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Assessing China's power sector low-carbon transition: A framing paper

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Assessing China's power sector low-carbon transition: a framing paper

CHINA ENERGY TRANSITION

OIES PAPER: CE4

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Executive Summary

China's low-carbon energy transition depends on the power sector taking the lead. In this assessment, we seek to answer three questions about China's power sector transformation:

1. **Is the power sector transition on track, in terms of non-fossil and renewable capacity and output?** Overall, hydro, wind, solar, and nuclear are scaling up capacity at a speed exceeding what would be necessary to peak power sector carbon emissions before 2030 and decarbonize the electricity sector by 2050. Renewable integration will be more of a challenge, and to some extent may depend on market reforms (see item 2 below). Technologies such as CCUS and hydrogen for seasonal energy storage face high uncertainty.

2. **Are market reforms in the power sector a prerequisite for China's low-carbon transition?** While the reform effort remains a priority of the government, with stated aims of efficiency and facilitating the low-carbon transition, not only is progress slow, but the long-term direction of power market institutions remains oriented towards administrative measures, with command-and-control policies retaining the upper hand over market forces. Not only does security remain a higher priority than market reform, but reforms may seek to "check the boxes" rather than allowing supply and demand to play a decisive role in the electricity sector. **Market reforms may be more accurately described as "market-oriented experiments"** and even though more thorough market reforms could incentivize investments and dispatch that would accelerate the low-carbon transition and reduce its cost, administrative policies can also keep the energy transition on track.

3. **As China pursues the low-carbon transition and power market reforms, do efforts at international experience sharing and topics of cooperative research require adjustment?** To date, international cooperation on power sector cooperation has focused on evaluating the potential benefits of a **target market model** in China. This approach is reflected both in power sector modelling of China, as well as in reports on best practices abroad. However, efforts to highlight progress in technology or policy – both inside and outside China – may have greater impact on future policy discussions. With this in mind, the concluding section of the paper sketches a few potential research topics on power sector technology and policy, including studies on green energy trading, clean heating with distributed PV, and EV charging. These represent just some of the promising topics for both modelling and comparative policy research that need not depend on progress with power market reforms. Such research can serve as a reference for international exchanges aimed at reducing carbon emissions and for firms seeking to understand China's clean energy development

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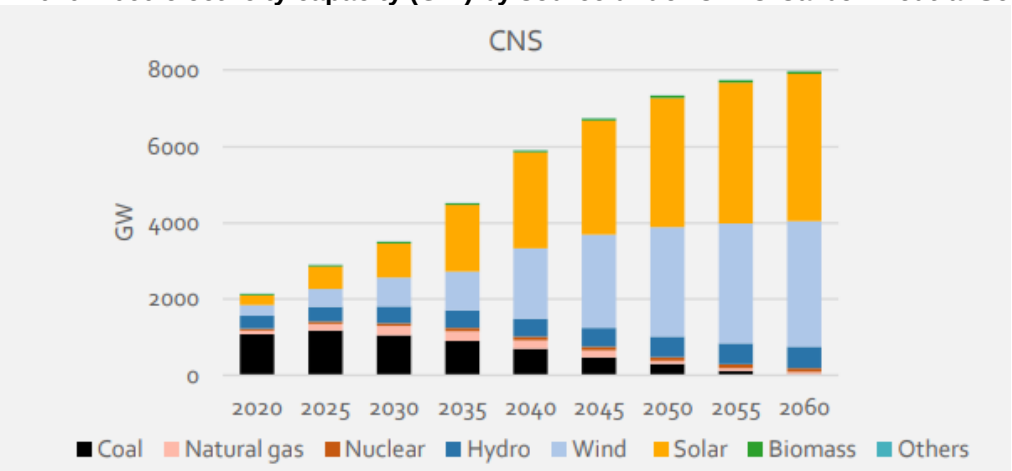
1. Introduction: Renewables and electrification are recognized as key

China's power sector decarbonization is critical to peaking carbon emissions and achieving carbon neutrality. Analysts consider decarbonizing the power sector as being relatively straightforward when compared to the decarbonization of buildings, industry, and transportation – and much more so than the hardest-to-abate industries such as aviation or long-distance heavy-duty trucking. Many are concerned that China's continued construction of coal plants will lock in high emissions, delaying decarbonization of the power sector.

Top leaders refer to coal as the foundation or "ballast stone" of the energy system,[1] while suggesting its role will change, especially in the power sector. Following President Xi Jinping's September 2020 announcement that China would peak carbon emissions before 2030 and strive for carbon neutrality by 2060,[2] several further announcements have highlighted the role of the power sector for achieving this vision. In late 2021, the director of China's National Energy Administration called coal the "ballast stone" of China's energy system, essential for maintaining energy security even during a low-carbon transition. On coal, roughly half of which is used to generate electricity, in April 2021 President Xi stated that China would strictly control coal power through 2025 and begin to phase out coal thereafter[3] – alleviating fears that a rapid build-out of coal power might lead to an emissions peak substantially above present levels, due to an anticipatory coal rush to lock in coal plant investments before a cut-off. Not only does China continue to build coal plants, but several influential government bodies, such as the China Electricity Council and the Electric Power Planning and Engineering Institute, continue to envision a major coal build-out to meet growing electricity demand.[4] However, various Chinese government documents specify that new coal plants, and eventually all coal plants, should transition to play a balancing role in the power system, rather than being mainly a baseload power source,[5] though using coal plants for ramping or peaking carries significant costs in terms of energy efficiency and maintenance. The role of coal as a balancing resource represents an ongoing area of potential research that could help clarify the need for coal, given rapid changes in clean energy technologies.

Major modelling studies also suggest that China will seek to decarbonize the power sector first. According to a prominent low-carbon development pathway study published by Tsinghua University's Institute of Climate Change and Sustainable Development (ICCSD) immediately following President Xi's 2030–2060 announcement, non-fossil energy would account for roughly 80 per cent of energy by 2050, the electricity sector would obtain 90 per cent of energy from non-fossil sources, while the electricity share in end-use energy consumption would rise to 55 per cent.[6] Similarly, the China Energy Transformation Outlook, published by the National Development and Reform Commission Energy Research Institute (NDRC ERI), anticipates achieving an electrification rate of 74 per cent in a carbon-neutral scenario for 2060, with 95 per cent of electricity obtained from renewable sources. Electricity consumption would more than double under this scenario.[7]

Figure 1: 2020–2060 electricity capacity (GW) by source under CETO Carbon Neutral Scenario (CNS)



Source: China Energy Transition Outlook, NDRC ERI, 2022[8]

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The vision of renewables scale-up and electrification as the primary paths to decarbonization aligns with analysis from international organizations and NGOs working on modelling China's low-carbon energy transition. The International Energy Agency anticipates that renewables – especially solar photovoltaics – will provide the largest contribution to decarbonization under an advanced policies scenario. Under this scenario, China would have 4.5 TW of PV and 1.5 TW of wind by 2060. The IEA expects that electrification and energy efficiency will play the largest role in industry, while electrification of buildings and transport is critical to those two sectors. Under the IEA's Announced Pledges Scenario (APS), electricity accounts for 50 per cent of China's final energy demand in 2060, compared to 25 per cent today. Electrification accounts for 60 per cent of transport carbon reduction, compared to 5 per cent hydrogen under this scenario. It anticipates electricity demand would roughly double by 2060.[9]

Other models present similar findings. In its 2018 Reinventing Fire: China, Low-Carbon Scenario, published by the Rocky Mountain Institute, Lawrence Berkeley National Laboratory, and the NDRC ERI, electricity would account for 41 per cent of end-use demand in 2050, 12 percentage points higher than in the reference case, with 82 per cent of electricity coming from non-fossil energy.[10] Similarly, the Energy Foundation China and University of Maryland's 2022 Synthesis Report on the effect of Electrification on China's Carbon Neutrality Pathways notes that "electrification is a core part of China's pathway to carbon neutrality," and this requires "simultaneous transitions of electrifying end-use sectors while decarbonizing the electricity sector." The report specifically targets electrification of building heating, EVs for passenger vehicles and heavy-duty trucks, and heat pumps and electricity demand-side flexibility from industry.[11] The report draws on earlier work from the University of Maryland on coal phase-out that incorporates assumptions on increased electricity demand from electrification of end-use demand.[12]

Background on China's power sector:

Ownership and operation of electricity grid and power generation assets: China's electricity sector is dominated by state-owned enterprises (SOEs). The transmission and distribution grids are owned by two main grid companies: State Grid Corporation of China, which runs the grid in most of China and is one of the world's largest firms; and China Southern Grid, which runs the grid in five southern provinces. Five SOE generation companies own approximately 60 per cent of the country's generation assets – both coal and renewables – with the remainder being owned by smaller companies, almost all state-owned or mainly state-owned. There are also two major state-owned nuclear companies.

Regulation and planning: China's national energy policy is set primarily by the National Development and Reform Commission, the main economic planning body acting under the State Council, and the National Energy Administration, which is a part of the NDRC. Provincial officials, along with provincial officials from these two agencies, have wide latitude to plan and manage the electricity sector at the local level. There is no independent regulator of China's grid or generation companies, and SOE power companies participate directly in energy policy planning.

Capacity and output: China has the world's largest electricity generation capacity, with over 2.5 TW of capacity installed at the end of 2022, of which thermal (mainly coal) accounted for 1.3 TW, hydro 413 GW, nuclear 55 GW, wind 365 GW, and solar 393 GW. Coal accounted for 58.4 per cent of electricity production, compared to 36.2 per cent for non-fossil energy.[13] Wind and solar combined produced 14 per cent of electricity in 2022, up from 12 per cent the previous year.

Wholesale and retail pricing: China has sought to gradually introduce market reforms in power pricing, both via mid-to-long-term (MLT) bilateral contracts (generally from one month to one year in duration) and limited spot market trading. However, wholesale prices are still regulated on the basis of a benchmark coal tariff and fluctuate above and below the benchmark subject to caps and floors, though certain energy-intensive industries may pay prices above the caps. Wind and solar plants typically receive either a fixed feed-in tariff payment for most of their energy, or are contracted under longer-term grid parity contracts, defined as renewable contracts set at or below the benchmark coal tariff.

Carbon emissions: The power sector is responsible for approximately 45 per cent of the country's greenhouse gas emissions, mainly from coal-fired power. China has set annual targets for increasing the efficiency of its coal fleet – which is newer than that of most other countries – as well as overall long-term targets for increasing the total share of non-fossil energy.

Further resources: For more on the power sector, including fuel mix and trends for capacity and generation, see the 2022 "Guide to Chinese Climate Policy", which also includes an updated chapter on power market reforms.[14] For more on the institutional governance of the power sector and how it both helps and hinders the low-carbon transition, see our 2021 paper, "Software versus hardware: how China's institutional setting helps and hinders the clean energy transition."[15]

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2. Are renewables and electrification on track for meeting the 2030–2060 goals? Yes.

China is leading in renewable energy capacity and generation, although its share in the energy mix remains small. Although wind and solar produced only 12 per cent of China's electricity in 2021,[16] their share has been rising at a steady pace of over 1 percentage point annually. On wind, China now has one-third of global capacity, and leads the world with 37 GW of new installations in 2022, reaching 365 GW in total.[17] In solar, year-end total capacity reached 307 GW, and China added 87 GW in 2022, up from 53 GW in 2021.[18] China also dominates the manufacturing of both solar PV and batteries. In 2020, China accounted for 76 per cent of global polysilicon production, 96 per cent of PV wafer production, 78 per cent of PV cell production, and 70 per cent of global PV panel production.[19] According to the IEA, China produces three-quarters of all lithium-ion batteries and is home to 70 per cent of production capacity for cathodes and 85 per cent for anodes.[20] China is also investing billions in renewable energy projects overseas, including in countries that are part of the Belt and Road Initiative (BRI).[21]

China's clean energy transition is accelerating rapidly, at least in the power sector and transportation. At the present rate of annual wind and solar capacity additions, China would exceed its 2030 target of 1200 GW of wind and solar by over 300 GW, reaching 1544 GW.[22] Even so, wind and solar installations are likely to continue to increase: installation levels for solar PV reached 87 GW for the first time in 2022, and provincial five-year plans suggest that China will add over 800 GW of wind and solar by 2025, topping the 2030 target at least five years ahead of schedule.[23] In terms of the wind and solar capacity needed to achieve China's carbon neutrality goals for 2060 – estimated at 4–6 TW wind and solar combined – this would put China on track to achieve a third or even half of the necessary total capacity by 2030. As for electricity generation share, wind and solar have grown their combined share by 1.3 per cent annually, from 3.9 per cent in 2015 to 11.7 per cent in 2021. Simply extrapolating this to 2030, and assuming nuclear and hydro shares remained constant, would imply China would roughly meet its target for a 39 per cent non-fossil electricity share by 2025. The actual change in generation share will depend on economic growth and electricity demand growth, which have shown increased volatility since the onset of the Covid pandemic in 2020. The 39 per cent non-fossil target may be conservative: with renewable capacity additions likely to grow, and an acceleration of nuclear construction, China's generation share targets could well be exceeded unless hydro underperforms due to climate factors.

Table 1: China generation mix, 2015–2021, and incremental increase in wind and solar share

	2015	2016	2017	2018	2019	2020	2021	2022
Hydropower	19.4%	19.5%	18.6%	17.6%	17.8%	17.8%	16.0%	15.6%
Thermal power	73.7%	71.8%	71.0%	70.4%	68.9%	67.9%	67.4%	65.8%
Nuclear power	3.0%	3.5%	3.7%	4.2%	4.8%	4.8%	4.9%	4.8%
Wind power	3.2%	3.8%	4.7%	5.2%	5.5%	6.1%	7.8%	8.8%
Solar power	0.7%	1.1%	1.8%	2.5%	3.0%	3.4%	3.9%	4.9%
Non-fossil share	26.3%	28.2%	29.0%	29.6%	31.1%	32.1%	32.6%	34.2%
Wind and solar share	3.9%	4.9%	6.5%	7.8%	8.6%	9.5%	11.7%	13.7%
Incremental wind and solar		1.0%	1.6%	1.2%	0.8%	1.0%	2.2%	2.0%

Source: Data adapted from CEC, table by Anders Hove, OIES, 2022

For electrification, the situation is more complex due to the number of sectors and technologies needed. For transportation electrification, China is again far ahead of its targets. China has an official target for new energy vehicles (battery electric vehicles, plug-in hybrids, and fuel cell vehicles) to achieve a 20 per cent share of new vehicle sales by 2025, but the 2022 market share surpassed 25 per cent, up from just 5 per cent in 2020.[24] While mineral and battery supply constraints are likely to slow the growth of EV adoption, at least in the near term,[25] electrification of transport is still vastly exceeding expectations.

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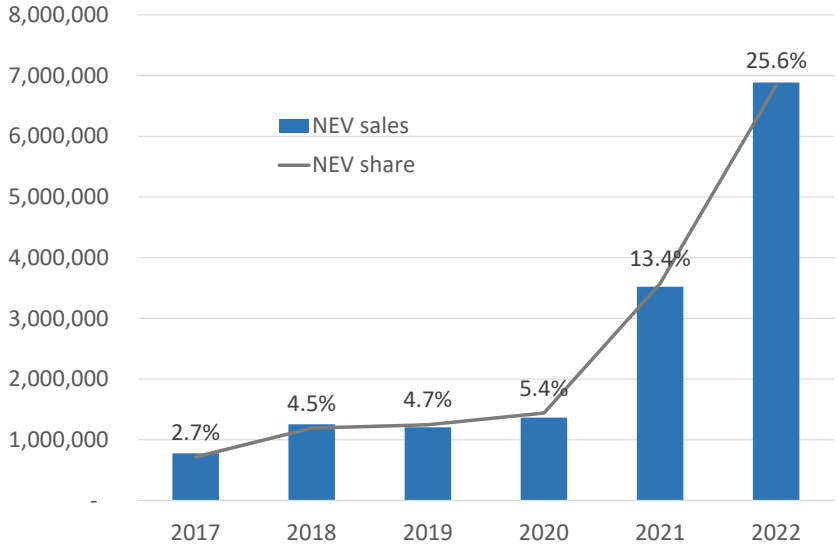
Figure 2: China new energy vehicle sales (NEV), 2017–2022



Source: CPCA and CAAM, 2021 and 2022

To date, the rapid increase in electric vehicles is having only a minor impact on carbon emissions. Though China had over 10 million EVs on the road in mid-2022, gasoline (used by almost all passenger cars) accounts for just 27 per cent of China's oil consumption, and diesel a further 26 per cent, mostly for freight but also for some industrial uses.[26] Bloomberg New Energy Finance estimates that EVs are already saving 1.5 million barrels per day of global oil demand, and the International Energy Agency in 2021 estimated that China will account for at least half the oil displacement from EV adoption in 2030.[27] On a life-cycle basis, with the present electricity mix, Chinese EVs offer emissions that are 40–60 per cent lower than internal combustion vehicles in all regions of China.[28] Based on this estimate, typical vehicle usage, and an assuming 15 million EVs on the road in China at the end of 2022, EVs would reduce annual transportation CO_2 emissions by a net 29 million tons, versus roughly 784 million tons of annual transportation CO_2 emissions in 2019.[29] Assuming EVs reach well over 50 per cent market share by later this decade, they will gradually begin to displace gasoline demand – although rising car ownership and long vehicle lifetimes in China will attenuate this shift. According to one study, replacing 60 per cent of the fossil vehicle fleet with EVs would raise electricity consumption by 410 TWh in 2050, or 4.5 per cent.[30] Changes in diesel demand for trucking are more uncertain given the lower penetration of EV trucks in long-haul shipping, but here as well China is making progress with electrification.

If China is exceeding expectations in renewable additions and electric vehicles, is that sufficient? Or are additional reforms needed to meet the country's decarbonization goals?

3. Are energy and power market reforms on track? This is less clear.

Analysts assume power sector decarbonization will be most efficient if China's power sector adopts practices used in other major power markets, while learning from their past mistakes. In this, various experts have advocated for China to adopt liquid, high-volume spot power markets covering a large geographical area, pricing electricity on the basis of short time intervals to encourage demand flexibility, and encouraging the participation of distributed generation and storage.[31]

Chinese documents also emphasize the need for major reforms in the power sector, speaking of a "revolution in energy production and consumption," the "decisive role" of markets in setting prices, and "market leading" the energy transition.[32] Furthermore, Chinese policy documents, including the 14th Five-Year Plan, emphasize international cooperation as an important pillar of the transition.

The stated goals of China's power market reforms incorporate both decarbonization as well as efficient price signals to improve economic efficiency of the power sector, including effective integration of clean energy. A November 2022 spot market policy draft issued by the NEA summarizes:

> "The goal of building an electric power spot market is to form electricity price signals that reflect time and spatial characteristics and reflect changes in market supply and demand, and play a decisive role in the allocation of electric power resources; to improve the regulation capacity of

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the power system, promote the consumption of renewable energy; ensure the safe and reliable supply of power; guide the long-term planning and investment of power; and promote the transformation of the power system to one that is clean, low-carbon, secure and efficient."

This list of goals is more specific than the list of principles in the 2015 Document No. 9 on Deepening Reform in the Power Sector, which included maintaining energy security and reliability, promoting competition, maintaining the people's livelihood (including low prices for residential consumers), energy conservation and emissions reduction, promoting technology innovation, and adhering to scientific management principles.[33]

Not unreasonably, China has moved cautiously in adopting reforms, piloting each element in turn, usually at a small scale. Analysts have noted that even after market instruments are adopted, major obstacles to markets playing a supporting role remain. Even as more market instruments come into play, the government continues to introduce new administrative controls, enhancing the role of planning over markets, while emphasizing the market elements rhetorically. Provincial and other state actors have wide-ranging abilities to design markets and intervene in their operations in ways that hinder the emergence of short- or long-term price signals.[34]

If China continues to pursue power market reforms that never reach this market model, can the country reach a high penetration of renewable energy by 2030 and full power sector decarbonization by 2060?

To answer this question, it is useful to consider **how the government has framed market reform over time, and whether this has changed.** (For a more complete timeline of electric power market reforms, see the "Guide to Chinese Climate Policy", chapter 8.[35])

Overall, high-level framing continues to emphasize the role of markets

While the present phase of electric power market reform kicked off in 2015, several important visions for market reforms in the energy sector preceded power market reforms. The communique issued after the Third Plenary Session of the 18th CPC Central Committee in November 2013 stated that markets should play a "decisive role" in the allocation of energy and environmental resources,[36] setting the stage for future reforms in the power sector, as well as for coal, oil, and gas. Market reforms and environmental policy should reinforce one another.

In 2014, Xi Jinping delivered his "energy revolution" speech, in which he listed "four revolutions and one cooperation":[37]

- A revolution in energy consumption, including controls on energy consumption, energy efficiency in industry, shifting the economic structure in an energy-efficient direction, and promoting thrifty energy consumption throughout society.
- A revolution in energy supply, including clean and efficient coal; integration of coal, nuclear, and renewables; and stronger power grids.
- A revolution in energy technology, promoting low-carbon energy technologies, and pursuing innovation in technology, business models, and integration of energy with other fields.
- A revolution in energy markets, "unswervingly" promoting market reforms, treating energy as a tradeable commodity, building a competitive market structure, determining prices mainly through the market, changing the way the government supervises the market, and improving the legal structure.
- Cooperation with other countries on the energy revolution "to achieve energy security under open conditions," while relying mainly on domestic energy sources for consumption.

Given this overall guidance, relevant government bodies moved quickly to institute reforms, particularly in the power sector. The 2015 publication of Document No. 9 on Deepening Reform in the Power Sector presented a list of power market reforms which China would eventually adopt – including spot markets and ancillary services markets – without a clear timeline for adopting these reforms.[38] In general, market reforms have made most progress in adopting mid-to-long-term bilateral power contracts between large consumers and generators, generally for periods of one month or one year. Pricing of transmission and distribution has also been reformed. Spot markets are at the pilot phase in roughly half of China's provinces, ancillary services markets are being piloted, and some provinces have also adopted capacity markets.

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Market reforms have also targeted renewable energy, above all by scaling back or withdrawing administratively-determined subsidies, starting with the elimination of feed-in tariffs for most new onshore wind and PV starting in 2019–2020. A new auction-based program, the Grid Parity projects, provided new wind and PV projects with 20-year negotiated power purchase agreements, starting in 2019, provided they could offer prices at or below prevailing grid tariffs.[39] A voluntary green power market was established in 2017, though its design primarily focused on replacing feed-in tariff subsidies, secondary trading was not permitted, and purchase volumes were almost non-existent.[40] In late 2022, a new green power market policy clarified that green credits will serve as an accounting system for implementing quotas for energy consumption; provinces can cover their excessive consumption with green certificates.[41]

To deal with high levels of curtailment, the government established new rules for minimum purchase of renewable energy in 2016, defining "full purchase" of wind energy as 1800–2000 hours per year, and 1300–1500 hours for solar.[42] For plants built prior to 2020 still receiving the subsidized feed-in tariff under 20-year contracts, only wind and solar production within this guaranteed minimum would qualify for the feed-in tariff payment. The policy encouraged provinces to set up additional markets for selling "excess" renewable energy production beyond these mandatory amounts, including via interprovincial trading. For years, some provinces had flouted even the reduced minimum operating hours requirements, and prevented renewable sources from selling power beyond obligatory minimums.[43]

Meanwhile, the government continues to promote market reforms in various high-level documents.

The 14th Five-Year Plan for a Modern Energy System incorporates a section calling for markets to play a "leading" role in the new energy system, and repeats language calling for markets to play a "decisive" role.[44] In a WeChat article, the NDRC introduced the "six principles and five simultaneouslies" of the modern power system, showing how China seeks to evolve from a centralized to a hybrid power sector model, while enabling markets to play a leading role.[45] "Market leading" is listed as the sixth principle. The five simultaneouslies specifically refer to ways to integrate renewable energy: The country will simultaneously pursue (1) central and distributed energy, (2) onshore and offshore energy, (3) local consumption of renewables and sending renewable energy to other provinces, (4) developing stand-alone and hybrid renewable plants, (5) developing single location facilities and aggregating multiple facilities.

Other five-year plan documents and publications have promoted ongoing market reforms, though the language is ambiguous in some instances. For example, the State Council's 2022 Notice on the Modernization Plan of Market Supervision of the 14th Five-Year Plan sets out the objective of establishing a unified, open, competitive, and orderly modern market system – to improve the socialist market economic system.[46] This builds on a 2021 State Council document stating that the 14th Five-Year Plan should strive to establish a high-standard market system, with "more dynamic" market players, and to show progress towards market-based allocation of factors.[47] Similarly, the Ministry of Commerce's five-year plan calls for markets to play a decisive role in resource allocation, plans to "stimulate market entities to create new development vitality," and improve the "efficiency and effectiveness of the allocation of productive factors."[48]

Various documents on energy storage have highlighted the role for markets. The 14th Five-Year Plan for New Energy Storage affirms the central role of an independent market for developing renewable energy storage, states that energy storage should participate in various power markets, and that new market mechanisms are needed to accomplish this.[49] The 14th Five-Year Plan includes "market-oriented development of new energy storage" as one step towards achieving carbon neutrality.[50]

In February 2022, the NDRC issued a guiding opinion setting out the clearest timeline yet for power market reforms.[51] The document envisions a preliminary integrated national power market by 2025, involving collaboration between the national market and the provincial or regional markets, joint operation of mid- and long-term bilateral contract markets, spot markets, and ancillary service markets. By 2030, the national market would be basically established, including full participation of renewable energy, and participation of all market players on an equal footing. The NEA's late-2022 spot market policy foresees the components of the national market design task as including the following eight elements:[52]

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1. Inter-provincial and provincial/regional spot markets, with day-ahead, intraday, and real-time markets.
2. Connections between the medium- and long-term market and the spot market.
3. Connections between the ancillary service markets – such as peak-shaving, frequency regulation and backup – with the spot market.
4. Participation of new energy (wind and solar) in the electricity market.
5. Participation of emerging market entities such as energy storage, distributed power generation, load aggregators, virtual power plants, and new energy micro-grids.
6. Participation of users who directly participate in the spot market, electricity sales companies, and third-party electricity purchasers – on an equal footing with generators.
7. Exploration of a capacity compensation mechanism.
8. Introduction of new market players into inter-provincial markets and strengthening their role in price formation.

Various documents and high-level speeches also call for integration of power markets, green power trading, and carbon markets. In November 2021, the State Council expressed its desire to "strengthen the coordination of power trading, energy use trading and carbon emission trading."[53] In 2022, Peng Li from State Power Investment Corporation, one of the Big Five power generation firms, said, "The three markets [power, carbon, and green certificates] are separate, but support each other and have different rules and functions, which effectively avoids the confusion of market trading rules under the multi-objective orientation."[54] Covering the 20th Party Congress, the *Economic Daily* reported President Xi's call for an economic system that "improves the carbon pricing mechanism, as well as strengthens the coordination of carbon emission rights trading, energy use rights trading, and power trading."[55]

The power shortages in September 2021 also led to important changes to the power markets, typically described as a sweeping market reform of power prices, even though the administratively-set benchmark coal tariffs continue to play an important role in setting market prices. The power shortage was primarily caused by a disconnect between high physical coal prices (coal prices were mainly set by markets) and power markets, where prices were capped. The NDRC announced that instead of fluctuating in a band of 10 per cent below and 15 per cent above the benchmark price, the band would widen to 20 per cent above and below the benchmark price, with energy intensive industries facing no cap. Administratively-set price schedules would be cancelled and all customers put into the bilateral mid-to-long term power markets, with the grid company acting as the purchaser for certain customer classes.[56]

Although prices remain tightly controlled, and the reform actually re-regulated physical coal prices and imposed new administrative controls on mines and power plants, **rhetorically the measure was portrayed as a major liberalization.** The NDRC stated this would "deepen the market-oriented reform of electricity prices for coal-fired power generation… China will orderly liberalize the on-grid electricity price for all coal-fired power generation, expand the range of fluctuations in market transaction electricity prices, and promote industrial and commercial users to enter the market." Wan Jinsong, Director of the Pricing Division at the NRDC stated, "The core of the reform is to truly establish a market-oriented electricity price mechanism that 'can fall and rise'."[57] Peng Shaozong, Deputy Director of Pricing Division stated that the reform would "make electricity prices more flexible to reflect changes in electricity supply and demand and cost changes, ease the operating difficulties of coal-fired power generation companies, encourage companies to increase electricity supply, curb unreasonable electricity demand, improve electricity supply and demand conditions, and better ensure a safe and stable supply of electricity."[58]

The 20th Party Congress included market reforms, though with fewer mentions than in previous years. The Party Congress Report's main emphasis is on energy security, with mentions of the economy or market reforms far down from earlier years. Regarding reform, the Report provides almost an equal balance of attention to markets and administrative measures. In the section on clean energy, the Report highlights in the first sentence the importance of China's longstanding energy consumption and intensity quotas, then pivots to improving the carbon emissions trading system. Notably, the Report does not mention the role of energy markets or price reforms in the energy sector.

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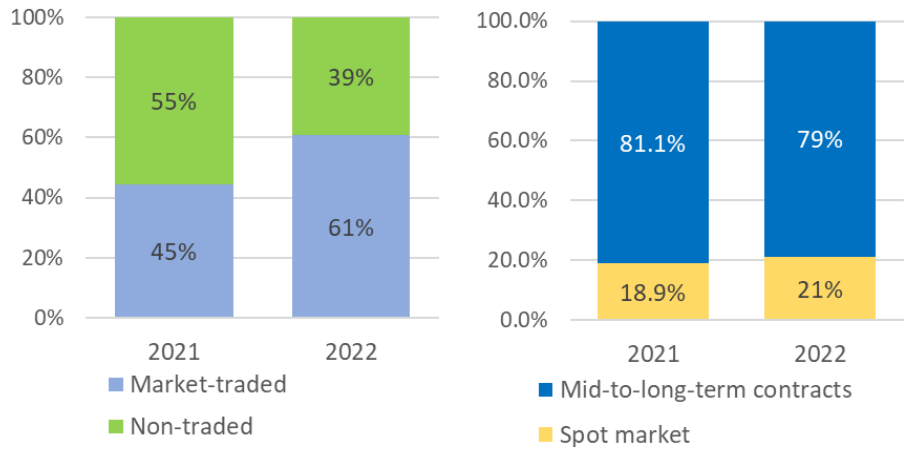
In practice, even energy regulators have noted the slow speed of market reforms. In November 2018, the National Energy Administration stated, "In the face of the slow progress of the construction of the electricity spot market pilot project and the difficulty in starting the trial operation before the end of the year as originally planned, the National Development and Reform Commission and the National Energy Administration have taken action to supervise the battle."[59] Four years on, China has spot market pilots in half of its provinces, but most are still operating at low volumes.

Where market reforms have taken place, they operate differently from those elsewhere.

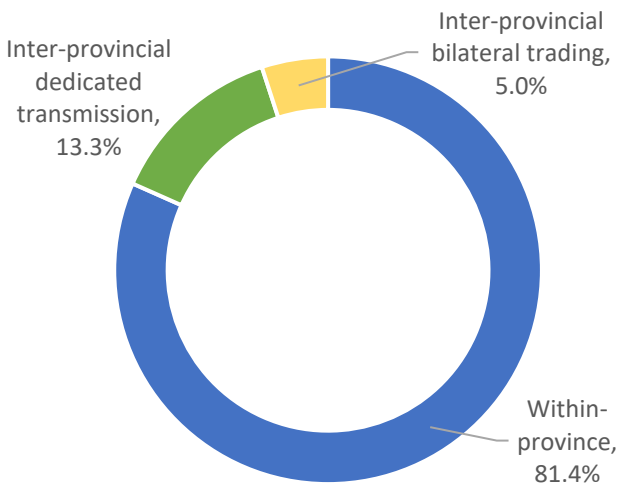
Mid-to-long-term bilateral markets account for 80 per cent of power trading volume, while spot markets occupy the remainder. Almost all trading is within province, with little trading among provinces, except on a long-term contract basis, often over dedicated, single-direction high-voltage transmission lines. Because MLT contracts are effectively physical contracts, as opposed to financial, they lock in transmission congestion (a condition where the lowest-price electricity cannot flow where it is needed) and non-merit-order dispatch.[60] Even during periods of physical shortages, long-term contract arrangements may take precedence. In 2021, during power shortages in Northeast China, short-term electricity exports were paused while medium- to long-term export contracts continued to be honoured.[61] Therefore, while local residents in the Northeast experienced blackouts in September 2021, the region continued to export electricity to Shandong.[62] During the recent Sichuan power crisis, bidirectional power lines required a declaration of emergency to provide power in the direction needed.[63]

Figure 3: 2021–2022 wholesale electric power trading shares



Source: CEC 2022, 2023

Figure 4: 2021 electric power sales by geography of trading



Source: Fang Xiaosong, EPPEI 2022

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In December 2022, the NDRC and NEA further reinforced the role of monthly and annual contracts. The notice stated that market reforms should be accelerated, but that 90 per cent of industrial electricity demand should be contracted through the mid-to-long-term market.[64] The work report also stated that planned inter-provincial power trades should be 90 per cent contracted on an annual basis. These policies appear designed to promote certainty on prices and energy supply, and relieve industry worries about energy shortages. However, such targets further signal the low priority attached to developing spot markets as a means of price discovery. Contracting transmission a year in advance also further reinforces the rigid, single-direction transmission model that prevents the emergence of flexible, regional markets.

Wholesale prices remain tightly regulated, while segmented spot market shows price volatility: Wholesale power prices, including spot market prices, are capped at 20 per cent above the benchmark coal tariff, with the exception of energy-intensive industries, which may face higher caps at the provincial level. As Yuan Jiahai of the North China Electric Power University notes, "At present, China's spot market price fluctuations are still too stable, and transaction prices are relatively low."[65] At the same time, lightly-traded interprovincial power markets can see huge price ranges: "In Gansu Province, which is a provincial pilot spot market, electricity frequently trades at either the lowest price or the highest price. The lowest price for inter-provincial transactions is less than RMB0.3/kWh, and the highest is more than RMB4/kWh, implying huge volatility."[66]

Renewable energy participates in certain spot markets as a price-taker, meaning its **low marginal costs do not affect the merit order directly through economic dispatch.** Spot markets have created problems for renewable generators, as spot prices often fall below the operating costs of thermal plants, which are able to rely on MLT markets for the majority of their output. For example, in Shanxi province, most coal power is traded on the MLT market, but most wind and solar trades in the pilot spot market at prices less than half of the coal benchmark tariff.[67] Overall, spot markets have yet to play a full role in setting prices. Provincial officials design markets to blunt any impact on preferred sectors, adjusting prices for local conditions to meet various industrial planning targets.[68] The lack of an effective spot market for price formation also prevents retail competition from having its full effect.

Provinces have also created capacity markets that potentially distort prices and effectively offer off-market subsidies to coal power. Capacity markets may offer flat, per-kW or even per-kWh payments to all thermal coal plants, potentially distorting spot prices further.[69] In 2020 Shandong introduced a capacity payment for coal generators with a flat RMB0.0991/kWh payment, and in 2022 modified this to multiply the RMB0.0991/kWh payment by a time-of-use price differential. (In other words, the per-kWh capacity payment may be doubled at peak hours, and halved at times of low demand.) According to the Shandong Power Trading Centre, "The compensation mechanism realizes the organic coordination of meeting peak load, priority consumption of renewable energy, and compensation for coal-fired capacity; gives a decisive role of markets in resource allocation; and promotes new energy consumption in the province."[70] The market-distorting effects of paying coal generators an administratively set price for all kWh generated is not acknowledged.

Provinces often saddle renewable energy with costs that might be determined by the market, or otherwise intervene in setting prices. In most provinces, renewable generators are mandated to install energy storage as a condition of approval, effectively placing the cost of new storage on renewable generators. Guizhou has required new renewable plants to pair with coal generators for flexibility upgrades, potentially transferring such upgrade costs to renewables.[71] Renewable generators may also be asked to pay for "ancillary services" – which in China includes coal plant ramping – effectively transferring the cost of flexible operations from the spot market to renewable generators. In 2021, Liaoning province "encouraged" wind and solar to sell a minimum proportion of power at RMB0.1/kWh, far below market prices or coal power tariffs.[72]

New 2022 national spot market rules give wide latitude for market intervention and provincial controls: In late November, the National Energy Administration issued a pair of policy drafts outlining principles and management rules for the spot markets.[73] Spot market rules are fairly general, and allow for significant variation among provinces. The rules call for establishing price caps and floors as well as capacity markets, essentially making these a requirement. Setting the price caps should consider affordability and national economic priorities. The rules list several circumstances that would require a market intervention. Potential interventions include suspension of trading and a return to regulated pricing. The circumstances include the vague statement that "others believe intervention is needed," as

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well as simply prices being "volatile" or "high" – terms which are not otherwise defined and may be left ambiguous to enable broad latitude for interpretation.

Carbon markets are an extension of the administrative state. Carbon markets and power markets are effectively separate, since carbon allowances are issued to generators on an intensity basis, and there is no overall emissions cap that would lead allowance prices to be incorporated in wholesale prices. The design of the market also appears intended to supply industry with a surplus of free allowances to alleviate any risk of high prices affecting operations or investment. Aside from these fundamental design-related aspects, the provincial-level implementation has also reinforced the role of the state in managing industry. As Goron and Cassisa wrote in 2017,[74] carbon market pilots did not result in regulatory institutions and incentives that would transfer responsibility to markets – an observation that remains valid in 2022. Local governments are not committed to market independence or transparency, and they expect market prices to remain subject to frequent political guidance and short-term management.

Markets also play little part in power sector planning and investment. Administrative planning often takes the form of quotas that resemble markets only superficially. The provincial renewable obligation, often compared to the Renewable Portfolio Standard (RPS) in many US states, is only set a year in advance, based on the capacity each province expects to have installed. Provincial planning and grid company calculations of "renewable absorption capacity" continue to dominate renewable planning. Coal plant investment also appears driven by what planners will approve rather than by the market.

> "At present, the 'dual-track' economic system with Chinese characteristics is based on a planned economy, *supplemented* by the market," writes Ye Ze, Director of the China Electricity Price Research Center. (Emphasis added.) "In terms of specific operation, the planned economy and the regulated economy mainly aim at the public and basic goals of the power industry, while the market economy focuses on the goal of resource allocation and efficiency."[75]

There are political and institutional obstacles to reform: Grid companies retain a central role in operating power markets, and are expected to lead and design power markets that will fundamentally affect their positions as transmission and distribution monopolies within the power sector.[76] The large role of SOE generation companies also affects market design. Both grid companies and generators know that in any power supply shortfall, they will be called upon to supply power,[77] not necessarily based on agreed market prices. For now, when coal power still dominates the power system in most regions, generation and grid companies have an interest in conserving a provincial-based system, with high-voltage corridors to carry power over long distances, rather than investing in a mesh grid that would enable more efficient and lower-cost market operation. The lack of independent regulation of the electricity sector inhibits progress towards such a design,[78] though transmission constraints and lagging investment in new transmission are also common worldwide.

Provincial governments continue to have a prominent role in the power sector, particularly during times of oversupply or undersupply. Conflicts between provinces also affect the overall design of the power system,[79] and the relative low volume of inter-provincial power trading. The influence of provincial planning can partly account for China's focus on building single-direction power lines dedicated to supplying firm, physical power to receiving provinces, as opposed to a more efficient mesh grid that could provide flexibility across wide regions. Provincial governments also play an active role in power markets, such as allocating operating hours for different types of power plants – often after the start of the year.[80] This affects the efficiency of dispatch within the province while also inhibiting the emergence of high-volume spot markets. Provinces also take the lead in approving power plants, and in calculating the "renewable consumption capacity" that determines how many wind and solar plants can be built. The central government has tried to counterbalance this influence with quotas for renewable consumption, minimum operating hours rules, and a traffic light system for approving new coal plants.

To sum up, China's central and provincial governments continue to promote power market reform with a steady introduction of new measures, but in many cases these new policies have a dominant administrative and planning component. In addition, provincial governments and other state actors retain wide latitude to intervene in or constrain markets, reducing or distorting the effect of price signals on dispatch, trading, and investment decisions. As Davidson and Pearson have written recently, Chinese policy makers appear to have a different perception of the nature and purpose of markets, seeing them as a way to extend or optimize administrative planning in the short-term, rather than as playing a leading role in guiding investment and power system operation to achieve national policy

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objectives. They write that **market reforms are best seen as "market-oriented experiments" rather than efforts to create markets that would reduce the role of administrative planning at any level.**[81] While more thorough market reforms could incentivize investments and dispatch that would accelerate the low-carbon transition and reduce its cost, administrative policies can also keep the energy transition on track.

4. What is the target market model?

For more than 25 years, international and Chinese experts have developed policy recommendations for China's low-carbon energy transition that incorporate various aspects of the following: (1) market reforms in the electricity sector, (2) distributed energy, and (3) sector coupling enabled by markets. Organizations providing such input include the World Bank, International Energy Agency, Energy Foundation China, the World Resources Institute, the Regulatory Assistance Project, the Natural Resources Defense Council, the UK Prosperity Fund, the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) Sino-German Energy Partnership, and Agora Energiewende.[82] There also exists a body of scholarly research along similar lines from Cambridge University, the Lawrence Berkeley National Laboratory, Harvard University, and others.[83]

In relation to establishing electricity markets, the top recommendations have included:

- Establishing an independent regulator;[84]
- Adopting economic dispatch, ideally via a spot power market with short trading intervals, and over a large geographical area;[85]
- Encouraging flexible interprovincial and inter-regional electricity trading;[86]
- Creating non-discriminatory capacity markets based on availability and speed of response;[87]
- Incorporating carbon prices and other externalities in wholesale power markets.[88]

The benefits of adopting such market measures are lower cost, greater efficiency, more efficient investment, and greater openness to more market players, which could spur innovation.

Subsequently, as China's power reform has evolved, various criticisms have emerged, generally drawing on the target market model described above. For example, MLT bilateral markets reliant on physical power supply have tended to inhibit economic dispatch and constrain power trading among provinces. Capacity markets that reward only coal plants, and compensate them on a per-kW or per-kWh basis set by officials, have gone in the opposite direction from the target market model.[89] Payments to coal plants to become more flexible have tended to crowd out less costly alternatives, such as inter-provincial power trading.[90] Green power trading and provincial renewable obligations have tended to resemble administrative quotas rather than markets. The national carbon market, with its free allocation based on historical emissions intensity benchmarks, has never incorporated cost pass-through to wholesale electricity prices, nor does it play a role in economic dispatch.

Experts often emphasize the physical differences of China that imply its energy revolution must depart from those elsewhere. For example, the concentration of the best wind and solar resources in the north and west is one of the reasons China has focused on long-distance, ultra-high voltage transmission lines, and can explain the high curtailment figures – with Northwest China accounting for 58 per cent of China's curtailment in 2016 despite having a relatively smaller share (33 per cent) of the country's wind and solar.[91] Such arguments tend to focus on the energy potential of remote areas, while overlooking the economic viability and attractiveness of wind and solar in populous regions.[92] In this line of argument, each region should focus mainly on certain power sources rather than others, and trade over long distances.[93]

Yet in 2021, over 70 per cent of new solar capacity was added in the most populous provinces of eastern and central China, and wind had become more evenly distributed among provinces than in previous years. This shift may result in part from transmission constraints that have slowed expansion of renewables in western regions, as well as from policies and subsidies targeted at distributed solar. While China's 14th Five-Year Plan emphasizes construction of clean energy bases in desert regions,

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such as the Gobi Desert, it also states that eastern provinces should seek greater self-sufficiency by consuming more local, distributed energy – an interesting contradiction, since eastern provinces are also marked on the map as recipients of energy from clean energy bases.

Figure 5: State Grid Energy Research Institute map of desert locations for new clean energy bases

Source: SGERI, 2022[94]

On distributed energy, various organizations have promoted greater attention to its potential versus the large renewable energy bases promoted by the grid and generation companies.[95] One study of Beijing showed that the city's greater metropolitan area had the potential for 11 GW of rooftop solar, enough to provide 49 per cent of the city's electricity during daylight hours, or 25 per cent of annual electricity consumption.[96] Studies of Wuhan and Nanjing also showed similar results.[97] A study by a team at China's Ministry of Natural Resources estimated that 11 per cent of China's urban rooftop area was suited for PV, sufficient for 14,000 square kilometres of solar, or 75 per cent more than estimated for the US. Shandong, Jiangsu, and Guangdong offered the largest amount of urban rooftop area suited to PV,[98] potentially equivalent to 830 GW of solar PV capacity.[99] Aside from highlighting the country's rooftop solar potential, analysts have also pointed to the benefits of distributed energy for reducing system costs.[100]

Chinese official views on distributed energy are favourable, but ambiguous. Though distributed energy is a major trend in China, as well as a focus of several policy documents, **there is a widespread view in China that the country is largely unsuited to distributed energy due to dense urban districts with high-rises and few single-family homes.** For example, Chen Kangping, CEO of Jinko Solar, has stated that "China's urban high-rises are unsuitable for distributed solar… This is due to potential changes in top floor property ownership. Such unclear ownership of building rooftops is also a concern for photovoltaic companies."[101]

Agrivoltaics (PV combined with agriculture) is an emerging subset of distributed energy that has faced specific barriers in China. **The 14th Five-Year Plan specifically calls for a wide range of agrivoltaics,** including in both crop and pasture areas. However, just a few months after the plan was issued, the Ministry of Natural Resources reiterated its opposition to agrivoltaics in any land devoted to food agriculture. In a document issued in mid-2022, MNR allows more flexibility for using state land and unused land for PV, while also tightening restrictions on using cultivated areas for PV.[102] This points to inter-ministerial and inter-governmental conflicts as a barrier to clean energy uptake in certain geographies (agriculture, urban areas). In some cases, international experience sharing could provide evidence of benefits or strategies for resolving competing goals that would help alleviate such disputes.

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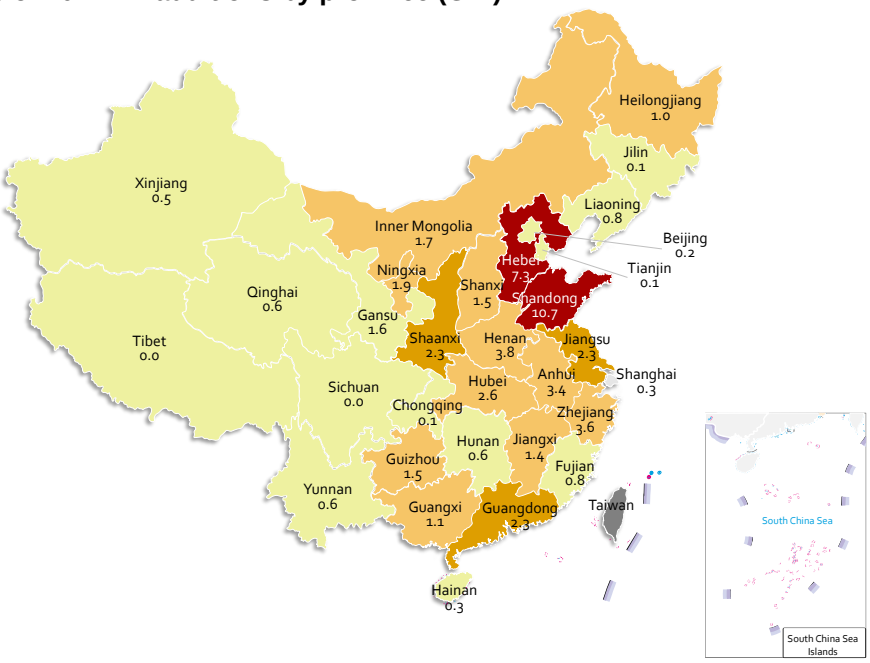
Figure 6: Map of 2021 PV additions by province (GW)



Source: GIZ 2022, based on NEA data

Several international and Chinese experts have also highlighted the **beneficial role of electrification**, in which electrification of end-use sectors provides positive value to the electricity market by providing low- or no-cost flexibility, thereby replacing the need for costly investments in centralized storage, transmission and distribution infrastructure, and generation assets. In 2019, the IEA noted the rise of the electric vehicle market in China, and modelled the benefits of using vehicle-to-grid technology instead of stationary batteries to balance renewable energy output when wind and solar achieve a high penetration. GIZ, NRDC, and others have analysed more specific cases where V2G could benefit the grid.[103] The German Energy Agency (dena) and NRDC have also promoted industrial demand response (demand-side flexibility), such as in the aluminium sector, as a field where electrification and power markets could be mutually reinforcing.[104] (The dena study suggested the aluminium sector on its own could provide flexible load equal to 2.3 per cent of China's average load, with the right incentives.)

5. Will the target model work?

China's unique circumstances are not the only factor arguing against adoption of some of the above recommendations. Indeed, reporting in China has often highlighted problems and difficulties in power markets abroad, calling into question their value for China. Occasionally, there are suggestions that other countries place less value on reliable electricity than China; indeed, the phrase "energy security" in China has tended to emphasize the country's domestic energy production and electricity supplies, as opposed to the vulnerability of imports.

Officially, China's central government endorses cooperation on the low-carbon energy transition at the highest levels. China's concept of an energy revolution explicitly includes international cooperation as one of five elements.[105] Notably, international cooperation on the low-carbon transition does not explicitly refer to study of international market models or trends, but tends to emphasize technology cooperation and participation in multilateral institutions. Yet, the text of the 14th Five-Year Plan explicitly notes the importance of international power market trends, alluding to several aspects of the "target model" described above:

> "Energy production is gradually changing to combine both centralized and decentralized models, from large bases and large networks to include a parallel transformation with microgrids and smart microgrids that promotes uptake of new energy sources and lower economic costs."

At the same time, in Europe and North America, electricity markets face new uncertainties, and the transition to distributed energy and electrification remains at an early stage. The current market conditions in the European electricity market, and proposals for an inframarginal price cap in the spot

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market, have been picked up in the Chinese media, as has Germany's activation of the country's coal plant capacity reserve.[106] For example, in early 2022, a State Grid expert commented, "The relatively aggressive energy transformation in European countries such as Germany has contributed to the rise in electricity prices during this crisis."[107] In August, a Chinese economic magazine called European energy markets "terminally ill," attributing this to "energy spot market prices linked to the cost of thermal power."[108] Similarly, major power outages in Texas and California – both of which have long experience with wholesale power markets – have provoked critical comments.[109]

Aside from these recent events, Europe is still in the process of developing a vision for a common energy market.[110] In practice, from the 1990s onwards, power market restructuring was initially intended to improve competition and reduce inefficient investment,[111] and was not narrowly tailored for the low-carbon energy transition, even though merit-order dispatch has clearly helped promote renewable integration. There is no uniform market design or clear exemplar for China to adopt.[112] As in China, local officials in countries with competitive power markets have occasionally opted for out-of-market payments for coal and nuclear capacity,[113] and the issue of capacity markets remains a contentious one.[114]

Problems with renewable integration are also evident in the field of building new transmission and distribution infrastructure, which is critical to both reliability and market efficiency.[115] Utilities in many regions, even those with competitive wholesale markets, have opted against opening up transmission planning. In Texas, one of the first states to adopt wholesale power markets, the lack of transmission to neighbouring states was partly responsible for power outages in 2021 (though other factors played a larger role).[116]

On distributed energy as well, barriers to market entry remain high, even when the economics support a greater role for distributed energy.

Similarly, for demand-side flexibility, progress outside of China has been slow. In the US and Europe, smart meter roll-outs have faced delays and resistance, and efforts to give customers greater access and control over their electricity meter data have made fitful progress.[117] While many markets – notably Germany and Australia – have seen uptake of home energy storage, aggregation of demand-sited storage remains at an early stage. For EV smart charging and V2G, the story is similarly one of slow progress, with many pilots but few countries operating such resources at scale. Electric heat pumps also offer a potential avenue for demand-side flexibility and beneficial electrification, but they face numerous barriers in practice, including the absence of a trained workforce,[118] a poorly-insulated building stock, lack of information for customers, and the lock-in of existing suppliers with their own preferred technologies.[119] (Many of these barriers are common in China as well.)

Competitive wholesale power markets are conducive to integrating renewable energy and encouraging the introduction of flexible energy technologies on the generation, storage, and user side.[120] However, international experience with markets is decidedly mixed in terms of resolving the energy trilemma of maintaining a reliable, affordable, and environmentally sustainable energy system. In addition, there are ongoing debates in many countries with long-functioning competitive wholesale power markets about how these markets may need to change to enable a nearly 100 per cent carbon-free energy system. While this simply reflects the incompleteness of the energy transition everywhere, not to mention global energy crises related to fossil fuel supply rather than clean energy, the fact that markets remain a work in progress in Europe and North America affects the attractiveness of more thorough power market reforms in China. With some justification, Chinese commentators portray the relative stability and deliberate slowness of China's clean energy adoption and market transition as a positive contrast with the experience of Europe or the US.

Administrative planning will retain the upper hand in guiding China's energy transition in the power sector and in several other fields. A faster transition to merit-order dispatch, spot markets covering a large geographical area, and a level playing field for all players would improve the efficiency and reduce the overall cost of the energy transition. However, in the near-term, China is likely to rely on administrative planning to guide its energy transition at all levels, and international low-carbon energy transition research should reflect this. This does not mean that international market models have no relevance, or that experience sharing on market design should be put on hold. Rather, actors in clean energy and energy transition cooperation should reduce the emphasis on market policy and enhance cooperation on technology policy. This includes, in particular, fields that are emerging in importance, such as sector coupling between renewable energy and hydrogen, EVs, and heating. After all, China is

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well ahead of other countries in scaling up renewable energy, battery manufacturing, and electric vehicles. China has the potential to transfer lessons on scale-up and integration from these technologies to other, more challenging fields such as heating and transport. Arguably, doing so does not depend on market reforms.

This does not imply that China's energy transition must defy expectations of energy transition theory. Resistance by incumbent players and their allies in government to clean energy-supportive market reforms is a type of sociotechnical regime resistance expected during any major sociotechnical transition, and such resistance has been common in the power sectors of other countries.[121] Even in countries with independent regulators, electric power companies have proven adept at blocking or slow-walking top-down reforms, thanks to information asymmetry and limited time available to pursue reform agendas at the highest levels.[122]

Further, the concept of niche management aligns well with the scale-up of clean energy technology in China to date: because of their small size and fundamentally different characteristics, disruptive technologies initially pose little threat to existing sociotechnical regimes, enabling them to grow within protected niches created either by policy makers or market demand.[123] While niches may depend on "market-like constructs," full market transformation is not a prerequisite, and more gradual transitions are common.[124] For renewable energy and electric vehicles, which have already reached commercial scale, these technologies will still constitute a small fraction of China's primary energy use or vehicle stock for years. The support of China's central government will likely remain strong, since it depends more on the economic development potential of these technologies than their potential to revolutionize markets. The state will likely attempt to muddle through – meaning, adopting incremental policy changes with lower political costs and fewer risks – promoting cleaner technologies through administrative means that keep existing regulatory or economic structures largely intact.

Will success in renewable energy and electric vehicles translate to other fields? This is obviously harder to know. In a 2021 "Software versus Hardware" paper,[125] my OIES colleagues and I argued that institutional constraints have the potential to slow China's low-carbon energy transition, especially as that transition shifts from simply scaling up the manufacturing of relatively modular and self-contained manufactured goods (solar, batteries, wind, EVs) towards the integration of clean energy technologies in broader energy systems, which will be required by the electrification of end-uses in transportation, buildings, and industry. However, the economic and technology development benefits for electrification will grow over time, and the administrative state has planning tools available to push forward changes in several of these fields. To accelerate integration of renewables on the demand side, research that models the benefits and shares practices from international cases will continue to have value for policy making audiences in China. This could include, for example, modelling the benefits of pairing heat pumps with solar, or case studies of policies to encourage vehicle-to-grid technology.

6. The research gap, and suggestions for filling it

The focus for research on China's energy transition emphasizes the adoption of clean energy, electrification, and renewables. The content of such research frequently focuses on either high-level modelling or on policy recommendations related to power market reform. This leaves a substantial gap, both in micro fields (such as EV charging, distributed energy, or green power markets), and in creative ideas for administrative policies and incentives. Here are some aspects of the energy transition that could benefit from greater research and cooperation, with an emphasis on three topics that OIES plans to pursue in the next year:

- **Research on green power markets and supply chains:** China first adopted a policy on green certificates in 2017, and began national trading of green power markets in mid-2021. Solar and wind power-purchase agreements are also increasing in number. However, green power trading volumes are still small, markets differ from province to province, and green power pricing has remained at a premium to spot market prices despite renewables being at or below grid parity in many regions. Companies seeking to green their supply chains and operations in China can benefit from objective research on the evolution and likely future development in green power markets, and renewable energy overall.
- **Research on EVs, EV charging, and EV charging to balance renewables:** China is leading the EV revolution, and the country has rolled out extensive charging infrastructure, which is

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critical since many lack access to home charging. However, China's charging experience suffers from many of the same deficiencies in interoperability and maintenance noted elsewhere. Smart charging, demand response, and vehicle-to-grid are at an early stage in China, though China already has hundreds of smart charging pilots, and at least 60 V2G demonstration stations in 14 provinces, providing 170 GWh of peak shaving capability.[126] Gathering and sharing data, experience, and projections of EV markets and EV charging will benefit from interdisciplinary and comparative research. Research and modelling with public data can also help clarify the role of EV adoption and different charging policies on China's renewable integration, carbon emissions, and future gasoline demand.

- **Studying and suggesting further evolution of successful Chinese policies where state coordination has created results:** Even in fields where China has lagged other countries, such as distributed solar, administrative incentives have created major successes at scale. For example, China's Whole County PV program, which covers over 600 counties (almost half of China's counties), mandates rooftop solar on 20 per cent of residential rooftops.[127] Could combining or expanding such a program to incorporate heat pumps or energy storage further boost its impact? More attention should be paid to such examples that combine strong elements of planning with economic incentives to create new markets.

Promoting research in the fields listed above does not detract from ongoing efforts to promote market reforms in China. Indeed, in the long run, the development of distributed energy and sector coupling with a wider variety of users could benefit from a more liberalized power market, where users can share the economic gains of more flexible technologies, while also accelerating those benefits through greater interaction with other users through the market. While market reforms are not a prerequisite for decarbonization, the field remains an important topic for research and international collaboration, given how markets interact with investment in new coal capacity and effective integration of renewable energy, and given the ongoing media coverage inside China of international power market developments and related energy security problems. Policy makers outside of China will continue to require regular updates on China's market reforms.

In summary, **technology adoption is likely to continue to outpace market reforms over the next few years.** The central government has remained committed, at least on paper, to high-level market reform goals. However, due to institutional barriers and competing incentives at the provincial and industry levels, it seems unlikely, so far, that market reforms will result in markets that play a decisive role in setting prices that influence the allocation of energy or environmental resources. This means that there is an increasing gap between the rhetoric and the reality of power market reform, with the central government accepting "market-oriented" reforms that leave administrative rules such as administrative planning targets, benchmark coal prices, price caps, and orderly power consumption rules in place as the main forces guiding investment in and operation of the power sector. Over time, the biggest factor that might help overcome this resistance could be a rising share of renewable energy that gives provincial and industry players the incentive to shift towards market pricing for its flexibility benefits.

While the lack of an efficient power market will result in investment inefficiencies – over-investment in coal capacity and large clean energy bases, less investment in flexible demand or distributed energy storage – the strong central government commitment to the 2030–2060 goals and to energy technology for economic development means that progress on clean energy adoption is likely to continue. International collaboration, and comparative research on China's energy policy, can have a greater impact if the focus is less on market pricing as a panacea, and more on the technical potential of policies and technologies for clean energy integration. These could include studies related to EV charging, electrification of heating, and distributed energy – fields that have already seen years of study, but where international experience and data are changing rapidly and where, due to their nascent state of development, substantial room remains for analysing and proving their benefits.

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