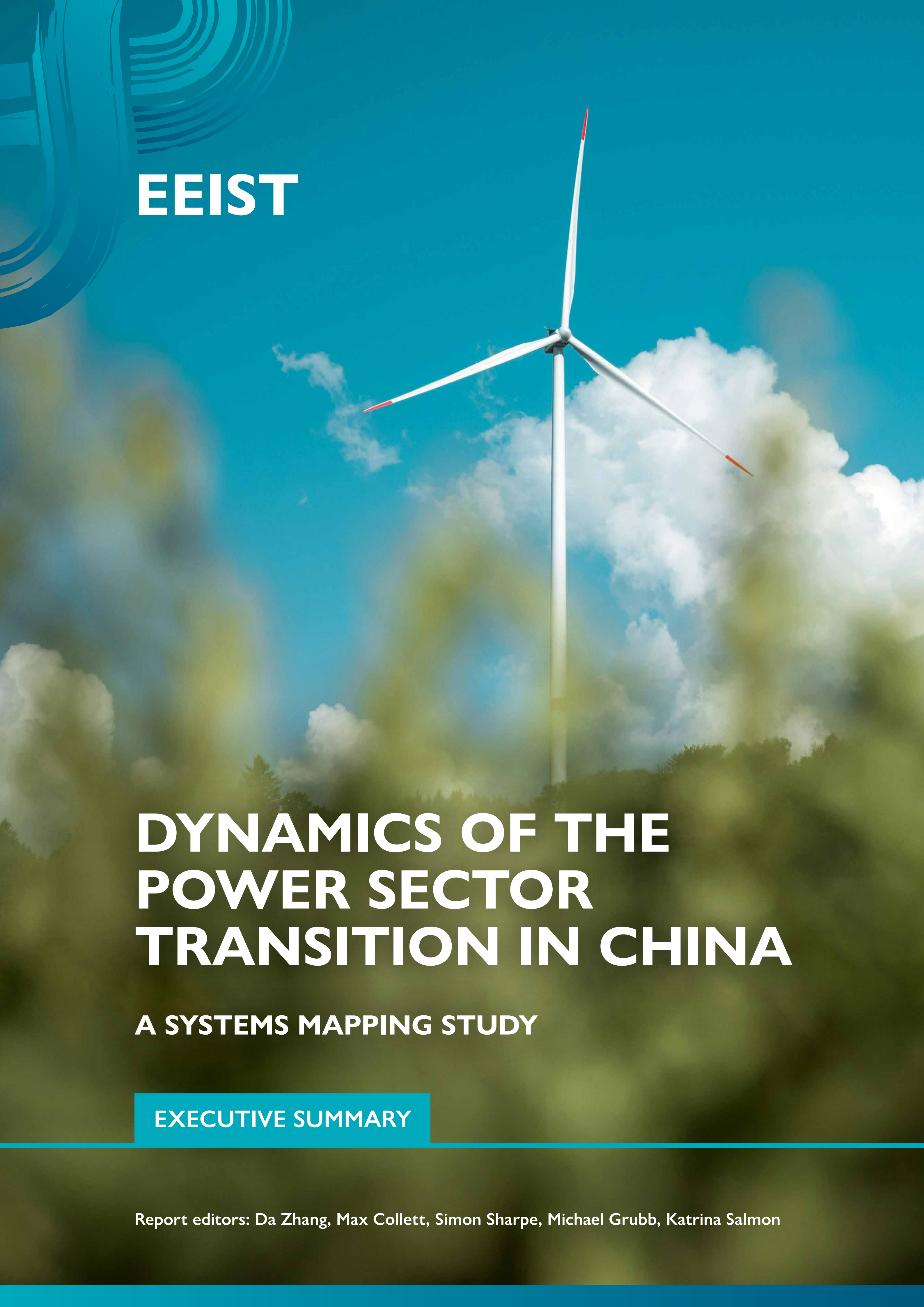

EEIST

DYNAMICS OF THE POWER SECTOR TRANSITION IN CHINA

A SYSTEMS MAPPING STUDY

EXECUTIVE SUMMARY

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Executive summary

The transition to clean technologies in the power sector is fundamentally transforming energy systems, with important implications for electricity costs, carbon emissions, and security of supply.

In this context of structural change, cause and effect are often disproportionate. This leads to surprises, which may be either beneficial or detrimental for policy objectives. Understanding the causal feedback loops in the system—reinforcing feedbacks that amplify change, and dampening feedbacks that inhibit change and preserve stability—can help to anticipate policies' dynamic effects, and distinguish those that are self-amplifying from those that are self-limiting. The analysis of feedbacks can also help to identify ways in which combinations of policies are mutually reinforcing or mutually offsetting.

China is undertaking the transition to clean power on an unmatched scale, and the UK is navigating it at an exceptional pace. While China is engaged in a process of electricity market liberalisation, the UK is considering a wide-ranging set of policy reforms centred around a liberalised wholesale market. Despite their different scales, starting points, and institutional structures, the two countries now face a similar set of challenges as they aim to adapt their power systems to new technologies.

In this report, we use systems mapping with causal loop diagrams—an analytical technique focused on feedback loops—to provide a new perspective on the dynamics of the power sector transition in China. Where relevant, we complement this with insights from the UK's experience.

Sustaining rapid growth of renewable power in the context of market liberalisation

A reinforcing feedback between investment, deployment, cost reduction, and profitability has driven non-linear growth in solar and wind power, which have greatly exceeded expectations. Keeping this feedback operating will be essential for meeting the policy goals of carbon peaking and neutrality in the power sector, and for keeping electricity costs low for consumers.

As variable renewable energy (VRE)—referring to wind and solar—provides a larger share of power generation, and as an increasing share of VRE is sold through competitive markets (instead of by guaranteed purchase), the combination of these trends brings into play a set of dampening feedback loops that risk undermining further investment in renewables. These feedbacks involve higher VRE penetration leading to i) lower prices at times of high VRE supply; ii) increased volatility of spot market prices, with less predictability of returns and potentially higher financing costs; and iii) increased volume risk, where VRE projects cannot sell their power due to technical curtailment, economic curtailment, or the supply of VRE exceeding total electricity demand.

In provinces where the renewable share of generation is highest, this may already be putting downward pressure on electricity prices, although the price of coal remains a dominant factor. There are signs of increasing price volatility in provinces with more advanced spot markets; and curtailment of renewables, after falling for many years, is again beginning to increase.

The sale of green electricity certificates (GECs) could, in principle, increase the revenues of renewables and encourage further investment. But for this effect to be realised, the price of a GEC would need to be significantly higher than its current level of around 0-3% of the coal benchmark power price. Maintaining a GEC price high enough to support investment is difficult because the policy has a built-in dampening feedback: if it succeeds in causing more renewables to be deployed, this will increase the supply of GECs, and that will tend to decrease the GEC price. Even if the GEC price were fixed, this would only partially offset one of the three dampening feedbacks that threaten to undermine investment in renewables.

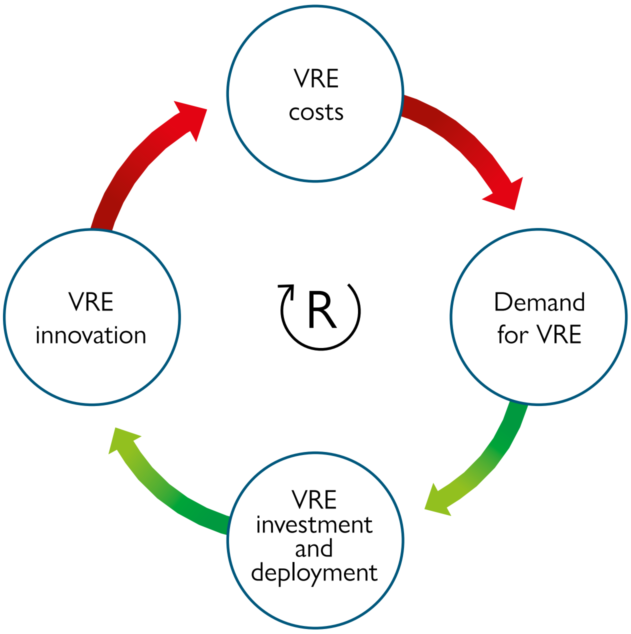

Figure 1: CLD of the learning-by-doing feedback loop between VRE costs and deployment.
Note: VRE costs is understood as the LCOE (levelised cost of energy) for VRE. Green arrows indicate a positive relationship (i.e. factors move in the same direction) and red arrows indicate a negative relationship (i.e. factors move in opposite directions). The letter "R" denotes a reinforcing feedback loop.

The UK has found contracts for difference (CfDs) to be an effective instrument for breaking the dampening feedbacks of price risk and price volatility, and maintaining investment in renewables. After the introduction of CfDs in 2013, the UK's offshore wind capacity deployed and contracted increased almost sevenfold over the following decade, while at the same time the cost of offshore wind power fell by more than a factor of three.

With VRE now accounting for over a third of the UK's generation, volume risk is becoming significant. In 2023, Great Britain (GB) had 214 hours of negative prices in the day-ahead electricity market—three times the level of the previous year. By 2030, VRE output could exceed electricity demand nearly 50% of the time in the absence of any system flexibility, with around 27-37% of wind power generated in 2030 potentially being wasted. Since the UK's current CfD guarantees the price at which renewable power is sold (but only for the volume that can be sold), it does not address the risk that this could pose to further investment in renewables. Consequently, the government has been considering alternative CfD designs—a deemed CfD or a capacity-based CfD—to break or constrain the volume risk dampening feedback, whilst the flexibility of the system is enhanced to make better use of surplus generation.

In China's medium- and long-term (MLT) electricity market, a CfD-like arrangement exists that can provide certainty of price for the part of a renewable generator's output that is covered by an MLT contract, even when some of this output is sold through the spot market. But since MLT contracts are typically for one year, these cover only a small fraction of the risks that are relevant to investment in a renewable plant with a 20-year lifetime. These contracts are therefore useful for budget forecasting, but not investment.

The new CfD instrument introduced by Document 136 in February 2025 will provide price certainty for the part of a renewable generator's output previously covered by guaranteed purchase policies, over a period of time aligned with the cost recovery of renewable investments. As renewable power generators are gradually forced to participate in market trading, the expansion of this mechanism could limit risk and price volatility feedbacks, which would support continued investment in renewable power.

Although the VRE share of generation in China nationally is around half that of the UK (19%, compared to 36%, in 2024), the provinces most advanced in the transition, such as Qinghai and Gansu, already have VRE shares similar to or higher than that of the UK, and the VRE share in all provinces is growing on a similar trajectory. We project that nine provinces could experience frequent VRE surplus events (in the range of 20-30% of the time) in 2030. This represents a significant volume risk, which, given the long payback period of VRE investments, could erode market-based revenues of VRE plants installed today.

Compared to the UK, China has an advantage of being able to experiment with different policy approaches in different provinces. We recommend encouraging provinces to experiment with alternative CfD designs, including deemed and capacity-based CfDs, to discover the most effective approaches to limiting the dampening feedback of volume risk that threatens to undermine continued investment in renewable power.

Maintaining security of supply in the context of technological change

The rapidly growing VRE share of power generation creates new challenges for system balancing and security of supply. As the revenues available to coal power plants decrease, closure of unprofitable plants could reduce dispatchable capacity, potentially threatening security of supply. At the same time, stronger operational flexibility is needed across the power system, with flexible generators needing to ramp up and down more quickly to accommodate variations in the supply of renewable generation.

The current policy of capacity payments to coal plants addresses the first of these problems, but has significant drawbacks. It risks overpayment, as well as over-investment in coal plants beyond the level of capacity that is actually needed. Unless other measures are introduced to drive coal out of the generation mix, these payments may lead to coal plants increasing their generation by bidding lower than their marginal cost in MLT markets, impeding the shift of coal plants to a more genuine back-up role. This approach risks promoting lock-in to incumbent technologies, rather than supporting new technologies to provide security, such as mid- or longer duration energy storage, and demand side response that could be beneficial for system flexibility as well as for reducing both costs and emissions.

Since 2014, the UK has used a capacity market in which existing and new-build power plants compete in auctions for contracts that provide fixed payments in return for being able to generate when called upon by the system operator during periods of system stress. This has achieved required levels of capacity availability with far lower procurement of new plants than was expected, and at lower-than-expected costs (below £20/kW/year for the first seven delivery years, compared to an expected £50/kW/year). This success has been due in part to the capacity market supporting a more diverse range of technologies than expected. While most contracts have been awarded to existing gas plants, contracts have also been won by nuclear plants, interconnectors, batteries, and demand side response. In recent years, most of the new-build capacity procured has come from battery energy storage systems.

The UK now faces the challenge of aligning the capacity market with the goal of achieving a fully zero emission power system over the next 5-10 years. The government is considering creating separate 'windows' within capacity market auctions—with different clearing prices and minimum procurement targets—for high- and low-emissions technologies, or for technologies with different operating characteristics, such as response time, duration, and location in the context of transmission constraints and interconnector availability. Other options under consideration include an emissions limit within the capacity market, and additional support for the conversion of gas plants to hydrogen-to-power or power with carbon capture and storage.

In China, replacing coal capacity payments with a capacity market could reduce risks of overpayment and over-investment, and support the deployment of technologies that contribute more to system flexibility. Since the extent to which new technologies could compete successfully against coal plants in a single undifferentiated capacity market is unclear, an option could be to create separate auction windows with one for established technologies, including coal, gas, and pumped hydro, and others for flexible technologies such as energy storage, demand side response, and virtual power plants. The capacity value of battery storage could be expressed through a de-rating factor reflecting provincial context as well as storage duration.

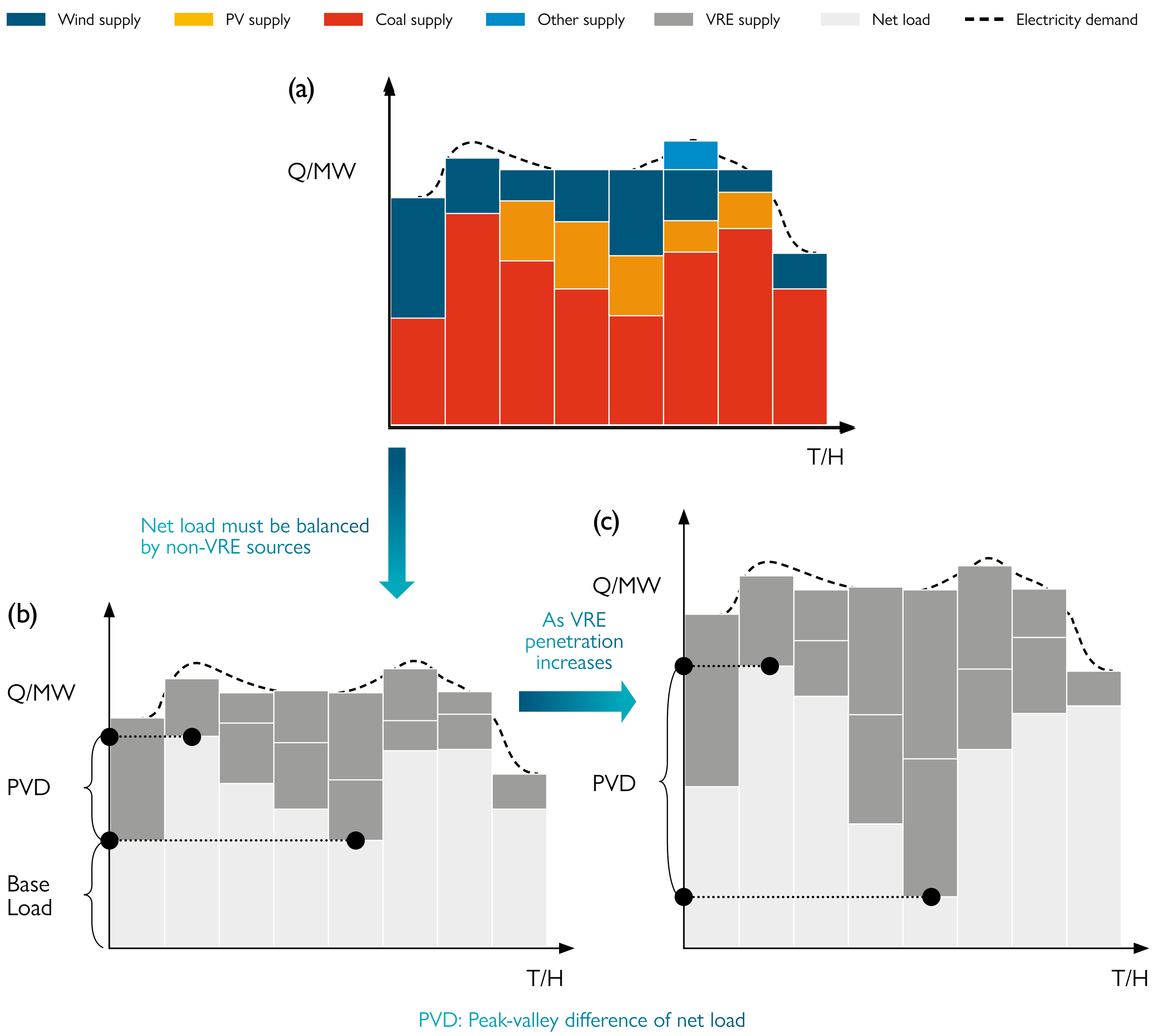

Figure 2: Trend in net load peak-valley difference amid growing VRE penetration.
Note: A typical daily dispatch mix and load curve is shown in (a). The net load in this scenario is highlighted in (b), along with the daily maximum and minimum net loads to show peak-valley difference. Over time, as both demand and VRE penetration increase, the peak-valley difference is expected to widen, as shown in (c).

Taking full advantage of the opportunities of energy storage

Energy storage systems including batteries (BESS) can contribute to security of supply by providing additional generating capacity and being able to respond rapidly to system stress events, and to system stability by providing frequency control services. Beyond this, storage of varied durations can absorb surplus VRE generation that would otherwise be curtailed, and transfer it to moments when it is needed to meet demand, based on needs reflected in a variable electricity wholesale price (i.e. arbitrage). A reinforcing feedback between renewable deployment increasing the arbitrage opportunities for BESS, and BESS deployment increasing the opportunity for profitable generation of renewable power, could be a powerful dynamic driving progress towards a power system that is carbon neutral, low-cost, and secure.

The energy storage mandate implemented in China since 2017 and abolished by Document 136 had an ambiguous effect on the reinforcing feedback between deployment of renewables and deployment of storage, because BESS assets were underutilised (the utilisation rate averaged just 9% in 2023) and at the same time it increased costs for renewables (by up to 10% for solar, and up to 20% for wind). Greater utilisation of BESS could be achieved by advancing the development of spot markets and loosening spot price floors and caps (increasing arbitrage opportunities); continuing development of competitive ancillary service markets with fair access and participation criteria; and including BESS in capacity remuneration mechanisms. The costs of energy storage could be met more efficiently by sharing them among all users of the system, reflecting the system-level benefits of storage, instead of allocating them only to renewable generators.

Long-duration energy storage (LDES) is expected to be important in a fully decarbonised power system, and could be valuable in the nearer term for utilising surplus renewable supply. Multiple technologies exist for LDES, at varied stages of development. Substantial

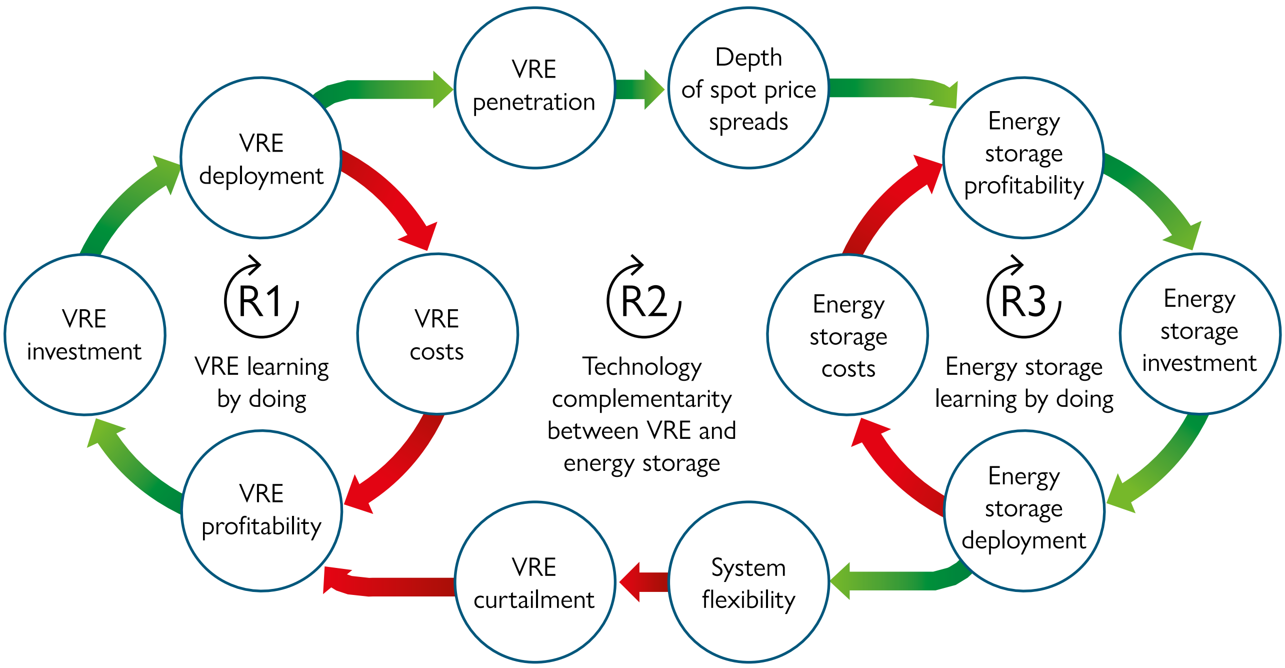

Figure 3: CLD of synergy effects between VRE deployment and storage deployment.
Note: Green arrows indicate a positive relationship (i.e. factors move in the same direction) and red arrows indicate a negative relationship (i.e. factors move in opposite directions). The letter "R" denotes a reinforcing feedback loop. Each feedback loop is accompanied by a brief explanation.

policy support is likely to be needed for deployment, given that capital costs remain high, frequency of utilisation may be low, and initial deployment is necessary to test, demonstrate, and improve performance.

The UK government has recently proposed a revenue cap-and-floor policy to support investment in LDES by reducing revenue uncertainty. This follows the UK's successful use of a revenue cap-and-floor policy to enable investment in interconnectors: under this policy, interconnector capacity has nearly tripled, while top-up payments to meet the revenue floor have never been required. In China, there is a need to complement the many LDES technology demonstration projects under way with an effective deployment policy. The package of policies being piloted in Shandong, including dedicated capacity payments, could be transformative if implemented on a national scale.

Managing the declining role of coal power

Thermal power plants' share of China's power generation has fallen from 73.7% in 2015 to 63.2% in 2024, and this decline is set to continue. Meanwhile, construction of nearly 95 GW of new coal plant capacity began in 2024. The challenge for policy is to manage the declining role of coal power cost effectively, maintaining enough to ensure security of supply while avoiding unnecessary investment in excess capacity.

The national emissions trading system (ETS) has contributed to increasing the efficiency of the coal fleet, but its effectiveness is limited by a dampening feedback. Any substitution of inefficient coal plants with other forms of generation tends to decrease net demand for emissions allowances, reducing their price and reducing the incentive for further substitution. The low carbon price that emerges (typically below ¥100/tCO_2, or €13/tCO_2, so far), combined with the net subsidy that the ETS pays to more efficient coal plants, means that at present the ETS provides little safeguard against unnecessary investment.

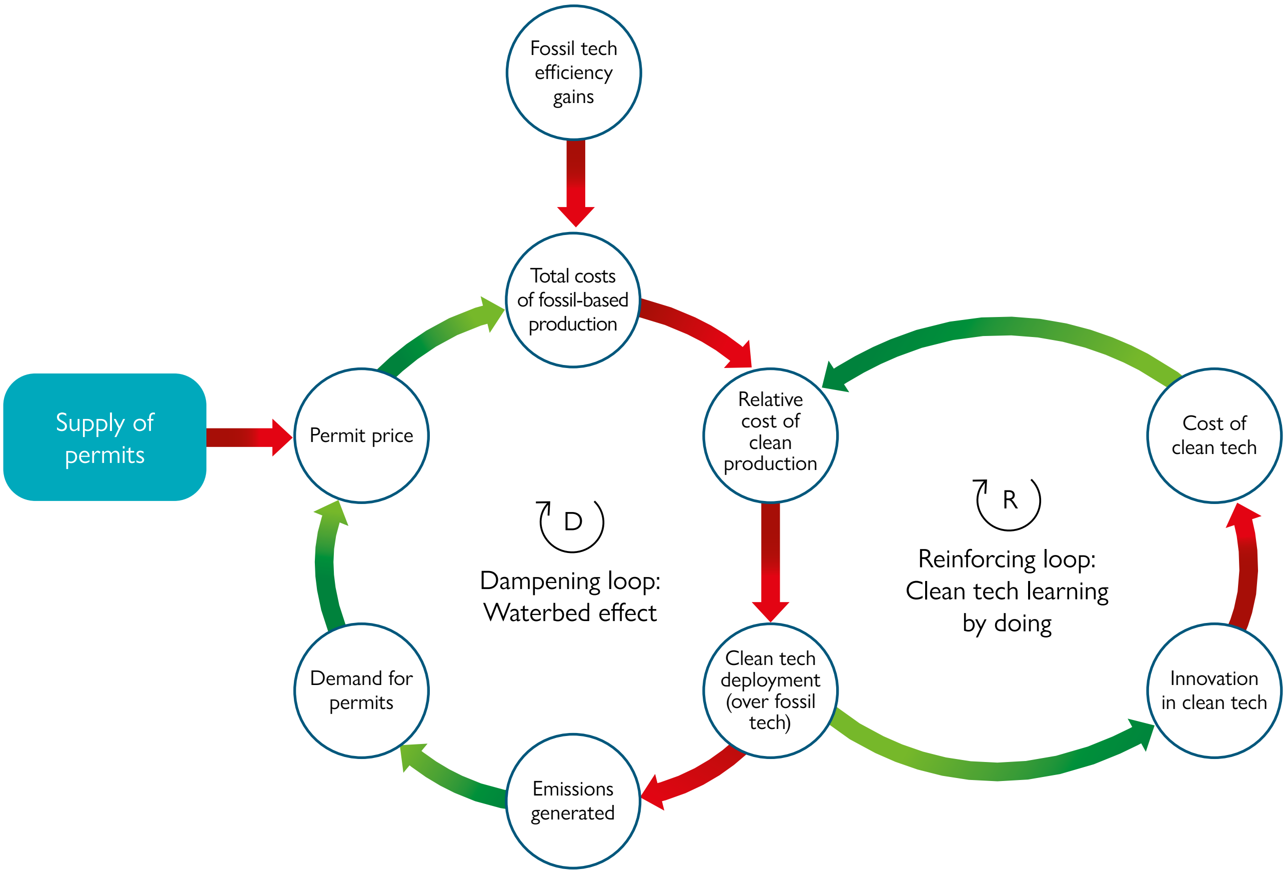

Figure 4: Interaction between feedback loops in a representative hard-cap ETS.
Note: The dampening loop on the left represents the waterbed effect, whereby emissions reductions among market actors depress permit prices and weaken incentives for further reductions. The reinforcing loop on the right represents a learning-by-doing effect of clean technology deployment. Green arrows indicate a positive relationship (i.e. factors move in the same direction) and red arrows indicate a negative relationship (i.e. factors move in opposite directions). White nodes represent variables in the system. Blue rectangular nodes represent policy factors. The letter "D" represents a dampening feedback loop, and the letter "R" represents a reinforcing feedback loop.

A hard cap on emissions could prevent overinvestment, but setting a stringent emission reduction trajectory for the cap would be difficult given growing electricity demand and uncertainty over the pace at which new technologies can replace coal in ensuring security of supply. A weak cap, on its own, could be inconsistent with China's emission objectives and lead to very low ETS prices. To complement an emissions cap, a carbon price floor could limit this dampening feedback within the ETS and allow it to remove the least efficient coal plants from the system. The level of the floor price could be amended annually to respond to any over- or under-achievement.

Retaining some coal plants in a strategic reserve instead of fully retiring them could give provincial governments increased confidence in security of supply, reducing the risk of overinvestment in thermal power capacity and allowing a strengthened ETS to remove coal plants from the system as they cease to be needed. By taking backup plants out of the market, it could also create more space for the growth of flexibility technologies.

Systemic interactions between power sector policies and market reforms

Almost all power sector policies involve some degree of trade-off between the energy trilemma objectives of reducing costs, cutting carbon emissions, and ensuring security of supply, even though the falling cost of renewables means the long-term objectives of low costs and low emissions are increasingly closely aligned. Two forms of intervention stand out for their potential to have positive effects across all three trilemma objectives, provided their costs are managed carefully: policies to increase the deployment of energy storage, with costs borne at the system level; and policies to enable cross-provincial electricity trading. Both increase the system's flexibility and its ability to absorb large volumes of low-cost variable renewable power.

The effect of the market liberalisation process on the trilemma objectives is highly uncertain and contingent on many factors. To ensure it leads to lower prices and lower emissions, it will be important to adopt contracting structures for renewables that break or limit the dampening feedbacks described above. To achieve a positive effect on security of supply, measures will be needed to ensure the full market participation of energy storage and demand-side response. A helpful reinforcing feedback between growth in the profitability and deployment of renewables and decline in coal power's share of generation could be activated, if the gradual removal of guaranteed purchase contracts for coal plants is accompanied by a loosening of price controls. Allowing market prices to vary by location both within and across provinces can bring into play several feedbacks that could contribute to lower prices by managing geographical imbalances.

The most significant mutually offsetting relationship between current policies is that between the coal capacity payments and the ETS. Creating a capacity market in which carbon intensity or energy efficiency are criteria in the allocation of capacity payments to coal plants could transform the relationship with the ETS from offsetting to synergistic. The feedback within the ETS also introduces an offsetting effect in its relationship with any other policies that move the transition forward. As the ETS is extended beyond the power sector, sector-specific carbon floor prices could be used to limit this effect, so that progress in the transition in one sector does not weaken the incentive for progress in another.

In some cases, a policy's direct effect on power system costs, emissions, or security of supply is directionally opposite to the effect that it may indirectly have on the same variable, when the feedbacks in the system are considered. This reflects the difference between marginal change and structural change, and underlines the need for dynamic analysis in the context of the power sector's technology transition.

> Policies to increase the deployment of energy storage and enable cross-provincial electricity trading can enhance system flexibility, simultaneously advancing the energy trilemma objectives of cost reduction, emission cuts, and supply security—provided their costs are carefully managed.

About **EEIST**

The Economics of Energy Innovation System Transition (EEIST) project began in 2020 as a three-year collaboration between researchers in the UK, China, India and Brazil, with funding from the Department of Business, Energy and Industrial Strategy and the Children's Investment Fund Foundation. The aim of the EEIST project is to apply a complex systems understanding of economics to inform policymaking on the low-carbon transition.

Following this initial phase, two subsequent projects—EEIST Phase II and the EEIST China Power Sector Reform project—were launched. This report contains the main findings of the China Power Sector Reform project. The partners in this project are University College London, S-Curve Economics CIC, the University of Oxford, the Energy Research Institute of the Chinese Academy of Macroeconomic Research, Tsinghua University, Beijing Normal University, and the World Resources Institute China

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Economics of Energy Innovation and System Transition

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change. By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

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