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A COMPARATIVE STUDY OF RENEWABLE ENERGY TRANSMISSION IN CHINA  
AND GERMANY

Jiahong Wei

Work project carried out under the supervision of:

Ilya Okhmatovskiy

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## **Abstract**

High-voltage transmission grids play a central role in sustainability transitions by enabling renewable energy to be delivered to demand centres. This study compares China and Germany from 2014 to 2023 to examine how state-capitalist and coordinated market-capitalist governance shape grid expansion, investment costs, and renewable integration. Using a comparative case-study approach based on harmonised grid indicators and policy evidence, the study finds that China achieves rapid and relatively low-cost grid expansion but faces recurrent grid-renewable mismatches. Germany, by contrast, expands its grid slowly and at higher cost while maintaining low curtailment through market-based operational measures. The results highlight institutional trade-offs in grid-based energy transitions.

**Keywords:** Electricity Grids; Sustainability Transitions; State Capitalism; Coordinated Market Capitalism; China; Germany

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## **1. Introduction**

The global urgency to combat climate change has driven wind and solar power into a phase of rapid expansion. Yet the construction of low-carbon energy systems depends not only on generation capacity, but critically on the electricity grid that connects generation, storage, and end-use demand. As the International Energy Agency emphasizes, “the grid is the backbone of the clean energy transition” (IEA 2023).

As renewable penetration increases, energy systems worldwide face growing challenges in adapting grid infrastructure. Compared with modular and quickly deployable renewable technologies, transmission grids require large upfront investment, long construction periods, and must navigate land-use regulation and public acceptance. These features make it difficult to align grid development with the fast pace of renewable deployment. Understanding what drives grid expansion, investment efficiency, and grid-renewable coordination has therefore become a central issue in energy-transition research.

What determines how quickly and effectively grids respond to renewable-energy growth? Purely technical explanations focus on engineering capabilities, but they cannot explain why countries with comparable technological levels follow very different grid-development paths. Sustainability transitions research offers a broader perspective by conceptualizing electricity grids as core elements of socio-technical regimes rather than neutral technical assets (Geels 2002). From this view, grid transformation involves institutional choices, governance structures, and societal coordination, not only technological upgrading.

Building on this insight, this study draws on the Varieties of Capitalism (VoC) framework (Hall and Soskice 2001) to examine how different institutional systems shape grid development. State

capitalism, exemplified by China, tends to rely on centralized planning, state-owned enterprises, and top-down mobilization to accelerate infrastructure construction. Coordinated market capitalism, exemplified by Germany, emphasizes regulatory oversight, market coordination, and multi-stakeholder negotiation, prioritizing procedural legitimacy and consensus building.

This distinction leads to two related research questions. First, how do China and Germany differ in the speed and cost of building high-voltage transmission grids? Second, how effectively do their grids support renewable energy to be transmitted and used in practice?

To address these questions, this study focuses on China and Germany during the period 2014-2023. This time window captures a common phase in which both countries experienced accelerated wind and solar deployment and rising pressure on transmission networks, despite differences in initial grid maturity.

Accordingly, the study advances two propositions:

**Proposition 1:** Under a state-capitalist model, China builds and upgrades its high-voltage transmission grid faster and at lower average cost than Germany.

**Proposition 2:** Under a coordinated market-capitalist model, Germany achieves better coordination between the grid and renewable deployment than China.

Chapter 2 reviews the literature on sustainability transitions, varieties of capitalism, and grid governance. Chapters 4 and 5 analyse China and Germany using comparable indicators and documentary evidence. Chapter 6 brings the cases together to assess the propositions and to draw broader conclusions and policy implications for grid-based sustainability transitions.

## **2. Literature Review**

### **2.1 Electricity Grid as a Key Infrastructure in Sustainability Transitions**

Research on sustainability transitions views transition processes as systemic reconfigurations of socio-technical regimes that combine technologies, infrastructures, institutions, and user practices (Markard, Raven and Truffer 2012). Within such regimes, infrastructures reflect historical design choices and institutional commitments, generating strong path dependencies that can either stabilize existing systems or constrain change (Geels 2002; Smith, Stirling and Berkhout 2005). As a result, analyses of sustainability transitions increasingly emphasize the role of key infrastructures.

In the sustainable transitions of energy system, electricity grids therefore stand out as one of the most consequential infrastructures and shape significantly the transition process. As the International Energy Agency (IEA) emphasizes: “without adequate grids to connect the new electricity supply with the demand, there is a risk that clean-energy transitions will stall” (IEA 2023). The centrality of grids in the energy transformation can be understood in at least two respects. First, existing grid architectures reinforce incumbent system structures and shape which renewable options can be integrated, where, and at what pace (Verbong and Geels 2007). Second, the Multi-Level Perspective (MLP), which provides a systematic framework for analysing sustainability transitions, suggests that grid infrastructure is conceived as a core component of the socio-technical regime that mediates between landscape pressures and niche innovations (Geels 2002).

Sustainability-transition research further highlights that infrastructures often evolve more slowly than generation technologies, policy frameworks, or markets. Sovacool and Geels (2016)

describe this as a problem of “multiple temporalities,” in which grid expansion tends to be the slowest-moving element due to planning, regulatory, and investment constraints. This insight underscores the need to pay attention to the temporal characteristics of grid infrastructure, as these may ultimately determine the pace and feasibility of system-wide decarbonization.

Taken together, the literature suggests that electricity grids, as core infrastructures of socio-technical regimes, deserve systematic attention in studies of sustainable energy transitions. Their influence extends beyond technical capacity, encompassing institutional embedding and slow-moving development dynamics. This implies that understanding energy transitions requires close examination of the societal and institutional factors shaping grid development.

## **2.2 Transition Pathways under Varieties of Capitalism**

As discussed above, societal and institutional factors play a central role in shaping how electricity grids are planned, financed, and implemented during sustainability transitions. Loewen (2022) notes that the “varieties of capitalism” framework has so far been underused, despite its clear relevance for understanding how different systems coordinate infrastructure development. Comparing energy transitions under state capitalism and coordinated market capitalism is therefore a useful way to examine how contrasting coordination logics shape grid development outcomes.

In state-capitalist systems, such as those typified by China, the state plays a dominant role in directing infrastructure investment, often through state-owned enterprises (SOEs). As Bremmer (2011) defines it, “state capitalism is a system in which the state functions as the leading economic actor and uses markets primarily for political gain.” Under this logic, long-term infrastructure goals can be rapidly translated into investment decisions, including national grid

expansion and renewable integration. Musacchio and Lazzarini (2015) further show that contemporary state capitalism leverages SOEs, sovereign wealth funds, and development banks to mobilize large-scale capital, enabling economies of scale and centralized coordination. For electricity grids, this translates into top-down planning and large-scale build-out with comparatively less administrative fragmentation.

In contrast, coordinated market capitalist systems (exemplified by Germany) distribute decision-making across private firms, independent TSOs, regulators, labour organizations, and civil society. Hall and Soskice (2001) argue that coordination in these systems relies on institutionalized cooperation rather than hierarchical control. As a result, infrastructure investment is shaped by regulatory negotiation, stakeholder consultation, and procedural oversight. While this approach strengthens legitimacy and social acceptance, it often slows implementation and may generate fragmented decision-making.

These institutional differences have direct implications for grid development performance. In coordinated market economies, extended permitting procedures, multi-level governance, and cost-allocation disputes can delay grid expansion (Szabó and Jelinek 2023). In state-capitalist regimes, grid build-out may proceed more rapidly and at lower cost, but may risk misalignment with decentralized renewable energy deployment. Rather than implying that one model is superior, this comparison highlights the different trade-offs between speed, efficiency and coordination that underpin the propositions examined in this study.

### **2.3 Comparable Indicators to Assess Electricity Grid's Performance**

To examine how different societal and institutional models influence grid development, it is necessary to clarify along which dimensions grid performance can be assessed.

Current research widely adopts indicators corresponding to two broad dimensions: investment efficiency and scale; and systemic integration and matching. On the investment dimension, transmission line length, CAPEX, and percentage of projects delivered within target timelines are frequently cited (Busuladzic 2020; ENTSO-E, CEDEC, E.DSO, EURELECTRIC and GEODE 2021). On the integration dimension, indicators include curtailment rates of renewables due to grid constraints and average queue time for grid connection (Pramangioulis et al. 2019; IEA 2023). Additional performance metrics such as resilience (outage time, adaptability), flexibility (bidirectional flows, digitalization readiness) and system support-capacity are emerging in recent studies (Che-Castaldo et al. 2021; Rodríguez-Pérez et al. 2024). These indicator clusters serve as the analytical bridge linking societal and institutional configurations with electricity grid outcomes. For example, under a state-capitalist institutional model, one might observe high performance in investment efficiency (fast build-out and CAPEX efficiency). Conversely, under a coordinated-market regime, integration between and renewables and queue times may perform better, reflecting higher systemic matching. Through these indicators, the variation in grid regime performance across countries becomes analysable and comparable.

## **2.4 Research Gaps and Contributions**

Although many studies discuss sustainability transitions and the institutional features of energy systems, existing work rarely looks closely at how different governance arrangements shape the development of transmission grids. Research on electricity grids often focuses either on engineering aspects or on single-country cases, leaving limited cross-national evidence on how

grid expansion, investment patterns and renewable integration outcomes differ across institutional settings.

This study reduces this gap in a focused way. By comparing China and Germany, it examines how state-led and market-coordinated arrangements influence the speed, cost and alignment of grid development with renewable expansion. Through a structured case comparison, this study brings together publicly available readings and harmonised indicators, showing how governance choices are reflected in observable grid outcomes. The analysis does not aim for comprehensive measurement or universal generalisation; instead, it examines how institutional context affects electricity-grid development.

### **3. Research Design and Methodology**

#### **3.1 Research Design**

This study adopts an explanatory comparative case-study design to examine how different institutional systems shape transmission-grid development and grid–renewable interaction in China and Germany between 2014 and 2023. The comparison follows a structured and focused logic: both countries are analysed using the same time window, the same system boundary (220 kV-and-above transmission networks), and a harmonised set of indicators.

China and Germany are selected as analytically contrasting cases. China represents a state-capitalist system characterised by centralised planning authority and state-owned grid enterprises, while Germany represents a coordinated market-capitalist system with decentralised regulation, strong procedural constraints, and market-based coordination. The purpose of the comparison is not to rank countries by absolute infrastructure levels, but to analyse how different institutional configurations respond to rising renewable-energy pressure

through grid expansion, investment decisions, and coordination mechanisms.

The 2014-2023 period is chosen because it captures a common phase in which both countries experienced accelerated deployment of wind and solar power and increasing stress on transmission networks. Although China and Germany entered this period with different levels of grid and renewable energy maturity, both faced the shared challenge of integrating rapidly growing variable renewables into existing power systems. This makes the period particularly suitable for analysing institutional response patterns.

Given the limited number of cases and annual observations, the study does not aim at statistical generalisation. Instead, it seeks to provide a systematic and comparable analysis of trajectories, magnitudes, and institutional mechanisms under clearly defined analytical conditions.

### **3.2 Data Sources and Collection Strategy**

All empirical material used in this study is drawn from authoritative public sources. For China, data are collected from the National Energy Administration's annual statistical bulletins, the China Electricity Council's Electric Power Statistical Yearbook, and public disclosures by the State Grid Corporation of China and China Southern Power Grid. For Germany, data are obtained from the Federal Network Agency's (Bundesnetzagentur, BNetzA) Monitoringberichte (2014-2023), statistical publications by ENTSO-E, and annual reports of the four transmission system operators (50Hertz, Amprion, TenneT, TransnetBW).

These sources provide consistent information on transmission-line length, AC/DC composition, capital expenditure, and renewable-integration outcomes. To ensure comparability, the analysis is restricted to AC and DC transmission lines at 220 kV and above. This voltage level represents the core infrastructure tier for long-distance and interregional power transmission and is directly

relevant for large-scale renewable integration in both countries.

Documentary materials used to contextualise indicator trends include policy documents on China’s ultra-high-voltage (UHV) strategy and renewable-base planning, German regulatory reports on congestion management (including Redispatch 2.0), and official documents explaining delays in major projects such as SuedLink. These materials are used to link changes in observed indicators to policy decisions, institutional frictions, and project-level developments.

### 3.3 Operationalization of Key Indicators

The empirical evaluation of the two propositions relies on a set of harmonised indicators designed to capture grid expansion, investment efficiency, and grid–renewable coordination.

**Transmission Grid Growth Rate:** Let  $L_t$  denote the total length (km) of 220 kV and above AC and DC transmission lines in year  $t$ . Annual grid-length growth is measured as:

$$g_t = \frac{L_t - L_{t-1}}{L_{t-1}}$$

This growth rate reflects the scale and speed of long-distance transmission expansion. Because the data represent net mileage, negative values may occur following decommissioning or reclassification of lines; such variation accurately reflects changes in the physical grid stock.

Given differences in initial grid maturity across countries, this indicator is not used to compare absolute expansion “performance”, but to capture how each system adjusts transmission construction intensity when facing rising renewable-generation pressure.

**Investment Efficiency:** Investment efficiency is measured using total capital expenditure per kilometre of existing transmission network:

$$CAPEX \text{ per km}_t = \frac{CAPEX_t}{L_t}$$

Total length  $L_t$  is used for two reasons. First, annual CAPEX includes not only new construction but also upgrades, reinforcements, and retrofits, making total mileage a more appropriate denominator for assessing annual capital intensity. Second, new-length values may become zero or negative in specific years, rendering the ratio undefined or misleading. Currency comparability is achieved by converting China's CAPEX into euro values using annual average market exchange rates.

**Sensitivity Adjustment for AC/DC Cost Structure:** A methodological challenge arises from asymmetric AC/DC reporting: China discloses AC/DC CAPEX and length separately, while Germany reports only aggregate CAPEX. Because DC infrastructure, especially UHVDC corridors, has substantially higher per-kilometre cost, direct comparison risks overstating China's unit costs. To address this, the study applies a sensitivity test, assuming that DC cost is 3 times than AC cost. An adjusted indicator is defined as:

$$\text{Adjusted CAPEX per km} = \frac{\text{CAPEX}_t}{L_{AC,t} + 3 \cdot L_{DC,t}}$$

The purpose is not to estimate true engineering costs but to test whether China's cost advantage under Proposition 1 remains robust once AC/DC structural differences are conservatively normalized.

**Strategic Matching Ratio (SMR):** Grid-renewable coordination is assessed using the Strategic Matching Ratio, defined as

$$\text{SMR}_t = \frac{g_t^{\text{grid}}}{g_t^{\text{RES}}}$$

Where  $g_t^{\text{RES}}$  is the annual growth rate of total installed wind and solar capacity. The ratio captures whether transmission expansion keeps pace with renewable deployment. An SMR close to 1 suggests alignment; values well below 1 signal structural lag, with potential

implications for congestion and curtailment.

SMR is treated as a diagnostic indicator rather than a precise efficiency measure. Because it is based on growth rates, it is influenced by baseline system size and maturity. The indicator is therefore not used to compare “how coordinated” countries are in absolute terms, but to reveal structural response patterns, namely whether grid expansion tends to lag behind, keep pace with, or temporarily overshoot renewable deployment during periods of rising pressure.

**Curtailment Rate:** Wind and solar curtailment rate are used as the system-integration metric:

$$\text{Curtailment Rate}_t = \frac{\text{Curtailed}_t}{\text{Potential}_t}$$

Wind and solar are selected because their non-dispatchability makes curtailment a direct reflection of transmission bottlenecks and system-flexibility constraints.

### 3.4 Research Limitations

As a comparative case study covering two countries over ten years, this analysis focuses on directional trends, relative magnitudes, and institutional interpretation rather than statistical hypothesis testing.

Differences in initial grid maturity between China and Germany present an inherent comparability challenge, particularly for growth-rate-based indicators. This study addresses this issue in three ways. First, it explicitly refrains from comparing absolute infrastructure levels and instead focuses on response patterns under rising renewable pressure. Second, growth-based indicators such as grid expansion rates and SMR are interpreted as signals of institutional adjustment strategies rather than measures of optimal coordination. Third, quantitative indicators are consistently interpreted alongside qualitative evidence and curtailment outcomes to avoid over-reliance on any single metric.

Additional limitations include the exclusion of distribution networks, which are increasingly important for renewable integration in Germany, and the inability to fully control for all political, geographic, and economic differences between the two countries.

#### **4. China Case: Grid Sustainable Transition under State Capitalism**

##### **4.1 Institutional Logic: State Capitalism and the “Developmental Grid”**

Institutionally, China corresponds closely to a form of “developmental state capitalism,” in which the state treats infrastructure investment as a central instrument for economic growth and structural upgrading (Musacchio and Lazzarini 2014; Musacchio et al. 2015). In the energy sector, this logic is reflected in a governance structure where the National Development and Reform Commission and the National Energy Administration control medium- and long-term planning and market access, while the two state-owned grid companies (State Grid Corporation of China and China Southern Power Grid) dominate asset ownership, project implementation, and system dispatch. As a result, the transmission grid is no longer viewed as a neutral technical network but as a strategic policy instrument embedded in national programs such as West-East Power Transmission, the “Three Northern Regions” wind and solar bases, and the “New Power System” agenda (IEA 2019).

Coordination within this system is largely top-down. Planning, investment, and operation are concentrated in a small number of central agencies and state-owned enterprises, while local governments and other actors are mainly integrated through administrative hierarchies and performance targets. This arrangement reduces negotiation and transaction costs for large infrastructure projects and allows political priorities to be translated quickly into concrete investments. At the same time, strong centralization means that planning errors can lead to

large-scale infrastructure lock-in, which then requires corrective policy campaigns and administrative intervention after the fact (Sovacool and Geels 2016).

#### **4.2 Grid Expansion and Investment Patterns: High Speed with Moderate Unit Costs**

Within this institutional framework, China's high-voltage transmission grid expanded at a consistently medium-to-high pace. Using harmonised data for networks at 220 kV and above, the total length of AC and DC transmission lines increased at an average annual rate of around 5% between 2014 and 2023 (Table 1 and Figure 1). This expansion reflects the strong capacity of the central government and state-owned enterprises to mobilise resources through unified planning. Over the same period, the share of inter-regional ultra-high-voltage (UHV) AC and DC corridors rose steadily. These corridors gradually formed a backbone network linking resource-rich north-western regions with major load centres in eastern and central China (IEA 2019).

In terms of cost, China's average capital expenditure (CAPEX) per kilometre for 220 kV and above transmission lines remains low by international standards. This holds both in the baseline calculation using total line length and in the sensitivity scenario that adjusts for higher DC costs (Tables 3 and 4). Existing studies point to several factors behind this outcome. First, large, project-based investment programmes allow grid SOEs to benefit from economies of scale in procurement. Second, China's largely domestic manufacturing base for towers, conductors, transformers and HVDC equipment reduces reliance on imports. Third, labour costs, land acquisition expenses and right-of-way compensation are generally lower than in most OECD countries (Agora Energiewende 2018; IEA 2019). Finally, policy-backed financing and the relatively low regulatory and political risk associated with state-led grid projects reduce the cost

of capital. Together, these factors contribute to lower unit investment costs across China's transmission network.

#### **4.3 Grid-Renewable Energy Coordination: SMR Trajectory and Curtailment Mitigation**

While transmission expansion followed a relatively smooth path, wind and solar capacity grew in a much more uneven way. Between 2014 and 2016, generous subsidies and tight project deadlines triggered a "rush to install," pushing annual growth rates of wind and solar capacity to very high levels. In some years, growth approached 50% (Table 5 and Figure 3). From 2017 to 2020, the phase-out of subsidies and a stronger policy focus on curtailment reduction slowed new installations. After 2021, the announcement of the "dual carbon" targets and further cost declines in solar modules led to another surge in renewable deployment, especially in photovoltaics. Annual growth rates again moved toward earlier peak levels (Table 5 and Figure 2).

Comparing the growth rate of the 220 kV and above transmission grid with the growth of wind and solar capacity produces the Strategic Matching Ratio (SMR) (Table 6 and Figure 3). Rather than showing steady improvement, China's SMR follows a clear cyclical pattern. During the initial installation rush, SMR remained low because renewable capacity expanded much faster than the transmission network. This gap indicates a pronounced lag in grid development.

This structural imbalance was closely associated with high levels of renewable curtailment (Table 7 and Figure 4). By 2016, the national average wind curtailment rate reached about 17%, and exceeded 30% in several northern provinces. Solar curtailment was also significant, at around 10% (NEA 2017; Liu et al. 2018).

From 2016 onward, a series of policy measures directly addressed this mismatch. These

included *the Administrative Measures for the Full Guaranteed Purchase of Renewable Energy*, *the Implementation Plan for Resolving Curtailment of Hydropower, Wind Power and Solar Power*, and *the Clean Energy Consumption Action Plan (2018-2020)*. Together, these policies strengthened renewable consumption obligations for energy companies and provincial governments, and tied performance more closely to local government evaluation (NDRC and NEA 2016, 2017, 2018). At the same time, several UHV inter-regional transmission lines entered operation, reinforcing the national grid. Pilot electricity markets and inter-provincial trading mechanisms also advanced (IEA 2019). These developments coincided with a rise in SMR between 2017 and 2019, as grid expansion continued at a medium-to-high pace while renewable growth slowed. Curtailment fell sharply during this period. By 2019, national wind curtailment had declined to about 4%, and solar curtailment to roughly 2% (NEA 2020; Chen et al. 2022).

After 2021, however, a new wave of large-scale solar projects and “base-plus-corridor” developments under the dual-carbon agenda again pushed renewable capacity growth ahead of grid expansion. As a result, SMR fell back to a lower level. This pattern suggests that pressures in grid-renewable coordination are not fully resolved, but instead tend to re-emerge when new investment waves occur.

#### **4.4 Institutional Patterns: Baseline Expansion and Campaign-Style Coordination**

Viewed from an institutional perspective, China’s grid transition follows a relatively stable pattern that can be described as “baseline expansion combined with campaign-style coordination.”

Centralized planning and state control over grid companies create a stable baseline for

transmission expansion. As a result, the grids grow at a relatively steady pace, even during periods of macroeconomic volatility. This reflects the state's view of the grid as a long-term strategic asset rather than a short-term commercial investment (Musacchio and Lazzarini 2014). When renewable deployment moves far ahead of this baseline, the central government responds through targeted coordination campaigns. These campaigns combine regulatory pressure, faster approval and construction of key grid projects, and adjustments to planning rules. Together, they temporarily increase the alignment between grid and renewable expansion and sharply reduce wind and solar curtailment. This shows that state capitalism provides not only strong capacity for rapid infrastructure build-out, but also a mechanism for institutional correction when systemic risks become visible.

This pattern results in a distinctive transition dynamic. Rather than progressing through smooth and continuous adjustment, China's grid transition advances through a series of state-led "sprint windows," during which network structures are reconfigured in discrete bursts (Geels 2002; Markard et al. 2012). While this campaign-based approach can deliver rapid structural change, it also creates a recurring risk of misalignment between generation growth and grid capacity.

## **5. Germany Case: Grid Sustainable Transformation under Coordinated Market Capitalism**

### **5.1 Institutional Logic: Coordinated Market Capitalism and Layered Grid Governance**

Germany is commonly regarded as a coordinated market economy, whose institutional strength lies in solving coordination problems through industry associations, long-term contracts, and consultative arrangements rather than through centralized state control (Hall and Soskice 2001).

In the electricity sector, this logic is reflected in a multi-layered system of grid governance. At the federal level, the Bundestag and the federal government set energy-transition targets and adopt core legislation, such as the Renewable Energy Sources Act and the Grid Expansion Acceleration Act. The Federal Network Agency (Bundesnetzagentur, BNetzA), acting as an independent regulator, approves transmission system operators' investment plans and network tariffs. The four transmission system operators (TSOs) are responsible for regional planning and system operation. At the same time, state governments and local authorities retain important veto powers over route selection and permitting, while civil society groups and environmental organizations can influence decisions through formal consultation procedures and legal challenges (Westphal et al. 2022).

Within this framework, the transmission grid is treated as a regulated natural monopoly, with a strong emphasis on transparency, procedural fairness, and local acceptance. As a result, major transmission projects typically emerge through lengthy and complex negotiation processes. National grid needs are first identified in the Network Development Plan (NEP). TSOs then submit detailed project proposals, which are assessed by regulators for economic viability. State governments oversee spatial planning and permitting, while public participation and judicial review are integrated throughout the process (BNetzA 2023). This system of multi-centred legitimacy provides political stability and social acceptance, but it also makes rapid, centralized restructuring of the transmission network difficult.

## **5.2 Grid Expansion and Investment Patterns: Slow Expansion and High Unit Costs**

Within this institutional framework, Germany's transmission network expanded only slowly between 2014 and 2023. Harmonised data for AC and DC lines show that total line length

increased only modestly over the decade, with several years recording negligible or even slightly negative net additions (Table 1 and Figure 1). The slow pace of physical expansion is illustrated by the long development timeline of key north-south HVDC corridors such as SuedLink. Although SuedLink was identified as a priority project in *the 2012-2013 Network Development Plan* and formally anchored in *the Federal Requirements Plan Act in 2013*, it is currently scheduled for commissioning only around 2028, and large-scale construction began only in 2023 (BNetzA 2023).

At the same time, transmission investment volumes have increased sharply. Monitoring reports from the Federal Network Agency document a strong rise in annual transmission CAPEX from the late 2010s onward (Table 2). When these expenditures are related to network expansion, the CAPEX-per-kilometre indicators calculated in this study and its sensitivity analysis show that Germany's average unit investment cost for 220 kV+ lines is consistently higher than China's over the 2014-2023 period (Tables 3 and 4). This gap reflects both hard cost factors and soft institutional costs. On the one hand, Germany faces stricter environmental standards, higher compensation requirements, and extensive use of underground cabling on politically sensitive routes. On the other hand, prolonged multi-layer approval procedures, public participation processes and legal challenges mean that a large share of CAPEX remains tied up in projects that are still in planning, permitting or construction, rather than in commissioned line kilometres (ACER/CEER 2022; BNetzA 2023).

### **5.3 Grid-Renewable Energy Coordination: Low Curtailment through High Operational Compensation**

Germany's wind and solar capacity have increased at a moderate but steady pace over the past

decade (Table 5 and Figure 2). Most new onshore and offshore wind capacity is concentrated along the North Sea and Baltic coasts, while major demand centres and much of the conventional generation fleet are located further south and west. This spatial mismatch places persistent pressure on north–south transmission corridors.

When growth in the 220 kV and above transmission network is compared with the expansion of wind and solar capacity, the resulting SMR remains low for most of the period (Table 6 and Figure 3). This is because transmission line length has grown only slowly, while renewable capacity has continued to increase. In some years, the commissioning of large individual projects, such as offshore grid connections or partial sections of the SuedLink corridor, temporarily raises the SMR. However, these increases are short-lived and do not fundamentally change the underlying structural imbalance.

Despite this slow pace of structural grid expansion, Germany’s reported curtailment rates for wind and solar have remained relatively low (Table 7 and Figure 4). Regulatory reports and academic studies largely agree that this outcome is achieved not through rapid physical reinforcement of the transmission network, but through increasingly sophisticated operational coordination mechanisms (Joos and Staffell 2018; ACER/CEER 2022). First, well-developed day-ahead and intraday electricity markets allow generators and consumers to respond to price signals, which helps smooth part of the variability associated with wind and solar output. Second, strong cross-border interconnection capacity enables surplus electricity to be exported when congestion arises in northern Germany. And most importantly, redispatch and re-scheduling measures implemented after market clearing have become central tools. Under these mechanisms, traditional power plants are instructed to adjust output to relieve congestion, and

the associated costs are passed on to consumers through grid tariffs (ACER/CEER 2022; BNetzA 2023).

Monitoring reports from ACER/CEER and BNetzA show that redispatch volumes and related expenditures increased steadily throughout the late 2010s, reaching new highs in 2021-2022 as renewable penetration rose further (ACER/CEER 2022; BNetzA 2023). Scenario studies suggest that, without a significant acceleration of grid reinforcement, congestion-management costs and grid-related curtailment could rise substantially toward 2040 (Thomassen et al. 2024).

#### **5.4 Institutional Patterns: Procedural Coordination and Operational Compensation**

First, multi-level consultation and legal procedures define the baseline mode of grid governance in Germany. Almost every major transmission investment must pass through multiple layers of planning, public participation and judicial review. Decisions on the expansion are shaped jointly by the federal government, Länder authorities, the regulator, TSOs, municipalities and civil-society organizations. This governance structure ensures a high degree of procedural justice and social acceptance. Conflicts are handled through institutionalized procedures rather than through unilateral state intervention. At the same time, the fragmentation of veto points slows down structural decisions. As a result, it is difficult to sustain a long and continuous period of rapid grid expansion.

Second, when growing renewable deployment puts increasing pressure on the existing transmission network, the German system does not respond mainly by accelerating grid construction. Instead, it relies on a sophisticated set of operational coordination tools. Day-ahead and intraday electricity markets, balancing markets, cross-border interconnectors and redispatch mechanisms are used to adjust generation schedules in response to transmission

constraints (Joos and Staffell 2018; ACER/CEER 2022; BNetzA 2023). These instruments help keep reported wind and solar curtailment at relatively low levels. In practice, market-based congestion management and compensation mechanisms offset structural bottlenecks. They preserve system security and renewable utilization in the short term, but they do so at the cost of rising redispatch volumes and congestion-management expenditures.

This combination of procedural coordination and operational compensation produces a distinct transition dynamic. Germany's grid transition proceeds through gradual, negotiated adjustments, while structural mismatching in the transmission network is tolerated as long as operational tools can manage congestion and maintain system reliability. However, the effectiveness of these short-term instruments may weaken political pressure for deeper grid restructuring, allowing bottlenecks to persist over time. In this sense, coordinated market capitalism delivers high legitimacy and refined day-to-day coordination, but it does so by trading off the speed of infrastructure transformation and relying on market-based compensation mechanisms.

## **6. Comparative Analysis, Conclusions and Policy Implications**

### **6.1 Assessment of Propositions**

Proposition 1 states that, under a state-capitalist model, China expands its high-voltage transmission grid faster and at lower average investment cost than Germany. The comparative evidence in Chapters 4 and 5 broadly confirms this proposition. Between 2014 and 2023, China's transmission network expanded at a medium-to-high annual rate, consistently exceeding Germany's near-stagnant growth. When transmission investment is harmonised and expressed per kilometre of line length, China also shows lower average CAPEX, and this advantage remains robust under conservative sensitivity assumptions.

These outcomes are consistent with the institutional features of state capitalism. Central planning, state-owned grid enterprises, and policy-backed finance allow large transmission projects to be mobilised quickly and implemented at moderate unit cost (Musacchio and Lazzarini 2014; Agora Energiewende 2018; IEA 2019).

Proposition 2 states that, under a coordinated market-capitalist model, Germany achieves better coordination between the grid and renewable deployment. The findings support this proposition with respect to operational coordination, but not with respect to long-term structural alignment. On the operational level, Germany has maintained relatively low wind and solar curtailment rates. This performance is supported by a sophisticated market design, strong cross-border interconnections, and an expanding set of redispatch mechanisms, although these come with rising congestion-management costs (Joos and Staffell 2018; ACER/CEER 2022). By contrast, China's first wave of rapid renewable expansion led to very high curtailment rates. Once curtailment became a political priority, however, a combination of consumption quotas, early-warning systems, and accelerated UHV construction reduced national wind curtailment to single-digit levels (NDRC and NEA 2016, 2017; NEA 2020; Chen et al. 2022).

From a structural perspective, the Strategic Matching Ratio (SMR) indicates that neither country achieves stable long-term synchronisation between grid expansion and renewable growth. China addresses mismatches through episodic, policy-driven catch-up cycles, while Germany combines moderate renewable growth with very slow grid expansion and manages congestion ex post through market mechanisms rather than through timely network reinforcement (ACER/CEER 2022; Thomassen et al. 2024).

Proposition 2 should therefore be interpreted as follows: Germany's coordination advantage

over China is primarily reflected in system operation, rather than in sustained structural alignment between transmission expansion and renewable deployment.

## **6.2 Conclusions and Policy Implications**

Taken together, the comparison shows that no single institutional configuration holds a comprehensive advantage in advancing grid-based sustainability transitions. The transmission grid is not merely a physical network; it reflects deeper institutional coordination choices and trade-offs between speed, cost and coordination across different varieties of capitalism.

In China's state-capitalist system, concentrated planning authority and state-controlled grid enterprises have enabled rapid grid expansion and large-scale physical restructuring at moderate unit cost. However, it has also produced recurring mismatches between renewable generation and grid capacity. When these mismatches become politically salient, they are corrected through campaign-style administrative interventions rather than continuous alignment mechanisms (Musacchio and Lazzarini 2014; Chen et al. 2022). In Germany's coordinated market-capitalist system, multi-level governance and strong procedural safeguards have led to a much slower reconfiguration of the transmission network. However, sophisticated market-based instruments have kept reported curtailment rates low. The pressure is therefore shifted away from physical grid expansion toward operational management, resulting in rising redispatch volumes and congestion-management costs (Hall and Soskice 2001; ACER/CEER 2022; BNetzA 2023).

The core conclusion is not that one model outperforms the other, but that each embeds a distinct bundle of strengths and vulnerabilities in how grid infrastructure shapes the pace and form of sustainability transitions.

The Chinese and German experiences also offer broader lessons for countries pursuing power-

sector decarbonization.

For emerging and developing economies with strong state capacity but underdeveloped grid infrastructure, China's experience suggests that centralized planning and state-owned enterprise leadership can rapidly expand transmission networks. At the same time, repeated episodes of structural pressure show that project-based corrections cannot substitute integrated planning and gradual market reform.

For mature market economies, Germany's experience highlights the value of robust market-based coordination mechanisms in maintaining low curtailment. Yet without institutional "fast track" for strategically critical transmission projects, grid development risks becoming a persistent bottleneck that must be managed ex post through costly measures (Thomassen et al. 2024; Westphal 2022). Reform efforts should therefore simplify decision-making for grid infrastructure and strengthening coordination across governance levels.

More broadly, the comparison shows that sustainability transitions cannot be delivered automatically by competitive markets, nor implemented linearly through hierarchical state control. Effective transitions require a rebalancing of roles between state and market. States must provide direction and absorb risk in long-lived grid infrastructure and system flexibility, while markets play a complementary role in operational dispatch and scarcity signalling. Although the exact balance will vary across institutional contexts, the combined Chinese and German experience points to a common conclusion: only when the grid is treated as a strategic institutional variable rather than a passive technical constraint, can energy-transition pathways become both institutionally robust and physically credible.

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Appendix

(km)	China				Germany			
Year	AC	DC	Total	Growth Rate	AC	DC	Total	Growth Rate
2014	552,621	24,984	577,605	6.20%	34,612	-	34,612	-0.70%
2015	583,685	25,429	609,114	5.46%	35,460	150	35,610	2.88%
2016	616,502	28,808	645,310	5.94%	35,224	990	36,214	1.70%
2017	648,169	37,399	685,568	6.24%	35,991	1,107	37,098	2.44%
2018	683,065	41,995	725,060	5.76%	34,475	1,107	35,582	-4.09%
2019	716,661	42,364	759,025	4.68%	34,683	1,300	35,983	1.13%
2020	766,605	46,324	812,929	7.10%	34,555	1,870	36,425	1.23%
2021	796,083	48,544	844,627	3.90%	32,820	3,059	35,879	-1.50%
2022	821,476	52,142	873,618	3.43%	34,430	1,870	36,300	1.17%
2023	865,953	52,142	918,095	5.09%	35,540	2,160	37,700	3.86%

Table 1. Circuit Length of High-Voltage Electricity Transmission Line, 2014-2023

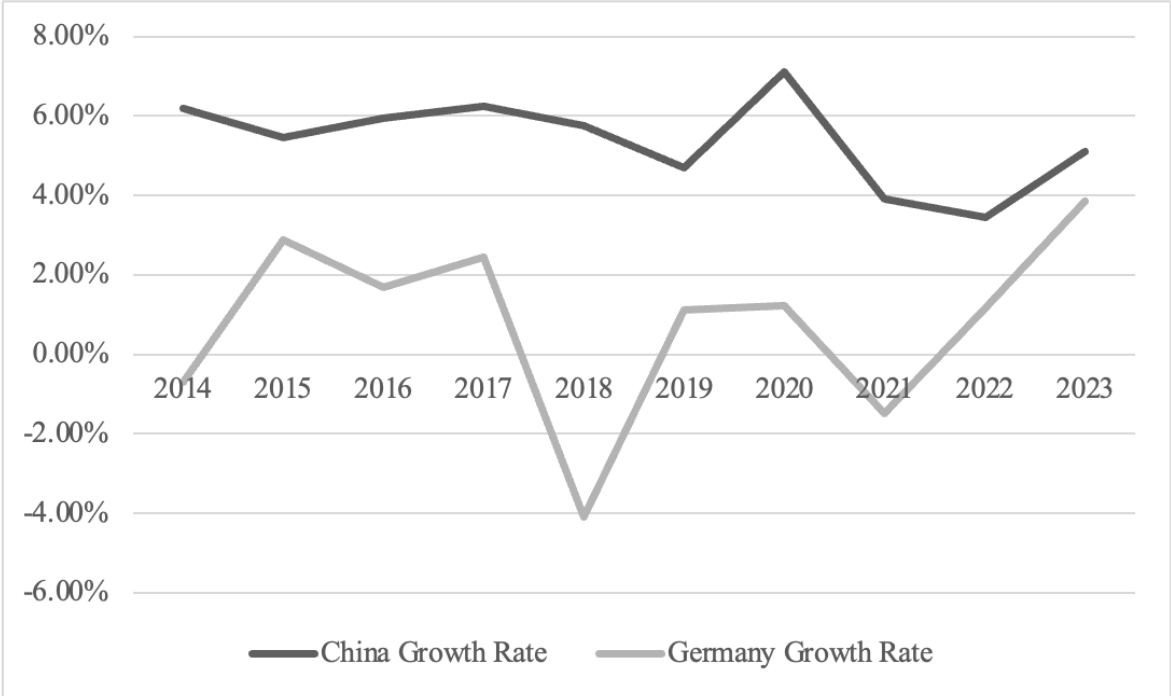


Figure 1. Growth Rate of Circuit Length of High-Voltage Electricity Transmission Line

(Million, EUR)	China				Germany	
Year	AC	DC	Total	Growth Rate	Total	Growth Rate
2014	38,951	2,051	41,002		1,525	
2015	51,344	3,098	54,442	32.78%	2,062	35.21%
2016	54,283	6,731	61,015	12.07%	2,073	0.53%
2017	47,557	11,257	58,815	-3.61%	2,708	30.63%
2018	50,747	6,664	57,412	-2.39%	2,954	9.08%
2019	50,108	3,219	53,327	-7.11%	2,727	-7.68%
2020	45,305	6,764	52,069	-2.36%	3,862	41.62%
2021	47,831	4,983	52,814	1.43%	4,677	21.10%
2022	52,745	4,458	57,203	8.31%	3,917	-16.25%
2024	54,689	1,906	56,596	-1.06%	6,989	78.43%

Table 2. CAPEX for High-Voltage Electricity Transmission Line, 2014-2023

(Thousand, EUR)	China	Germany
2014	70.99	44.06
2015	89.38	57.91
2016	94.55	57.24
2017	85.79	73.00
2018	79.18	83.02
2019	70.26	75.79
2020	64.05	106.03
2021	62.53	130.36
2022	65.48	107.91
2023	61.64	185.38
<b>Average</b>	<b>74.38</b>	<b>92.07</b>

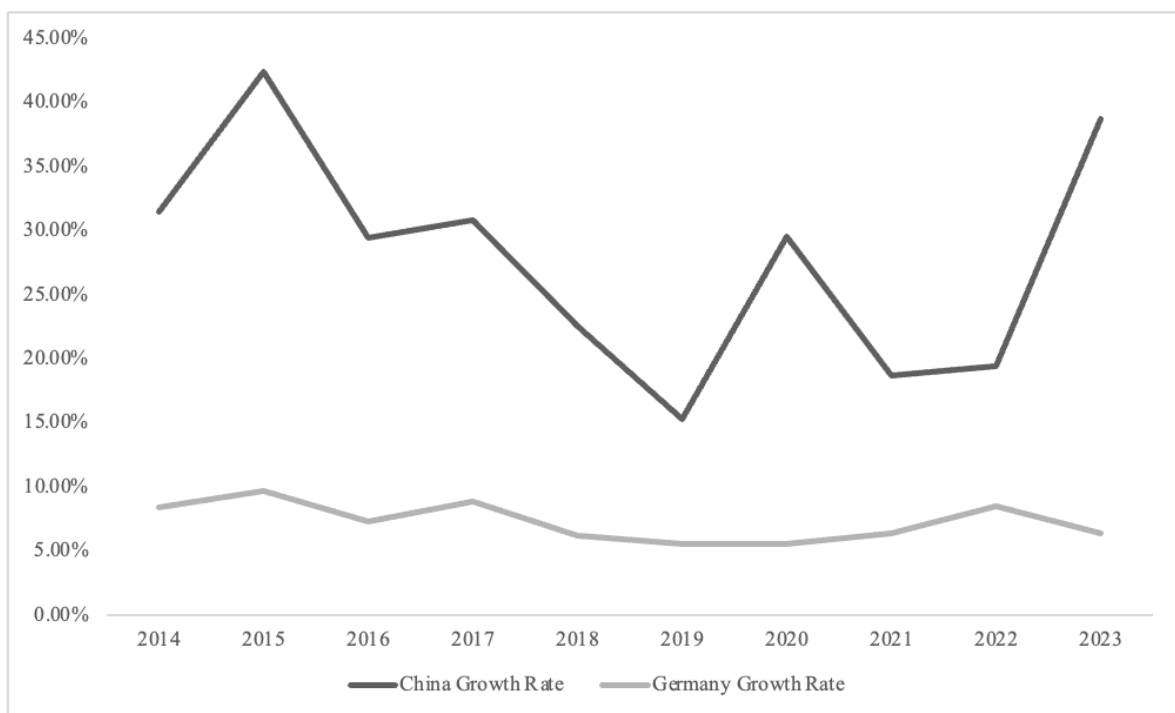
Table 3. CAPEX per kilometre, 2014-2023

(Thousand, EUR)	Sensitivity Factor	China	Germany
Year		Adjusted CAPEX/Total km	Adjusted CAPEX/Total km
2014	3×	65.33	44.06
2015	3×	82.49	57.42
2016	3×	86.80	54.28
2017	3×	77.35	68.88
2018	3×	70.96	78.16
2019	3×	63.20	70.68
2020	3×	57.50	96.15
2021	3×	56.08	111.37
2022	3×	58.50	97.83
2023	3×	55.36	166.33
<b>Average</b>		<b>67.36</b>	<b>84.52</b>

Table 4. Sensitivity Analysis of CAPEX per kilometre, 2014-2023

(MW)	China				Germany			
Year	Solar	Wind	Total	Growth Rate	Solar	Wind	Total	Growth Rate
2014	24,860	96,570	121,430	31.40%	38,236	38,335	76,571	8.39%
2015	42,180	130,750	172,930	42.41%	39,332	44,670	84,002	9.70%
2016	76,310	147,470	223,780	29.40%	40,679	49,435	90,114	7.28%
2017	129,420	163,250	292,670	30.78%	42,339	55,719	98,058	8.82%
2018	174,330	184,270	358,600	22.53%	45,230	58,843	104,074	6.14%
2019	204,180	209,150	413,330	15.26%	49,096	60,721	109,817	5.52%
2020	253,560	281,650	535,210	29.49%	53,721	62,188	115,909	5.55%
2021	306,540	328,710	635,250	18.69%	59,423	63,832	123,255	6.34%
2022	392,680	365,640	758,320	19.37%	67,479	66,163	133,642	8.43%
2023	610,480	441,440	1,051,920	38.72%	73,975	68,154	142,129	6.35%
<b>Average</b>				<b>27.81%</b>				<b>7.25%</b>

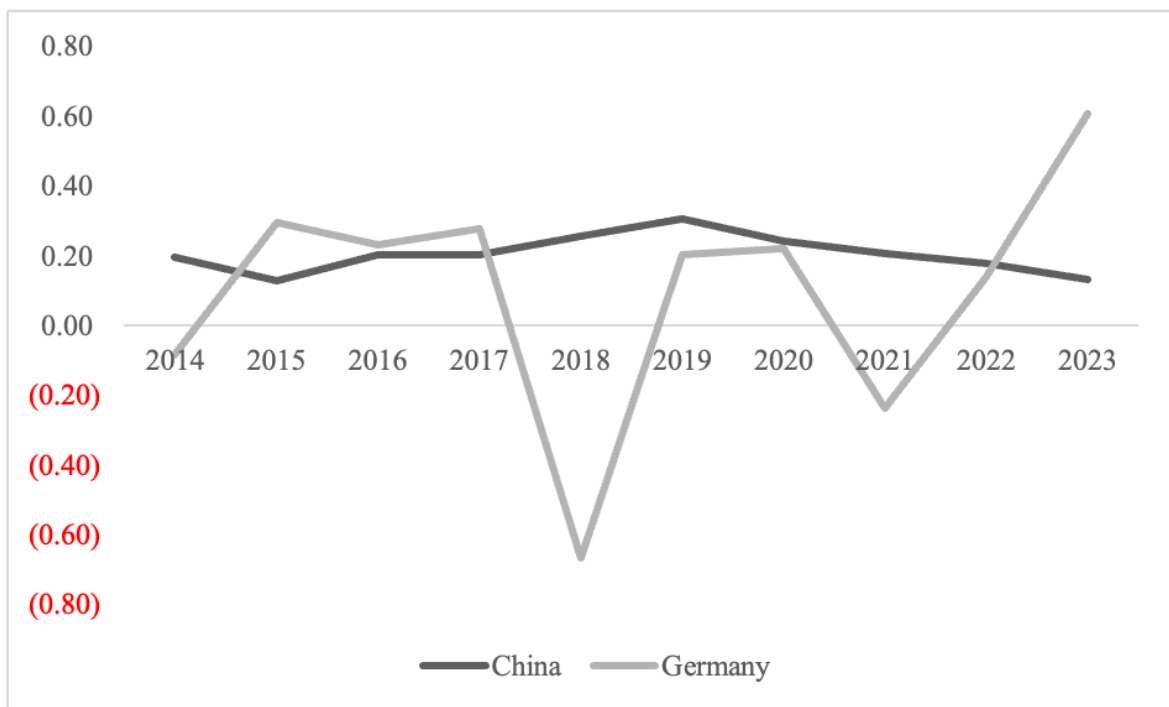
**Table 5.** Installed Capacity of Solar and Wind Energy Generation, 2014-2023



**Figure 2.** Growth Rate of Installed Capacity of Solar and Wind Energy Generation

<b>Year</b>	<b>China</b>	<b>Germany</b>
<b>2014</b>	0.20	-0.08
<b>2015</b>	0.13	0.30
<b>2016</b>	0.20	0.23
<b>2017</b>	0.20	0.28
<b>2018</b>	0.26	-0.67
<b>2019</b>	0.31	0.20
<b>2020</b>	0.24	0.22
<b>2021</b>	0.21	-0.24
<b>2022</b>	0.18	0.14
<b>2023</b>	0.13	0.61
<b>Average</b>	<b>0.21</b>	<b>0.10</b>

**Table 6.** Strategic Matching Ratio, 2014-2023



**Figure 3.** Strategic Matching Ratio, 2014-2023

	China		Germany	
Year	Solar	Wind	Solar	Wind
2014	5.49%	8.00%	0.74%	2.08%
2015	9.20%	15.00%	1.12%	4.95%
2016	10.30%	17.20%	0.53%	4.31%
2017	6.00%	12.00%	1.14%	4.58%
2018	3.00%	7.00%	0.28%	4.64%
2019	2.00%	4.00%	0.18%	4.78%
2020	2.00%	3.00%	0.11%	5.40%
2021	2.00%	3.10%	0.53%	4.67%
2022	1.70%	3.20%	1.15%	5.64%
2023	2.00%	2.70%	1.29%	5.06%
<b>Average</b>	<b>4.37%</b>	<b>7.52%</b>	<b>0.71%</b>	<b>4.61%</b>

Table 7. Curtailment Rates for Solar and Wind Energy, 2014-2023

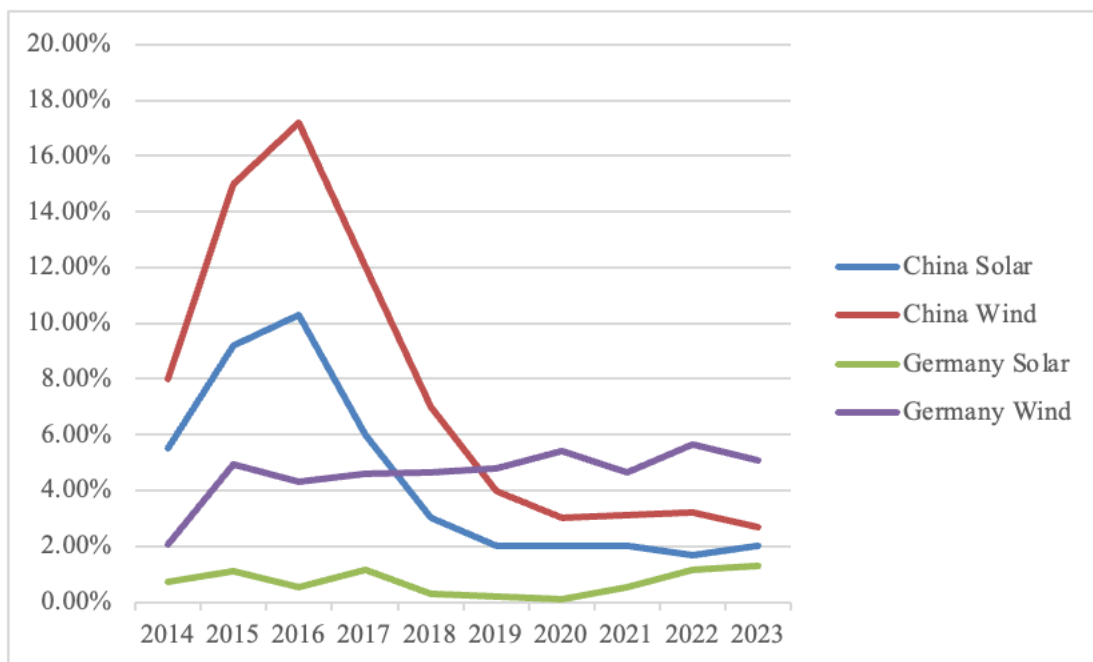


Figure 4. Curtailment Rates for Solar and Wind Energy, 2014-2023