. This constraint may limit further renewable integration (Bistline, 2017). Consequently, reform of the current dispatch system has become a policy priority. Introducing competitive participation in strategic reserves or market-based capacity mechanisms could strengthen investment incentives, improve allocative efficiency, and facilitate decarbonisation in the electricity sector.

Promoting Cross-Regional Trade and Transmission Investment

Strategic imbalances between eastern and western regions have generated substantial efficiency gains and supported renewable integration. Abundant renewable resources in western China create strong demand for further expansion of cross-regional trade and interconnector capacity. Achieving this requires improved open-market access and adequate transmission infrastructure. To encourage investment — particularly to expand interconnector capacity from around 310 GW to 600 GW — we propose a dual-pricing scheme combining a fixed regulated tariff with

⁷ 曾德君, 杨立兵, 李晓刚 国家电网有限公司华东分部 (2021) '华东电网在中国统一电力市场体系中的角色及作用', 2021/2/22, 中国电力网 <https://m.bjx.com.cn/mnews/20210222/1137261.shtml>

a flexible market-based price. This approach could mobilise both public and private capital for transmission expansion.

Implications for UK Market Design

China and the UK are converging toward similar electricity market architectures from opposite directions: China from zonal to national integration, and the UK from national toward zonal pricing (REMA, 2024). When zonal markets are introduced, imbalance provides important signals for long-term investment in transmission or generation, since price signals alone may be insufficient. Analysis of imbalance helps determine whether local generation or imports are more cost-effective under capacity constraints.

China's experience highlights several questions for the UK: whether strategic imbalance should be permitted, whether transmission capacity is adequate, how imbalance-driven trade should be prioritized, and how private investment in interzonal transmission can be incentivised. Addressing these issues will be central to designing a resilient, efficient, and decarbonised electricity market.

8.3 Broader Implications

More broadly, this paper contributes to the literature on electricity-market design by showing that imbalance is not merely a short-term operational problem, but a structural feature shaped by competition for efficient supply, renewable integration, transmission investment, and system operation. Imbalance improves efficiency. Distinguishing between anticipated and unpredictable imbalance provides a framework for analysing how markets, interconnectors, and dispatch mechanisms jointly sustain security while improving efficiency. It highlights the need for further study of market disequilibrium and its impacts on investment, efficiency, and energy security during the shift to renewables, particularly, from the aspect of changing demand or demand-sided response to offset imbalance. This paper opens a new avenue of research into the economics of electricity and the role of policy in relation to imbalance in shaping future electricity markets.

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