

INSTITUTE OF ENERGY, PEKING UNIVERSITY

FROM SUPPLY ANXIETY TO DEMAND-SIDE RESILIENCE

China's Energy Security Strategy Redefined Amidst Global Shifts





北京大学能源研究院
INSTITUTE OF ENERGY

The Institute of Energy at Peking University is an independent energy think tank affiliated with Peking University. It focuses on strategic policy research, cutting-edge technology research and development, education and training, as well as international exchange and cooperation in the fields of energy and climate.

Leveraging Peking University's strong academic foundation, broad disciplinary strengths, and distinguished faculty from both within and beyond the university, the Institute works closely with partners worldwide to deliver innovative solutions for the sustainable energy transition.

Should you have any comments or suggestions regarding this report, please kindly contact us via email: www.energy@pku.edu.cn

FROM SUPPLY ANXIETY TO DEMAND-SIDE RESILIENCE

**China's Energy Security Strategy Redefined
Amidst Global Shifts**

Institute of Energy, Peking University

April 2026

Acknowledgments

During the preparation of this report, we were fortunate to benefit from the generous guidance and support of many distinguished experts. We would like to express our profound gratitude to **Academician Zhou Xiaoxin** (Honorary President of the China Electric Power Research Institute), **Wu Yin** (former Deputy Administrator of the National Energy Administration of China), and **Professor Xia Qing** (Tsinghua University) for their strategic guidance and invaluable insights, which helped shape the final report.

We also sincerely thank experts from a wide range of sectors for their professional feedback on the draft analysis of typical energy-use scenarios. In particular, we extend our appreciation to **Wang Min** (China National Petroleum & Chemical Planning Institute), **Li Dingjie** (China Petroleum and Chemical Industry Federation), **Zhang Zhaosheng** (National Engineering Research Center of Electric Vehicles at Beijing Institute of Technology), and **Jin Leiming** (DiDi Energy). We are likewise deeply grateful to **Academician Du Xiangwan**, **Senior Research Fellow Li Junfeng**, and **Professor Wang Peng** for their early review and contributions.

Much of the content of this report draws on our sustained research efforts over the years. We would like to thank all partner institutions and experts who supported us throughout this journey. Their valuable perspectives significantly enhanced the quality of this work, although the final content does not necessarily reflect their individual views.

This report was primarily authored by **Zheng Ping**. **Wang Weiwei**, **Wang Qianyu**, **Han Qinke**, **Guo Lingyan**, and **Zhang Lanying** contributed to the preliminary research and drafting of several sections. **Huang Yikun**, **Zheng Mingze**, and **Yu Siyuan** assisted with data compilation and processing. **Yang Lei** served as idea initiator and project planner. The views expressed herein are solely those of the author team and do not represent the official position of Peking University. Any errors or omissions remain the sole responsibility of the authors.

TABLE OF CONTENTS



- Global Energy Transition at a Crossroads and the China Case 1**
- Executive Summary 4**
- Chapter 1 Divergence and Convergence of Energy Strategies Among Major Economies 10**
 - 1.1 Perspective 1: Resource Endowment and Geopolitical Impact 12
 - 1.2 Perspective 2: Clean Energy Supply Chain and Manufacturing 20
 - 1.3 Perspective 3: Transition Agility and Challenges in the Transition 28
 - 1.4 Perspective 4: Infrastructure Capacity and System Vulnerability 34
- Chapter 2 Challenges Facing China 39**
- Chapter 3 Building a Distributed Energy System Driven by “Demand-Side Resilience” 43**
 - 3.1 Concept Redefined 45
 - 3.2 Unlocking Flexibility Resources 46
 - 3.3 Decentralization 49
 - 3.4 Advantages and Barriers 50
- Chapter 4 Typical Scenarios 53**
 - 4.1 Scenario 1: AI Computing Power and Data Centers 55
 - 4.2 Scenario 2: Traditional Heavy Industry (Iron and Steel) 62
 - 4.3 Scenario 3: Chemical Industry 69
 - 4.4 Scenario 4: Electric Vehicles and Vehicle-Grid-Integration 77
 - 4.5 Scenario 5: Industrial Parks 85
- Chapter 5 Mechanism and Policy 92**
 - 5.1 Optimizing Pricing and Market Mechanisms 92
 - 5.2 Redefining the Role of the Dispatch System and the Grid 95
 - 5.3 Rebuilding the Data Infrastructure 98
 - 5.4 Improving Transition Finance Mechanisms 100



Global Energy Transition at a Crossroads and the China Case

As the U.S.-Israel conflict with Iran—set against the backdrop of the ongoing Russia-Ukraine conflict—continues to unfold, the world has been gripped by a renewed sense of energy insecurity. With no clear resolution in sight, countries are being compelled to reassess their energy strategies while managing immediate concerns over oil and gas supply.

A nation's energy strategy is often shaped by two narratives that are at once competing and overlapping: one centered on national security, and the other driven by the moral imperative of climate mitigation and sustainable development. At the strategic level, neither holds inherent moral superiority; both carry strong domestic legitimacy.

Only a year ago, framing energy policy through the lens of decarbonization was widely regarded as unquestionably politically correct. Clean energy dominated the discourse, while fossil fuels were increasingly treated as a problem to be solved within the broader climate agenda. Yet with the recent shift in U.S. policy, the global climate consensus—painstakingly built over the past two decades—has begun to fracture. This has given rise to growing divergence in development pathways, as well as a sober reassessment of energy security and supply-chain competition.

With instability once again engulfing the Middle East, global concern over oil and gas supply has intensified. At this critical moment, attention is returning to non-fossil energy sources—renewables and nuclear power—but from a different perspective. The focus has shifted toward their strategic security advantages. For the first time, the security and climate attributes of clean energy are revealing an unprecedented degree of alignment.

While supply disruptions linked to Middle Eastern tensions have unsettled major economies, many observers note that China—an especially important case in global energy transition strategy—appears comparatively calm and resilient. This is widely attributed to China's sustained efforts to electrify

transport in order to reduce oil dependence, combined with its long-term commitment to expanding renewable energy. Together, these measures are helping to build an energy system that advances both security and decarbonization goals.

Indeed, while the new U.S. administration in 2025 shifted its policy focus back to fossil fuels, China moved in the opposite direction. In its 15th Five-Year Plan (2026-2030), released in early 2026, China explicitly committed to a “ten-year doubling initiative” for non-fossil energy capacity.

At present, the energy choices facing major economies can be broadly divided into two contrasting models: one seeks “energy independence” through the large-scale expansion of non-fossil energy, as exemplified by China; the other doubles down on traditional fossil fuels to preserve existing advantages in market dominance and cost competitiveness, as seen in the United States.

Many other economies now find themselves in a state of hesitation, caught in a wait-and-see mode between these two approaches.

Objectively speaking, however, it would be premature to conclude that China has already made an irreversible transition toward a clean energy system that will fully displace fossil fuels. China’s vast economy remains anchored in a coal-heavy energy structure, with coal still accounting for more than half of primary energy consumption. Even as wind and solar generation have only recently surpassed 20 percent of total electricity output, significant challenges have already emerged: rising system costs, increasing curtailment rates, institutional barriers to market-based resource allocation, and mounting domestic and international pressure on clean energy technology enterprises. These realities suggest that if China is to become a true energy powerhouse, it must undertake deeper structural reforms to enable much higher levels of renewable integration. As acknowledged in Chinese official policy documents, reform has entered “deep waters.”

The window of opportunity for China to demonstrate that a green transition can deliver tangible economic and environmental gains—and thereby shape global perceptions—is narrowing. Over the past year, the United States has not only reversed its energy strategy with remarkable speed, but has also leveraged its low-cost oil and gas resources (with natural gas prices less than one-third of China’s) and geopolitical influence to pull the world back toward a fossil-fuel trajectory. As the U.S. Secretary of Energy has stated, oil and natural gas are the bedrock of restoring American energy dominance. Will clean energy become the foundation of China’s future energy strength—and if so, how long will it take?

This report offers a multi-dimensional analysis to help readers navigate these complexities. Using China as a principal case study in global energy transition, it examines the country's current energy landscape, structural challenges, and historic opportunities, while proposing pathways to overcome existing bottlenecks. We hope that China's experience can provide valuable insights for other economies. In the twentieth century, energy security was defined largely by the possession and control of fossil fuel resources. In this new era, however, it may increasingly be redefined as the ability to maintain an efficient, self-balancing energy ecosystem that remains resilient in the face of external volatility.

Of course, in discussing today's macro-level energy issues, it is neither sufficient to focus solely on energy security or carbon reduction, nor realistic to ignore factors such as geopolitical rivalry and supply-chain fragmentation. To do so would risk detachment from reality. Accordingly, this report adopts a more candid and pragmatic approach, paying particular attention to energy transition through the lenses of security and risk—an emphasis especially evident in its first section.

Nevertheless, we firmly believe that amid the current turmoil in the Middle East, the objectives of energy security and carbon reduction are increasingly converging, especially in relation to clean energy development. We also believe that in shaping national energy strategies, national security and climate governance should be treated as equally important core considerations.

Executive Summary

Focusing on China's energy consumption, production, and manufacturing sectors, this report finds that the country's large-scale deployment of wind and solar capacity over the past decade has delivered globally remarkable achievements on the supply side. However, in the coming decade, unless **"distributed demand-side resilience"** is effectively activated and restructured, this vast expansion of renewable energy may fail to generate meaningful transition benefits. Instead, it could become a growing burden, constrained by limited grid integration capacity and rapidly rising system operating costs.

Traditionally, "resilience" has referred to the grid's ability to restore service quickly after natural disasters, equipment failures, or other disruptions. On the demand side, conventional policy tools have largely centered on electricity conservation, energy-efficiency improvements, or administratively enforced "orderly power consumption." These approaches are increasingly inadequate for addressing the challenges posed by high shares of intermittent renewable energy and broader energy-security risks.

The concept of "demand-side resilience" proposed in this report shifts the focus from simply reducing electricity consumption to enhancing the dynamic adaptability, flexibility, and self-sustaining capacity of end-use energy actors—such as industrial parks, energy-intensive enterprises, data centers, electric vehicles, commercial buildings, and residential communities.

Addressing the challenges of China's energy transition requires a clear understanding of the country's comparative strengths and structural constraints, as well as a fundamental shift from a model of "supply-side breakthrough" to one of "demand-side transformation." Building "distributed demand-side resilience" is not only essential for mitigating external geopolitical energy risks, but also foundational to achieving high-quality economic development.

China's Energy Transition Amid Geopolitical Turbulence: Advantages, Challenges, and the Renewable Energy Integration Dilemma

Against a backdrop of intensifying geopolitical tensions and a rising tide of anti-globalization, China's energy transition exhibits a pronounced duality, with renewable energy integration emerging as the pivotal challenge.

1. China's Structural Vulnerability: Fossil Fuel Dependence and Geopolitical Exposure

China's primary energy vulnerability stems from its continued reliance on the traditional fossil-fuel system. More than 70 percent of crude oil and over 40 percent of natural gas are imported, with supply sources increasingly exposed to geopolitical uncertainty. Transportation routes remain heavily concentrated through critical maritime chokepoints such as the Strait of Malacca and the Strait of Hormuz. Under extreme scenarios, such supply insecurity could become a major constraint on China's energy system.

2. China's Strategic Advantage: The Rise of Renewable Energy

China's relative composure in navigating the energy transition is underpinned by its dominant position across the renewable energy value chain, spanning wind power, solar photovoltaics, and batteries. Accelerating renewable deployment is not only critical for reducing dependence on imported oil and gas and strengthening energy security, but also a strategic response to emerging green trade regimes such as the EU Carbon Border Adjustment Mechanism (CBAM). By leveraging abundant, low-cost green electricity, China's manufacturing sector is well positioned to build a dual competitive moat of low cost and near-zero emissions.

3. Core Challenge: Capacity Expansion Outpacing Renewable Integration

China has achieved globally recognized growth in renewable energy capacity. Yet it now faces a critical challenge: a widening mismatch between rapid capacity expansion and lagging system integration. The inherent variability and intermittency of wind and solar generation are placing increasing strain on the power system. Rising curtailment rates, more frequent negative electricity prices, and escalating system operating costs are beginning to erode the benefits of renewable energy growth.

4. The Way Forward: From Supply-Side Expansion to Demand-Side Resilience

Traditionally, China has sought to address integration challenges primarily through supply-side measures—such as expanding ultra-high-voltage (UHV)

transmission lines and backbone grids, investing heavily in pumped-storage hydropower and battery storage, and adding large amounts of underutilized coal-fired capacity for peak shaving. However, these capital-intensive approaches are facing sharply diminishing marginal returns, and their rising costs are ultimately passed on to end users, thereby undermining broader national competitiveness.

This report therefore advances a central argument: **resolving the renewable energy integration challenge—and achieving a genuine energy transition—cannot rely on supply-side expansion alone. The more urgent and cost-effective priority is to systematically strengthen demand-side resilience.** This means transforming vast end-use loads from passive consumers into active, flexible participants, using distributed, micro-level adaptability to absorb macro-level pressures created by variable renewable generation.

Removing Physical Constraints: Typical Scenarios for Activating Demand-Side Resilience

China possesses the world's largest and most comprehensive industrial and transportation base, providing enormous potential for demand-side flexibility. This report identifies and analyzes five representative scenarios for strengthening demand-side resilience. Preliminary estimates suggest that these scenarios alone could deliver hundreds of gigawatts of low-cost flexible capacity—roughly equivalent to the combined installed capacity of pumped-storage hydropower, battery storage, and flexible gas-fired generation currently in operation.

- ◎ **Scenario 1: Spatiotemporal Coordination Between AI Computing and the Power System.** Data centers are set to become major electricity consumers. Under the “East Data, West Computing” strategy, large volumes of non-real-time computing tasks from eastern regions—such as large-model training—can be dynamically scheduled to align with fluctuations in renewable generation in western regions, enabling millisecond-level workload shifting between eastern and western data centers. This effectively transforms computing networks into a powerful source of flexible demand for renewable integration.
- ◎ **Scenario 2: Electricity-to-Heat Conversion in Heavy Industry.** Hard-to-abate, energy-intensive sectors such as iron and steel and non-ferrous metals should not be viewed solely as decarbonization burdens. Heat-intensive industries can deploy technologies such as molten-salt thermal storage with large temperature differentials and high-temperature

industrial heat pumps to absorb surplus renewable electricity at low cost and convert it into stored thermal energy. This would not only reduce overall energy costs for enterprises, but also transform traditional industrial facilities into large-scale flexible assets that help stabilize the grid.

- ◎ **Scenario 3: Molecule Switching and Flexible Hydrogen Production in the Chemical Industry.** This approach can reduce the chemical sector’s structural dependence on oil, gas, and coal. By deploying flexible electrolyzers to produce green hydrogen at scale during periods of abundant renewable generation, it enables cross-carrier energy storage from electrons to molecules. This would not only create a new growth pathway for the chemical industry with less exposure to fossil-fuel price volatility, but also enhance overall power-system flexibility.
- ◎ **Scenario 4: Building a Hundred-Gigawatt-Scale Vehicle-Grid Integration (VGI) Network.** Electric vehicles are not only transportation tools, but also mobile energy storage units distributed across households and businesses. Through the widespread adoption of smart charging and bidirectional vehicle-to-grid (V2G) technologies, aggregating hundreds of millions of electric vehicles could create a vast mobile storage system, with total capacity far exceeding the country’s installed pumped-storage hydropower capacity.
- ◎ **Scenario 5: Highly Autonomous Zero-Carbon Microgrids in Industrial Parks.** Industrial parks should be encouraged to develop integrated microgrids that combine generation, grid, load, and storage. Through internal multi-energy coordination and complementary resource use, these systems can achieve a high degree of self-sufficiency. In the event of extreme disruptions or large-scale grid outages, such parks could continue operating, providing a resilient foundation for national industrial capacity.

Strengthening Institutional Support: Mechanisms for Enhancing Distributed Demand-Side Resilience

While the potential of these physical scenarios is immense, under the current system most demand-side resources remain largely “dormant.” To convert latent resilience into real operational capability, China must advance reforms in several key areas of top-level institutional design.

1. Price Signals and the Equal Monetization of Flexibility Resources

The current electricity pricing system does not adequately reflect the real-time supply-demand dynamics created by renewable energy. Building on the ongoing development of electricity spot markets, it is essential to accelerate the transmission of spot price signals to a broad base of industrial and commercial users. At the same time, a demand-side capacity compensation mechanism should be established so that enterprises' "negawatts" (their ability to reduce, shift, or optimize electricity consumption) can become tradable assets on a par with generation capacity. This would allow administratively imposed power rationing to be progressively replaced by market-based mechanisms.

2. Grid Reform and the Distributed Sharing of Security Responsibilities

Given the increasingly large-scale and fragmented nature of demand-side resources, the traditional centralized dispatch model is becoming insufficient. It is therefore urgent to redefine the roles and operating models of transmission and distribution networks and to deepen institutional reform. The transmission grid should adopt a system-wide perspective focused on cross-regional balancing, while greater operational autonomy should be delegated to distribution networks and microgrids. Distribution networks, microgrids, and zero-carbon industrial parks should be granted an appropriate degree of dispatch authority and permitted to engage in direct local electricity transactions. At the same time, clear boundaries for system security responsibilities must be established, based on the principle that beneficiaries should bear corresponding costs and risks.

3. Establishing a Foundational Framework for National Energy-Carbon Digital Twins Based on Data Equity

Distributed coordination depends on seamless data connectivity. At present, metering and communications data remain highly concentrated, limiting third-party aggregation and control. Regulators should elevate IoT-enabled energy-carbon digital infrastructure to a strategic priority and establish a clear principle of data rights: namely, that ownership resides with the data creator. A neutral and transparent data exchange platform should be developed to serve as the "nervous system" for microgrid dispatch, while also providing internationally recognized, dynamic carbon-footprint data to support Chinese manufacturers in global markets.

4. Improving Transition Finance and Fiscal Incentives

Flexible retrofits in heavy industry and industrial parks require significant upfront investment, and reliance solely on peak-valley price arbitrage is insufficient to ensure timely cost recovery. Policymakers should introduce

targeted transition-finance instruments, including exploring the securitization of demand-response capabilities as underlying assets so that investors can realize returns at an earlier stage. At the same time, China should implement tangible fiscal incentives to accelerate resilience upgrades across the economy—for example, through investment tax credits and accelerated depreciation for flexibility-enhancing equipment.

The strategic shift from “supply anxiety” to “demand-side resilience” represents a systemic transformation requiring both physical reconfiguration and institutional reform. Over the critical decade ahead (2026–2035), by leveraging its vast renewable energy capacity and activating hundreds of millions of distributed demand-side resilience “cells,” China can not only address the pressing challenge of renewable energy integration and gradually reduce its dependence on imported oil and gas, but also build a highly resilient and green energy system that underpins the low-carbon development of the real economy.

Chapter 1 Divergence and Convergence of Energy Strategies Among Major Economies

Energy has always been closely intertwined with national development. In the 20th century, it was primarily viewed as a cost factor and a form of logistical support for economic and social activities. Today, however, building on traditional energy trade, clean energy industries have emerged as one of the most important engines of economic growth. From 2013 to 2022, global trade in solar energy equipment grew by 56%, while trade in wind energy equipment increased by 39%, significantly outpacing the 23% growth¹ in overall industrial goods trade. In 2023, clean energy industries contributed approximately \$320 billion to global economic growth, accounting for around 10% of total global GDP growth.²

More profound transformations are being driven by the interplay between technology and geopolitics. First, the artificial intelligence (AI) revolution has entered a phase of explosive growth in computing demand, making the stability and cost of energy supply critical determinants of a country's AI competitiveness. Second, as the consensus underpinning globalization weakens, the United States has adopted an “America First” policy, while Europe appears to be moving—actively or passively—toward a more “Europe First” orientation. In this context, energy systems are no longer viewed merely

-
- 1 UNCTAD. Trade in renewable energy powers ahead, but barriers slow transition. November 2025. [<https://unctad.org/news/trade-renewable-energy-powers-ahead-barriers-slow-transition>]. The report highlights the significant contribution of the green energy equipment manufacturing sector and its associated activities to global GDP growth.
 - 2 IEA. Clean energy is boosting economic growth. April 2024. <https://www.iea.org/commentaries/clean-energy-is-boosting-economic-growth>. The study analyzes three categories of clean energy-related economic activities: the manufacturing of clean energy technologies, the deployment of clean power capacity, and clean equipment sales (such as electric vehicles and heat pumps). The analysis reveals that in 2023, while the U.S. GDP grew by 2.5%, the contribution from clean energy growth accounted for 6%—a figure comparable to the contribution of the highly sought-after AI-related industries. During the same period, China's GDP grew by 5.2%, with clean energy contributing a staggering 20%. Furthermore, some analyses suggest that in 2025, the clean energy technology sector contributed nearly 30% of China's total GDP growth. Carbon Brief. Analysis: Clean energy drove more than a third of China's GDP growth in 2025. February 2026. <https://www.carbonbrief.org/analysis-clean-energy-drove-more-than-a-third-of-chinas-gdp-growth-in-2025/>

in terms of resource development and supply capacity, but are increasingly linked to supply chain resilience and the ability to hedge against geopolitical risks.

This chapter updates the analysis of energy development in China, the United States, the European Union, and other major economies from four perspectives: resource endowment, supply chains, transition performance, and infrastructure. It argues that the global consensus on the energy transition—still widely embraced just a year ago—has been shattered, giving way to divergent strategies centered on security and resilience.

Taking China and the United States as examples, their energy strategies reflect two distinct priorities: one pursuing energy independence and sustainability through the large-scale deployment of clean energy such as wind and solar,³ and the other seeking to preserve energy competitiveness by reverting to a fossil fuel-based system dominated by oil, gas, and coal. Since the new U.S. administration took office in 2025, the United States has aimed to leverage its geopolitical influence and domestic resource endowment to steer both itself and the rest of the world back toward a traditional fossil fuel trajectory in which it holds absolute dominance.

China, by contrast, has pursued an alternative pathway by placing strategic emphasis on clean energy. Over the past decade, it has significantly expanded its installed clean energy capacity and established strong advantages in clean energy technologies, equipment manufacturing, and critical mineral processing—factors that have also contributed substantially to economic growth. However, China’s fundamental objective extends beyond export-driven growth: it seeks to strengthen control over its energy lifelines and gradually reduce its heavy reliance on energy imports.

However, the key to achieving China’s strategic objectives does not lie in how many solar panels or wind turbines it can manufacture, export, or install domestically. Rather, it hinges on whether China can realize large-scale, highly stable utilization of clean energy within its vast energy system—what is referred to in policy context as a “high level of renewable energy integration.” This represents the most critical and challenging step toward energy independence. If successful, China will gain greater flexibility in navigating future geopolitical energy tensions, assume a leading role in the global low-carbon transformation of supply chains, and provide a replicable model for other economies pursuing energy transition.

³ In the context of Chinese policy, wind, solar, and biomass are collectively referred to as “New Energy,” with a particular emphasis on the former two. To avoid repetition, within this report—and unless otherwise specified—the terms “Clean Energy”, “Renewable Energy” and “New Energy” are used synonymously within the scope of wind, solar, and biomass power.

1.1 Perspective 1: Resource Endowment and Geopolitical Impact

Today, the definition of “resources” has expanded beyond a narrow focus on underground energy reserves to encompass a broader mix of fossil fuels, renewable energy potential, and critical mineral supply chains (such as lithium, cobalt, nickel, and rare earth elements). Within this multidimensional resource landscape, China, the United States, and Europe display distinct endowments and strategic choices.

United States: Reasserting Its Fossil Fuel Dominance and Geopolitical Leverage

Since Donald Trump returned to the White House in 2025, U.S. energy strategy has undergone a marked policy reversal. The administration declared a “national energy emergency” and issued the executive order *Unleashing American Energy*, emphasizing expanded development of oil, natural gas, and coal, as well as accelerated energy infrastructure construction, in order to fully leverage the United States’ advantage in fossil fuels.⁴ In 2025, U.S. crude oil production reached a record 13.6 million barrels per day,⁵ consolidating its position as the world’s largest producer of oil and gas and a major exporter.⁶

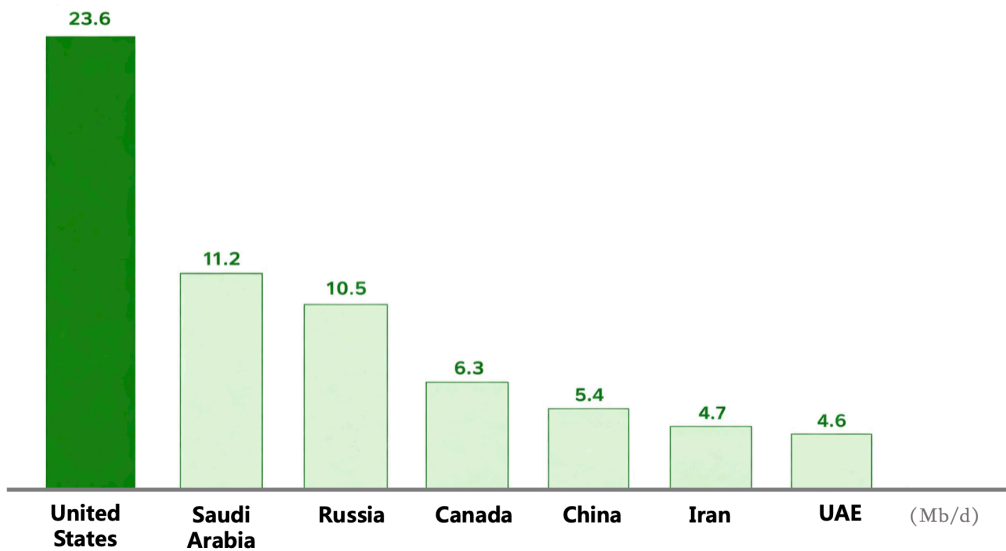
4 The White House. Executive Order 14154 — Unleashing American Energy. January 2025. <https://www.whitehouse.gov/presidential-actions/2025/01/unleashing-american-energy/>. The White House issued directives to federal agencies to suspend, revise, or rescind regulations deemed unnecessary or even obstructive to energy development, particularly in sectors such as oil, natural gas, coal, and hydropower.

5 EIA (The U.S. Energy Information Administration). EIA forecasts near-term U.S. crude oil production will remain near 2025 record, <https://www.eia.gov/todayinenergy/detail.php?id=67045>.

6 According to EIA data, in 2025, U.S. crude oil production maintained its position as the world leader in 2025, reaching a record average of 13.6 million barrels per day (b/d). Natural gas production reached approximately 47.7 trillion cubic feet (1.35 trillion cubic meters), also ranking first globally. Crude oil exports totaled approximately 1.455 billion barrels per year (nearly 4 million b/d), placing the U.S. among the world’s top three crude oil exporters. Furthermore, with natural gas exports reaching 0.254 trillion cubic meters, the U.S. continued to hold its status as the world’s largest natural gas exporter. https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbldpd_a.htm

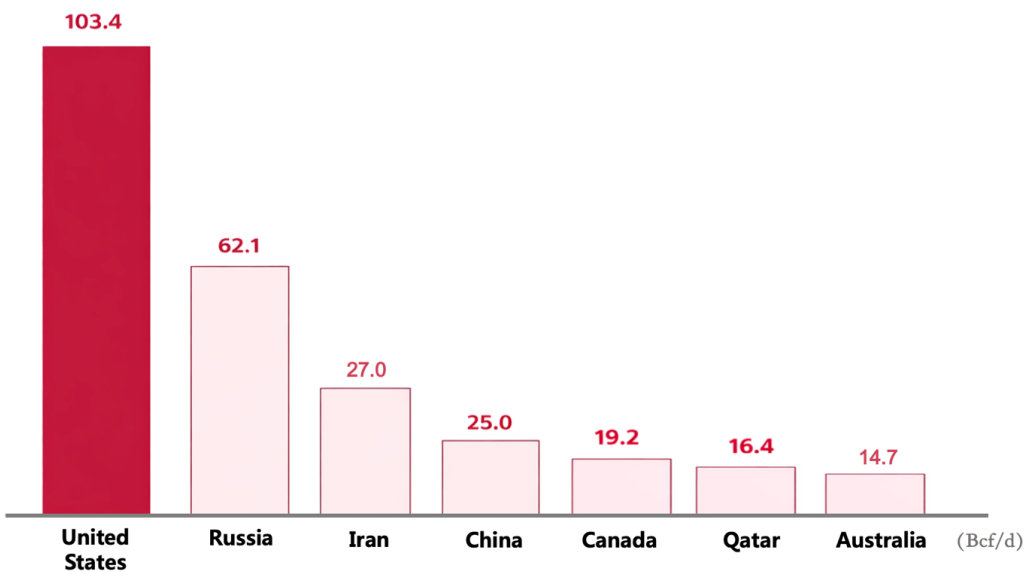
According to information from the U.S. Department of Energy (DOE) and the EIA, since the Trump administration took office in 2025, U.S. oil and gas production and exports have both reached new records. The nation’s production of oil and other liquid fuels now exceeds the combined output of Saudi Arabia and Russia (ranked second and third, respectively). Furthermore, U.S. natural gas production has surpassed the combined total of Russia, Iran, and China—the world’s second, third, and fourth largest producers. <https://www.energy.gov/state-american-energy-promises-made-promises-kept>; <https://www.energy.gov/articles/fact-sheet-delivering-us-oil-and-natural-gas-production>; <https://www.eia.gov/international/data/world/petroleum-and-other-liquids/annual-petroleum-and-other-liquids-production?>; <https://www.eia.gov/international/data/world/natural-gas/dry-natural-gas-production?>

Figure I-1: Oil and Liquid Fuels Production in the United States and Selected Countries (2025)



Source: US Energy Information Administration (EIA)

Figure I-2: Natural Gas Production in the United States and Selected Countries (2025)

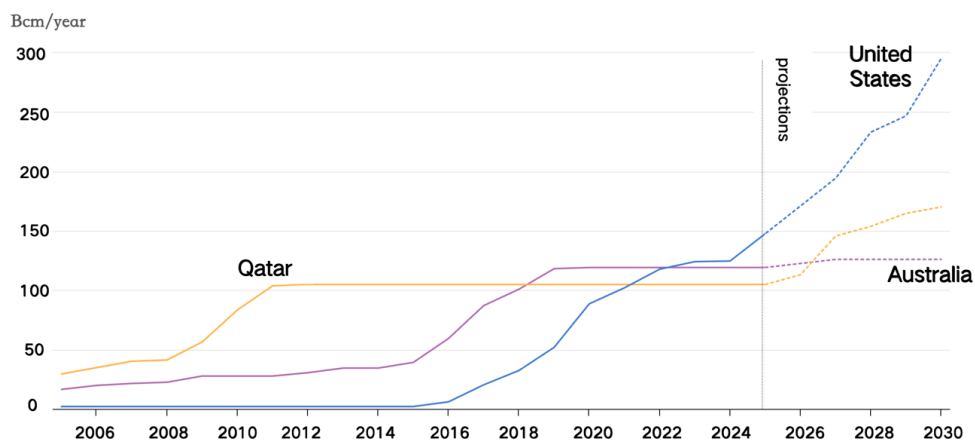


Source: US Energy Information Administration (EIA)

It is important to note that while the Trump administration's energy policies tilt toward fossil fuels, this does not imply a rapid cooling of domestic clean energy development. In fact, due to the surging electricity demand from end-users such as data centers—combined with the advantages of shorter construction cycles and lower costs—clean energy continued to dominate new power capacity additions in the U.S. in 2026. According to EIA statistics, planned utility-scale capacity additions in the U.S. for 2026 are set to reach a record 86 GW. Of this total, solar PV, battery storage, and wind power account for 51%, 28%, and 14%, respectively, while natural gas-power generation accounts for only 7%. EIA. New U.S. electric generating capacity expected to reach a record high in 2026. February 2026. <https://www.eia.gov/todayinenergy/detail.php?id=67205>

The United States’ influence extends well beyond its role as a major energy exporter. Through diplomatic pressure and security arrangements with key oil-producing countries in the Middle East, as well as targeted sanctions and restrictions on countries such as Russia, Venezuela, and Iran,⁷ U.S. energy influence has been further strengthened. In global markets, the United States plays a central role in shaping the flows and pricing dynamics of fossil fuels.⁸ Its strategic logic is clear: as long as the lifeline of the global economy continues to depend on oil and natural gas, the United States can exert effective leverage over other economies through its position within this critical energy supply system.

Figure I-3: LNG Export Capacity of the United States and Selected Countries (2005–2030)



Source: International Energy Agency (IEA)

In the field of critical minerals, although the United States has limited domestic extraction capacity, it is seeking to build supply chains less dependent on China⁹ through strategic alliances such as the Minerals Security Partnership, leveraging a “friend-shoring” strategy.¹⁰ In February 2026, the United States convened a Critical Minerals Ministerial meeting, bringing together participants including the European Union, Japan, India,

7 In the opening months of 2026, as this paper was nearing completion, the United States expanded its involvement in Venezuela’s energy sector in early January; subsequently, in late February, tensions involving the U.S, Israel, and Iran intensified.

8 IEA. World Energy Outlook 2025. <https://www.iea.org/reports/world-energy-outlook-2025/executive-summary>; <https://iea.blob.core.windows.net/assets/81980a53-9716-47f1-904e-b92a2c4d2ea4/WorldEnergyOutlook2025.pdf>.

9 U.S. Department of State, House of Representatives. Minerals Security Partnership Authorization Act. July 2025. <https://www.congress.gov/bill/119th-congress/house-bill/4391/text/ih>. The document explicitly states that the United States must reduce its reliance on critical mineral supply chains that are heavily concentrated in certain countries, including China.

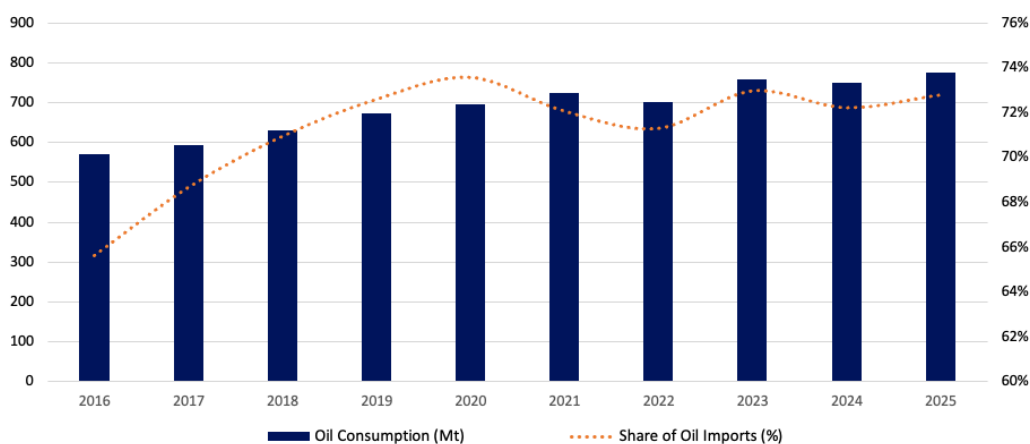
10 In simple terms, “friend-shoring” refers to shifting supply chains and production activities to trusted partners with shared values, with the aim of reducing reliance on concentrated supply sources.

and Australia to discuss supply chain resilience and strategic security.¹¹ The meeting signaled that the United States is advancing supply chain restructuring across mining, processing, and investment in critical minerals through multilateral cooperation. Its core objective is to reduce reliance on China in critical minerals supply chain and to build a more independent supply system.

China: Oil and Gas Vulnerabilities, Coal as a Stabilizer, and Structural Breakthroughs in Clean Energy

China’s energy resource endowment exhibits a somewhat pronounced structural imbalance. On the one hand, China is the world’s largest energy importer, with over 70% of its crude oil and more than 40% of its natural gas reliant on imports.¹² Supply security risks associated with critical chokepoints such as the Strait of Malacca and the Strait of Hormuz, as well as the potential disruption of imports under extreme geopolitical conflicts, remain a persistent strategic vulnerability for China.

Figure I-4: China’s Oil Consumption and Import Share (2016–2025)

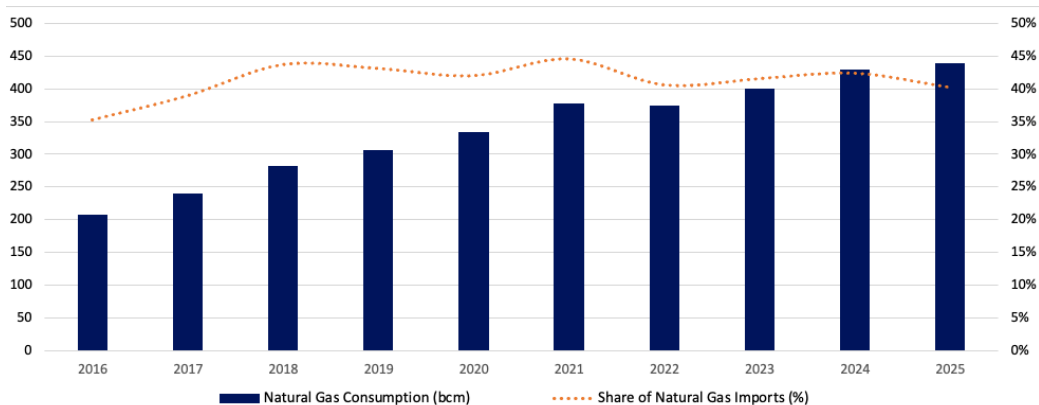


Sources: National Bureau of Statistics (NBS), National Energy Administration (NEA), General Administration of Customs (GACC)

Figure I-5: China’s Natural Gas Consumption and Import Share (2016–2025)

11 U.S. Embassy in China. 2026 Critical Minerals Ministerial (CMM). February 2026. <https://china.usembassy-china.org.cn/zh/2026-critical-minerals-ministerial/>

12 National Bureau of Statistics. <https://www.stats.gov.cn/sj/ndsj/2025/indexch.htm>



Sources: National Bureau of Statistics (NBS), National Energy Administration (NEA), General Administration of Customs (GACC)

To address this systemic vulnerability, China has adopted a “dual-track” strategy. First, under adverse geopolitical conditions, it continues to rely on coal—its most abundant domestic energy resource—as a strategic anchor. In 2025, China’s coal production reached a record high, further reinforcing its role as an “emergency stabilizer.”¹³ In extreme scenarios involving geopolitical conflict or supply chain disruption, China’s massive domestic coal capacity serves as a critical safeguard for economic and social stability.¹⁴ Second, China is advancing renewable energy development at an astonishing pace, aiming to transform it into an “endogenous” domestic resource that can progressively substitute for imported oil and gas, as well as high-carbon coal. However, the transition has now reached a critical juncture, shifting from quantitative expansion to qualitative transformation. The pressing challenge lies in converting these abundant natural resources into reliably usable electricity and other forms of energy.

In terms of critical energy mineral reserves, China holds approximately 10% of global lithium, 28% of graphite, 49% of rare earth elements, and 20% of zinc. At the same time, China also dominates global extraction (including through overseas equity stakes) and refining activities. For example, China accounts for 22% of global lithium extraction, 61% of rare earth production, and 87% of natural graphite output, while controlling 44% of global copper refining, 70–75% of lithium and cobalt processing, and over 90% of rare earth and battery-grade graphite refining.¹⁵

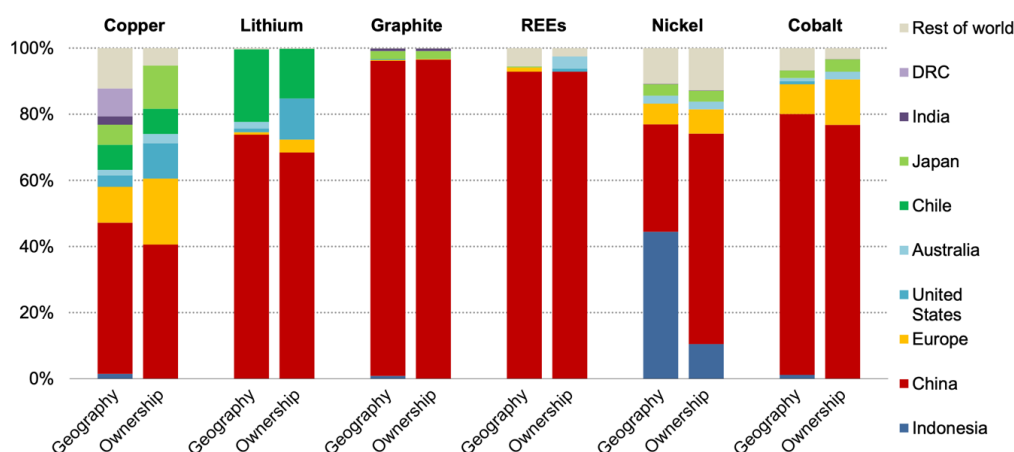
13 National Bureau of Statistics (NBS). *Energy Production in December 2025*. January 19, 2026. https://www.stats.gov.cn/sj/zxfb/202601/t20260119_1962322.html Data reveals that China’s raw coal production from enterprises above designated size reached a record high of 4.83 billion tonnes in 2025, representing a 1.2% year-on-year increase.

14 National Development and Reform Commission (NDRC). *Implementation Opinions on Establishing a Coal Capacity Reserve System* (NDRC Energy Regulation [2024] No. 413). April 2024. https://www.gov.cn/zhengce/zhengceku/202404/content_6944907.htm. The document specifically highlights the backup role of coal in ensuring energy security and supply.

15 IEA. *Global Critical Minerals Outlook 2025*. June 2025. <https://iea.blob.core.windows.net/assets/ef5e9b70-3374-4caa-ba9d-19c72253bfc4/GlobalCriticalMineralsOutlook2025.pdf>. The report notes that China holds a

However, this dominance is a double-edged sword: large volumes of raw materials still need to be imported from regions such as Africa and Latin America, meaning that China’s position in critical minerals ultimately depends on a vulnerable transnational supply chain that is highly exposed to geopolitical disruption.

Figure I-6: Regional Distribution of Critical Mineral Refining Capacity (2024)



Source: IEA analysis based on S&P Global and Wood Mackenzie. Notes: DRC = Democratic Republic of the Congo. Ownership based on company headquarters location. For projects run by multiple companies, production is assigned to the company with the largest share. For copper, data are on the top 20 mining companies in 2024 representing 56% of production. For lithium, data cover 100% of production in 2024. For rare earths, data cover 94% of production. For nickel, data cover 91% of production. For cobalt, data cover 94% of production. Rare earths are total rare earths.

OPEC and Russia: Traditional Producers and Strategic Anchors

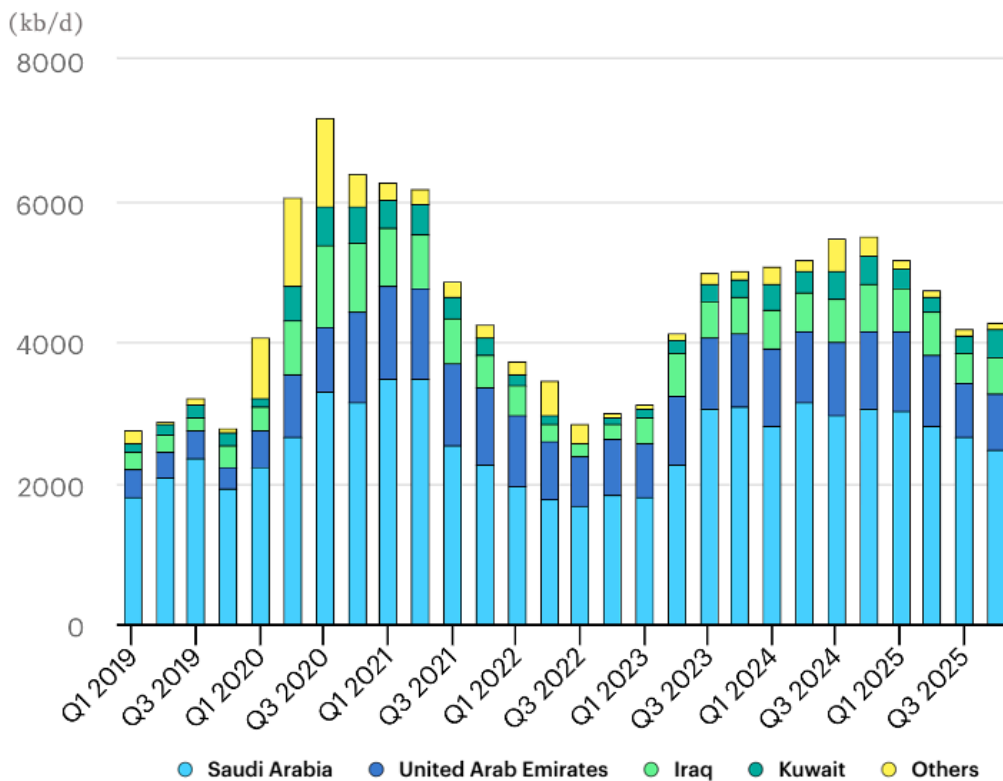
In today’s multipolar energy landscape, OPEC members led by Saudi Arabia, together with Russia, remain pivotal levers of resource leverage. Saudi Arabia, with its substantial spare capacity and central role in future supply expansion, exerts significant influence over supply flexibility and overall market balance.¹⁶ Despite ongoing sanctions following the Russia-Ukraine conflict, Russia remains a highly consequential force in global supply, through its “shadow fleet” and expansion into Eastern markets.

significant share of the global reserves, extraction, and processing of many critical minerals.

16 IEA. Oil 2025. <https://www.iea.org/reports/oil-2025>. The report predicts that Saudi Arabia will lead the overall capacity growth of OPEC+ through 2030.

IEA. Strait of Hormuz Factsheet. February 2026. <https://www.iea.org/about/oil-security-and-emergency-response/strait-of-hormuz>

Figure I-7: OPEC Oil Effective Spare Capacity (2019–2025)



Source: International Energy Agency (IEA). Note: Others includes the rest of OPEC-13 but excludes Iranian and Venezuelan crude under sanctions.

European Union: Governance-Based Breakthrough Amid Resource Constraints

Compared with China and the United States, the European Union (and several major European economies) faces a structural disadvantage in physical resource endowments. Following the 2022 Russia-Ukraine conflict, Europe incurred substantial economic costs in reducing its reliance on low-cost Russian pipeline gas, exposing its pronounced vulnerability in fossil fuel supply.¹⁷

However, this very scarcity has propelled Europe to the forefront of global innovation in energy efficiency management, demand-side response, and governance frameworks. The EU is not only accelerating the deployment of offshore wind in its domestic waters and the North Sea, but also seeking to

¹⁷ European Commission. EU action to address the energy crisis. https://commission.europa.eu/topics/energy/eu-action-address-energy-crisis_en. The article points out that the Russia-Ukraine conflict triggered an unprecedented energy crisis within the European Union, while summarizing the measures taken by Europe to address the crisis.

transform its leadership in “green rules” into a new form of strategic resource. Through measures such as the Carbon Border Adjustment Mechanism (CBAM), Europe aims to set carbon thresholds that reduce the cost advantages of fossil fuel-rich economies, thereby establishing its influence in the low-carbon economic order despite its lack of fossil fuel resources.¹⁸

18 European Union. Carbon Border Adjustment Mechanism. 2026. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en. Within the European Union, carbon pricing is applied to domestic production through the EU Emissions Trading System (EU ETS), while the Carbon Border Adjustment Mechanism (CBAM) imposes a carbon price adjustment on imported goods. By increasing the cost of exports from carbon-intensive economies entering the EU market, these mechanisms thereby help to safeguard the competitiveness of European industries.

1.2 Perspective 2: Clean Energy Supply Chain and Manufacturing

While resource distribution is largely determined by nature, the manufacturing landscape is shaped by deliberate industrial policy and capital allocation. Over the past decade, clean energy technologies—such as solar and wind power, battery storage, heat pumps, and grid equipment—have evolved from niche environmental sectors into major engines of global economic growth. In 2025, global investment in the energy transition exceeded \$2.3 trillion, and value added from related manufacturing has become a key driver of GDP growth across major industrial economies.¹⁹

In this domain, China commands the majority of global manufacturing capacity and associated manufacturing benefits, while the United States and Europe, in pursuit of “supply chain security,” are seeking to build parallel supply chains domestically and among trusted partners—albeit at the cost of a “security premium.”

China: Absolute Dominance and Domestic Cutthroat Competition

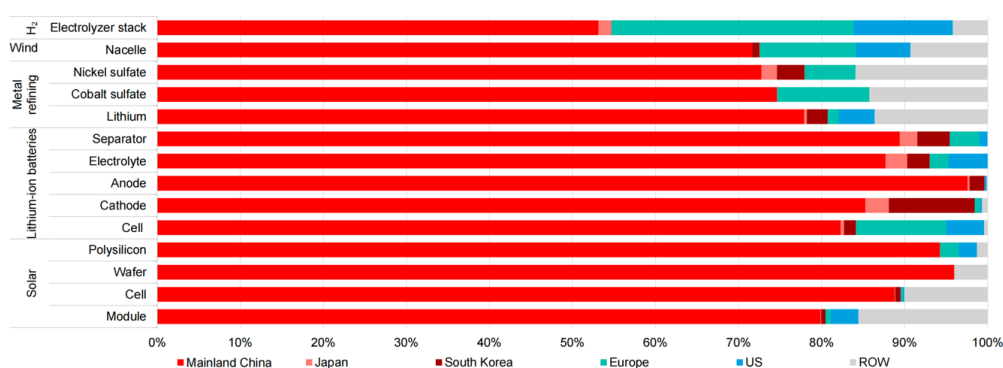
In its efforts to strengthen energy security through the aggressive development of clean energy, China has generated an unexpected “byproduct”—a technological edge in clean energy. In the manufacturing of clean energy equipment, China now occupies a dominant position, extending well beyond final assembly to encompass the entire vertically integrated value chain, from raw material processing to the production of core components.

Manufacturing benefits: As of 2025, China has established a highly concentrated advantage across key segments of the global solar manufacturing industry, producing 96.0% of polysilicon, 96.2% of wafers,

¹⁹ BloombergNEF (BNEF), <https://about.bnef.com/insights/clean-energy/bloombergnef-finds-global-energy-transition-investment-reached-record-2-3-trillion-in-2025-up-8-from-2024/>. January 2026. BloombergNEF (BNEF) reports that global energy transition investment reached \$2.3 trillion in 2025, with \$127 billion flowing into the manufacturing segment of the clean energy supply chain. Investment in electrified transport, renewable energy, and power grids emerged as the primary drivers, indicating that the energy transition is becoming a vital force in driving global industrial investment and structural upgrading.

91.3% of batteries, and 80.1% of modules.²⁰ In the power and energy storage battery sector, China remains a dominant player, with nearly 85% of global battery cell production capacity.²¹ This massive scale has translated into substantial manufacturing benefits. Against the backdrop of a slowdown in domestic real estate and traditional infrastructure investment over the past two years, the clean energy industry—represented by the “new three” sectors (electric vehicles, lithium batteries, and solar cells)—has emerged as a major engine of economic growth and high-quality employment in China.

Figure I-8: Clean Energy Manufacturing Capacity by Location (2024)



Source: BloombergNEF. Notes: Chart reflects the share of capacity by market and is based on the locations of production facilities (not location of corporate parents). Solar photovoltaic, hydrogen and battery components expressed in megawatts, megawatt-hours, square meters or metric tons.

The paradox of “excessive domestic competition” and strategic losses:

Despite its dominant position, China is experiencing intense, and at times destructive, competition within its domestic industrial ecosystem. Following aggressive capacity expansion in previous years, the solar and battery sectors have experienced rapid growth with substantial excess capacity. Taking the solar sector in 2025 as an example, earnings guidance from A-share listed companies suggests that the industry remains broadly loss-making, with the majority of firms continuing to operate at a loss. TCL Zhonghuan, for instance,

20 Beijing Daily. *China’s Solar Power Supply Chain Maintains Global Dominance; Addressing Internal Cutthroat Competition Remains the Top Priority*. February 2026. <https://xinwen.bjd.com.cn/content/s69853eb9e4b0687a2890d6b7.html>. At the seminar on “2025 Development Review and 2026 Outlook” hosted by the China Photovoltaic Industry Association (CPIA), Wang Bohua, an advisor to the association, released statistics confirming that China’s solar power supply chain continues to hold a dominant position globally.

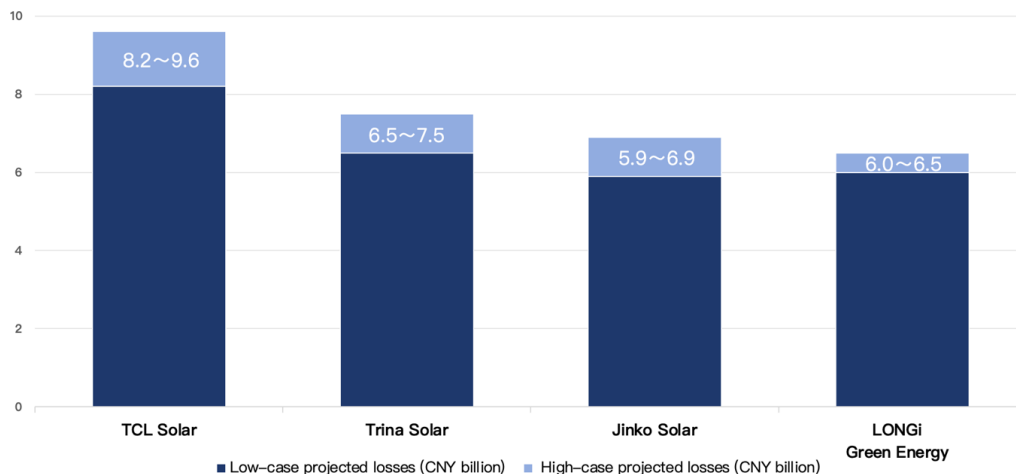
21 IEA. *Status of battery demand and supply*. 2025. <https://www.iea.org/reports/batteries-and-secure-energy-transitions/status-of-battery-demand-and-supply>.

BloombergNEF. *Clean Energy Trade and Emerging Markets*. October 2025. <https://about.bnef.com/insights/clean-energy/clean-energy-trade-and-emerging-markets-the-impact-of-tariffs-on-the-energy-transition/>

Regarding the production capacity of products such as solar panels, wind turbines, and lithium batteries, statistical data varies across different organizations due to discrepancies in statistical scope and methodology. For instance, there are slight differences in specific figures provided by the China Photovoltaic Industry Association (CPIA), the IEA, and BloombergNEF (BNEF).

is expected to report losses of RMB 8.2–9.6 billion, while other leading players such as Trina Solar, LONGi Green Energy, and JinkoSolar are projected to post losses in the range of RMB 6–7.5 billion.²²

Figure I-9: Loss Amount of Listed Companies in China’s Photovoltaic Industry (2025)



Source: CNINFO

This has produced a seemingly paradoxical situation: many Chinese companies that have achieved absolute global leadership, while expanding rapidly in international markets, are incurring huge financial losses. From a purely commercial perspective, this is a “Pyrrhic victory.” However, at the national level, the fact that such fierce competition has driven prices to global lows has effectively created a formidable cost moat. As a result, other economies seeking to rebuild domestic clean energy manufacturing face this cost moat. At the same time, how to steer the industry toward more rational and sustainable growth remains a shared challenge for both China and the rest of the world.

22 People’s Daily. *Listed Solar Power Companies Continue to Face Earnings Pressure in 2025*. January 2026. https://paper.people.com.cn/zgnyb/pad/content/202601/26/content_30136309.html; CNINFO. *2025 Annual Corporate Earnings Guidance Reports*. <http://www.cninfo.com.cn/new/fulltextSearch?>

United States: Uncertainty in Manufacturing Reshoring and the Pursuit of Nuclear

In response to China's manufacturing dominance, the United States has, over the past five years, sought to accelerate the reshoring of manufacturing. It aims both to bring supply chains and key production processes back onshore and to attract foreign investment into U.S.-based manufacturing. In particular, the landmark Inflation Reduction Act (IRA) of 2022 has deployed hundreds of billions of dollars in fiscal subsidies to redirect supply chains. However, the United States still has some challenges to overcome, despite some progress.

Progress and uncertainty in reshoring: Following the implementation of the IRA, fiscal incentives—such as the Section 45X Advanced Manufacturing Production Tax Credit—have driven manufacturing to become the fastest-growing segment of U.S. clean energy investment, particularly in batteries, solar modules, and electric vehicles. Investment nearly tripled from \$2.5 billion in Q3 2022, when the IRA was enacted, to \$14 billion in Q1 2025. Over this period, companies announced a total of 380 manufacturing projects, nearly half of which were operational by early 2025, thereby strengthening domestic manufacturing capacity and local supply chains.²³ The clean power manufacturing sector contributes approximately \$18 billion annually to U.S. GDP and supports more than 120,000 jobs.²⁴ However, some projects have been canceled or delayed due to the Trump administration's policy shifts toward fossil fuels, as well as trade tensions and increasing uncertainty in market demand.

Small modular reactors (SMRs)—the United States' strategic hedge: Given its limited prospects for securing a competitive position in wind and solar energy and storage supply chains, as well as emerging sustainability challenges in the current energy system, the United States is exploring the possibility of leapfrogging through technological shifts. Amid surging electricity demand from AI-driven computing and data centers, both the U.S. government and major technology companies—such as Google, Amazon, and Microsoft—are shifting their strategic focus toward small modular reactors (SMRs) and next-generation nuclear technologies.²⁵ An increasing number of technology firms

23 Clean Investment Monitor. The State of US Clean Energy Supply Chains in 2025. April 2025. According to the report's tracking data, U.S. domestic manufacturing capacity for batteries and solar modules is already sufficient to meet local demand. Furthermore, it is anticipated that market demand for electric vehicles (EVs) and grid-scale energy storage can also be met by 2035. <https://www.cleaninvestmentmonitor.org/reports/us-clean-energy-supply-chains-2025>

24 American Clean Power Association (ACP). The State of Clean Energy Manufacturing in America. May 2025. <https://cleanpower.org/resources/america-builds-power/>

25 CNBC. Google signs deal with nuclear company as data center power demand surges. October 2024. <https://www.cnbc.com/2024/10/14/google-signs-deal-with-nuclear-company-as-data-center-power-demand-surges.html> Google has signed an agreement with Kairos Power, a Small Modular Reactor (SMR) company, to purchase electricity from the latter.

are incorporating nuclear energy into their long-term energy strategies to meet the massive power demand of data centers.

The United States is not only a global leader in SMR design and development, but also views this technology as a key technological pillar of its future energy competitiveness. By shaping global standards in SMR technology and manufacturing, the U.S. aims to build a new energy supply chain aligned with its “America First” strategy, thereby strengthening its position in the future competition over both computing power and energy.

European Union: Defensive Industrial Policy and the Pain of “De-risking”

While the United States retains the confidence to regain its advantage by returning to familiar pathways or forging new technological trajectories, the European Union faces a far more difficult and painful process in restructuring its supply chains.

Challenges in reviving manufacturing: In 2024, the EU introduced the Net-Zero Industry Act, setting an ambitious target for domestic net-zero technology manufacturing capacity to meet 40% of annual deployment needs by 2030.²⁶ However, intense competition from low-cost Chinese solar components, combined with the pull of U.S. IRA subsidies, has placed Europe’s domestic clean energy manufacturing sector under significant pressure.

For example, Meyer Burger, a long-established European solar firm, has closed its solar module manufacturing facilities in Germany and had planned to shift production to the United States; however, it subsequently fell into financial distress and entered restructuring.²⁷ In wind turbine manufacturing, former

An increasing number of tech companies are incorporating nuclear energy into their strategic energy plans to satisfy the massive power demands of their data centers.

<https://www.constellationenergy.com/news/2025/constellation-meta-sign-20-year-deal-for-clean-reliable-nuclear-energy-in-illinois.html>.

<https://ir.talenenergy.com/news-releases/news-release-details/talen-energy-expands-nuclear-energy-relationship-amazon>.

<https://www.constellationenergy.com/news/2024/Constellation-to-Launch-Crane-Clean-Energy-Center-Restoring-Jobs-and-Carbon-Free-Power-to-The-Grid.html>

26 European Commission. Net-Zero Industry Act Fact Sheet (2024). June 2024. <https://eur-lex.europa.eu/EN/legal-content/summary/eu-net-zero-industry-act.html>.

27 Reuters. Swiss solar panel maker Meyer Burger files for US Chapter 11 bankruptcy relief. June 2025. <https://www.reuters.com/legal/litigation/swiss-solar-panel-maker-meyer-burger-files-us-chapter-11-bankruptcy-relief-2025-06-25/>. Unable to compete with its Asian peers, the Swiss solar company Meyer Burger was forced to shut down its solar module manufacturing facility in Arizona, USA, in May 2025; subsequently, its German subsidiary also initiated insolvency proceedings. https://gb.meyerburger.com/en/gb2023/letter-to-shareholders.html?utm_source. In 2024, the company had decided to close its module plant in Freiberg, Germany, as part of a strategic shift to the United States.

European champions such as Siemens Gamesa have been plagued by quality issues and heavy losses, while the rapid rise of Chinese turbine manufacturers has further intensified global competition.²⁸

In March 2026, the European Commission formally adopted a new legislative proposal—the Industrial Accelerator Act (IAA)—aimed at promoting “Made in Europe,” with a target of increasing manufacturing’s share of EU GDP from 14.3% in 2024 to 20% by 2035. Whether the EU can achieve this goal remains uncertain.²⁹

“Defensive” tariffs and the transition paradox: In response to the manufacturing strength of other economies—particularly China—the EU introduced defensive tools such as the Foreign Subsidies Regulation (FSR) in 2023³⁰ and has also launched investigations into Chinese companies manufacturing or selling wind turbines in Europe.³¹ However, this creates a fundamental paradox: the EU has set highly ambitious climate targets and urgently requires low-cost clean energy equipment to achieve decarbonization, but has chosen to erect trade barriers to protect domestic manufacturing, leading to higher costs for consumers to purchase costly European products.

This inherent contradiction—between the pursuit of low-cost energy and the protection of domestic industry—will raise the cost of Europe’s energy transition and may, in turn, erode the global competitiveness of its broader industrial sectors, such as chemicals and automotive.

28 BloombergNEF (BNEF). Chinese Manufacturers Lead Global Wind Turbine Installations. March 2025. <https://about.bnef.com/insights/clean-energy/chinese-manufacturers-lead-global-wind-turbine-installations-bloombergnef-report-shows/> BloombergNEF’s (BNEF) 2024 global wind turbine shipment statistics reveal that Chinese companies secured the top four market positions, a ranking not seen since 2013. Among the global top 10, Chinese manufacturers claimed six spots, while European and U.S. manufacturers held only a minority of the rankings.

29 European Commission. Commission proposes Industrial Accelerator Act to strengthen industry and create jobs in Europe. March 2026. https://ec.europa.eu/commission/presscorner/detail/en/ip_26_515. https://single-market-economy.ec.europa.eu/publications/industrial-accelerator-act_en. The *Industrial Accelerator Act* aims to increase manufacturing’s share of EU GDP from 14.3% in 2024 to 20% by 2035. It outlines four primary implementation pathways: supporting domestic manufacturing, imposing additional restrictive conditions on Foreign Direct Investment (FDI) in specific sectors (primarily batteries, EVs, solar energy, and critical raw materials), streamlining approval processes, and promoting sustainable manufacturing.

30 European Commission. Foreign Subsidies Regulation. https://competition-policy.ec.europa.eu/foreign-subsidies-regulation_en July 2023.

31 European Interest. Commission opens in-depth foreign subsidies investigation into Chinese Goldwind’s wind sector activities in Europe. 2026.02. <https://www.europeaninterest.eu/commission-opens-in-depth-foreign-subsidies-investigation-into-chinese-goldwinds-wind-sector-activities-in-europe/>. The European Commission has launched an in-depth investigation into Chinese wind turbine manufacturer Goldwind under the *Foreign Subsidies Regulation* (FSR), suspecting that it may have gained a competitive advantage in the EU market through state subsidies. The inquiry was initially launched in 2024 and was escalated to an “in-depth investigation” in 2026.

India and Other Economies: Secondary Beneficiaries of Parallel Supply Chains

In assessing global energy supply chains, one must not overlook the rapidly emerging “third-party forces,” including India, Mexico, and ASEAN economies.

India—an ambitious alternative to China: India is seeking to replicate China’s industrial rise over the past two decades. Through the Production Linked Incentive (PLI) scheme and high tariff barriers (such as a 40% tariff on imported solar modules), it aims to promote domestic manufacturing and attract international capital.³²

In 2025, India added approximately 81 GW of solar module manufacturing capacity under the Approved List of Models and Manufacturers (ALMM) List-I³³—nearly doubling the additions in 2024. As of November 2025, India’s cumulative installed solar capacity had reached 132.85 GW.³⁴ For the U.S. market pursuing “de-risking,” India represents a compelling alternative.

However, its supply chain remains vulnerable, with most capacity concentrated in lower-value assembly segments, while upstream components—such as wafers, cells, and manufacturing equipment—continue to rely heavily on imports from China. In effect, India currently serves as an assembly hub, converting Chinese upstream intermediate goods into end products that meet U.S. political requirements, though it seeks to move up the value chain.

ASEAN and Mexico—hubs of “bypass” strategies: A role similar to India’s is also played by ASEAN economies such as Vietnam, Thailand, and Malaysia, as well as Mexico. These countries import intermediate goods from China, complete final assembly, and then export finished products to the United States and Europe.³⁵ To some extent, they are benefiting from trade tensions between China and the United States.

32 PLI Scheme: Powering India’s Industrial Renaissance. <https://www.pib.gov.in/PressNoteDetails.aspx?ModuleId=3&NotelId=155082®=3&lang=2>, August 2025

33 Approved List of Models and Manufacturers (ALMM) List-I for Solar PV Modules. <https://mnre.gov.in/en/notice/approved-list-of-models-and-manufacturers-alm-list-i-for-solar-pv-modules-extension-in-validity/>

34 Solar Now. India Adds 81 GW Solar Module Manufacturing Capacity In 2025. January 2026. <https://now.solar/2026/01/07/india-adds-81-gw-solar-module-manufacturing-capacity-in-2025-taiyangnews/>. India is building a domestic demand-driven manufacturing system through a framework of “tariff protection + PLI subsidies + ALMM localization requirements,” accelerating its transformation from a major solar energy consumer into a nation with enhanced manufacturing capabilities. However, its industrial upgrading remains largely concentrated in the modules and cells, and it has not taken any measure in attempt to secure control over the core upstream segments of the supply chain.

35 HKUST Li & Fung Supply Chain Institute. Global Supply Chain Report. https://ustfsci.hkust.edu.hk/sites/default/files/2025-12/Global_Supply_Chain_Report_DEC2025_Solar.pdf The report points out that manufacturing enterprises are restructuring their global production footprints in response to trade barriers and market risks. For example, several Chinese companies have relocated production lines to Southeast Asia—including Vietnam, Thailand, Malaysia, and Cambodia—to bypass tariffs.
EBRD. Connector Economies in a Fragmenting World. February 2025. <https://www.ebrd.com/home/news-and-events/publications/economics/working-papers/connector-economies-fragmenting-world.html>.

Whether the Trump administration will adopt tougher measures to restrict the trade activities of these “intermediary economies” remains uncertain. This phenomenon suggests that political “de-risking” may, at times, amount to little more than physical “re-routing.” While the United States and Europe seek to diversify their supply chains, they must also strike a balance between risk and cost. Continuing—directly or indirectly—to procure energy equipment linked to Chinese technology and capital may therefore represent a rational, interest-maximizing choice.

In summary, from the perspective of “clean energy supply chain and manufacturing,” China has established a leading position in clean energy manufacturing, underpinned by its massive scale, vertically integrated industrial ecosystem, and cost advantages forged through intense domestic competition. However, this dominance is increasingly triggering concerns and defensive policy responses from economies such as the United States and the European Union. The United States, by pivoting back toward fossil fuel systems, is in part seeking to circumvent China’s advantages in clean energy manufacturing, while Europe is attempting to mitigate the impact of Chinese manufacturing through policy measures. Meanwhile, countries such as India are striving to capture opportunities from supply chain relocation amid these geopolitical tensions.

For China, building on its manufacturing strengths, large volumes of cost-effective clean energy equipment have been rapidly deployed in domestic renewable energy development, at a pace that has exceeded expectations globally. Yet alongside this rapid growth, a structural challenge has emerged: while generation capacity can be built quickly, it is not always effectively integrated. This imbalance between supply and utilization has become one of the most pressing challenges facing China’s energy system.

1.3 Perspective 3: Transition Agility and Challenges in the Transition

When assessing a country's progress in the energy transition, a common pitfall is to equate installed clean energy capacity with actual transition outcomes. However, in today's highly volatile energy markets and geopolitical environment, the actual effectiveness of the energy transition is no longer determined simply by how many wind turbines or solar panels have been manufactured or installed, but rather by “system transition agility.”³⁶

Here, “system transition agility” refers to the ability of a country's or region's energy system to maintain real-time supply–demand balance at low cost and high efficiency—through physical flexibility, market mechanisms, and demand-side response—while integrating a high share of intermittent renewable energy, thereby enabling the substantive replacement of fossil fuels.

From this perspective, the world's three major economies exhibit distinct trajectories: Europe, constrained by resource scarcity, has become a benchmark for system agility; the United States has shifted its energy strategy back toward fossil fuels, with a significantly diminished emphasis on the transition; and China, despite possessing the world's largest clean energy capacity, faces a structural dilemma of being “large but unagile,” which has become the greatest challenge for its strategic energy initiative.

European Union (Germany as a case in point): A Market-Driven “Agility Benchmark”

Despite lacking local fossil fuel resources as a backup (a disadvantage in Perspective 1) and facing the decline of its manufacturing supply chain (a

36 Oxford Institute for Energy Studies. Flexibility Case Studies for the Clean Energy Transition: Suggestions for China from European Experience. November 2025. <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2025/11/CE18-Flexibility-Case-Studies-for-the-Clean-Energy-Transition.pdf> The report highlights that the rapid expansion of renewable energy has introduced significant system operational challenges, necessitating a higher degree of flexibility than in the past. Estimates from the European Commission indicate that flexibility requirements as a percentage of total electricity demand will rise from 11% in 2021 to 24% by 2030, reaching 30% by 2050. This implies that the core constraint of the power system must shift from capacity expansion toward operational balancing capacity. European Commission. March 2023. https://energy.ec.europa.eu/topics/research-and-technology/energy-storage/key-facts-energy-storage_en

disadvantage in Perspective 2), the EU—particularly Germany—has made notable progress in enhancing system agility.

Price signals as a guiding mechanism: Germany’s system agility is not primarily derived from large-scale physical storage systems or fossil fuel-based peak shaving, but from a continuously evolving electricity spot market (such as EPEX SPOT). In Germany, when surges in wind and solar generation lead to oversupply, electricity prices can quickly fall into negative territory. In the first half of 2025, the German electricity market even experienced nearly 400 hours of negative power prices.³⁷ These extreme price signals act like a conductor’s baton, automatically activating demand-side flexibility: industrial users ramp up energy-intensive operations, storage systems begin charging, and surplus electricity is exported via cross-border grids to neighboring countries.

Distributed “virtual power plants” integrated with micro-level units: Germany has successfully broken away from the traditional model of centralized dispatch in grids by widely deploying virtual power plants and encouraging the development of aggregators through mechanisms such as the balancing mechanism. Enabled by a highly digitized system paired with micro-level units, millions of distributed assets—including household heat pumps, rooftop solar panels, and electric vehicle charging points—are aggregated into a “flexible sponge” capable of responding to grid signals within seconds.

Building on the continued expansion of installed capacity, Europe’s energy transition is gradually shifting its focus toward system optimization. As conventional dispatchable generation is retired, the share of renewable energy rises, and electrification accelerates, demand for flexibility across intra-day, weekly, and seasonal timescales has increased significantly. Flexibility is thus becoming a critical prerequisite for the secure and stable operation of power systems.³⁸

37 PV Magazine. Germany’s day-ahead market posts 389 hours of negative prices in H1. June 2025. <https://www.pv-magazine.com/2025/06/30/germanys-day-ahead-market-posts-389-hours-of-negative-prices-in-h1/> In the first half of 2025 alone, Germany recorded 389 hours of negative electricity prices, nearly matching the total for the entire year of 2023. This highlights the strong role of price signals in balancing periods of peak solar generation. The frequent occurrence of negative prices reflects a market-based mechanism that enhances system flexibility through economic incentives, and has become a key driver enabling Germany to integrate a high share of renewable energy without relying on additional coal-fired backup capacity.

38 Oxford Institute for Energy Studies. Flexibility Case Studies for the Clean Energy Transition: Suggestions for China from European Experience. November 2025. <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2025/11/CE18-Flexibility-Case-Studies-for-the-Clean-Energy-Transition.pdf>. The report points out that the rapid expansion of renewable energy has introduced significant operational challenges for the power system, necessitating a much higher degree of system flexibility than in the past.

European Commission. March 2023. https://energy.ec.europa.eu/topics/research-and-technology/energy-storage/key-facts-energy-storage_en. Estimates from the European Commission indicate that flexibility requirements as a percentage of total electricity demand will rise from 11% in 2021 to 24% by 2030, reaching 30% by 2050. This implies that the core constraint of the power system must shift from capacity expansion toward operational balancing capacity.

United States: A Shift in Focus Amid Policy Reversal

From the perspective of a conventional green transition, the United States has made relatively slow progress, and its power grid remains outdated, with limited system transition agility. However, under the Trump administration's energy strategy since 2025, the United States has, in effect, proactively shifted its energy policy direction.

Natural gas as a “flexibility advantage”: Natural gas-fired generation offers strong ramping capability and operational flexibility, making it a relatively traditional yet highly effective physical tool for managing fluctuations in wind and solar output as well as load variability. In 2025, natural gas accounted for around 40% of total U.S. electricity generation.³⁹ This means that in the event of fluctuations in renewable output, extreme weather, or surging demand, the U.S. power system can rely on abundant and low-cost domestic natural gas (priced at less than one-third of that in China) to quickly stabilize the system.

As the Trump administration has re-emphasized fossil fuel development,⁴⁰ U.S. energy policy has, to some extent, shifted its focus from integrating high shares of renewable energy toward rapidly expanding overall power supply capacity to meet rising electricity demand from data centers and domestic manufacturing. Even with a higher share of renewables in its energy mix, the United States can still rely on its abundant shale gas and coal resources to construct a “fossil fuel advantage.”

It should be noted that the slow pace of the green transition and limited grid agility are not necessarily strategic weaknesses, but rather a resource-based “active choice.” The United States is not prioritizing the resolution of renewable integration challenges; instead, its strategic focus is on leveraging low energy costs—particularly cheap natural gas and coal—to accelerate the

European Parliament. Increasing Flexibility in the EU Energy System. March 2025. [https://www.europarl.europa.eu/RegData/etudes/STUD/2025/769347/ECTI_STU\(2025\)769347_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/STUD/2025/769347/ECTI_STU(2025)769347_EN.pdf). The report studies the increasing demand for flexibility under a high-penetration renewable energy scenario from the perspectives of institutional framework and market design; it also provides a systematic assessment of solutions such as energy storage, demand response, and grid interconnection.

Cédric PHILIBERT. The Strategic Dimension of Power System Flexibility: Opportunities in Europe. Studies, Ifri. May 2025. <https://www.ifri.org/en/studies/strategic-dimension-power-system-flexibility-opportunities-europe>. The IFRI report highlights that, as dispatchable capacity retires and electrification advances, flexibility needs at weekly and seasonal scales are increasing, while insufficient system flexibility may exacerbate price volatility and systemic risk.

39 EIA. Short-Term Energy Outlook: Natural Gas as the Unyielding Backbone of US Generation. February 2026. <https://www.eia.gov/outlooks/steo/report/natgas.php>

40 The White House. Reinvigorating America's Beautiful Clean Coal Industry and Amending Executive Order 14241. April 2025. <https://www.whitehouse.gov/presidential-actions/2025/04/reinvigorating-americas-beautiful-clean-coal-industry-and-amending-executive-order-14241/>. The Trump administration has issued an executive order aimed at revitalizing the American coal industry.

U.S. Department of Energy (DOE). Funding Notice: Restoring Reliability: Coal Recommissioning and Modernization. September 2025. <https://www.energy.gov/hgeo/funding-notice-restoring-reliability-coal-recommissioning-and-modernization> In September 2025, the U.S. Department of Energy announced a \$5.25 billion investment to support the upgrading and expansion of the coal sector.

reshoring of global manufacturing and computing infrastructure, thereby strengthening its broader economic fundamentals.

China: The Systemic Challenges Facing an Installed-Capacity Giant

By contrast, China's push for renewable energy carries a strong sense of strategic urgency. China seeks to accelerate the substitution of clean energy to reduce its dependence on imported oil and gas, while simultaneously expanding its clean energy equipment manufacturing sector to support economic growth. However, this strategic ambition has come into conflict with a relatively rigid domestic energy system, exposing China's key vulnerability in Perspective 3.

The transitional paradox of “increment without substitution”: China's total installed capacity of wind and solar power far exceeds that of other economies. However, utilization data reveal a significant gap between installed capacity. As of 2025, China's cumulative installed wind and solar capacity exceeded 1.84 billion kW, accounting for as much as 47% of total installed capacity—historically surpassing coal-fired power. However, wind and solar generation accounted for only around 22% of total electricity generation.⁴¹ Correspondingly, the risk of curtailment remains significant.

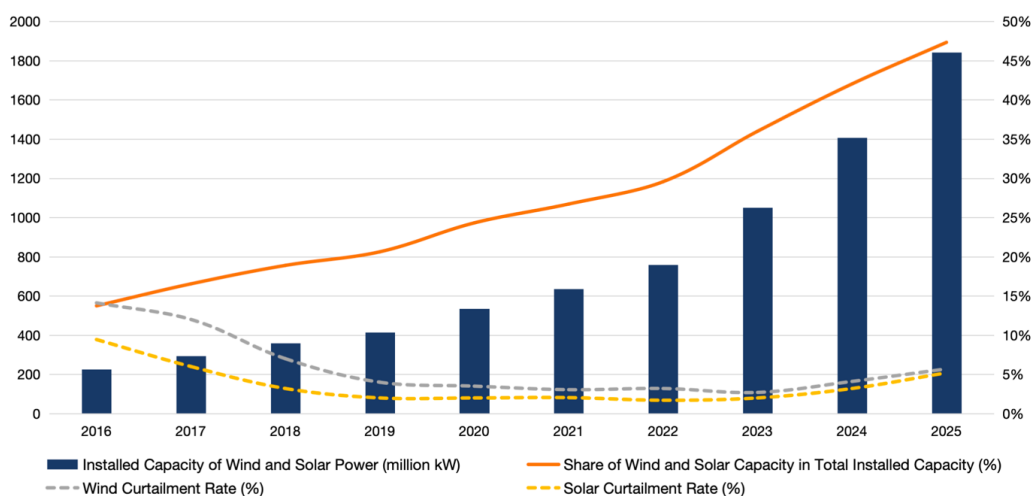
In recent years, utilization rates for wind and solar have declined. According to data from the National Energy Administration, China's wind and solar power curtailment rates were approximately 2.0–2.7% in 2023, 3.2–4.1% in 2024, and 5–6% in 2025.⁴² Taking 2025 as an example, the national average utilization rate was around 94% for wind power and 95% for solar power. In some provinces, officially reported curtailment rates have approached 10%,⁴³ and actual curtailment during certain periods of the years can be even higher.

41 National Energy Administration (NEA). China's Cumulative Installed Wind and Solar Capacity Exceeds 1.8 Billion Kilowatts for the First Time. <https://www.nea.gov.cn/20260130/503483f133e44016a66ddd6fad8ab695/c.html>; Renewable Energy Integration in 2025. <https://www.nea.gov.cn/20260212/742b8c6a078347b0b39de676c05c5d58/c.html>

42 National Energy Administration (NEA). *Renewable Energy Integration in 2025; National Monitoring and Evaluation Results of Renewable Energy Power Development, 2023–2025*. https://zfxgk.nea.gov.cn/2024-10/10/c_1310787115.htm; <https://www.nea.gov.cn/20250221/e10f363cabe3458aaf78ba4558970054/c.html>; <https://www.nea.gov.cn/20260212/742b8c6a078347b0b39de676c05c5d58/c.html>.

43 Power Industry Planning Research and Monitoring & Early Warning Center. *National New Energy Grid Integration and Consumption in 2025*. February 2026. <https://mp.weixin.qq.com/s/OLJUhiavT3CHAKBDYLviWg>

Figure I-10: Installed Capacity of Wind and Solar Power and Curtailment Rates in China (2016–2025)



Sources: National Energy Administration (NEA); National New Energy Consumption Monitoring and Early Warning Center

The underlying system issues warrant close attention. Due to the intermittency of wind and solar energy, and in order to ensure reliable power supply and grid stability amid rising demand, China has continued to approve large numbers of coal-fired power plants for peak regulation while rapidly expanding renewable capacity. Data indicate that China added nearly 80 GW of new coal-fired capacity in 2025, with around 290 GW still under construction by the end of the year—equivalent to nearly one-fifth of the existing operational coal fleet.⁴⁴

This dilemma—building coal capacity in part to accommodate renewable energy—may persist through 2035, resulting in an challenging situation: while renewable capacity continues to expand rapidly, it is unable in the near term to substitute for the existing stock of fossil fuels.⁴⁵ Rather than diminishing, the legacy burden of fossil energy may, under the requirements of system stability, become further entrenched in the foreseeable future.

Grids and “generation-following-load”: A key reason behind the above paradox lies in China’s long-prided “strong grid” architecture and its traditional institutions and mechanisms.

For a long time, China’s power system has operated under the principle of “generation following load”, whereby the supply side must meet demand,

44 Centre for Research on Energy and Clean Air & Global Energy Monitor. Built to peak: Coal power expansion runs out of room in China. <https://energyandcleanair.org/publication/built-to-peak-coal-power-expansion-runs-out-of-room-in-china/>

45 Although not all newly added coal power capacity is intended for renewable integration and peak regulation—some of it is built to meet new electricity demand—this nonetheless indicates that, despite the rapid expansion of renewable installed capacity, fossil fuels have not yet been effectively displaced.

while the demand side (industrial, commercial, and residential users) has not been regarded as an integral part of the energy system. The balancing and coordination of supply and demand have been managed by highly centralized grid operators. This high degree of centralization is reflected not only in the physical architecture of the grid, but also in the dispatch system. In traditional power systems, where both generation and demand are relatively stable, such a centralized dispatch model can operate efficiently and deliver economies of scale. However, it becomes increasingly inadequate in the face of a high share of renewable energy. As the system grows larger, it tends to become less flexible and less responsive.

1. Physical and institutional inflexibility: Taking ultra-high-voltage (UHV) transmission lines as an example, if sudden weather changes in western China lead to a sharp drop in transmitted power, the stability of receiving grids in the east can be significantly affected, requiring the rapid dispatch of natural gas, coal-fired generation, or energy storage for balancing.

Beyond UHV lines, China has also made considerable nationwide investments in grid infrastructure. While these modern grid systems should, in principle, support the integration of renewable energy, the rapid expansion of both centralized and distributed renewables in central and eastern regions has created new challenges. The vast majority of these generation resources are still coordinated through a single, highly centralized channel—the grid companies' dispatch system—which is often strained. As a result, many provinces have begun to designate so-called “red zones,” where renewable energy projects are restricted from grid connection.

2. Lack of market mechanisms: Unlike Europe, most regions in China have not yet established user-side spot pricing mechanisms that reflect real-time supply–demand conditions. Although spot market development has accelerated since 2025, long-standing rigid pricing schemes—such as time-of-use tariffs and regulated catalog prices—have masked the true system costs caused by renewable variability. At times when system flexibility is most constrained, end users lack effective price signals and therefore have little incentive to reduce or shift their load.

Without an effective dispatch system, demand-side response mechanisms, and flexible pricing, the burden ultimately falls on the supply side. The result is the steadily rising curtailment rates mentioned earlier. With annual additions of 200 GW or more of wind and solar capacity projected over the next decade, curtailment is likely to increase further under the current model. This not only represents a massive waste of resources, but also significantly undermines returns on investment in clean energy projects, thus posing a major systemic risk to the energy transition.

1.4 Perspective 4: Infrastructure Capacity and System Vulnerability

Energy infrastructure—including physical pipeline networks and power transmission and distribution systems⁴⁶—forms the backbone of any energy system. Against a backdrop of increasingly frequent extreme weather events and ongoing geopolitical conflicts, evaluating infrastructure performance is no longer just about the length of lines or voltage levels; it must instead pass a harsh “ultimate test”: when confronted with extreme external shocks (such as severe weather or cyberattacks) or internal structural changes (such as surging AI-driven power demand or high shares of renewables), can the system continue to operate efficiently, or will it suffer system-wide failure?

Overall, the United States has well-developed oil and gas infrastructure but relatively underdeveloped power grids, while Europe maintains strong resilience through highly interconnected systems.

China, by contrast, is attempting to build a highly robust “backbone” of power infrastructure. However, this highly centralized system carries significant systemic risks. In peaceful times, it can act as an economic accelerator; but in the face of extreme natural disasters or geopolitical crises, its vulnerabilities may quickly be exposed. True energy security cannot rely on overly optimistic assumptions—that timely responses or large reserve capacities alone can safeguard the entire transmission and distribution network. Only by restructuring system architecture and reducing absolute reliance on a single massive grid can China build infrastructure capable of supporting its energy transition ambitions.

The United States: A Computing-Driven Grid Capacity Challenge Amid Highly Uneven Infrastructure

U.S. infrastructure shows a stark contrast: a well-developed fossil fuel transport network with an aging and outdated public power grid.

⁴⁶ This report’s analysis of energy infrastructure focuses on the primary systems within a single economy, excluding overseas assets and giving limited attention to hydrogen- or nuclear-related systems.

Oil and gas networks: U.S. oil and gas infrastructure forms a solid foundation for its energy strength. Dense pipeline networks stretching from inland shale gas basins to the Gulf Coast, along with large coastal LNG export terminals, provide the United States with strong capabilities for energy distribution and export.⁴⁷ This highly market-oriented physical network, with built-in redundancy, has withstood multiple natural disasters such as hurricanes, serving as the backbone of the domestic energy system and a key channel for exports to trading partners. With the Trump administration's renewed emphasis on fossil fuels, this system has further consolidated its position.

A structural mismatch between aging grids and AI-driven demand: However, in terms of power infrastructure, the United States faces a severe capacity challenge. Multiple studies by the U.S. Department of Energy and grid research institutions show that much of the country's grid infrastructure is aging, with more than 70% of transmission lines and transformers having been in operation for over 25 years.⁴⁸

At the same time, the rapid rise in computing demand driven by large-scale AI models is sharply increasing electricity consumption. As multiple gigawatt-scale data center campuses are planned or under construction across North America, the United States is under growing pressure to accelerate the pace of grid expansion.

Although the Trump administration has sought to strengthen grid development, such efforts will take time.⁴⁹ Moreover, if these technology companies rely entirely on the existing public grid to meet their data center electricity needs, this could drive up power costs for households and small and medium-sized enterprises, as well as contribute to broader inflationary pressures.

In response, under pressure from the Trump administration, several major technology companies have signed commitments to bear the costs of building or expanding power generation and transmission infrastructure required to supply their data centers.⁵⁰ However, even if these companies construct

47 U.S. Energy Information Administration (EIA). Natural gas explained: Natural gas pipelines. March 2024. <https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php>. The U.S. natural gas pipeline network spans the mainland, with a total trunkline length of approximately 3 million miles.

48 American Society of Civil Engineers. Infrastructure Report Card. 2025. <https://infrastructurereportcard.org/cat-item/energy-infrastructure/>. The report notes that the growing reliance of consumers and enterprises on data storage facilities and AI has placed immense pressure on an already fragile and aging power grid.

49 The White House. Executive Order 14262 - Strengthening the reliability and security of the United States electric grid. April 2025. <https://www.whitehouse.gov/presidential-actions/2025/04/strengthening-the-reliability-and-security-of-the-united-states-electric-grid/>

50 The Guardian. US tech firms pledge at White House to bear costs of energy for datacenters. March 4, 2026. <https://www.theguardian.com/us-news/2026/mar/04/us-tech-companies-energy-cost-pledge-white-house>. Companies such as Google, Microsoft, Meta, and Amazon signed this pledge at the White House in early March 2026. Furthermore, according to statistics from the U.S. Energy Information Administration (EIA), overall U.S. electricity prices in 2025 rose compared to 2024, driven by increasing natural gas prices.

their own power plants, significant challenges remain in grid interconnection. For example, in large regional transmission organizations such as PJM, interconnection queue times for new projects have been extended to more than four years.⁵¹

European Union: Cross-Border Interconnection and Decentralized “Topological Resilience”

In contrast to the aging infrastructure in the United States and the highly centralized system in China, Europe has pursued a path in power infrastructure centered on “topological resilience.”

Europe does not have a single “supernational grid.” Instead, through the European Network of Transmission System Operators for Electricity (ENTSO-E⁵²), the grids of more than 30 countries are woven into a tightly interconnected, cross-border network topology. The greatest advantage of this network lies in its high level of redundancy and mutual balancing capability. When a country faces a major energy shortfall—for example, due to nuclear outages in France or prolonged periods of low wind and solar output in Germany—interconnected neighboring systems can provide timely electricity supply support.

Notably, following the outbreak of the Russia-Ukraine conflict, vulnerabilities in Europe’s energy system—particularly in terms of security and resilience—have been significantly exposed. Large-scale centralized energy facilities are particularly vulnerable as critical targets in high intensity conflict scenarios. Against this backdrop, the European Union has, building on its existing energy transition pathway, strengthened its focus on distributed energy and networks. Approximately 70% of future energy assets are expected to be connected at the distribution level, with investment priorities gradually

<https://www.eia.gov/todayinenergy/detail.php?id=67106>

51 Berkeley Lab. Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection. 2025. <https://emp.lbl.gov/queues>. From 2000 to 2007, the median duration from a power plant applying for integration to reaching operational status was less than two years; however, between 2018 and 2024, this process has extended to more than four years.

52 ENTSO-E Strategic Roadmap February 2024. https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/ENTSO-E%20general%20publications/entso-e_strategic_roadmap_WEB_240215.pdf The report points out that the interconnected network, represented by ENTSO-E, links 40 transmission system operators (TSOs) across 36 countries, achieving dynamic equilibrium through cross-border corridors. Under the unified coordination of Regional Coordination Centres (RCCs), this topological structure effectively mitigates power deficits in individual nations caused by extreme weather—such as nuclear cooling disruptions or dark doldrums (a period of time in which little or no energy can be generated with wind and solar power). By leveraging redundant capacity from neighboring countries for transnational mutual assistance, this system significantly bolsters overall risk resilience and security of supply.

shifting toward distributed networks and digitized management capabilities.⁵³

China: The Strength and Hidden Risks of a Centralized Grid

China possesses a comprehensive and highly efficient power infrastructure system built on coal and coal-fired power generation, while its oil and gas infrastructure is also impressive. However, it is the power system that is likely to have the most profound impact on China's future energy system. As noted earlier, China is committed to expanding clean electricity to reduce its dependence on fossil fuels—especially oil and gas—and in this transition, the grid-based transmission and dispatch system serves as a critical component of the energy infrastructure.

For many years, China has sought to build the world's largest, highest-voltage, and most "robust" power grid system. On the surface, this effort has achieved significant results: the world's most extensive network of ultra-high-voltage (UHV) AC and DC transmission lines crisscrosses the country, tightly linking western energy bases with eastern economic centers; in major cities, power supply reliability has even reached an extraordinary 99.999%. However, this pursuit of extreme high degree of centralization and large physical scale has also created systemic risks.

Unstress-tested "robustness": The reliability currently demonstrated by China's power grid reflects a form of "relative stability" under largely peaceful conditions and in the absence of major external shocks. It is important to recognize that, over the past 75 years, China's core energy infrastructure has rarely been subjected to systematic, high-intensity disruption.⁵⁴ As such, the true stability and resilience of this power system remain largely untested.

Real-world cases of extreme natural disasters and modern warfare—such as the destruction of energy infrastructure during the Russia-Ukraine conflict—provide a cautionary example: the larger, more centralized, and more dependent a grid system is on long-distance transmission, the greater the potential risk of systemic collapse. Under extreme scenarios of natural disasters or deliberate attacks, the failure of just a few ultra-high-voltage

53 European Commission. Study on network development planning, tariff structures and connection requests for electricity distribution grids. 2025. https://energy.ec.europa.eu/topics/infrastructure/european-grids_en. The report notes that approximately 70% of future energy assets are expected to be connected at the distribution level, reflecting the ongoing transition of the power system from a centralized to a decentralized architecture.

54 The 1976 Tangshan earthquake and the 2008 Wenchuan earthquake were two localized natural disasters that caused catastrophic damage to social infrastructure, including energy systems.

(UHV) hub converter stations, or the destruction of several major substation nodes, could be sufficient to trigger widespread blackouts affecting economic activity and daily life.⁵⁵

Misalignment between power system design and clean energy integration:

Beyond external security risks, highly centralized grid systems also exhibit institutional and physical mismatches in adapting to domestic energy transition needs. China's power system is dominated by two super-large grid operators—State Grid and China Southern Power Grid. Among them, State Grid's operating area covers nearly 88% of the country's territory and serves more than 1.1 billion people.⁵⁶ The underlying logic of this operational model is top-down control, whereas the physical characteristics of renewable energy—such as wind and solar—are inherently decentralized, variable, and bottom-up.

This misalignment between infrastructure architecture, management models, and the nature of renewable energy creates major challenges for system integration. Existing large-scale centralized grids are well suited to dispatching large and ultra-large coal-fired power plants, but they are far less efficient in managing millions of distributed rooftop solar systems and geographically dispersed wind turbines. To maintain frequency and voltage stability across such a vast network, grid operators often resort to the most conservative measures—curtailing renewable generation (commonly referred to as “curtailment”) or relying on continued operation of high-carbon coal-fired units and costly energy storage systems (see “Perspective 3” in this chapter). It may well be that this centralized grid structure—designed to coordinate everything—is, to some extent, constraining improvements in the flexibility of China's clean energy system.

55 Congressional Research Service (CRS). Attacks on Ukraine's Electric Grid: Insights for U.S. Infrastructure Security and Resilience. 2024. <https://www.congress.gov/crs-product/R48067>. The article examines the damage to the Ukrainian power grid in the context of the Russia-Ukraine conflict and discusses its broader implications for power system resilience in other regions, including the United States. High-voltage substations and large power transformers are critical node in power systems; their failure can trigger regional or even trans-regional cascading outages, leading to significant impact on system reliability.

56 State Grid Corporation of China http://www.sgcc.com.cn/html/sgcc_main/gb/gywm/gsj/index.shtml

Chapter 2 Challenges Facing China

In Chapter 1, through a multi-perspective assessment, we provided a preliminary comparison of the similarities and differences in energy strategies among China, the United States, and the European Union, as well as their respective development characteristics (see Table 2-1).

Table 2-1: Energy Development Characteristics and Comparative Performance of China, the United States, and the EU (2026)

Perspective of Assessment	China	United States	European Union
Perspective 1: Resource Endowment and Geopolitics	Moderate/weak. Highly dependent on imported oil and gas; exposed to potential supply disruption risks; coal serves as the backup.	Very strong. The world's largest oil and gas producer; reshaping flows and pricing through alliances.	Weak. Extremely limited domestic fossil resources; relies on rule-setting to offset disadvantages.
Perspective 2: Supply Chain and Manufacturing	Very strong. Holds significant advantages in manufacturing equipment such as solar power, wind turbines, batteries, and EVs, with a dominant share of the global market.	Moderate/weak. Subsidy-driven reshoring efforts is constrained by high costs; attempts to leapfrog via SMR nuclear technology.	Weak. Domestic manufacturing has declined; currently experiencing challenges associated with "de-risking" strategies.
Perspective 3: Transition Agility	Moderate. Large installed capacity but constrained by institutional barriers to integration; lacks flexible response.	Moderate. Transition is not a strategic priority; relies on gas-fired generation as a natural buffer.	Strong (benchmark). Advanced spot markets; mature virtual power plants and distributed microgrids.
Perspective 4: Infrastructure Capacity	Moderate (centralization risks). Large grids lack redundancy against disruptions.	Moderate. Strong oil and gas networks; but aging public grids constrain the expansion of AI computing power.	Relatively strong (topological resilience). Strong cross-border interconnections; evolving toward decentralization.

After a decade of rapid expansion, China has achieved remarkable success in both the manufacturing and supply sides of clean energy. However, this scale-driven capacity advantage now faces severe systemic bottlenecks that hinder its conversion into energy transition benefits.

Integration Crisis: New Energy Mismatched by the Old Model

At present, China's most prominent internal challenges are concentrated in Perspective 3 (agility) and Perspective 4 (infrastructure). A large volume of clean electricity is being generated but cannot be effectively integrated by the system; much of it is either considered as "waste electricity" that is difficult for the grid to manage or directly excluded from the existing grid system. If the issues of integration and system capacity cannot be resolved swiftly, China risks rapidly losing its first-mover advantage in the clean energy sector and may struggle to realize its ambitious strategic vision of gradually replacing fossil fuels with clean energy. At the same time, the inefficient allocation and accumulation of massive capital in this process could become a drag on the broader economy.

The key problem lies in the fact that China is attempting to manage a 21st-century "new energy structure" with a 20th-century "legacy grid management model." For a long time, China's energy strategy has been heavily focused on supply-side expansion and the centralized construction of transmission networks.

One underlying logic is as follows: large-scale wind and solar bases are developed in the western regions, with electricity transmitted over thousands of kilometers to the east via ultra-high-voltage (UHV) backbone grids. At the same time, centralized and distributed renewable generation is also deployed at scale in central and eastern regions, all coordinated through centralized dispatch by grid operators. Meanwhile, end users on the demand side continue to play a passive, rigid, and largely uninformed role as "passive consumers," much as they did in the era of coal-fired power.

However, facts and data are sending a stark warning: this one-way, linear model—characterized by an emphasis on supply expansion and centralized transmission, with limited demand-side interaction—has already reached its physical and economic limits.

In multiple provinces across China, clean energy utilization rates have fallen below 90%, with widespread curtailment of wind and solar power. At the same time, to maintain the stability of this vast grid during peak summer demand

or extreme weather events, many outdated coal-fired units that should have been phased out have been brought back online and repurposed as backup capacity. In addition, a large number of new coal power projects have been commissioned over the past five years under the justification of “ensuring supply” and “peak shaving,” with a similarly large pipeline of projects planned for the coming years (see “Perspective 3” in Chapter 1 for details).

Sudden Strategic Shifts and a Rapidly Narrowing Time Window

If the international landscape were to evolve in a gradual and orderly manner, China might still have sufficient time to integrate this large volume of clean electricity through incremental grid upgrades. However, the greatest challenge lies in the fact that abrupt shifts in the external environment are narrowing China’s time window.

Since the new U.S. administration took office in 2025, its energy policy has undergone a clear shift, placing renewed emphasis on the development of fossil fuels such as oil and gas.⁵⁷ At the same time, its geopolitical and energy strategies have become increasingly aligned and mutually reinforcing—for example, by strengthening ties with Middle Eastern allies, influencing Venezuela’s energy development and trade, and maintaining sanctions on Russia and Iran to constrain their oil and gas exports.⁵⁸ As a result, within a short span of time, the United States has gradually consolidated and expanded its dominance in the traditional energy sector, while seeking to steer the global energy order back toward a trajectory in which it holds decisive control.

At this “accelerated” pace, China could in principle maintain strategic focus in its own energy policy. However, if the external environment were to shift decisively back toward a fossil fuel-dominated trajectory, China would face significantly greater difficulty in advancing its energy transition. The global energy transition and climate agenda would also become far more uncertain. Under such circumstances, a more pragmatic strategic pathway for China is to “look inward”—to rapidly address the challenge of integrating high shares of clean energy, accelerate the substitution of fossil fuels, and thereby

57 The White House. Unleashing American Energy. 2025. <https://www.whitehouse.gov/presidential-actions/2025/01/unleashing-american-energy/>.

58 In late March 2026, in response to the shocks to energy markets caused by shipping disruptions in the Strait of Hormuz, the U.S. Treasury’s Office of Foreign Assets Control (OFAC) announced a temporary easing of sanctions and export restrictions on Russian oil. OFAC. <https://ofac.treasury.gov/recent-actions>. Whether through the extension of sanctions or their temporary lifting, it points to the direct influence of the United States on Russia’s oil and gas trade.

strengthen the resilience of its energy system. This represents both a pressing challenge and a major potential opportunity for China.

From Domestic Bottlenecks to Opportunities for Global Cooperation

It is worth noting that the challenge of integrating clean energy is not unique to China. As the share of renewables continues to rise, power systems in Europe, Latin America, and the United States are also experiencing growing pains, including grid congestion and insufficient flexibility. If China can take the lead in successfully addressing the global challenge of integrating ultra-large-scale renewable energy and build a highly flexible and shock-resilient energy system, it will not only advance its own energy strategy but also position itself as a provider of “energy governance” solutions to the world. This, in turn, could expand opportunities for cooperation with a broader range of countries in the field of energy transition.

Chapter 3 Building a Distributed Energy System Driven by “Demand-Side Resilience”

Having identified “lack of system flexibility” and centralized infrastructure as the primary sources of challenges and risks, the next critical question is: what actions should China take next?

In response to integration challenges and security risks associated with high shares of renewables, traditional energy managers often instinctively resort to three conventional “supply-side and grid-side” measures:

- 1. Continued expansion of supply-side capacity:** This has been China’s most familiar approach in recent years. Even when much of the installed renewable capacity cannot be effectively utilized, additional wind and solar projects continue to be approved in order to meet decarbonization targets. However, experience shows that when integration channels are congested, increasing supply will only lead to more intense competition and lower returns on investment. While supply-side expansion must continue to sustain industrial momentum, it is no longer the primary solution to current challenges.
- 2. Expansion of centralized grids:** When facing renewable integration challenges, grid operators often respond by restricting renewable integration while seeking massive investments to build additional UHV lines and expand the grid.⁵⁹ However, as discussed in Perspective 4 of Chapter 1, this approach is facing rapidly diminishing marginal returns. More critically, it may transform the national energy system into an even

⁵⁹ State Grid Corporation of China (SGCC). *State Grid to Invest RMB 4 Trillion During the 15th Five-Year Plan to Construct a New Power System*. <http://wap.sasac.gov.cn/n2588025/n2588124/c35325777/content.html>

larger and more vulnerable physical target for external attackers.

3. Promotion of centralized physical energy storage: In previous years, regulators at times required renewable projects to include 10–20% storage capacity, with many distributed projects also mandated—directly or indirectly—to deploy storage. However, due to the absence of effective spot price signals, these costly storage facilities have generally been underutilized, leading to significant asset waste. For example, in 2025, although performance improved compared to 2024, the average utilization rate of renewable-oriented storage remained only around 40%.⁶⁰ Since then, China has accelerated market reforms and abolished mandatory storage requirements⁶¹, which may unlock potential in some projects; however, the economic viability of most such investments remains highly uncertain.

A Shift in Logic: The Strategic Transition Toward “Demand-Side Resilience”

When supply-side capacity exceeds current dispatch and integration capabilities, when further expansion of centralized grids begins to create both security and cost risks, and when storage facilities face growing challenges of economic viability, a more realistic and forward-looking solution lies in turning to the long-neglected domain at the endpoint of energy flows—the demand side.

The traditional one-way linear model of supply-side generation → grid transmission → passive demand-side consumption must be fundamentally rethought. To truly achieve China’s strategic energy objectives, a decisive shift in priorities is required.

A shift is needed from simply expanding supply and grid capacity to fundamentally reconfiguring the demand-side system. Vast end-use sectors—including industry, commerce, buildings, and transportation—should be transformed from “passive burdens” into “active system players”. Distributed, micro-level energy networks should be redesigned so that

60 China Electricity Council (CEC). *2025 Industry Statistical Data for Battery Storage Stations*. March 25, 2026. <https://mp.weixin.qq.com/s/CGL-PxNGbTcnMC7Fwxq1rQ>. Data show that in 2025, the average utilization rate of energy storage paired with renewables reached 40%, up 8 percentage points from 2024; the average utilization rate of grid-side independent energy storage was 60%, and that of commercial and industrial behind-the-meter storage was 63%.

61 National Development and Reform Commission; National Energy Administration. *Notice on Deepening the Market-Oriented Reform of New Energy On-Grid Tariffs to Promote High-Quality Development of New Energy* (Price [2025] No. 136). The policy document states that energy storage must not be used as a prerequisite for the approval, grid connection, or feeding-in of newly built new energy projects. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202502/t20250209_1396066.html

dormant demand-side resources become powerful tools for absorbing volatility on the supply side. Once demand-side potential is fully unlocked, rapidly growing wind and solar capacity can become a pillar of energy security rather than a burden on the system.

The key to this strategic transition is demand-side resilience. Building a distributed energy system centered on demand-side resilience is not only a technical solution to today's renewable integration challenge, but also a core strategy for reshaping the very foundation of national energy security.

3.1 Concept Redefined

In traditional energy discourse, the concept of “resilience” is typically applied to power grids or generation facilities, referring to the ability of the system to rapidly restore power supply in the event of natural disasters, equipment failures or other disruptions. On the demand side, conventional policy tools have largely been limited to “energy conservation,” “efficiency improvements,” or administratively enforced measures such as “orderly power consumption.” These measures are increasingly inadequate for addressing the challenges posed by high shares of variable renewables and broader energy-security risks.

The concept of “demand-side resilience” proposed in this report represents a redefinition. **It does not focus on how users can “consume less electricity,” but rather on how end-use energy actors—such as industrial parks, energy-intensive enterprises, data centers, electric vehicles, commercial buildings, and communities—can develop high levels of dynamic adaptability and strong self-sufficiency under extreme circumstances.** Specifically, it comprises two core elements:

First, flexible responsiveness: from “power generation follows load” to “power generation-load interaction:” In fossil fuel-based systems, power generation follows load, with plants burning coal or gas to match user demand. In systems dominated by wind and solar energy, however, the variability of sunlight and wind makes the supply side inherently uncontrollable. A defining feature of demand-side resilience is that major electricity consumers—industry, commerce, computing infrastructure, and even electric vehicles—develop flexible adjustment capabilities. When new energy is abundant, they can rapidly increase consumption to integrate

excess power; when supply declines or the grid is under stress, they can promptly reduce non-essential loads.⁶² This ability to transform traditionally inelastic demand into a system-level regulatory resource is key to overcoming renewable integration challenges.

Second, survivability: from “passive dependence” to “active micro-circulation:” In extreme scenarios—such as geopolitical crises, cyberattacks, or major natural disasters that disable the main grid—a non-resilient demand side can quickly become paralyzed. Another key feature of demand-side resilience is that each critical energy node—such as advanced manufacturing facilities or core communication hubs—can rely on its own or nearby distributed energy resources (e.g., rooftop solar, local wind and solar installed, small gas turbines) and storage systems to respond actively, or quickly disconnect from the main grid and enter “island mode” to sustain essential operations.

The essence of demand-side resilience lies in transforming end users from “passive consumers” into “flexible prosumers” capable of production, regulation, and self-protection.

3.2 Unlocking Flexibility Resources

In the process of building demand-side resilience, another common technical misconception is to equate resilience improvement simply with the large-scale deployment of pumped-storage hydropower and battery storage, as well as the retrofitting or construction of coal-fired power plants.

There is no denying that these approaches are effective in smoothing renewable energy variability. However, under China’s current market conditions, deploying a high share of such storage resources at the generation, grid, or end-user level would significantly increase energy costs for the real economy. From an investment perspective, the unit capital costs of these commonly used flexibility resources are generally high—several times

62 IEA. The Value of Demand Flexibility. December 2025. <https://www.iea.org/reports/the-value-of-demand-flexibility>. Research by the International Energy Agency provides a detailed analysis of the value of “load following generation,” while a study from Cornell University also conducts simulation-based analysis of its application scenarios. https://arxiv.org/abs/2208.12966?utm_source.

those of demand-side flexibility resources—while their marginal costs can be tens to hundreds of times higher.⁶³ Moreover, as noted earlier, due to the lack of effective price signals, a large share of storage systems mandated for centralized renewable projects in previous years has remained underutilized, with asset value not fully realized. In addition, the large-scale expansion of electrochemical and other storage technologies may exacerbate geopolitical risks in the supply chains of critical minerals such as lithium and cobalt—as discussed in Chapter 1, these supply chains remain vulnerable to external constraints and strategic competition.

Therefore, this report argues that, **in unlocking demand-side resilience, activating the demand side’s inherent “flexibility resources” is a more cost-effective—and more strategically significant—approach than relying on the accumulation of costly deployment of physical storage assets.**

In fact, the demand side possesses vast flexibility resources with near-zero marginal costs. Through mechanisms such as virtual power plants, these physically dispersed resources can be aggregated into massive system-level balancing capacity:

1. Flexible transformation of industrial and data center loads: Many energy-intensive industries—such as iron & steel, electrolytic aluminum, cement, and chemicals—possess inherent operational flexibility and adjustment potential. By upgrading industrial control systems, these facilities can fine-tune their energy consumption in response to real-time power supply-demand conditions and variations in renewable generation, while still maintaining overall output levels. This can enhance renewable energy utilization and improve overall power system stability.⁶⁴ Similarly abundant

63 Pei Shanpeng. State Power Investment Corporation Economic Research Institute. *Cost Analysis of Flexibility Resources in Power Systems on a per-kilowatt Basis*. October 2025. According to this study, the average upfront investment cost of new-type energy storage is RMB 2,600/kW; coal-fired power flexibility retrofits cost RMB 2,340/kW; new coal-fired power plants cost RMB 4,000/kW; pumped hydropower storage costs RMB 6,000/kW; demand-side flexibility costs only RMB 200/kW; and vehicle-grid-integration costs RMB 900/kW. In terms of marginal cost, 4-hour standalone energy storage is RMB 86/kW/year; coal power flexibility retrofits are zero; new coal power is RMB 368/kW/year; 4-hour pumped-storage hydropower is RMB 279 or 186/kW/year; demand-side flexibility is RMB 3.6/kW/year; and V2G is RMB 8.3/kW/year. <https://mp.weixin.qq.com/s/XWN88MwAAjkPARXQRLHJbg>

64 Zhao Xudong et al. A Review of Market Mechanisms and Dispatch Models for Unlocking Flexibility in Different High Energy-Consuming Industrial Loads. *Electrical Engineering Magazine*. April 2025. <https://dgjxb.ces-ttransaction.com/EN/abstract/abstract10134.shtml#>. This study quantitatively verifies that energy-intensive industries possess inherent minute-level flexibility in energy use without affecting total output.

flexibility resources also exist in the rapidly growing data center sector.⁶⁵

- 2. Mobile bidirectional networks of electric vehicles (new energy vehicles⁶⁶):** Electric vehicles are not only means of transportation but can also function as “distributed batteries” moving across urban areas. China’s EV fleet has reached nearly 44 million units, with total onboard battery capacity amounting to several billion kilowatt-hours. Through smart charging and vehicle-to-grid (V2G) technologies, EVs can help absorb surplus renewable electricity during off-peak periods and feed power back to community microgrids during peak demand or when the main grid is under stress.
- 3. Thermal inertia in buildings and HVAC systems:** The air-conditioning systems of commercial buildings and large venues exhibit significant thermal inertia, making them a primary source of demand-side flexibility in buildings. By leveraging advanced control models and incorporating dynamic pricing signals into optimization targets, building operators can flexibly adjust cooling loads—through subtle changes such as fine-tuning temperature setpoints or modulating compressor operations—without noticeable impact on occupant comfort. Coordinated control of urban commercial building clusters, if implemented citywide, can unlock enormous flexibility resources while also delivering meaningful electricity cost savings, thereby creating dual benefits in peak load management and economic efficiency.⁶⁷

The key to activating these flexibility resources lies not in technological breakthroughs, but in the restructuring of market mechanisms. Flexibility is a highly valuable service and cannot be requisitioned without compensation through administrative mandates. As the International Energy Agency (IEA) points out in its reports, dynamic price signals are the foundation of demand-side response.⁶⁸

65 A team from University of California, Riverside proposed the EcoCenter framework when assessing the flexibility and decarbonization potential of data centers. By coordinating data processing task allocation, GPU power capping, and multi-GPU workload scheduling, the framework enables significant frequency regulation capability and carbon reduction—without compromising core service quality—thereby helping the grid accommodate more renewable energy. Ali Jahanshahi; Sara Rashidi Golrouye et al. *Coordinating Power Grid Frequency Regulation Service with Data Center Load Flexibility*. January 2026. <https://arxiv.org/abs/2601.22487>

66 The terms “electric vehicles” and “new energy vehicles” are often used interchangeably. In 2025, battery electric vehicles accounted for approximately 69% of China’s new energy vehicle stock, representing the dominant share. This report does not strictly distinguish between the two terms, but instead focuses on their electric attributes and interactions with the power system.

67 Lawrence Berkeley National Laboratory (LBNL). Commercial building HVAC demand flexibility with model predictive control: Field demonstration and literature insights. 2025. <https://eta.lbl.gov/publications/commercial-building-hvac-demand>. Studies have found that applying model-based forecast and control to building HVAC systems can reduce energy demand by 40% to 65% and cut annual energy costs by up to 61%.

68 IEA. The Value of Demand Flexibility. 2025. <https://www.iea.org/reports/the-value-of-demand-flexibility>. The report emphasizes that clear price signals are a prerequisite for translating demand-side potential into grid resilience.

China must move quickly to move away from heavily planned tariff schedule and time-of-use pricing systems, and allow real-time spot market prices—including negative prices and extreme peak prices—to be directly transmitted to end users.⁶⁹ Only when actions such as “reducing load when needed” or “absorbing surplus renewable electricity during periods of oversupply” generate substantial financial returns will capital and enterprises have sustained incentives to develop algorithms, upgrade equipment, and build microgrids.

3.3 Decentralization

To support and unlock substantial demand-side resilience, it is essential to break path dependence on large-scale centralized physical architecture and vigorously promote the decentralization of the energy system.

China’s ultra-high-voltage (UHV) transmission networks and cross-provincial and cross-regional transmission grids have made an indelible contribution to the country’s economic rise over the past decades, and their engineering achievements are highly recognized globally. However, as in nature—where larger organisms often exhibit weaker adaptability to sudden environmental changes—the marginal costs of managing and securing centralized power systems are rising rapidly as the share of clean energy continues to increase.

Building a distributed energy system does not mean abandoning the backbone grid altogether. Rather, it involves deconstructing and complementing it through “cellular, micro-circulation systems.” This represents an architectural evolution from a “pyramid-shaped, centralized management model” to a “decentralized, interconnected network of nodes.”

Reshaping industrial and urban foundations: Under this new paradigm, every large industrial park and every AI computing center should, from the outset, move beyond simply applying for “capacity access” to the main grid and instead plan for an internal microgrid. By maximizing the deployment of distributed solar PV and decentralized wind within the park, and leveraging generation-grid-load-storage integration, energy can be produced and consumed locally “within the fence.”⁷⁰ If a large industrial economy like China

69 Although China has accelerated the development of its spot electricity market since 2025, it is evident that progress still falls short of actual needs.

70 Ministry of Industry and Information Technology of the People’s Republic of China. *Guidelines for the*

shifts a portion of its manufacturing load into such self-balancing microgrid systems, the need for reserve capacity investment in the backbone grid could be significantly reduced, while overall system resilience and fault tolerance would be substantially enhanced.

Mitigating transmission risks and reshaping energy security: The mainstreaming of distributed systems will fundamentally reshape the logic of national energy security. In a highly centralized grid, the failure of just a few critical ultra-high-voltage (UHV) converter stations or major hub substations could trigger widespread cross-provincial blackouts. By contrast, in an “energy fortress network” composed of countless distributed micro-circulation units, any localized physical disruption would affect only a limited number of nodes, rather than paralyzing the entire system. This “disaggregation into smaller units” represents a more sophisticated approach to safeguarding critical national infrastructure in an era where geopolitical tensions may become frequent. Moreover, in the face of extreme weather events, local natural disasters, or other disruptions, such distributed systems are better able to respond adaptively and maintain operational continuity.

3.4 Advantages and Barriers

In the strategic transition toward “demand-side resilience,” physically, China possesses what it takes to build a robust and flexible energy system. At the same time, however, it faces deep-rooted institutional constraints. To truly unlock this resilience—and, within the shortest possible timeframe, accelerate the substitution of fossil fuels (especially oil and gas) with renewable energy and achieve genuine energy independence—China will need to demonstrate strong resolve to reform the traditional electricity pricing system, break path dependence, and dismantle entrenched grid monopolies.

Distinct Natural Advantages:

Construction and Utilization of Industrial Green Microgrids (2026–2030). 2026. https://www.miit.gov.cn/jgsj/jns/gzdt/art/2026/art_7895da36bdd943aebdf8a2c0fe9cb7e9.html.

The guidelines require that, for newly built renewable energy generation systems such as solar and wind in industrial parks, the annual on-site consumption rate should generally not be less than 60%.

- 1. A vast industrial base as a balancing reservoir:** China is one of the world's most comprehensive industrial economies, with industrial electricity consumption accounting for more than 60% of total demand.⁷¹ This means that, compared with economies in Europe and the United States—where residential and commercial consumption account for a larger share—China possesses the largest and most substantial load-balancing resource base in the world. This flexibility potential, if unlocked with appropriate policies and guidance, could be astonishing.
- 2. A clear first-mover advantage in vehicle-grid-integration:** With the world's largest fleet of electric vehicles and an extensive charging infrastructure network, China is well positioned to transform tens of millions of EVs into the world's largest “distributed mobile energy storage network.”
- 3. Strong infrastructure execution capacity:** If demand-side microgrids and virtual power plants are elevated to the level of national strategic projects, China's institutional capacity to mobilize resources for large-scale initiatives can rapidly drive nationwide upgrades of underlying digital infrastructure, including 5G/IoT networks and smart metering systems.

Entrenched Institutional Barriers:

- 1. Blocked transmission of price signals:** This remains the core weakness in the development of China's power spot markets. In most provinces, spot market development remains an unfinished project. Extreme price signals—such as scarcity-reflecting peak prices or surplus-reflecting negative prices—are largely confined to the generation side and rarely transmitted to end users. Without tangible financial incentives, enterprises lack the motivation to invest in equipment upgrades to provide demand-side response.⁷²
- 2. Institutional constraints under grid monopoly:** This is often the most immediate and entrenched obstacle at the implementation level. While the development of distributed microgrids (or integrated “generation-grid-load-storage” systems), direct green power supply, and virtual power

71 According to data from National Energy Administration, the electricity consumption of China's secondary industry reached 6,636.6 billion kWh in 2025, accounting for approximately 64% of total national electricity consumption. <https://www.nea.gov.cn:10443/20260121/715f79826488476a9162da7c8bd77c80/c.html>.

72 Hu Chaoyang. China Power Enterprise Management. *Analysis and Reflections on Key Issues in Advancing the Electricity Spot Market*. 2025. <http://www.ceppc.org.cn:42808/zx/hyfx/20250805/282331.html>. The paper analyzes several existing problems, noting that provincial electricity spot markets remain largely single-sided markets dominated by generators, and that price signals have not been effectively transmitted to end-users—both of which are the major obstacles to current market development.

plants can significantly enhance renewable energy absorption and align with national interests, their deployment in practice often encroaches on the sales revenues and dispatch authority of traditional grid companies. For a long time, local grid operators have cited “security assessments” to impose cumbersome grid-connection barriers on microgrids and other emerging models developed by industrial parks or enterprises. In many cases, even local governments find it difficult to coordinate these issues, making this one of the most significant yet least visible barriers to decentralization.

3. Path dependence of the “security of supply” mindset: Local governments have long relied on a rigid approach— “turn to the grid when problems arise, and ramp up coal generation when power is in short supply”—and often lack both trust in and governance experience with market-based mechanisms and demand-side flexibility as tools for crisis management.

In the constantly evolving landscape of global energy competition, the main battlefield of China’s next phase of energy development no longer lies in the winds and deserts of its western regions, but within countless factories, data centers, electric vehicles, and smart buildings. The strategic shift from “supply-side expansion” to “demand-side resilience” is not only the essential pathway for converting hundreds of gigawatts of renewable capacity into economic gains, but also the bedrock for building a highly resilient new energy system. China is well positioned to achieve this transformation, but it will require decisive institutional reform.

Chapter 4 Typical Scenarios

Next, we will conduct an in-depth analysis of several representative industry scenarios to examine how “demand-side resilience” can be effectively implemented in practice. The selection of these scenarios is primarily based on the following considerations:

- 1. Load Scale and System Impact (Scalability):** The current or projected load is sufficiently large that even small demand-side changes can provide meaningful “backup support” or “peak-shaving” effects at the national energy system level.
- 2. Physical and Process Flexibility (Flexibility):** The industry’s production processes are not entirely rigid. They exhibit forms of physical “inertia” (e.g., thermal inertia) or operational “transferability” (e.g., non-real-time data processing), allowing for load reduction, interruption, or temporal/spatial shifting in response to price signals without causing catastrophic economic losses.
- 3. Multi-Energy Complementarity and Carrier-Switching Capability (Multi-Source Diversity):** The sector can utilize multiple energy carriers—such as electricity, heat, hydrogen, ammonia, and methanol—in an integrated manner. Under extreme conditions, it can flexibly switch between “electrons” (grid-delivered electricity) and “molecules” (pipeline- or storage-based fuels), thereby enhancing system resilience. This model is also reflected in the “Matter-Energy Network” concept proposed by PipeChina.
- 4. Potential for Oil and Gas Substitution (Substitutability):** The sector’s transformation can directly and significantly reduce China’s dependence on imported oil and natural gas.

Based on these four criteria, we select five representative industries/scenarios as key case studies (see Table 4-1) and provide a systematic analysis of the mechanisms through which demand-side resilience operates, along with the opportunities it presents and the institutional challenges that remain.

Table 4-1: Selected Typical Scenarios for Demand-Side Resilience

Scenario	Description	Scalability	Flexibility	Multi-source Diversity	Substitutability
Scenario 1: AI Computing Power and Data Centers	Computing power is the frontier of the global tech competition. Its resilience is manifested through the temporal shifting of “non-real-time computing tasks” (following the troughs of electricity spot prices) and spatial migration (the “East Data, West Computing” strategy—where data follows the green energy supply).	✓	✓		
Scenario 2: Traditional Heavy Industry (Iron and Steel)	These are the traditional big energy consumers. Their resilience lies in utilizing “process scheduling flexibility” and “energy carrier flexibility” as a buffer against the sharp fluctuations of wind and solar power generation.	✓	✓	✓	
Scenario 3: Chemical Industry	The chemical industry is a big consumer of both energy and oil (as feedstocks). Its resilience is achieved not just through the adjustment of production loads, but more importantly through the conversion of multiple energy carriers.	✓		✓	✓
Scenario 4: Electric Vehicles and Vehicle-Grid-Integration	China possesses the world’s largest fleet of electric vehicles. Every vehicle is a mobile energy storage node. In normal times, they act as “sponges” to absorb surplus green power; during a major system failure, these tens of millions of vehicles transform into micro-mobile power stations that defend the last-mile security of the energy system.		✓		✓
Scenario 5: Industrial Parks	This scenario covers a broad range of manufacturing activities and urban last-mile nodes. In normal times, they participate in demand-side response via Virtual Power Plants; under extreme scenarios of main grid failure, they utilize microgrid technology to physically disconnect from the main grid and enter the “Island Mode,” ensuring that essential functions remain operational across society.	✓		✓	

4.1 Scenario 1: AI Computing Power and Data Centers

1. Current Situation and Challenges

Artificial intelligence (AI) large models and massive data processing have become a core infrastructure component of future national competitiveness. As the saying goes, “the ultimate constraint on computing power is electricity.” While somewhat rhetorical, this statement increasingly reflects a pressing reality.

Research by the International Energy Agency indicates that global data center electricity consumption reached 415 TWh in 2024, accounting for 1.5% of total global electricity demand—roughly equivalent to the annual consumption of the United Kingdom. Data centers in the United States, China, and Europe accounted for approximately 45%, 25%, and 15% of this total, respectively. The report projects that, driven by surging demand for AI training and inference, data center electricity consumption will more than double to 945 TWh by 2030, representing around 3% of global electricity demand.⁷³

In China, with the full rollout of the “East Data, West Computing” initiative and the rapid emergence of domestic large models with tens to hundreds of billions of parameters, data centers are becoming one of the fastest-growing sources of electricity demand in the power system. By the end of the 15th Five-Year Plan period, computing-related electricity consumption is expected to account for more than 5% of total national demand.⁷⁴

High energy consumption also brings a range of challenges, including rising carbon emissions. The IEA estimates that global data center emissions will increase from 180 million tons in 2024 to 300 million tons by 2035. Although this represents only about 1.5% of total emissions from the energy sector, data centers are already among the fastest-growing sources of emissions.⁷⁵

73 IEA. Energy and AI. April 2025. <https://www.iea.org/reports/energy-and-ai>

74 China Academy of Information and Communications Technology. *Research Report on the Coordinated Development of Computing Power and Electric Power*. 2025. <https://www.caict.ac.cn/kxyj/qwfb/ztbg/202505/P020250509511369626787.pdf>.

The report projects that under a high-growth artificial intelligence scenario, China's computing centers could consume over 700 billion kWh of electricity by 2030, accounting for 5.3% of total electricity consumption.

75 IEA. Energy and AI. April 2025. <https://www.iea.org/reports/energy-and-ai>

Under traditional energy and IT management models, data centers are treated as “rigid loads.” To ensure uninterrupted operation and data flow, conventional data centers require 24/7 power supply with extremely stable voltage and frequency. This characteristic poses significant challenges to the current energy system:

- 1. Exacerbating renewable energy integration pressures:** If newly built data centers continue to operate under the traditional “24/7 full-load” model, they will be unable to absorb surplus renewable electricity during specific periods (such as midday peaks). On the contrary, to ensure uninterrupted power supply for these facilities, the grid must retain a substantial fleet of high-carbon coal-fired units as baseload capacity, thereby directly slowing the pace of the national energy transition.
- 2. Competition for computing power and pressure on the grid:** Many data centers, seeking proximity to end users or talent hubs, remain heavily concentrated in eastern coastal regions and major urban clusters—such as the Yangtze River Delta and the Beijing–Tianjin–Hebei region—where power resources are already strained. During periods of extreme heat, when electricity demand surges, these energy-intensive facilities may compete directly with residential users and advanced manufacturing plants for limited power supply, placing additional strain on local grids.

2. Resilience Mechanism

Addressing these challenges requires a “demand-side resilience reconfiguration” of computing loads. The underlying logic is to tap into their inherent spatiotemporal flexibility. Put simply, transmitting and storing data is far easier than transmitting and storing energy.

Not all data center workloads require millisecond-level responsiveness (e.g., financial transactions or autonomous driving navigation). In fact, the primary drivers of rising computing-related energy consumption—such as AI model training, large-scale historical data analysis, cold data storage, and cloud-based rendering for film and media—largely consist of non-real-time (delay-tolerant) batch-processing tasks. These tasks are not sensitive to the exact timing or geographic location of computation, providing two key levers for resilience-oriented reconfiguration:

- 1. Temporal load shifting:** Data centers can dynamically adjust the intensity of AI training based on real-time electricity spot prices or forecasts of renewable generation. During midday periods of abundant solar output and low prices, tens of thousands of GPUs can operate at full capacity for large-model training. In the evening, when grid load peaks and renewable

generation declines, non-urgent training tasks can be suspended, allowing servers to enter low-power standby mode.⁷⁶

- 2. Spatial load shifting:** Computing power is arguably the only “energy equivalent” that can be transmitted at the speed of light across regions—or even globally. Through fiber-optic networks, computing tasks can be instantaneously shifted from eastern nodes—where wind and solar resources are scarce and electricity supply is tight—to northwestern regions where wind and solar energy is plentiful. In essence, this replaces the physical dispatch of ultra-high-voltage (UHV) transmission networks with the dispatch of data flows.

Case Studies:

- ◎ **Google’s carbon-intelligent computing platform:** By tracking real-time carbon intensity and renewable generation across major grids, Google has developed a system for cross-regional load shifting. When renewable energy supply is insufficient at a given data center, the system automatically shifts workloads—such as video processing for YouTube and other large-scale internal computing tasks—to data centers located in regions where renewable energy is abundant at that time.⁷⁷
- ◎ **Flexible data centers in Texas (Electric Reliability Council of Texas):** U.S. data center developer Lancium has built “flexible data centers” near wind farms in Texas, specifically designed for energy-intensive computing. These facilities are closely integrated with the ERCOT grid. When the grid faces stress—such as during extreme weather events (e.g., winter storms) or when renewable output drops sharply and prices spike—Lancium’s data centers can reduce several megawatts of load within seconds in exchange for financial compensation from the grid. In doing so, they transform from a burden on the grid into a super stabilizer for grid operations.⁷⁸

76 A research team from University of California, Riverside proposed the EcoCenter framework when assessing the flexibility and decarbonization potential of data centers. By coordinating data processing task allocation, GPU power capping, and multi-GPU workload scheduling, the system can achieve significant frequency regulation capability and carbon emission reductions without affecting core service quality, thereby facilitating greater integration of renewable energy into the grid. Ali Jahanshahi; Sara Rashidi Golrouye et al. Coordinating Power Grid Frequency Regulation Service with Data Center Load Flexibility. <https://arxiv.org/abs/2601.22487>

77 Google Cloud. Our methodology for carbon-intelligent computing, Google Sustainability. 2025. <https://cloud.google.com/blog/products/infrastructure/using-demand-response-to-reduce-data-center-power-consumption>. Google has publicly detailed how its carbon-intelligent computing platform shifts non-latency-sensitive workloads—such as YouTube video processing—across different data centers in time and space, based on real-time carbon intensity and renewable energy availability across global power grids.

78 Lancium. Broad Reach Power and Lancium Partner to Support Grid Stability Through Flexible Data Centers.

3. Opportunities and Potential

Once the data center industry fully develops this spatiotemporal flexibility, it could deliver far-reaching, system-wide benefits for China's energy competitiveness and security.

- 1. A “super sponge” for renewable energy integration:** AI computing demand may be one of the few electricity-consuming sectors capable of matching the scale of China's vast wind and solar bases in the western regions. By establishing a new model of integrated “generation–grid–load–storage–computing” data centers, China can convert curtailed wind and solar power—otherwise wasted due to constraints in ultra-high-voltage (UHV) transmission capacity—into high-value AI computing power locally (i.e., “power-to-computing conversion”).⁷⁹ This would not only help restore renewable energy utilization rates in northwestern provinces to above 95%, but also significantly improve the financial performance of wind and solar developers by activating trillions of RMB worth of underutilized assets.⁸⁰
- 2. A national-level energy security buffer:** In extreme scenarios—such as a recurrence of the severe drought and heatwave that swept through the Yangtze River Basin in 2022, leading to a sharp drop in hydropower output—the East China grid could face widespread power rationing. With demand-side resilience in place, the national dispatch center would not need to forcibly curtail power supply to manufacturing facilities. Instead, through a combination of administrative directives and market-based price signals, large data centers in the Yangtze River Delta could rapidly place more than 50% of their non-real-time AI training workloads into “sleep mode,” and shift these tasks via high-speed computing networks to computing hubs in provinces such as Gansu and Ningxia. This shift alone could free up several gigawatts (GW) of load for the East China grid within seconds. This ability to instantaneously shift computing loads across regions may become a strategically significant buffer for the power system in the face of extreme weather events or cyberattacks.

Texas, 2022-2024. <https://lancium.com/2022/07/07/broad-reach-power-and-lancium-partner-to-support-grid-stability-through-flexible-data-centers/>. Lancium has built Clean Campuses across multiple locations in the United States, which are specifically designed to adjust power consumption on a second-by-second basis in response to spot electricity prices and grid frequency. During extreme weather events in Texas, these facilities have successfully provided critical demand-side response support to the power grid.

79 In fact, due to the abundant and competitively priced renewable electricity available in Western China, some global technology companies are relocating AI computing workloads to China. Southern Energy Observer. *Why “Token Export” Is Also an Opportunity for New Energy Integration in China*. March 2026. <https://mp.weixin.qq.com/s/x4deeuOlhsYoDHjieBTgg?scene=1>

80 At the hub nodes of the “East Data, West Computing” initiative, newly built data centers are now required to source more than 80% of their electricity from renewable energy.

4. Implementation Barriers and Policy Responses

However, under China's current institutional framework and industry rules, this theoretically ideal model of "computing-power synergy" still faces obstacles at the implementation level. To overcome these "last-mile" barriers, China will need to adopt highly targeted policy measures over the next five years.

× **Barrier 1: Distortions from the PUE Metric, Leading to "Adverse Selection"**

At present, the primary metric used by governments at all levels in China to assess whether data centers are "green" is PUE (Power Usage Effectiveness), defined as the ratio of IT equipment energy consumption to total facility energy consumption—the closer the value is to 1, the higher the efficiency. This has created a problematic situation: if a data center invests in energy storage to support grid operations, or proactively curtails part of its server load during periods of power shortage, its total facility energy consumption (the denominator) may increase or its IT equipment energy consumption (the numerator) may decrease, resulting in a worse PUE score. As a result, such facilities may face regulatory pressure, including mandated rectification or even the loss of quotas. This rigid metric—focused solely on physical energy performance while overlooking grid-friendliness—has, to some extent, constrained the development of data center resilience.

✓ **Policy Response 1: Move Beyond PUE by Introducing CUE and Grid-Friendly Performance Metrics**

Within the next one to two years, the National Development and Reform Commission (NDRC) and the Ministry of Industry and Information Technology (MIIT) could jointly issue new regulations to support flexible data centers that actively participate in demand-side response and help absorb curtailed renewable energy. Measures could include granting "PUE exemptions" or allowing renewable energy credits within the dual-control framework for energy consumption. The focus of assessment should shift from "how much electricity is consumed" to "when and from what sources electricity is consumed."

× **Barrier 2: Zero Tolerance for "Interruption" in Cloud Service Business Models**

At present, major cloud providers typically commit to Service Level Agreements (SLAs) with availability of 99.99% or higher. Customers have grown accustomed to accessing computing power at full capacity anytime and anywhere. To avoid substantial penalty payments for SLA breaches,

cloud providers are reluctant to adjust server power and thus lack commercial incentives to offer “flexible compute” services.

✓ **Policy Response 2: Establish and Promote a Dedicated Market and Standards for “Interruptible Computing”**

Drawing on the “Spot Instances” model of Amazon AWS,⁸¹ national authorities should encourage and collaborate with leading cloud providers to introduce “low-carbon/interruptible cloud service packages” directly linked to fluctuations in renewable generation. AI developers should be clearly informed that if their training tasks can be paused during power shortages and resumed when renewable energy is abundant, they will benefit from significantly discounted computing prices. Through such pricing mechanisms, the flexibility needs of the power grid can be effectively transmitted to AI computing companies.

× **Barrier 3: “Compute–Power Silos” Caused by Lack of Cross-Departmental Coordination**

Currently, the regulatory departments responsible for the power system (such as the National Development and Reform Commission and the National Energy Administration) operate in parallel with those overseeing computing infrastructure networks (such as the Ministry of Industry and Information Technology and the Cyberspace Administration). The power grid lacks visibility into data center workloads, while computing scheduling platforms are unable to interpret grid conditions such as power flows and spot prices.

✓ **Policy Response 3: Mandate a Standardized “Compute–Power Coordination API”**

In newly established national “East Data, West Computing” hub nodes, it should be mandatory to break down data silos between power dispatch centers and computing scheduling platforms. Within the next three years, a unified “compute–power coordinated dispatch communication protocol” should be developed, enabling real-time grid data—such as frequency fluctuations and spot electricity prices—to be transmitted in machine-readable format directly to data center AI schedulers. This would enable true machine-to-machine (M2M), second-level automated responses.

81 Amazon Web Services (AWS), Amazon EC2 Spot Instances. <https://aws.amazon.com/cn/ec2/spot>. This is a relatively mature “interruptible computing” business model in the cloud computing sector, which allows customers to use idle computing resources at steep discounts. When full-price demand arises, the system can reclaim servers and interrupt low-cost services, enabling more flexible resource allocation.

5. Scaled Deployment

The underlying logic of resilience demonstrated in AI compute scenarios can be summarized as follows: replacing the high-cost transmission of watts (energy flows) with the frictionless movement of bits (information flows), and leveraging the temporal flexibility of non-real-time tasks to offset the inherent intermittency of wind and solar power.

Once this resilient “compute-power coordination” mechanism is proven at scale in hyperscale data centers, its core logic can be extended across the nation’s broader digital infrastructure:

- 1. 5G/6G base station networks:** China operates a vast network of millions of 5G base stations, which are also major electricity consumers. Applying the same logic, the energy system at these stations can interact with the power grid, enabling a nationwide reduction in base load on the grid as well as in carbon emissions.⁸²
- 2. Biopharmaceutical and scientific computing clusters:** Research workloads such as protein folding simulations and deep-space data rendering are typical non-real-time batch-processing tasks. They can be seamlessly integrated into such a “flexible compute pool.”

Economies of Scale: When digital and ICT infrastructure—previously accounting for an ever-growing share of total electricity consumption—transitions from being a major load and protected entity of the grid into a large-scale flexible resource, the energy system gains a powerful form of “soft buffering capacity.” Through algorithms and digital dispatch alone, this could unlock tens of gigawatts of balancing capacity. According to research by a team at Beijing Institute of Technology, by 2030 China’s data center power load is expected to reach approximately 105 GW, of which 20–40% could be converted into flexibility resources—equivalent to roughly 23–40 GW.⁸³

82 A paper published in Nature Reviews Electrical Engineering proposes using artificial intelligence to promote the coordinated optimization of low-carbon energy systems and information networks. The study finds that AI-driven strategies such as dynamic base station sleep modes and workload migration can, through algorithmic optimization alone (without additional energy storage investment), enable 5G networks to achieve more than 50% of their net-zero targets while maintaining user experience. Junliang Ye; Yuxi Zhao; Yue Yu et al. Artificial intelligence for low-carbon energy and information networks. March 2026. Nature Reviews Electrical Engineering. <https://www.nature.com/articles/s44287-026-00271-0>

83 Wang Yongzhen, Tang Hao, Wei Yiming et al. *Comprehensive Energy Consumption and Flexibility Forecast of China’s Data Centers*. Journal of Beijing Institute of Technology. March 2025. <https://journal.bit.edu.cn/sk/cn/article/pdf/preview/10.15918/j.jbitss1009-3370.2025.7124.pdf>

4.2 Scenario 2: Traditional Heavy Industry (Iron and Steel)

1. Current Situation and Challenges

The iron and steel industry is a key pillar of national industrialization and infrastructure development, while also being a major energy consumer. China's crude steel output currently remains at around one billion tons, accounting for roughly half of global production. The sector's energy consumption structure is both massive and complex, with coal as the dominant energy source.

According to data from the National Bureau of Statistics Statistical Yearbook, in 2023 China's ferrous metal smelting and rolling processing industry (primarily iron and steel) consumed a total of 680 million tons of coal equivalent, accounting for about 12% of the country's total energy consumption. Electricity consumption reached 707.3 billion kWh, representing 7.5% of national power usage.⁸⁴ In recent years, China has accelerated efforts in scrap steel recycling and short-process steelmaking. As short-process production relies primarily on electricity,⁸⁵ the power demand of the iron and steel industry is expected to continue rising. The sector is also a major source of carbon emissions, second only to the power industry.⁸⁶

Under traditional management thinking, iron and steel production is often viewed as a rigid production line in which "a single change affects the entire system." The systemic burden created by this rigidity is reflected in the following aspects:

- 1. Slow progress in energy transition among energy-intensive producers:** Traditional steel plants typically pursue 24/7 full-capacity continuous

84 National Bureau of Statistics of China. *China Statistical Yearbook*. 2025. <https://www.stats.gov.cn/sj/ndsj/2025/indexch.htm>

85 The production processes in the iron and steel industry are currently mainly divided into two categories: the long process and the short process. In simple terms, the "long process" typically uses iron ore and coke as raw materials, and the production chain mainly includes sintering (or pelletizing), coking, ironmaking, steelmaking, and rolling. The "short process" mainly uses scrap steel as the raw material and relies on electric arc furnaces (EAFs), completing production through steelmaking and rolling. In general, the "short process" refers to electric arc furnace steelmaking.

86 Wang Xuying, Li Bing, Lyu Chen et al. *Research on the Peak Pathway of Carbon Dioxide Emissions in China's Iron and Steel Industry*. Research of Environmental Sciences, 2022. <https://www.hjkxyj.org.cn/article/doi/10.13198/j.issn.1001-6929.2021.11.11?viewType=HTML>

operation to spread depreciation costs, and are often among the largest energy users in their regions. The long-process route still dominates China’s iron and steel industry. To ensure production continuity and stability, coal remains the primary energy source, leaving limited room for integrating intermittent renewable energy such as wind and solar. This creates a structural mismatch: despite China’s large installed renewable energy capacity, energy- and carbon-intensive sectors—including iron and steel and cement, which significantly influence national energy consumption and carbon emission trends—have not maximized renewable energy utilization to accelerate the substitution of fossil fuels.

- 2. Exposure to “green trade barriers”:** With mechanisms such as the EU’s Carbon Border Adjustment Mechanism (CBAM) coming into force, high-carbon steel products—characterized by low flexibility and heavy reliance on fossil fuels—may face the risk of substantial tariffs. Although the EU accounts for a relatively small share of China’s direct iron and steel exports, downstream industries such as automotive and machinery manufacturing may also be affected by similar trade barriers.⁸⁷

2. Resilience Mechanism

To equip a traditionally “heavy, rigid, and inflexible” sector like iron and steel with demand-side resilience, it is necessary to unlock potential **along two dimensions**: process scheduling flexibility and energy carrier flexibility, thereby transforming the industry into a “resilience stabilizer” for the grid.

- 1. Short-process route: process scheduling flexibility — load shifting and interruption based on physical inertia.** Not all stages of iron and steel production require strictly continuous operation. In particular, electric arc furnace (EAF) steelmaking in short-process routes, as well as downstream rolling processes, possess strong short-term load adjustment capabilities. When the power grid is under stress, steel plants can reduce EAF power or delay the next heat; when electricity supply is ample—especially during peaks in wind and solar generation—and power prices are low, they can resume high-load operations. This enables optimization of electricity costs while providing flexibility to the grid. In essence, such “off-peak production” turns steel plants into large-scale “virtual pumped-storage power stations.”

87 European Commission. Commission strengthens the Carbon Border Adjustment Mechanism. 2025. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_3088. The European Union plans to expand the Carbon Border Adjustment Mechanism (CBAM) from 2028 to cover 180 categories of carbon-intensive products, including steel and aluminum products, while also introducing anti-circumvention measures.

2. Long-process route: energy carrier flexibility – “power-heat switching” and green hydrogen substitution. For blast furnaces and reheating furnaces that require continuous medium- to high-temperature operation, resilience can be achieved through cross-carrier energy conversion. For example, large electric boilers can convert surplus electricity into heat above 500°C during periods of abundant renewable power and low electricity prices. This thermal energy can then be stored using materials such as molten salts and insulating refractory bricks. During peak electricity price periods, power input can be cut off, and the stored heat released to sustain production, or operations can switch to natural gas boilers or combined heat and power (CHP) units.

In addition, most long-process steel plants are equipped with captive power plants, typically fueled by by-product gases, along with corresponding gas storage facilities. By dynamically adjusting the storage and release of these gases and coordinating with generating units, plants can respond flexibly to fluctuations in electricity supply and demand.⁸⁸ Beyond “power-heat” switching, the steel industry can also use renewable electricity to produce green hydrogen via electrolysis, partially replacing coke as a reducing agent (hydrogen-based metallurgy), thereby further reducing the industry’s rigid dependence on coal.⁸⁹

Case Studies:

◎ **China’s time-of-use (TOU) electricity pricing and corporate practices:** As early as 2021, the National Development and Reform Commission introduced policies to widen the peak-valley electricity price differential.⁹⁰ Today, many domestic short-process (electric arc furnace, EAF) steel producers have made it standard practice to shift operations away from peak-price periods, conducting maintenance during the daytime and shifting smelting to late-night hours, thereby helping reduce peak loads on local power grids.⁹¹

88 Zhao Lei. *Analysis of Green Electricity Application Strategies in China’s Iron and Steel Industry*. China Steel. 2025 (01).

89 IEA. IEA Hydrogen TCP Task 52 - Hydrogen for Iron and Steelmaking. 2025. <https://www.ieahydrogen.org/task/task-52-hydrogen-for-iron-and-steelmaking/>. Relevant projects by the International Energy Agency analyze the technological maturity, supply chain feasibility, and global transition pathways of hydrogen-based ironmaking. The study highlights that hydrogen, as a reducing agent in direct reduced iron (DRI) processes, provides a feasible alternative to traditional fossil-based reducing agents.

90 National Development and Reform Commission. *Notice on Further Improving the Time-of-Use Electricity Pricing Mechanism* (Price Reform [2021] No. 1093). July 2021. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202107/t20210729_1292067.html. This policy serves as a foundational document in China’s recent demand-side response reforms. By widening peak-valley price differentials, it has effectively encouraged energy-intensive enterprises to shift production away from peak periods.

91 Central Iron and Steel Research Institute; Natural Resources Defense Council. *Promoting the Development*

◎ **Molten salt energy storage and industrial thermal battery solutions:**

Shanxi Jianlong Industrial Co., Ltd., an iron and steel enterprise in Shanxi Province, has adopted a molten salt thermal storage system integrated with by-product gas and renewable energy-based peak-shaving technologies to enhance the flexibility of its energy system. By converting surplus blast furnace gas and excess renewable electricity into storable and dispatchable thermal energy—stored in molten salt form—and integrating it with steam systems and gas-fired generation units, the company has transformed its originally rigid gas-based power system into a flexible, multi-energy coordinated system capable of load balancing.⁹²

Meanwhile, Rondo Energy in the United States uses low-cost refractory bricks for thermal storage, converting intermittent wind and solar power into stable, industrial-grade continuous steam and hot air. Its solutions have already been commercialized in multiple traditional manufacturing facilities across Europe and North America.⁹³

3. Opportunities and Potential

Once equipped with demand-side resilience, heavy industries can make substantial contributions to the national energy system:

1. Unlocking GW-Scale, Low-Cost Virtual Storage Potential

Electricity consumption in heavy industries such as iron and steel and cement is immense. If even one-tenth of China's steel production capacity were integrated into demand response systems, it could rapidly unlock gigawatt-scale flexibility resources. This would significantly ease the challenges of large-scale renewable energy integration—without requiring costly lithium battery deployment or additional investment in transmission lines and transformers.

of Scrap Steel-EAF Short Process Steelmaking: A Case Study of Sichuan Province. 2025. <https://www.nrdc.cn/Public/uploads/2025-11-17/691a9672e1f55.pdf>.

The report notes that in Sichuan Province, many short-process steel enterprises have adopted off-peak electricity pricing (“valley power”) as a standard operating model to reduce electricity costs.

92 Molten salt thermal energy storage coupled with coal gas and renewable energy generation for peak-shaving. https://www.csm.org.cn/col/col6317/art/2026/art_b911ea68808f4a3ba724e0ed7bac7545.html; http://www.csteelnews.com/qypd/qydt/202405/t20240514_87939.html

93 Rondo Energy. October 2025 . <https://www.rondo.com/news-press/rondo-powers-up-worlds-largest-industrial-heat-battery>. In Alameda, California, USA, a 100 MWh thermal energy battery has been put into operation.

2. Coordinated Energy Use Under Extreme Circumstances

In extreme scenarios, such as a rare cold wave causing severe icing on ultra-high-voltage (UHV) transmission lines—which can disrupt inter-provincial power flows—demand-side resilience would enable grid operators to avoid indiscriminate load shedding. Instead, through the highest level of emergency demand response, dozens of steel plants across a province could simultaneously shut down electric arc furnaces and large rolling equipment, while maintaining only essential power for core blast furnace insulation and safety systems, or rapidly releasing stored by-product gas for power generation.

The large volume of electricity freed up within seconds in this way would be sufficient to safeguard critical lifelines, including tertiary hospitals, communication hubs, and residential heating systems.

4. Implementation Barriers and Policy Responses

At present, the main obstacles preventing traditional industries from unlocking this vast resilience potential are no longer technological challenges, but rather rigid market mechanisms and entrenched interest structures.

× **Barrier 1: Low Spot Market Penetration Among Large Industrial Power Users**

China's electricity spot market has made significant progress over the past two years, even exceeding earlier conservative expectations. However, it remains far from reaching the majority of end users. If “real-time” prices—updated every 15 minutes in the spot market—cannot be directly passed through to steel and cement plants, enterprises will lack the economic incentive to invest in automated control systems capable of second-level load response.

✓ **Policy Response 1: Mandate Full Market Participation for Energy-Intensive Enterprises and Subsidize Automated Demand Response**

Within the next one to two years, provincial power trading centers should require all energy-intensive enterprises above a certain consumption threshold to fully participate in spot market settlement. At the same time, targeted financial support should be provided to companies willing to upgrade distributed control systems that will enable automatic and instantaneous load adjustment in response to grid dispatch signals.

× **Barrier 2: Weak Economic Incentives for Cross-Carrier Transformation (Electricity for Coal, Electricity for Gas, Hydrogen for Coal, etc.)**

Take hydrogen-based metallurgy as an example. The stable and cost-competitive supply of hydrogen remains a key challenge, and the production costs of hydrogen-based shaft furnaces are significantly higher than those of the conventional blast furnace–basic oxygen furnace (BF–BOF) route, thus making sustained stable operation difficult.

✓ **Policy Response 2: Integrate Flexibility Upgrades with Transition Finance**

The People’s Bank of China could introduce dedicated policies to explicitly include industrial flexibility upgrades—such as power–heat decoupling, green hydrogen applications, and flexible production scheduling—within the scope of transition finance. Long-term concessional loans below the Loan Prime Rate (LPR) could be provided. Such measures would not only value emissions reduction, but also enable the monetization of the peak-shaving capacity that enterprises provide to the power system.

5. Scaled Deployment

The underlying logic of resilience demonstrated in these scenarios lies in the ability to break rigid dependence on a single fossil fuel by leveraging the physical interruptibility of industrial processes (temporal shifting), as well as the flexibility of thermal energy conversion. This “process load shifting + thermal energy conversion” resilience model can be horizontally extended to most basic heavy industries:

- 1. Cement and building materials industry:** The raw material grinding process in cement production is a typical interruptible load and can be easily shifted away from peak grid demand periods. Meanwhile, the high-temperature calcination stage can adopt a “power-heat switching” model, replacing coal with renewable electricity.
- 2. Non-ferrous metals and glass industries:** These sectors similarly possess the ability to adjust production schedules in response to grid fluctuations.
- 3. Paper, textile, and dyeing industries:** With substantial demand for low- to medium-pressure steam, these sectors are well suited for low-cost renewable energy-based thermal energy storage systems.

Economies of Scale: Based on analysis of representative industrial enterprises, flexible loads account for approximately 20% of total production load in the iron and steel industry, 24% in cement, 25% in glass, and up to 35%

in textiles.⁹⁴ China hosts one of the world's largest and most comprehensive manufacturing systems. Under favorable policy conditions, the flexible load potential of energy-intensive industries could reach 100 GW,⁹⁵ exceeding the total installed capacity of all operating pumped-storage hydropower stations.

This form of energy system resilience—built upon a vast and deeply integrated industrial base—is a strategic energy security safeguard that deindustrialized Western economies are structurally unable to replicate.

94 Cheng Yuan, Rao Yao, Ding Sheng. China Electric Power Research Institute. *Analysis of Flexible Load Potential on Industrial Demand Side*. *Energy Engineering*, January 2023. <https://nygc.cbpt.cnki.net/portal/journal/portal/client/paper/41f9a3d0e71a48661c31c7f58c75b2dc>.

Liu Ziyi, Xie Jun, Liu Yujing, Gong Feixiang et al. *Series on Electricity Demand-Side Flexibility: Industrial Flexibility Potential and Development Status*. Rocky Mountain Institute, 2023. <https://rmi.org.cn/insights/industrial-dsf/>.

95 Gong Feixiang, Sun Wenqiang, Li Dezhi et al. *Technological Outlook for the Low-Carbon Green Development of the Iron and Steel Industry from an Integrated Energy Perspective*. *China Sustainability Tribune*, 2023 (08). The paper notes that, based on current estimates of energy-intensive industrial load scale, the flexibility potential could reach 108 million kW (108 GW).

4.3 Scenario 3: Chemical Industry

1. Current Situation and Challenges

The chemical industry is one of China's national economic pillars. China hosts the world's largest integrated petrochemical refining capacity, as well as the most extensive modern coal-to-chemicals capacity (including coal-to-olefins, coal-to-oil, and coal-to-gas). At the same time, it is also the industrial sector with the fastest growth in energy consumption and carbon emissions in China, and a major consumer of oil and gas.⁹⁶

According to data from the National Bureau of Statistics Statistical Yearbook, in 2023 China's chemical raw materials and chemical products manufacturing industry (excluding refining, coking, and some coal-to-chemicals segments) consumed a total of 738 million tons of coal equivalent, ranking first not only within the manufacturing sector but also across all industrial sub-sectors listed in the Statistical Yearbook. Electricity consumption reached 674.8 billion kWh, ranking third among manufacturing industries, following non-ferrous metal smelting and rolling (e.g., aluminum electrolysis) and ferrous metal smelting and rolling (e.g., iron and steel).⁹⁷

Globally, according to the International Energy Agency, the chemical industry is currently the largest industrial energy-consuming sector. A distinctive feature of the chemical industry is that fossil fuels (oil, coal, and natural gas) are used not only as fuels to provide heat and steam, but also as feedstocks that are chemically transformed into plastics, fertilizers, synthetic fibers, and other materials.⁹⁸

“Chokepoint” risks arising from high import dependence: Crude oil is the

96 CarbonBrief. Analysis: China's CO2 emissions have now been 'flat or falling' for 21 months. 2026. <https://www.carbonbrief.org/analysis-chinas-co2-emissions-have-now-been-flat-or-falling-for-21-months/>. This analysis finds that coal consumption in China's chemical industry increased by 15% and oil consumption increased by 10%, leading to a 12% rise in total carbon emissions from the sector. Against a backdrop where emissions in major sectors such as transportation, power, and cement generally declined, the chemical industry became the only significant source of emission growth that year, thus producing a critical impact on overall national emission trends.

97 National Bureau of Statistics of China. *China Statistical Yearbook*. 2025. <https://www.stats.gov.cn/sj/ndsj/2025/indexch.htm>

98 IEA. Chemicals-Energy System Overview. 2023. <https://www.iea.org/energy-system/industry/chemicals>. The report highlights the chemical sector as the largest industrial energy-consuming industry globally. Its distinctive feature is that more than half of fossil fuels are used as feedstock for chemical synthesis rather than being combusted for energy.

primary feedstock for the chemical industry, yet China's import dependence has remained above 70% for many years. The chemical supply chain represents a concentrated manifestation of the geopolitical vulnerabilities highlighted in Perspective 1, Chapter 1. In the event that import sources are disrupted due to geopolitical conflicts or maritime energy routes are blocked, supplies of essential materials such as plastics, rubber, fibers, and other key chemical intermediates required for the normal functioning of the national economy would face severe shortages, thus posing a significant threat to economic stability.

Continuous production and requirements for the power system: Chemical production typically emphasizes “safe, stable, long-duration, full-capacity, and optimized operation.” Once production facilities are started up, they generally operate continuously for several months to a year. This makes chemical plants large-scale electricity consumers with extremely low operational flexibility. They are not only unable to effectively integrate high shares of renewable energy locally, but also require dedicated high-capacity and highly stable power supplies to ensure safe and reliable operations.

2. Resilience Mechanism

Unlike other energy-intensive industries that rely primarily on off-peak electricity use, the chemical industry possesses a unique capability for multi-energy carrier switching, giving its demand-side resilience a far more diverse and flexible advantage. If handling complex molecular-level chemical reactions and material transformations is already a core strength of the industry, then managing comparatively less complex tasks—such as peak shaving and energy carrier switching—may not be as difficult as commonly assumed. Its resilience mechanism can be understood along two main pathways.

1. Near-term, economically viable pathway: thermal storage-based regulation through “electricity-for-steam” and “electricity-for-gas” substitution (power-heat carrier switching). Chemical production requires large volumes of industrial steam at various pressure levels. This steam is typically used for thermal processes (e.g., distillation, drying, polymerization) or for power generation (e.g., driving turbines to operate pumps and compressors). Traditionally, such steam is produced by burning coal or natural gas.

However, in regions rich in wind and solar resources, chemical plants can deploy high-voltage electrode boilers to meet thermal demand. When renewable electricity is abundant and prices are low, the system can automatically switch to electric boilers to produce “green steam.” Excess

steam can then be stored in relatively low-cost steam accumulators or high-temperature molten salt thermal storage systems. When renewable power supply declines, electric boilers are shut down, and production is maintained using stored “green steam” or backup coal-fired boilers.

This dual-source thermal energy network provides chemical plants with strong, low-cost peak-shaving capabilities.⁹⁹ At the same time, during periods of high renewable generation, plants can replace steam-driven systems with electric drives for power purposes, and substitute fuel gas with electricity through processes such as electric cracking¹⁰⁰—both of which are key energy-consuming units in large chemical facilities. When renewable supply is insufficient, plants can switch back to conventional energy modes using captive power plants or stored fuel gas.

Through this flexible switching between electricity and thermal energy carriers, the chemical industry can significantly enhance renewable energy integration and reduce reliance on coal and natural gas by fully leveraging its inherent demand-side resilience.

2. Medium- to long-term strategic pathway: substitution via green hydrogen, ammonia, and methanol (power-molecule carrier switching).

This pathway represents a distinctive strength of the chemical industry. Renewable electricity can be used to electrolyze water to produce green hydrogen, which can then be further synthesized into green ammonia or green methanol. With ongoing technological advances, proton exchange membrane (PEM) and alkaline (ALK) electrolyzers now exhibit strong second- to minute-level load-following capabilities, enabling them to closely track the variability of wind and solar generation. The resulting green hydrogen can be fed into downstream ammonia synthesis or refining processes, effectively converting otherwise curtailed or surplus electricity into chemical products that are suitable for long-term storage and transport.

99 International Renewable Energy Agency & State Grid Corporation of China. Electrification with Renewables: Driving the transformation of energy services. 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_RE-Electrification_SGCC_2019.ashx; https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Feb/IRENA_Smart-Electrification_Renewables_2022.pdf The report points out that by deploying “hybrid boilers” capable of rapidly switching between electricity, gas, or coal, industrial facilities can take advantage of electricity price fluctuations. During periods of excess renewable generation and low electricity prices, they can switch to electric heating combined with thermal energy storage, thereby transforming industrial loads into flexible resources and enabling low-cost load balancing.

100 In chemical production, fuel gas is sometimes required to heat materials to very high temperatures. For example, the cracking furnace used in ethylene production typically operates at around 800°C and requires large amounts of fuel gas (including natural gas) to provide heat. However, emerging electric heating technologies can potentially replace fuel gas in such processes.

Case Studies:

⦿ **“Electricity-for-steam/gas” substitution and thermal storage:**

The Phase II project of the China Coal Yulin Coal Deep Processing Base adopts electrically driven air separation. Its 3 × 85,000 Nm³/h (oxygen) air separation units form one of the largest clusters of electrically driven ASUs in China. The German chemical company BASF is advancing the electrification of steam cracking units at its Ludwigshafen site and Zhanjiang Verbund site, replacing natural gas with electric heating furnaces to enable flexible interaction with the power grid. By the end of 2025, China National Petroleum Corporation’s Dushanzi Petrochemical is expected to commission a pilot electric cracking furnace, completing validation for cracking ethane/propane, LPG, and naphtha. Sinopec Zhenhai Refining & Chemical is also advancing industrial-scale pilot tests.

⦿ **Renewable-based green hydrogen production:** Sinopec has completed the world’s largest solar-based green hydrogen demonstration project (20,000 tons per year) in Kuqa, Xinjiang. The project uses solar power to produce green hydrogen, which is transported via pipeline to the Tahe Refining and Chemical Plant, replacing hydrogen previously produced from natural gas.¹⁰¹

3. Opportunities and Potential

Chemical hubs equipped with multi-energy switching capabilities can serve as a powerful stabilizing force for China’s energy system and geopolitical security:

1. A Major Sink for Renewable Energy in Northwest China

China’s largest wind and solar bases geographically overlap with its major modern coal-to-chemicals hubs (e.g., Inner Mongolia, Xinjiang, Ningxia, and northern Shaanxi). By adopting “electricity-for-steam” substitution combined with partial green hydrogen integration, large-scale chemical parks can be transformed into flexible, generation-responsive loads. In Inner Mongolia alone, such clusters could provide gigawatt-scale flexibility capacity to the

101 Sinopec Luoyang Engineering Company. *Xinjiang Kuqa Green Hydrogen Demonstration Project Fully Completed and Put into Operation*. September 2023. http://lpec.sinopec.com/lpec/news/com_news/20230904/news_20230904_550906974984.shtml.

The project leverages abundant solar resources in Xinjiang and has preliminarily demonstrated the feasibility of green hydrogen-based refining at industrial scale.

local grid. This would significantly alleviate renewable curtailment caused by constraints in ultra-high-voltage (UHV) transmission capacity and enable the localized conversion of green electricity into high-value chemical products.

2. A Strategic Buffer Against Geopolitical Supply Disruptions

Under extreme scenarios—for example, when a major geopolitical conflict in the Middle East has severely disrupted China’s seaborne oil and gas imports—traditional refineries could face widespread shutdowns, triggering nationwide shortages of chemical feedstocks. By contrast, resilient, modern chemical industrial parks could rapidly scale up renewable-powered production of green hydrogen and green methanol, while deeply integrating with coal chemical processes. For instance, green hydrogen can compensate for hydrogen deficits in coal-to-chemicals pathways, while CO₂ can be fully converted into chemical products.

This integrated “electron-to-molecule conversion network,” anchored in domestic renewable resources with coal as a strategic backup, would help ensure the supply of essential fuels (e.g., methanol as a substitute for gasoline and diesel) and critical materials (including synthetic resins, rubber, and fibers for both civilian and defense applications). In doing so, it could help mitigate vulnerability to external energy supply disruptions.

4. Implementation Barriers and Policy Responses

As the cost of renewable electricity continues to decline, the chemical industry has shown strong interest in its adoption. Some companies have already achieved 100% renewable electricity consumption for their existing power demand through the purchase of green certificates. However, it must be acknowledged that the direct production of hydrogen, ammonia, and methanol using green electricity remains economically uncompetitive. For example, the cost of green hydrogen is often two to three times that of coal-based hydrogen, making it difficult for large-scale deployment to occur purely through market forces. To scale up this system, a coordinated approach combining short- and long-term measures, supported by appropriate policy mechanisms, is required.

× Barrier 1: Economic Disadvantage of Green Hydrogen and Capacity Charge Burdens on Electrolyzers

To utilize low-cost surplus renewable electricity, electrolyzers and electric boilers typically operate intermittently (e.g., only 8–10 hours per day). However, under the current electricity pricing framework, large industrial

users must pay substantial fixed “capacity charges” for grid connection. As operating hours decrease, the capacity cost allocated per unit of electricity rises, which significantly undermines the economic viability of using off-peak power for energy carrier switching.

✓ **Policy Response 1: Exempt Capacity Charges for Flexible P2X (Electricity-to-X) Facilities and Adopt Volumetric Pricing**

Over the next 1-2 years, the National Development and Reform Commission could introduce targeted policy measures. For electrolysis-based hydrogen production systems and electric boilers that commit to being fully interruptible, demand-responsive to the grid, capacity charges (including basic capacity fees or maximum demand charges) could be fully waived. This would allow such facilities to absorb surplus renewable electricity during low-price periods without incurring additional fixed cost burdens.

× **Barrier 2: Lack of an End-Use Market Willing to Pay a “Green Premium”**

Chemical companies that invest heavily in replacing fossil fuels with renewable electricity to produce “green chemicals” face significantly higher production costs. However, the value of low-carbon attributes is not yet fully reflected in end products in the domestic market, thereby weakening incentives for corporate transition.

✓ **Policy Response 2: Establish Integrated Certification Linking “Green Electricity–Green Hydrogen–Carbon Assets,” and Connect to Export and Shipping Markets**

Leveraging the national carbon market, China should rapidly establish internationally recognized carbon footprint accounting standards for green methanol and green ammonia within 1-3 years. These high-cost but near-zero-carbon “green molecules” can then be directed toward sectors more sensitive to carbon taxes—such as international aviation and long-distance maritime shipping—as well as export-oriented manufacturers facing compliance pressures under the EU’s Carbon Border Adjustment Mechanism (CBAM). Revenues generated through carbon market mechanisms can, in turn, be used to subsidize the flexible transformation of chemical production bases.

× **Barrier 3: Lack of Interest Among Coal-to-Chemicals Producers to Adopt Green Electricity and Green Hydrogen**

For coal-to-chemicals enterprises, existing coal-based hydrogen production technologies are mature and cost-competitive. In the absence of binding carbon constraints, switching from inexpensive “grey hydrogen” to higher-

cost green hydrogen would directly raise production costs. Moreover, the continuous operation of coal chemical processes is inherently mismatched with the intermittent nature of renewable-based hydrogen production, creating challenges in maintaining a stable hydrogen supply even when producers are willing to partially substitute or fully transition to green hydrogen.

✓ **Policy Response 3: Phase in Mandatory Requirements for Higher Shares of Green Electricity and Green Hydrogen in the Coal-to-Chemicals Industry**

China could introduce phased mandates requiring both new and existing coal chemical projects to incorporate no less than 20–30% flexible energy capacity, while gradually increasing the share of green hydrogen in synthesis gas. Projects meeting green hydrogen integration standards could be rewarded under dual carbon control assessment frameworks, while lagging enterprises would face stricter constraints on capacity expansion.

5. Scaled Deployment

The resilience logic demonstrated in chemical industry scenarios can be summarized into three core elements: breaking down barriers between energy carriers, deploying physical buffer systems (such as hydrogen storage and thermal storage) as an alternative form of “battery” within the energy system, and substituting fossil-based inputs with non-fossil feedstocks at the source—thereby transforming a traditionally resource-dependent sector into a technology-driven manufacturing industry.

This mechanism of “multi-energy carrier switching” is not just confined to traditional petrochemical and coal chemical sectors. It is rapidly extending into several emerging trillion-yuan industries with strong growth potential in China:

- 1. Green transport and sustainable aviation fuel (SAF):** For long-distance transport sectors such as aviation and deep-sea shipping, large-scale electrification remains constrained, as aircraft and vessels cannot feasibly carry heavy battery systems. Green methanol, green ammonia, and SAF—produced through flexible, renewable-integrated chemical systems—represent viable decarbonization pathways for long-haul transport. In particular, SAF is expected to be the primary long-term solution for decarbonizing the aviation sector.
- 2. Synthetic biology manufacturing:** In the future, green hydrogen produced from renewable electricity, combined with captured CO₂, could be used to directly synthesize proteins, starches, and polymer materials via enzymatic

catalysis. This pathway has the potential to become a low-carbon alternative to conventional petrochemical-based agriculture and chemical production.

Economies of Scale: As chemical industrial bases—traditionally rigid and energy-intensive consumers—evolve into integrated networks capable of both absorbing surplus electricity (“electron sinks”) and producing green molecules through technologies such as electrolyzers and electrode boilers, China’s energy and chemical system will undergo a structural transformation. The power grid will no longer operate as a rigid, one-way system, nor will it remain tethered to massive volumes of oil and gas as its primary feedstock or fuel. This model can be replicated across sectors such as transportation and iron and steel, which will not only effectively bolster the resilience of China’s energy and power systems, but will also drastically reduce the carbon footprint of these industries. These measures will also help position China’s industrial system advantageously in the global transition toward low-carbon supply chains.

4.4 Scenario 4: Electric Vehicles and Vehicle–Grid-Integration

1. Current Situation and Challenges

Our focus now shifts from large, centralized heavy industry to a highly distributed yet massive category of end-use load: new energy vehicles (NEVs, mainly electric vehicles).

China has the world’s largest NEV fleet and the highest level of market penetration. By the end of 2025, the total number of NEVs had reached 43.97 million, accounting for 12.01% of all vehicles nationwide. Of these, battery electric vehicles (BEVs) totaled 30.22 million, representing 68.74% of the NEV fleet. In 2025 alone, 12.93 million NEVs were newly registered, accounting for 49.38% of all new vehicle registrations¹⁰²—an increase of 1.68 million units (up 14.93%) compared to 2024. The total onboard battery capacity across this fleet exceeds several terawatt-hours (TWh). In 2025, annual charging demand from NEVs accounted for approximately 1% of total electricity consumption; by 2030, this share is projected to rise to 2–4%.

These vehicles are not only central to decarbonizing the transport sector and reducing dependence on oil imports, but are also emerging as a significant source of electricity demand. In theory, they collectively form a vast “mobile battery” system—far exceeding the combined capacity of all pumped-storage hydropower stations nationwide. However, data show that private vehicles remain parked and idle more than 90% of the time, leaving their potential role as distributed energy storage within the power system largely untapped.¹⁰³ In the absence of effective coordination mechanisms, uncoordinated charging and discharging behaviors risk turning this massive fleet into a burden on the power system rather than a source of flexibility.

102 Ministry of Public Security of the People’s Republic of China. *China Has 469 Million Motor Vehicles and 559 Million Drivers*. January 2026. <https://www.mps.gov.cn/n2254314/n6409334/c10383533/content.html>.

103 Autohome Research Institute; National Big Data Alliance of New Energy Vehicles. *Annual Report on Battery Electric Vehicle Market Development and Usage*. 2024. <https://www.autohome.com.cn/news/202404/1295064.html>The study shows that the average daily driving time of private vehicles is 2.2 hours, with 60% of vehicles being driven for only 1–4 hours per day, meaning that most vehicles remain unused for the majority of the time.

1. “Evening Peak” Overlap and Load Collision

A large number of EV owners habitually plug in their vehicles shortly after returning home in the early evening (18:00–20:00). This coincides with the residential demand peak and the sharp decline in solar power output, leading to a rapid surge in net load over a short period and significantly increasing peak-balancing pressure on the grid.

2. Localized Overload in Distribution Networks

With the rapid proliferation of fast-charging infrastructure, transformers in older residential communities and commercial districts are often unable to accommodate the simultaneous high-power charging demand of dozens of vehicles. This can result in localized outages or tripping events, forcing grid operators into costly and inefficient reactive capacity upgrades.

2. Resilience Mechanism

To transform this potential “disruptive force” into a source of system flexibility, a vehicle-grid integration framework can be adopted. Its resilience operates on two levels: smart charging and bidirectional charging/discharging (V2G).

- 1. Load shifting through coordinated charging:** Under this model, vehicles draw power unidirectionally from the grid, while charging behavior is dynamically optimized through smart chargers that respond to system signals. Charging power can be modulated or deferred—for example, shifting evening demand to late-night hours when wind generation is abundant and system load is low, or enabling high-power daytime charging in office parking lots to integrate excess rooftop solar generation. This approach serves as a low-cost, fast-acting “flexibility sponge” for renewable energy integration.
- 2. Distributed “virtual power plants” enabled by V2G:** With bidirectional capability, vehicles can both charge and discharge electricity via onboard converters or dedicated DC V2G chargers. In the event of sudden power shortages or extreme weather disruptions—such as cold snaps that disable major generation units—vast numbers of parked EVs can be rapidly aggregated into a distributed “virtual power plant.” They can feed stored electricity back into the grid or supply nearby loads, providing critical, spatially distributed emergency support.

Case Studies:

- ◎ **Shenzhen virtual power plant and V2G practice:** The Shenzhen Virtual Power Plant Management Center has already integrated a large number of charging stations equipped with vehicle-grid capabilities. In multiple demand-response trials, EV owners discharged electricity back to the grid, helping smooth peak loads while earning attractive per-kWh financial incentives.¹⁰⁴
- ◎ **Volkswagen wallbox application in Germany:** The wallbox developed by the Volkswagen Group is an intelligent home EV charging device. It integrates control chips and algorithm modules that can access real-time electricity spot market prices and automatically optimize charging behavior. When electricity prices are low, the system initiates charging autonomously, while prioritizing rooftop solar generation and drawing from the grid only when on-site solar generation is insufficient. In effect, the device enables charging to respond directly to real-time market signals, minimizing charging costs through the automated selection of off-peak hours and the maximization of self-consumption rates.¹⁰⁵

3. Opportunities and Potential

1. Everyday utilization: a low-cost “reservoir” for wind and solar energy

Compared with large-scale, capital-intensive centralized battery storage systems—whether deployed on the generation side, grid side, or user side—smart charging requires minimal additional battery investment. Through software-based optimization and modest hardware upgrades, it can unlock massive flexible capacity at very low marginal cost.

104 Xinhua News Agency. *Shenzhen Achieves First Electricity Settlement for Electric Vehicles Discharging Power to the Grid*. 2026. <http://gd.news.cn/20260114/bf5f31aa6cd34a8483df4a84d89934c0/c.html>.

Shenzhen launched a large-scale vehicle-grid-integration pilot in March 2025, involving more than 760 charging stations across the city and over 17,000 charging/discharging sessions.

https://hmo.sz.gov.cn/zx/gqdt/content/post_1539201.html.

According to a joint study by the International Council on Clean Transportation and the Regulatory Assistance Project based on the case of France, compared with uncoordinated charging and discharging, by 2040, smart charging and V2G could reduce peak grid load by 15%. Smart charging alone could also reduce grid reinforcement costs for transmission lines by 23% and transformer upgrade costs by 37%.

Savings from smart charging electric cars and trucks in Europe: A case study for France in 2040. March 2025. <https://theicct.org/publication/smart-charging-cars-trucks-europe-mar25/>

105 Elli (a charging brand under Volkswagen). 2025. *Wallbox Smart Charging Stations*. <https://www.elli.eco/en/b2c/products/wallbox>

2. Extreme disruption scenarios: a “mobile lifeline” for cities

In the event that a major city is struck by severe typhoons or freezing disasters—leading to the disruption of key transmission corridors and partial failure of the urban distribution network—millions of dispersed EVs, even at only 30% state of charge, could rapidly form a valuable distributed emergency energy supply system. Through V2G or vehicle-to-load (V2L) capabilities, these vehicles could support basic household lighting and heating. When aggregated, their stored energy could sustain critical infrastructure—such as hospitals, communication base stations, and water supply systems—for several days until the main grid is restored. In this sense, EVs function as a mobile, distributed energy reserve embedded within society, providing a resilient backbone for urban energy security.

4. Implementation Barriers and Policy Responses

However, this journey from blueprint to reality remains hindered by severe systemic and institutional barriers. To unlock its vast potential, targeted, “breakthrough” measures must be implemented within the next 1-5 years.

× **Barrier 1: Ineffective price signals and market access barriers**

The current time-of-use (TOU) pricing structure for residential consumers is relatively coarse, with long adjustment cycles—typically updated only once a year in most provinces. This makes it difficult to reflect the highly dynamic, weather-dependent output of wind and solar energy. Furthermore, aggregators (Virtual Power Plants)—which represent the vast fleet of EV owners in grid dispatch—still face significant entry barriers to the spot market.¹⁰⁶

✓ **Policy Response 1: Introduce Dynamic Charging Tariffs and a “Greenlight Mechanism” for Aggregators**

Local pricing bureaus should pilot “dynamic peak and deep-valley charging tariffs” for residential users, ensuring that these price signals are transmitted directly to charging apps. Simultaneously, the National Energy Administration

¹⁰⁶ Aggregators mainly face two entry barriers: The first barrier is technical requirements. For example, Jiangxi Province requires aggregator platforms to upload data at intervals no longer than 15 minutes, ensure latency below 500 ms, and maintain control deviation within $\pm 20\%$. https://drc.jiangxi.gov.cn/jxsfzhggwyh/col/col14590/content/content_1981633111050883072.html. The second barrier is qualification restrictions. Under current electricity market rules, market participants in spot trading are typically confined to power generators, electricity retailers, and recognized virtual power plants or large demand-side entities. Aggregators are also generally required to have an initial flexibility capacity of at least 5 MW. For most electric vehicle charging and battery-swapping aggregators, participation in the market still faces challenges such as unclear identity status and excessively high capacity thresholds. https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202512/t20251226_1402666.html.

(NEA) must significantly lower the capacity thresholds for load aggregators to participate in electricity spot markets and ancillary services markets. By explicitly defining their status as independent market entities, regulators can incentivize capital to organize and mobilize dispersed EV owners.

× **Barrier 2: Gaps in Hardware Infrastructure and Technical Standards**

At present, the majority of the existing charging infrastructure consists of “dumb piles” that lack the communication modules required for intelligent power adjustment. Furthermore, most new energy vehicle (NEV) models currently on the market are either not equipped with, or have not enabled, V2G-compatible hardware at the factory. Additionally, V2G DC chargers face challenges such as high manufacturing costs and a lack of standardized technical specifications.¹⁰⁷

✓ **Policy Response 2: Mandate National Standards for “Smart Chargers” and Accelerate V2G Integration in Vehicles.**

The Ministry of Industry and Information Technology (MIIT) should issue mandatory national standards requiring all newly installed AC charging piles to be equipped with communication interfaces for “smart coordinated charging.” Relevant authorities must expedite the development of a unified, highly compatible nationwide V2G vehicle-to-pile communication protocol and grid-connection technical specifications. Furthermore, China should also consider mandating that all new energy vehicles (NEVs) launched from 2027 onward be V2G-capable.

× **Barrier 3: Battery Degradation Concerns and Unclear Allocation of Responsibilities**

This remains the most critical commercial bottleneck to scaling V2G. At current technology levels, frequent charging and discharging under V2G operation accelerates battery degradation. Yet existing “lifetime warranty” policies for core EV components (battery, motor, and electronic control system) typically exclude V2G usage.¹⁰⁸ The absence of transparent, third-party battery health data further discourages vehicle owners from

107 China introduced a national standard for V2G vehicle-charger communication in 2025. However, in practice, there is also a separate standard established by State Grid Corporation of China. The coexistence of these two standards makes it difficult for automakers to determine a unified technical system for vehicle-level V2G implementation.

108 The current mainstream warranty systems of automakers are mainly linked to vehicle mileage or years of ownership and do not cover the cycle degradation caused by frequent charging and discharging in V2G applications. As a result, automakers tend to exclude V2G activities from warranty coverage.

participating, while automakers are reluctant to assume liability.¹⁰⁹ At the same time, compensation for reverse power flow is too low to offset the cost of battery wear.

✓ **Policy Response 3: Establish a “Battery Health Blockchain” and Introduce a “V2G Premium Pricing Mechanism”**

China should introduce third-party certification or adopt blockchain-enabled BMS (Battery Management System) data tracking to clearly differentiate “driving-induced” from “V2G-induced” degradation. It should also accelerate testing of charging and discharging cycles under real V2G conditions and mandate that V2G usage be included within warranty coverage. In parallel, insurers should be encouraged to develop dedicated products, such as “V2G battery degradation insurance.”

On the pricing side, regulators should establish a V2G discharge tariff linked to spot market transactions and ancillary service compensation. During periods of extreme peak demand, V2G discharging should be rewarded with a substantial premium—several times the standard electricity price—as “extreme peak compensation,” thereby incentivizing aggregators and alleviating vehicle owners’ depreciation concerns.

✗ **Barrier 4: Grid Operator Inertia and Limited Proactive Engagement**

Within China’s highly centralized dispatch framework, grid operators tend to rely on large-scale coal-fired generation, centralized battery storage, or pumped-storage hydropower storage to balance peak and off-peak demand. Large industrial consumers may also be dispatched when needed, while distributed resources such as EVs and air conditioners are typically considered only as a last resort. Grid operators often view the coordination of massive, dispersed EV fleets as “burdensome and unreliable.” Consequently, they rarely initiate demand-side response commands, making it nearly impossible for vehicle owners and charging aggregators to participate in grid balancing.

✓ **Policy Response 4: Revise Grid Operator KPIs and Mandate a “Flexible Resource Quota”**

China should reform the performance evaluation framework for power

109 China.com. *Why the State of Health of New Energy Vehicle Batteries Is Not Transparent: Owners’ Frustration and Confusion*. December 2025.

<https://3g.china.com/act/news/10000169/20251216/49078161.html>. In actual use, electric vehicle owners are often concerned about battery degradation and a lack of transparency regarding state of health. In our preliminary research, automakers and battery manufacturers stated that, because there is no clear and stable profit model for vehicle-grid-integration, companies are unable to directly benefit from it and therefore are generally unwilling to unilaterally assume liability for potential battery degradation caused by discharging behavior.

dispatch entities by introducing binding targets for provincial grid operators. These should require the annual procurement of a meaningful share (e.g., 8%–10% or more of peak load) of “demand-side flexibility resources” (including V2G), in lieu of building new coal-fired capacity or additional energy storage capacity.¹¹⁰ Such administrative mandates would compel grid operators to actively mobilize these underutilized distributed EVs.

5. Scaled Deployment

The resilience logic enabled by EVs lies in digital aggregation—such as virtual power plants—through which vast numbers of small, distributed, micro-scale energy storage assets are transformed into system-level resources with macro-level grid-balancing capability.

Once the “communication–dispatch–settlement” chain for electric vehicles is fully established, this virtual power plant model can rapidly spill over into every corner of the urban “last mile”:

- 1. Two- and three-wheeled EVs and battery-swapping networks:** China has hundreds of millions of two- and three-wheeled electric vehicles, supported by an extensive network of battery-swapping stations that are built specially to serve the food and parcel delivery sectors. Together, they constitute an ideal distributed energy storage system.¹¹¹
- 2. Smart appliances and building microgrids:** High-power devices, such as smart air conditioners and heat-pump water heaters, can be connected to aggregation platforms via IoT modules. During peak summer demand, a coordinated temperature adjustment of just 1°C across a city’s air-conditioning load could free up capacity equivalent to that of a mid-sized power plant.¹¹²

Economies of Scale: By 2030, China’s NEV fleet is expected to reach or exceed 100 million units. In theory, this could translate into hundreds of

110 A series of policy documents issued by relevant government ministries—including the *Electricity Demand-Side Management Measures (2023 Edition)*, the *Electricity Load Management Measures (2023 Edition)*, and the *Implementation Opinions on Strengthening the Integration and Interaction of New Energy Vehicles and the Power Grid (2024)*—explicitly state that by 2025, demand response capacity in each province should reach 3%–5% of peak load. The policies encourage new-type energy storage systems, distributed generation, electric vehicles, and other flexible load resources to participate in demand response, and classify load flexibility resources as equivalent to distributed generation for unified dispatch by power grid operators. In combination with the *Action Plan for Accelerating the Construction of a New Power System (2024–2027)*, the current policy is shifting from merely “encouraging participation” toward a dual approach combining administrative quantitative targets and normalized dispatch, with the aim of increasing the share of flexible resources to partially substitute traditional coal-fired power for system balancing.

111 No other economy in the world has a food-delivery and parcel-delivery network as advanced as China’s. Attention is usually focused only on its enormous scale and high efficiency, but the significant value it embodies as a distributed energy network is often ignored.

112 In Shanghai, for example, by centrally coordinating air-conditioning temperature control in commercial buildings through a virtual power plant platform, it is possible to achieve a load reduction of more than 1.16

gigawatts of flexible capacity¹¹³—on par with the country’s entire portfolio of conventional flexibility resources (including coal, gas, pumped-storage hydropower, and battery storage as of 2024). More importantly, unlike these traditional assets, unlocking this capacity requires virtually no additional upfront capital investment.

As millions of EVs and smart devices are transformed into “energy sponges,” China’s energy system would undergo a step-change in its ability to absorb volatility. This “energy stored among the people” paradigm could fundamentally reshape the current, top-down equilibrium dominated by large centralized power plants. Even in the event of major grid disruptions, a vast network of tens of millions of distributed energy devices could function as an emergency lifeline—preserving system stability and ensuring energy security under extreme conditions.

GW within minutes—an effect equivalent to instantly activating a large-scale peak-shaving power plant.
<https://www.shanghai.gov.cn/nw4411/20250816/d0e15b73a42c400f8876d83061db7d50.html>.

113 According to projections by the China Automotive Strategy and Policy Research Center, if China’s new energy vehicle fleet reaches 100 million units by 2030, the theoretical grid balancing capacity could reach approximately 1 billion kW (1,000 GW). April 2025. <https://www.news.cn/tech/20250410/cc15b716e3ba4e59bc11d00fe4e674d7/c.html>.

In addition, according to analysis by Prof. Hu Junjie of North China Electric Power University, if China’s EV fleet reaches 80 million vehicles with 70 million charging piles by 2030, each charging pile can provide 10 kW of flexibility capacity, each EV has an average battery capacity of 60 kWh, and 20% of EVs participate in grid interaction (mainly through coordinated charging), these resources could provide nearly 140 million kW of balancing capacity. This would be sufficient to meet about 28% of renewable energy fluctuation needs (estimated at around 500 million kW). December 2023.
https://www.autoreview.com.cn/m/show_article-20298.html.

According to preliminary research by a team from Peking University and the National Engineering Research Center for Electric Vehicles at Beijing Institute of Technology, based on China’s 2025 EV fleet, within a single dispatch period (one hour), the total adjustable charging and discharging energy over a one-hour dispatch period ranges from -154 million kWh to 219 million kWh (with negative values indicating electricity fed back to the grid by EVs).

In another practical application by Didi Energy in Shanghai, the company aggregated approximately 300 MW of flexible public charging load. During the summer peak-demand period of 2025, roughly 80 MW of this capacity was successfully dispatched through coordinated charging participation—representing a 27% utilization rate—with a total response volume exceeding 600,000 kWh.

4.5 Scenario 5: Industrial Parks

1. Current Situation and Challenges

Industrial parks are the major engine of China's economic growth. According to the *China Industrial Parks Green and Low-Carbon Development Report (2023)*, there are 2,543 national- and provincial-level development zones listed by the National Development and Reform Commission. Roughly 80% of industrial enterprises are clustered within these parks, which together generate over 50% of total industrial output and account for approximately 31% of national carbon emissions.¹¹⁴

Most traditional industrial parks depend heavily on centralized, external energy supply. Electricity is drawn from the grid, while heating and steam are typically provided by centralized coal- or gas-fired boiler systems, resulting in a highly rigid energy structure.

- 1. Fragmented energy systems and low efficiency:** Energy streams—electricity, heat, cooling, and gas—are managed in isolation through separate pipeline networks. As a result, large volumes of industrial waste heat remain unused, even as parks burn expensive natural gas to produce hot water or steam. This structural mismatch leads to substantial energy inefficiencies and unnecessary carbon emissions.
- 2. Vulnerability to disruptions and operational shutdowns:** Traditional industrial parks are passive energy consumers. In the face of extreme weather events, system failure leading to power rationing, or geopolitical shocks that disrupt natural gas supply, production lines—especially those involving precision manufacturing—face a high risk of forced shutdowns across entire parks.
- 3. Mounting pressure from carbon tariffs and supply chain traceability:** As multinational corporations such as Apple and Tesla, along with key

¹¹⁴ Chen Lujun et al. School of Environment, Tsinghua University. *Current Status, Challenges and Outlook for Comprehensive Energy Efficiency Improvement in Industrial Parks*; <https://www.env.tsinghua.edu.cn/info/1129/7732.htm>; <https://www.env.tsinghua.edu.cn/info/1129/8369.htm>; *Industrial Parks Must Contribute to Carbon Peaking and Carbon Neutrality*. <http://society.people.com.cn/n1/2021/0310/c1008-32048271.html>. According to research by Chen Lujun's team at the School of Environment, Guo Yang and other colleagues, industrial parks are major consumers of resources and energy, and their greenhouse gas emissions account for approximately 31% of the national total.

trading partners, impose increasingly stringent requirements on carbon footprints and renewable energy use across supply chains—and with the implementation of mechanisms such as the EU’s Carbon Border Adjustment Mechanism (CBAM)—the “coarse” and often poorly monitored emissions data typical of traditional industrial parks is becoming a major barrier to exports for manufacturers operating within these parks.

2. Resilience Mechanism

To transform energy-intensive industrial parks into “super energy sponges,” the core of resilience restructuring lies in achieving deep cross-energy coordination and digital reconfiguration in which load follows supply.

- 1. Seamless Switching Between Electricity and Non-Electric Energy (Multi-Energy Coordination):** A key priority is to break down the physical boundaries between electricity and molecular/thermal energy. When surplus renewable electricity is available—either within or outside the park—it can be efficiently converted into the high-temperature steam required for industrial processes through large high-temperature heat pumps and large temperature-difference heating technologies. Alternatively, micro-electrolyzers can convert green electricity into green hydrogen for direct use in fine chemicals or metallurgical production. This flexible substitution—replacing heat and gas with electricity—reduces dependence on any single fossil fuel.
- 2. Digital Twin and Microgrid Self-Balancing (Load Follows Supply):** The energy system should be upgraded by integrating 5G, IoT, and AI algorithms to connect all “sources” and “loads” within the park—including rooftop solar systems, distributed wind turbines, V2G-enabled charging infrastructure, thermal storage systems, and central HVAC—into a microgrid system. When the main grid faces electricity shortages, the microgrid system can automatically shed non-critical loads, adjust building temperatures by 1–2°C, dispatch parked EVs via V2G, and activate thermal storage or even hydrogen fuel cells to maintain supply. This transforms the industrial park from a passive load into a self-sustaining provider of flexibility.¹¹⁵

¹¹⁵ Such practices have occasionally been piloted in some industrial parks in China, but they are not yet the norm.

Case Studies:

- ◎ **Envision Group Ordos Net-Zero Industrial Park:** This park integrates multiple industrial value chains—including battery manufacturing, energy storage, electric vehicles, solar power, and hydrogen equipment—into an IoT-driven renewable energy system. Through dynamic coordination of solar and wind generation, storage charging and discharging, and grid conditions, it achieves a 100% renewable electricity supply for the park.¹¹⁶
- ◎ **Kalundborg Industrial Symbiosis Network:** In Kalundborg,¹¹⁷ power plants, refineries, pharmaceutical facilities, and district heating systems are connected by pipelines. Through these connected pipelines, waste outputs from one enterprise—such as excess heat or process gases—are directly utilized as energy or raw materials by others, exemplifying the resilience potential of deep multi-energy integration.

3. Opportunities and Potential

1. Building a “Green Haven” and Cost Advantage for Advanced Manufacturing

In regions rich in wind and solar resources, zero-carbon industrial parks should break down system silos and leverage low-cost local renewables, combined with thermal energy storage, to reduce total energy costs to 70% or less of the average electricity price from the grid. This not only provides China’s advanced manufacturing sectors—such as semiconductors and power batteries—with a “green passport” against international carbon constraints, but also creates a structural cost advantage capable of attracting renewed investment from multinational corporations.

116 World Economic Forum & Envision Group. Transitioning Industrial Clusters towards Net Zero. 2023. <https://www.weforum.org/publications/transitioning-industrial-clusters-towards-net-zero/>; https://reports.weforum.org/docs/WEF_Unleashing_the_Potential_of_Industrial_Clusters_2025.pdf. The report analyzes the business model and technical architecture of the Ordos Zero-Carbon Industrial Park, presenting it as a global case study of achieving wind-solar-storage-hydrogen synergy and breaking the “grid island” effect in industrial parks.

117 Case Study: Kalundborg Industrial Symbiosis. <https://www.councilfire.org/guides/case-study-kalundborg-industrial-symbiosis/>; <https://www.iisbe.org/iisbe/gbnp/documents/policies/instruments/UNEP-green-ind-zones/UNEP-GIZ-ppt-kalundborg%20case.pdf>

2. “Self-Balancing” Operation Under Extreme Conditions

Under extreme scenarios—such as serious natural disasters on the transmission grid or cyberattacks that disrupt regional grid supply—zero-carbon industrial parks equipped with multi-energy integrated microgrids can island themselves and switch into autonomous, self-balancing operation. Local battery storage and hydrogen fuel cells can provide instantaneous frequency support, thermal storage can supply critical steam in the short term, and V2G-enabled vehicle fleets can act as mobile emergency power sources. Together, these resources enable the park to sustain critical production lines and data centers for hours or even days.

4. Implementation Barriers and Policy Responses

China officially launched large-scale pilot programs for zero-carbon industrial parks in 2025. However, typical case studies reveal that progress remains hindered by entrenched institutional and regulatory barriers. Only by decisively addressing these constraints can such parks truly evolve into “special zones” and “testing grounds” for advancing the energy revolution.

× **Barrier 1: Monopoly Constraints in Power Dispatch and the Dilemma of Cross-the-fence Electricity Trading**

At present, enterprises within industrial parks face significant barriers when attempting to directly procure low-cost renewable electricity from nearby distributed wind or solar projects. In practice, such transactions are often subject to a de facto “veto” by grid operators. Wheeling charges (transmission and distribution tariffs) remain high, and obtaining legitimate power supply status is also difficult. Although China’s energy authorities have promoted “direct green power connections,” implementation has been constrained by difficulties in aligning the interests of generators, consumers, and grid operators. The grid’s effective veto power continues to impede progress.

✓ **Policy Response 1: Designate Industrial Parks as “Special Zones” for Incremental Distribution Networks and Direct Green Power Supply**

The National Development and Reform Commission (NDRC) could formally grant zero-carbon—and potentially all—industrial parks the status of “independent power supply zones.” Within these zones, restrictions on incremental distribution networks and direct green power connections should be substantially relaxed, allowing generators and consumers to establish Cross-the-fence Electricity Trading (a possible Chinese pilot mechanism enabling direct electricity transactions between adjacent users—typically

within industrial parks or incremental distribution networks—bypassing the traditional grid company retail layer) and thereby breaking the traditional model in which the grid company serves as the sole intermediary. At the same time, grid operators should be encouraged to explore cooperation opportunities leveraging their existing assets. Furthermore, spot markets within industrial parks should be developed, using highly dynamic pricing and other market-based mechanisms to incentivize enterprises to shift loads and actively participate in demand response.

× **Barrier 2: Policy Bias Toward Electricity Over Heat and Gas, with Insufficient Incentives for Multi-Energy Integration**

Current policy support is heavily skewed toward renewable power generation and battery storage, while “non-electric” sectors critical to industrial decarbonization—such as high-temperature heat pumps, large temperature-difference (high- ΔT) heating, and renewable-based hydrogen production—lack adequate policy support. As a result, corporate retrofits tend to focus on electricity rather than thermal energy.

✓ **Policy Response 2: Establish a Special Fund for “Full-Spectrum Multi-Energy Integration”**

The Ministry of Industry and Information Technology (MIIT) and the Ministry of Finance should jointly establish a dedicated fund to support the development and deployment of high-temperature industrial heat pumps. Projects that utilize off-peak electricity to produce industrial steam or green hydrogen should be exempted from capacity charges. In addition, all newly approved national-level industrial parks should be required to submit integrated energy plans covering electricity, heat, cooling, and gas, replacing the traditional fragmented planning approach.

× **Barrier 3: Lack of Transparency and Accuracy in Energy and Carbon Data**

At present, energy and carbon accounting in most industrial parks still relies on manual reporting—such as month-end meter readings and year-end settlements. The resulting data is often outdated and insufficient to meet the stringent requirements of domestic and international certification bodies, let alone support second-level dispatch within microgrids.

✓ **Policy Response 3: Mandate IoT-Enabled, Real-Time Energy and Carbon Measurement**

All entities applying for “zero-carbon industrial park” status should be required to accelerate the IoT-enabled upgrade of their energy and carbon

metering systems. It is also critical to establish real-time, transparent, and tamper-resistant management platforms, shifting data collection from “monthly reporting” to millisecond-level acquisition. Beyond tracking energy flows, equal emphasis should be placed on carbon flows—assigning every product manufactured within the park a dynamically updated, internationally recognized carbon footprint label. This label would serve as a passport to global green finance and trade.¹¹⁸

5. Scaled Deployment

The underlying resilience logic of this model can be summarized as a shift from “local optimization” to “system-wide optimization.” By breaking both energy boundaries (through multi-energy integration) and institutional barriers (through Cross-the-fence Electricity Trading), it enables decentralized and autonomous operation at the level of end-use physical nodes. Once this model—characterized by “microgrid autonomy + multi-energy integration”—is proven successful in large industrial parks, it can be rapidly extended to a much broader range of settings across the economy.

1. **Large Transport Hubs (Airports, High-Speed Rail Stations) and Ports:**

These areas offer substantial rooftop space and feature stable heating and cooling demand, making them ideal for microgrid deployment. In extreme scenarios, such systems can help ensure the continued operation of critical logistics infrastructure.

2. Rural Areas: By leveraging abundant rooftop and other available land resources, rural regions can deploy solar power generation and smart microgrid systems to provide low-cost green electricity for local businesses, agriculture, and households. This supports local energy self-sufficiency and rural industrial revitalization—such as accelerating the electrification of agricultural machinery and the development of flexible-load industries like agricultural product processing. At the same time, surplus green power can be fed back into the grid when needed.

3. Urban Residential Communities: A significant share of energy demand in urban residential areas is for heating and cooling—particularly in regions with extreme winters or summers, where thermal demand often drives peak loads. Yet low-grade thermal energy is among the easiest forms of energy to store. In northern China, large-scale underground seasonal

¹¹⁸ National Development and Reform Commission et al. *Opinions on Accelerating the Establishment of a Product Carbon Footprint Management System*. November 2023. The policy document highlights, at the national level, the urgent need to accelerate the development of a digital and traceable product carbon footprint accounting system.

thermal energy storage systems have already been deployed commercially and show strong potential for smoothing seasonal demand fluctuations.

4. Remote Islands: Through wind-solar hybrid systems combined with moderate energy storage capacity, remote islands can achieve a high degree of energy self-sufficiency.

Economies of Scale: As thousands of industrial parks across China evolve from passive, grid-dependent energy consumers into integrated energy systems with their own “self-generation” and “self-resilience” capabilities, the country’s energy system will gradually shift from a “tree-like” structure to a “networked” architecture. As these integrated energy units expand beyond industrial parks to major transport hubs, commercial buildings, and vast rural areas, each unit will not only become more self-sufficient but also contribute to system-wide balancing under market-based coordination (such as a unified national power market). This interconnected system can unlock massive flexibility, providing strong, system-level resilience for the national economy.

Chapter 5 Mechanism and Policy

In the preceding analysis, we have sought to illustrate—through several representative scenarios—that China possesses enormous potential for flexibility on the “hardware” side. However, these micro-level innovations are constrained by a macro-level institutional “ceiling.” Without deep reforms to power system governance, benefit-sharing arrangements, and price discovery mechanisms, this vast physical potential will remain largely dormant.

Demand-side resilience is a central lever for China to respond to global geopolitical shocks, hedge against energy import risks, and maintain the competitiveness of its manufacturing sector in the race toward carbon neutrality. At this critical juncture in the energy transition, China needs to elevate “demand-side resilience” to the same strategic importance as “capacity growth” and “grid expansion” within its top-level industrial design.

To fully leverage this key lever, it is imperative to strengthen institutional frameworks in several critical areas, enabling a generational shift in the energy system—from rigidity to resilience.

5.1 Optimizing Pricing and Market Mechanisms

China is actively advancing the development of electricity spot markets. However, to achieve true demand-side resilience, market mechanisms still suffer from significant “signal gaps”: price signals are not transmitted to end-use loads in a timely or effective manner. To fully unlock demand-side flexibility, China must not only accelerate market development, but also prioritize real-time signal transmission, proper valuation of capacity, and demand-based pricing of supply reliability.

1. Promoting the Real-Time Transmission of Spot Market Price Signals to End Users

At present, although spot prices on the generation side fluctuate significantly, the retail electricity prices faced by most industrial users remain constrained within a relatively rigid time-of-use tariff framework. This form of “signal blocking” means that even when enterprises are willing to adjust their loads, they are unable to benefit from transient price troughs in the spot market.

- ◎ **Policy Recommendation:** China can mandate that energy-intensive enterprises above a certain annual electricity consumption threshold, large-scale data centers, and load aggregators fully participate in spot market settlement. It is also essential to establish a “direct transmission mechanism for spot prices,” allowing end users with flexibility capabilities to automatically respond to spot prices at 15-minute intervals. Only when users can see “zero” or even “negative” electricity prices in real time—and capture the benefits from directly arbitraging such price fluctuations—will they be fully incentivized to invest in thermal energy storage, hydrogen storage systems, and flexible production lines.

2. Establishing a “Demand-Side Flexibility Capacity Compensation” Mechanism

In traditional electricity markets, capacity compensation is typically directed only at the supply side (e.g., standby payments for backup coal-fired power units). This approach ignores a key reality: during periods of system stress, the value of end users actively reducing consumption is fully equivalent to that of power plants increasing generation.

- ◎ **Policy Recommendation:** A “demand-side flexibility capacity market” should be established. Industrial users willing to accept interruptible load agreements or equipped with electricity-to-heat conversion and microgrid islanding capabilities should receive base availability payments from the grid based on their declared and verified flexible capacity—even if their power supply is not actually curtailed during a given period. In essence, this assigns a price to the “right not to consume electricity,” which will help guide private-sector capital toward flexible industrial retrofits rather than the blind expansion of redundant thermal power capacity.

3. Introducing “Dynamic Transmission and Distribution Tariffs” to Unlock the Economic Value of Cross-Carrier Conversion

Under the current industrial electricity pricing system, fixed transmission and distribution (T&D) charges and government levies account for a substantial share of total costs. As a result, even when generation-side prices fall to extremely low levels, the final end-user cost—after adding these fixed charges—remains relatively high, thus undermining the economic viability of producing heat or hydrogen from renewable electricity.

- ◎ **Policy Recommendation:** China can pilot a system of “flexible T&D tariffs.” For new industrial loads dedicated to renewable energy integration and equipped with interruptible capabilities (such as industrial thermal batteries and large-scale electrolyzers), T&D charges can be exempted or significantly reduced during periods of abundant renewable generation. This would transform T&D pricing from a “fixed, volume-based charge” into a “dynamic lever reflecting real-time grid congestion,” thereby breaking through the break-even point for electricity-to-molecule conversion.

4. Exploring “System Reliability Pricing” to Give Enterprises the Option to Trade Reliability for Lower Costs

For a long time, the grid has provided all industrial users with uniformly high reliability (e.g., “99.999%” uptime). While this ensures system security, it comes at the cost of high grid connection capacity fees and T&D charges. However, enterprises with “demand-side resilience” (e.g., those operating their own microgrids, energy storage systems, or flexible production lines) do not necessarily require such a system redundancy from the main grid.

- ◎ **Policy Recommendation:** China should consider establishing a “differentiated system reliability pricing mechanism” that allows energy consumers (such as zero-carbon industrial parks and flexible data centers) to sign customized reliability agreements with power suppliers. Enterprises could rationally lower their required level of supply reliability (for example, allowing the grid to curtail up to 20% of their load during specified periods without compensation) in exchange for significantly reduced grid connection capacity requirements.

This market mechanism — “trading self-provided resilience for lower grid charges”—would not only save enterprises substantial fixed capacity and

T&D costs, but also significantly reduce the grid’s need for costly backup capacity investments. Ultimately, it would enable a fundamental shift from “centralized reliability provision” to “distributed, self-managed resilience.”

5.2 Redefining the Role of the Dispatch System and the Grid

As new energy evolves toward massive scale and greater dispersion, the traditional centralized grid dispatch system is approaching both physical and economic limits. To fully unlock the vast distributed resilience on the demand side, the role of the power grid must be fundamentally redefined, and the dynamism and latent potential of the distribution network—the grid’s “peripheral nervous system”—must be fully unleashed. This is not merely about “decentralization”; rather, it is about enabling a more rational, efficient, and cost-effective sharing of national energy security responsibilities across society in the face of extreme weather events or geopolitical risks.

1. Breaking Away from the Traditional Centralized Dispatch Model, and Extending Renewable Energy Development Benefits to the Real Economy

At present, grid enterprises—operating as state-owned monopolies bearing both authority and responsibility—are attempting to manage and dispatch hundreds of millions of distributed renewable assets, EV charging points, and flexible loads through a traditional centralized approach. However, when confronted with massive, high-dimensional, and second-level fluctuations across distributed nodes, this single-entity centralized dispatch model faces not only computational and communication challenges, but also incurs substantial system balancing and grid expansion costs (such as redundant distribution network upgrades and energy storage investments). These significant sunk costs are ultimately passed on to end users through transmission and distribution tariffs. This explains why, despite the dramatic decline in the levelized cost of wind and solar power, end consumers and manufacturing enterprises have yet to fully benefit from genuinely low-cost green electricity.

- ◎ **Policy Recommendation:** China must acknowledge the economic and technical limits of centralized management and establish a dispatch principle of “putting distributed, self-managed resilience first.” Regulatory authorities should also encourage the local balancing of regional loads. By reducing dependence on long-distance transmission and large-scale centralized dispatch, the energy system can significantly cut inefficient and redundant capacity investments. This will ensure that the cost-reduction benefits of renewable energy are effectively extended to both traditional manufacturing sectors and emerging strategic industries.

2. Advancing Institutional Reform of the Transmission and Distribution Networks to Share National Energy Security Responsibilities Through a “Distributed Network”

For a long time, grid enterprises have borne the ultimate responsibility for ensuring the absolute safety and stability of the national power system—and have achieved remarkable success. However, in practice, this has also allowed them to expand their authority over local distribution networks and the end-user side, including centralized procurement, sales, and dispatch, and in many cases to have de-facto veto power over most electricity- and energy-related projects.

However, in the event of sudden geopolitical shifts and increasingly frequent extreme climate events, concentrating all security responsibilities in a single, highly centralized grid may itself constitute the greatest source of systemic vulnerability.

- ◎ **Policy Recommendation:** China should reassess the roles and operating models of transmission and distribution networks, and initiate deeper institutional reforms in this area. In the early stage of the “15th Five-Year Plan” period, China should leverage revisions to key legislation—such as the Electricity Law and the Renewable Energy Law—to guide and support the development of a new energy system and the large-scale integration of renewables.

State-owned grid enterprises with natural monopoly characteristics should be strategically repositioned to focus on the construction and operation of cross-provincial and inter-regional backbone grids (the “energy superhighways”) and on macro-level balancing. Meanwhile, distribution networks should be progressively opened to other market participants and private-sector capital.

This is not merely a decentralization of authority, but a “downward” allocation and shared assumption of security responsibilities. As tens of thousands of zero-carbon industrial parks, commercial buildings, and V2G-enabled microgrids develop capabilities for “self-generation” and “self-resilience,” the supply burden on the backbone grid will be significantly alleviated. Only then can China have a truly robust, distributed national energy network.

3. Granting Microgrids and Virtual Aggregators Independent Dispatch and Operational Authority to Build a “Transmission-Distribution-Microgrid” Hierarchical Coordination Architecture

Under the current system, even when enterprises or industrial parks are equipped with advanced microgrids integrating solar generation, thermal energy storage, and flexible production lines, they are still treated by grid dispatch centers as passive “load points,” without autonomous operational or dispatch authority—on the grounds that granting such autonomy could affect overall grid security. As a result, most innovative models that facilitate renewable energy development and integration—such as direct green power supply and generation-grid-load-storage integration—are often stalled midway due to direct or indirect opposition by grid enterprises.

- ◎ **Policy Recommendation:** China should establish a boundary-based hierarchical dispatch framework of “main grid-distribution grid-microgrid” coordination. The transmission grid dispatch center should focus solely on controlling power exchanges at the interconnection points between the transmission and distribution networks. Distribution network operators should, in turn, manage power exchanges at the interconnection points with microgrids or virtual power plants. Within microgrids, decisions regarding the deployment and coordination of generation, storage, heat, and electric vehicles should be fully determined by the microgrid control system.

Granting load aggregators and microgrid operators genuine independent dispatch authority and physical operational control would fully unlock flexibility potential at the micro level.

5.3 Rebuilding the Data Infrastructure

Without a unified data language, credible metering standards, and transparent data ownership frameworks, tens of millions of electric vehicles, millions of heat pumps, and countless industrial thermal storage systems distributed across the country will remain fragmented. They will be unable to aggregate into “virtual giants” capable of supporting system-wide energy resilience, nor will they be able to credibly demonstrate their greenness in international carbon markets.

1. Advancing the Shift from “Post-Event Settlement” to “Distributed Real-Time Acquisition” in Energy and Carbon Data Management

At present, energy and carbon management in most Chinese industrial enterprises and industrial parks still relies on manual reporting based on “month-end meter reading and year-end settlement.” Such static data, lacking temporal and spatial granularity, cannot support second-level aggregation and dispatch of flexible loads by virtual power plants. It is also highly likely to be deemed invalid or falsified under stringent international scrutiny, such as under the EU’s Carbon Border Adjustment Mechanism (CBAM).

- ◎ **Policy Recommendation:** China should incorporate “distributed energy-carbon digital infrastructure” into the national New Infrastructure agenda. It should be mandated that industrial nodes, large commercial buildings, and EV charging infrastructure participating in demand-side response or flexibility programs be equipped with IoT- and edge-computing-based intelligent sensing devices. It is also necessary to build a blockchain-enabled, tamper-proof “energy-carbon traceability digital ledger,” ensuring that “flexible energy-use behaviors” and “carbon reduction contributions” achieve financial-grade credibility.

This would provide a verifiable data foundation for monetizing green electricity premiums and enhancing the global competitiveness of Chinese manufacturing.

2. Establishing “Plug-and-Play” Standards for Multi-Energy Integration

Cross-carrier energy conversion and large-scale vehicle-grid-integration, as highlighted in the previous scenarios, are currently constrained by severe communication barriers among different equipment manufacturers. For example, battery management system (BMS) data from automakers is not accessible to charging infrastructure, while solar inverters are often incompatible with traditional industrial distributed control systems (DCS).

- ◎ **Policy Recommendation:** It is imperative to establish unified, cross-sector “plug-and-play” communication protocols and data interface standards (e.g., a unified national V2G communication standard for EVs and chargers, and standardized interfaces for generation-load-storage coordination in industrial microgrids). This effort should be led by the Standardization Administration of China, in collaboration with relevant ministries such as those responsible for energy, industry and information technology, and transport. China must decisively break down proprietary ecosystem barriers imposed by major equipment manufacturers, ensuring that all distributed physical assets can seamlessly integrate into aggregation platforms.

3. Breaking Down Energy Data Barriers to Ensure “Data Equity” for Distributed Entities

At present, the most critical real-time electricity consumption data on the user side is largely controlled by grid enterprises. Third-party microgrid operators, load aggregators, and energy storage investors often face high access barriers and opaque processes when attempting to obtain user load profiles for business model analysis and demand response dispatch. This significantly hinders innovation in distributed energy business models.

- ◎ **Policy Recommendation:** The principle that data ownership resides with the data producer should be established. Neutral, national- or provincial-level energy-carbon public data exchange platforms should also be created. With end-user authorization, power system operators at all levels should be required to provide third-party service providers with real-time, non-discriminatory, and free access to relevant smart meter data through standardized API interfaces. By promoting “data equity,” this approach would help break information monopolies and foster a vibrant market for integrated distributed energy services.

5.4 Improving Transition Finance Mechanisms

Reconstructing demand-side resilience requires substantial upfront investment (such as replacing blast furnaces with electric arc furnaces and adding molten salt thermal storage at iron and steel plants; deploying high-voltage electric boilers at chemical companies; and building new heating and cooling pipeline networks in industrial parks). It is unrealistic for enterprises to recover these costs solely through long-term arbitrage of peak-valley electricity price differentials. Instead, national-level financial innovation and fiscal incentives are essential to help enterprises alleviate their initial cost burden.

1. Expanding the Green Finance Taxonomy to Shift from “Large-Scale Centralized Infrastructure Construction” to “Mass Distributed Retrofits”

In recent years, a significant share of central bank carbon reduction support tools and green credit has flowed to large-scale centralized infrastructure projects on the supply side. In contrast, demand-side enterprises investing in flexible retrofits to integrate renewable electricity often struggle to access comparable low-cost financing due to their smaller scale and highly dispersed nature.

- ◎ **Policy Recommendation:** The People’s Bank of China and the National Financial Regulatory Administration should explicitly include projects such as “demand-side flexibility retrofits,” “multi-energy integrated microgrid development,” and “industrial high-temperature-difference thermal energy storage/hydrogen storage systems” in the *Green Bond Endorsed Project Catalogue* and the *Common Ground Taxonomy for Transition Finance*.

Commercial banks should be guided to move beyond their traditional preference for large-scale projects and instead develop tailored financial instruments—such as “flexible capacity loans” and “distributed resilience financing instruments”—targeted at zero-carbon industrial parks and small and medium-sized manufacturing enterprises. This would significantly reduce financing costs for distributed assets.

2. Innovating Mechanisms for Asset Securitization and Front-Loaded Monetization

For capital-intensive industrial enterprises, investing tens of millions of RMB in cross-carrier retrofits—merely to achieve annual electricity cost savings of a few hundred thousand RMB—often results in internal rates of return (IRR) that fail to meet board-level approval thresholds. Financial leverage is therefore essential to transform long-term, incremental returns into upfront cash inflows.

- ◎ **Policy Recommendation:** Financial institutions should be encouraged to pursue innovative practices, including allowing enterprises to use China Certified Emission Reductions (CCER)—calculated based on real-time IoT data—as well as demand-side response capacity (validated through grid capacity testing), as underlying assets for securitization or collateralized financing. Through such financial mechanisms, future revenue streams—such as green electricity consumption premiums and capacity compensation payments—can be monetized upfront, thereby alleviating enterprises' cash flow constraints.

3. Implementing Targeted Fiscal and Tax Incentives and Accelerated Depreciation to Shorten Investment Payback Periods

In addition to financing support, direct fiscal and tax relief is an effective catalyst for mobilizing large-scale distributed investment.

- ◎ **Policy Recommendation:** The Ministry of Finance and the State Taxation Administration should introduce targeted investment tax credits or value-added tax (VAT) refund policies for “demand-side flexibility equipment” (such as high-temperature industrial heat pumps, large-scale molten salt or water-based thermal energy storage systems, and bidirectional V2G charging infrastructure). At the same time, enterprises should be allowed to adopt accelerated depreciation for resilience-enhancing fixed assets. Through tangible tax incentives, the typical investment payback period—originally as long as 8-10 years—can be reduced to 3-5 years, thereby promoting broad-based participation in the development of micro-level distributed energy systems.

Institute of Energy, Peking University

Add.: Room 603, 6th Floor, Peking University Science and Technology Building, No. 298 Chengfu Road, Haidian District, Beijing, China.

Z.C.: 100871

Email: www.energy@pku.edu.cn

Tel: +86-10-62751150



This report used environmental friendly paper.