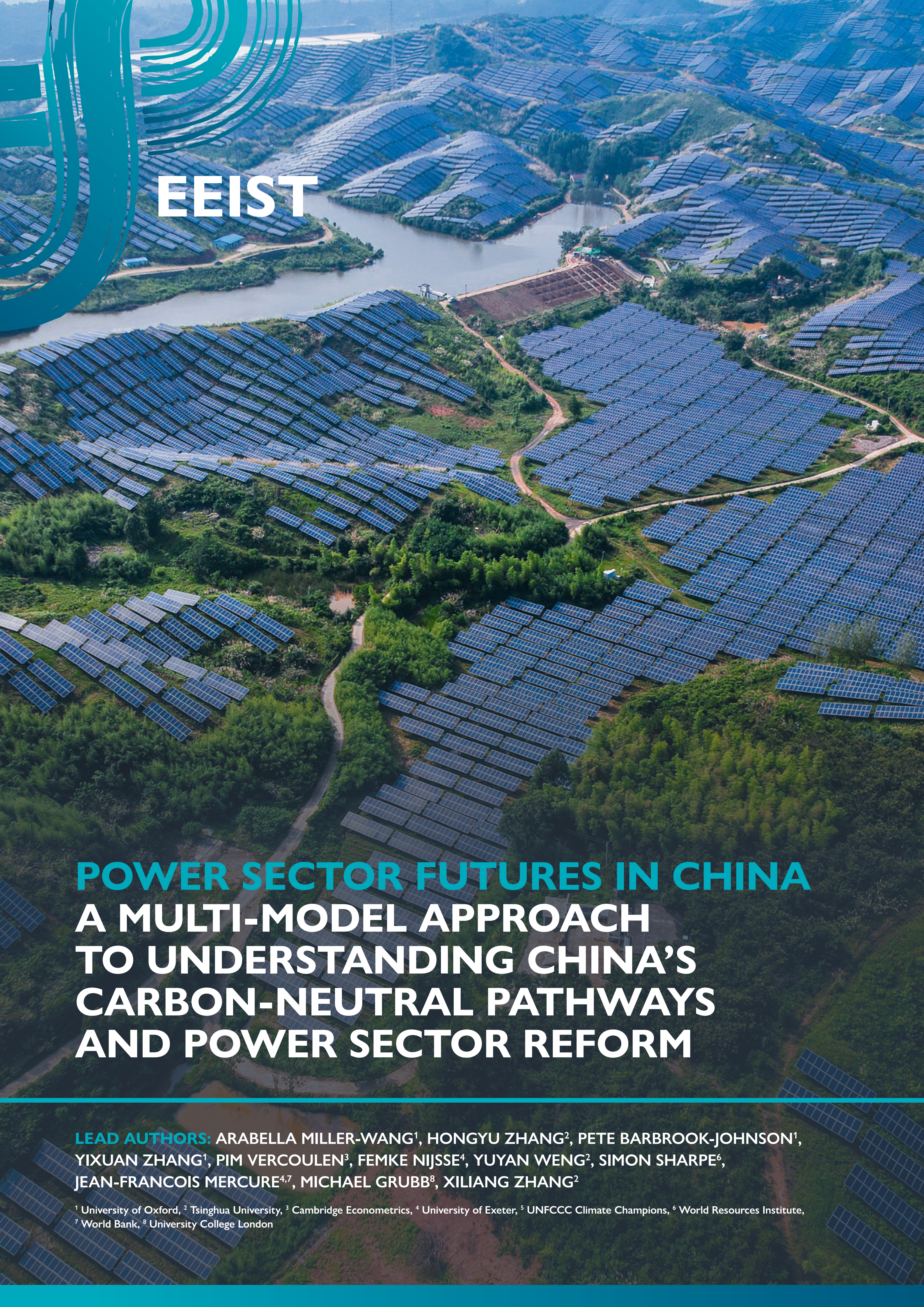

EEIST

POWER SECTOR FUTURES IN CHINA

A MULTI-MODEL APPROACH TO UNDERSTANDING CHINA'S CARBON-NEUTRAL PATHWAYS AND POWER SECTOR REFORM

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This report is jointly published by Tsinghua University's Institute of Energy, Environment, and Economy (3E) and other partners in the Economics of Energy Innovation and System Transition (EEIST) project. Its purpose is to showcase and compare some of the new economy-energy modelling that 3E and its partners in the EEIST project have conducted on the Chinese power sector. These models are used to explore the power sector's role in China's pathway to carbon neutrality and the potential impact of different electricity pricing systems.

Contents

About

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.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are: **UK** – University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies; **Brazil** – Federal University of Rio de Janeiro (UFRJ), University of Brasilia (UNB), University of Campinas (UNICAMP); **EU** – Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna (SSSA); **China** – Beijing Normal University, Tsinghua University, Energy Research Institute; **India** – The Energy and Resources Institute, World Resources Institute.

The EU partner SSSA contributed as a leading organisation with focus on Brazil context and research.

Contributors

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Executive summary

This report outlines power sector reforms developing in China and the increasingly complex landscape of climate and energy policies intended to support carbon neutrality. It then presents two different but complementary energy-economy models of the energy transition and power sector in China: the REPO model developed by 3E at Tsinghua University and the E3ME-FTT:Power model developed by the University of Exeter and Cambridge Econometrics.

These models are used to illuminate possible futures for the Chinese power sector. In combination, they show that, whichever modelling approach we take, the impending dominance of solar and wind power in China is clear. However, the implications of this transition for costs and wider macroeconomic impacts are more subtle. Costs could increase or decrease depending on what pricing mechanisms are used and our assumptions about the exact power mix. Impacts on GDP and investment appear to be positive in high renewable scenarios, but the impacts on employment vary by sector and are more balanced in our analysis.

These findings have serious implications for a range of policy issues in China. They suggest power sector reforms, and specifically market-based pricing mechanisms, have the potential to support China's carbon neutrality goal. They also make clear the role of the ETS in supporting the goal, through a meaningful carbon price. Finally, both sets of analysis make clearer than ever the need to address a range of potential barriers to rapid deployment of renewables, whether financial, technical, legal or otherwise.

1. Introduction

Over the past four years, the EEIST project has developed several cutting-edge economic and energy models aimed at equipping policymakers with tools to inform policies that encourage the energy transition. Among these is the Future Technology Transformations Power model, (referred to as FTT:Power). This dynamic, non-equilibrium model simulates competition between various power generation technologies, taking into account factors such as cost, performance, technological learning and policy impacts. The model encompasses 71 regions, including China. FTT:Power is coupled with the E3ME macroeconomic model.

The Renewable Electricity Planning and Operation (REPO) Model, on the other hand, is a capacity expansion and dispatch model tailored specifically for China by the 3E Institute at Tsinghua University. This model aims to minimise the total discounted cost of the power system, offering optimal capacity and power generation solutions for each technology, transmission capacities between provinces, and carbon emission levels.

This report showcases and compares the design and outputs generated by these two models for China's power sector. It aims to highlight key outputs and policy implications, as well as the similarities and differences in model design and purpose. We do this against the policy landscape of significant discussion and action on power reform in China.

Our objective is twofold:

1. to gain a deeper insight into China's power sector using cutting-edge economic-energy models, and
2. to deepen collaboration and understanding between modelling teams and analysts inside and outside China.

The report comprises three sections. The rest of this introduction offers an overview of China's power sector and the policy context, including plans to transition towards low-carbon energy production. The second section describes the FTT:Power and REPO models, detailing their principles, assumptions, scenarios and results. This includes a direct comparison of model results, identifying areas of alignment and divergence. Finally, we consider the policy implications for China derived from these model analyses.

1.1. China’s long-term climate objectives

In September 2020, President Xi Jinping announced the goals of achieving carbon peaking before 2030 and carbon neutrality before 2060, to address climate change. The goals are also reflected in China’s updated 2030 Nationally Determined Contributions (NDC)[1] in accordance with the Paris Agreement, and China’s first long-term low greenhouse gas emission development strategy in the middle of this century.[2]

China’s energy system is facing profound transformation. In October 2021, the Central Committee of the Chinese Communist Party and the State Council issued the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy, as well as the Action Plan for Carbon Peak before 2030. These documents outline that the proportion of non-fossil energy consumption needs to reach around 25% by 2030, and the carbon dioxide emissions per unit of GDP needs to decrease by more than 65% by 2030 compared to 2005.[3] By 2060, the proportion of non-fossil energy consumption needs to exceed 80%.[4]

The Central Financial and Economic Affairs Commission has proposed to build a new type of power sector with ‘new energy’ (i.e. renewables) as the main energy source for the first time. A target total installed capacity of wind and solar power reaching over 1200 GW by 2030 was set out by the State Council.[6] New targets have also been set for the development of energy storage, to meet the high proportion and large-scale development needs of new energy. By 2025, the installed capacity of new energy storage needs to reach over 30 MW, and the installed capacity of pumped-hydro storage needs to exceed 62 GW. By 2030, the installed capacity of pumped-hydro storage needs to be around 120 GW.[7]

To promote the achievement of these goals, China has launched a series of policies, including on green electricity,[8] the renewable portfolio standard (RPS)[9] and a carbon market.[10] In addition, in terms of market mechanism, China will further promote the reform of the power sector, and will initially establish a nationwide unified power market system by 2025, and basically establish a nationwide unified power market system by 2030.[11] These are described in detail below.

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[1] State Council, China’s Achievements, New Goals and New Measures for Nationally Determined Contributions. 2021. **https://www4.unfccc.int/sites/NDCStaging/Pages/Party.aspx?party=CHN**

[2] State Council, China’s MidCentury Long-Term Low Greenhouse Gas Emission Development Strategy. 2021. **https://unfccc.int/sites/default/files/resource/China%E2%80%99s%20MidCentury%20LongTerm%20Low%20Greenhouse%20Gas%20Emission%20Development%20Strategy.pdf.**

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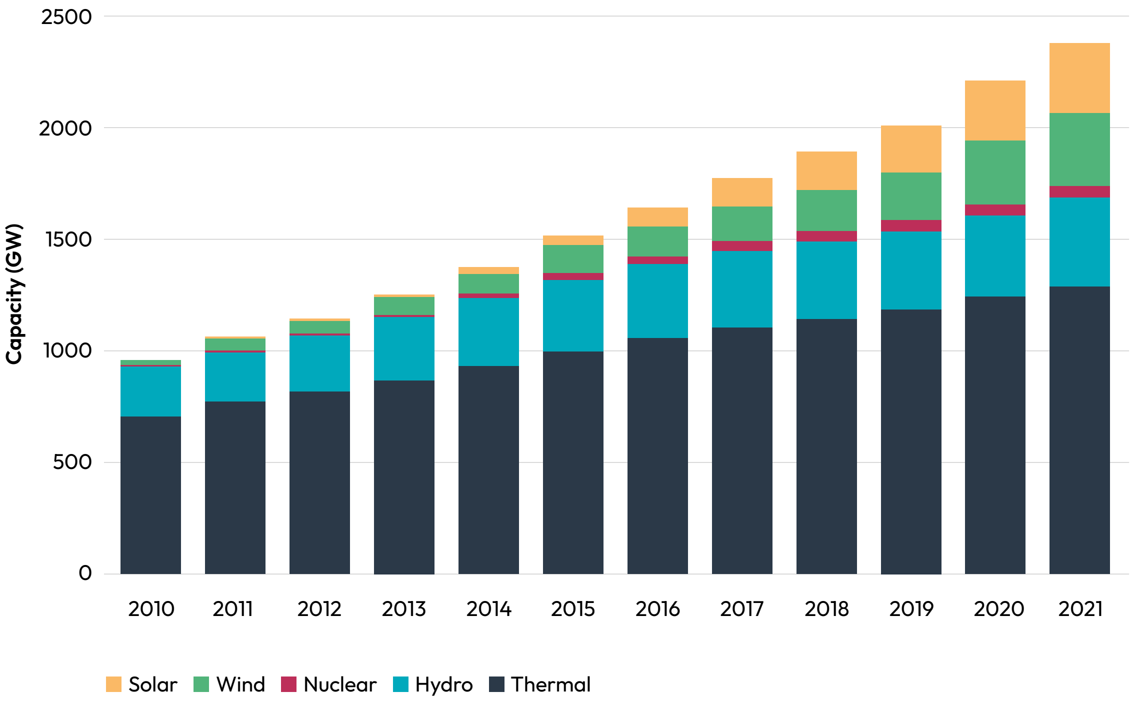
1.2. China's power sector

Capacity

The development of installed capacity in China from 2010 to 2021 is shown in Figure 1, using data from the China Electricity Council (CEC). In the past decade, the total installed capacity of China's electricity has been continuously increasing to meet growing demand, from 966 GW in 2010 to 1,525 GW in 2015, and further increasing to 2,378 GW in 2021.

While both fossil fuel (thermal) power and hydropower have seen increases in their installed capacities over the past 10 years, their proportions within China's power mix have decreased. From 2010 to 2021, China has witnessed a substantial rise in the installed capacities of nuclear, wind and solar power. Compared to thermal and hydropower, the installed capacity of nuclear, wind and solar power in China has grown significantly in the past decade. Preliminary 2022 and 2023 figures from the CEC suggest these trends have continued.

Figure 1: Generation capacity of China's power sector in 2010–2021. Source: CEC.[12]



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[12] CEC, China Electric Power Statistical Yearbook. 2022.

Generation

The changes in China's electricity generation structure from 2010 to 2021 are shown in Figure 2. In the past decade, China's total power generation has shown a continuous upward trend, almost doubling between 2010 and 2021 to 8400 TWh. Affected by the economy and the epidemic, China's total power generation slowed significantly in 2015 and from 2019-2020. However, in 2021, with the economic recovery following the epidemic, China's total power generation showed rapid growth. Preliminary CEC figures for 2022 suggest total generation then plateaued again.

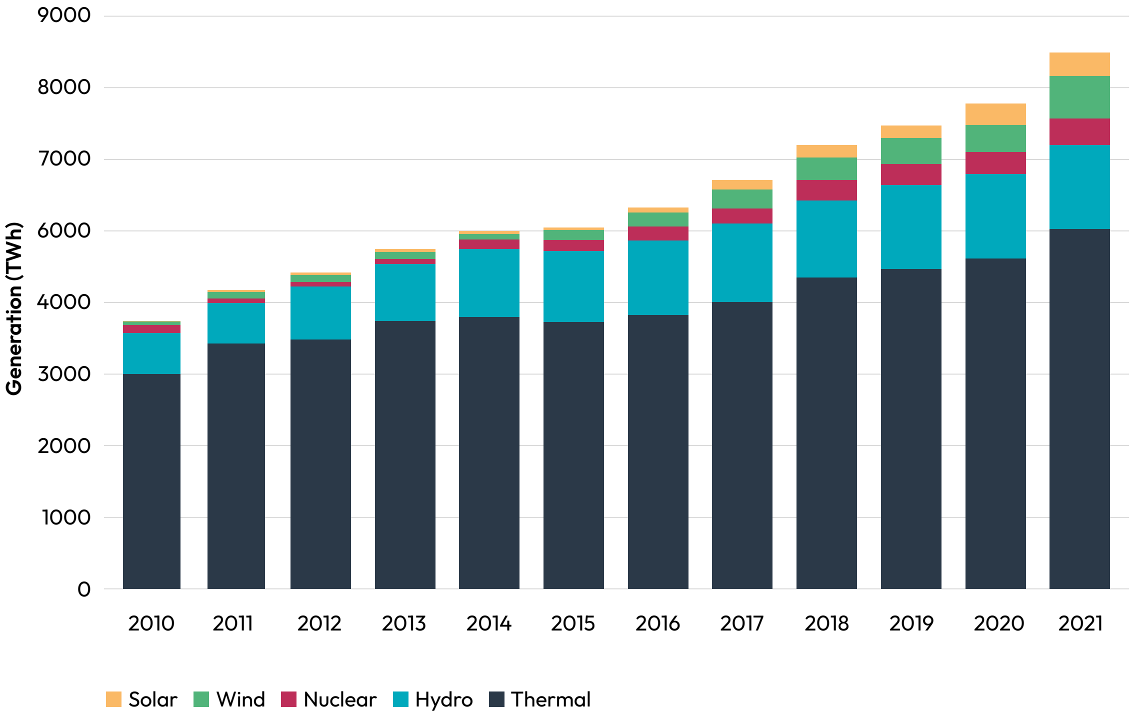
China's electricity supply has been mainly based on thermal power technology for a long time, accounting for about 70%, followed by hydropower, accounting for about 20%. In the past decade, the proportion of thermal power technology in power generation has gradually decreased, from 81% in 2010 to 68% in 2021. However, in absolute terms, thermal power generation has continued to grow, from just under 3,500 TWh in 2011 to over 5,500 TWh in 2021. It will still be the largest source of electricity generation in China in the near future. Preliminary figures for hydropower for 2022 and 2023 suggest its percentage contribution to generation may be falling.

In the past decade, the overall hydropower generation has also shown a growth trend, while the proportion of power generation has remained at around 20%, with little change. Hydropower generation has doubled from 670 TWh in 2010 to 1340 TWh in 2021. At the same time, hydropower is also the main source of renewable energy generation in China, accounting for 16% of the total electricity generation in 2021.

Nuclear power, wind power and solar power technologies were developed relatively late and occupy a small proportion in the electricity generation structure. However, these technologies have been widely developed and deployed in the past decade, and their proportion has been continuously expanding.

Nuclear power generation grew from 75 TWh in 2010 to 408 TWh in 2021. The growth rate of nuclear power generation has stayed high, generally above 10%. Wind power has also developed rapidly in the past decade, with an electricity generation of only 49 TWh in 2010 and reaching 656 TWh in 2021, achieving a more than tenfold expansion. Although the growth rate of wind power generation has fluctuated significantly in recent years, it has remained at a relatively high level, achieving a 40% growth in 2021, indicating its increasingly important position in the power generation system in recent years. Solar power generation was almost negligible in 2010, but in recent years has developed faster than any other power generation technology, surpassing 100 TWh in 2017, 200 TWh in 2019 and 327 TWh in 2021.

Figure 2: Electricity generation of China's power sector in 2010–2021



Energy storage

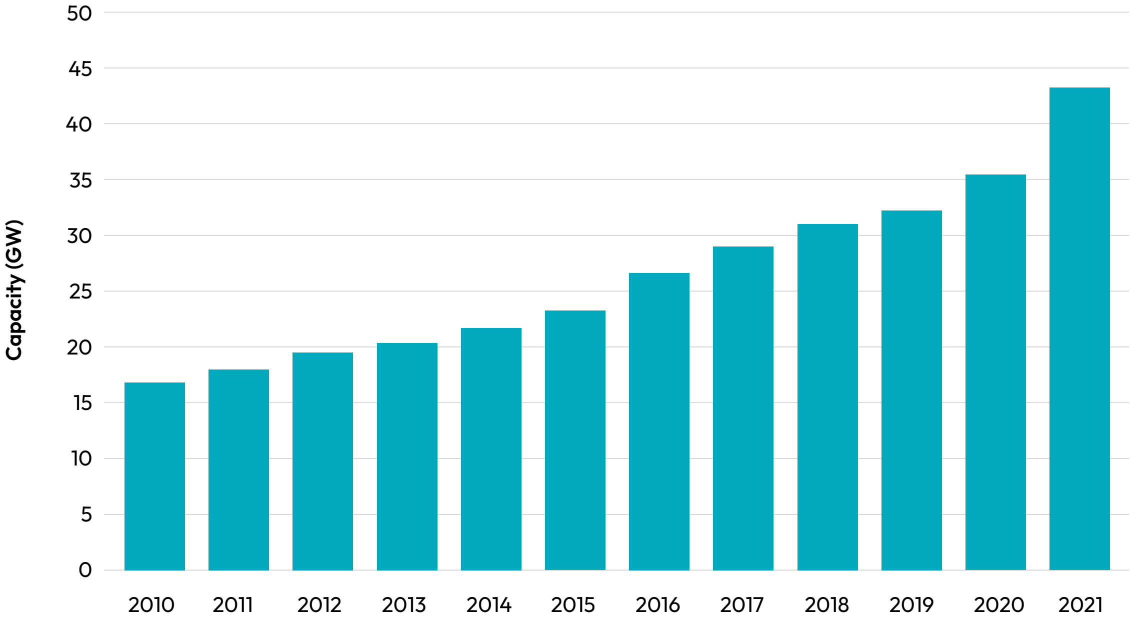
As a key technology to maintain the balance between supply and demand of power systems, energy storage is also developing in China. The country's total installed capacity increased from 17 GW in 2010 to 23 GW in 2015, and further increased to 43 GW by 2021[14] (Figure 3). In addition, China's energy storage capacity has shown an accelerating growth trend in recent years, with an additional 3.3 GW installed in 2020 and 7.8 GW installed in 2021, both of which are the highest levels of installed capacity growth in the past decade.

Despite the current predominance of pumped hydro storage in China, there has been a notable increase in the deployment of battery storage. Pumped hydro storage is the most mature energy storage technology at present. It uses the potential energy difference of water resources to achieve electricity loading or unloading. It has the advantages of long lifetime, low unit cost and large capacity. This type of energy storage capacity can reach more than several thousand megawatts, which is suitable for large-scale and system-level applications on the grid side and mainly used in the transmission and distribution sector of large power grids.

China's long-term energy storage mainly relies on pumped hydro storage, and the proportion of pumped storage installed capacity in the total energy storage capacity has been above 85% for a long time. However, pumped hydro storage has the disadvantages of slow response, long construction period and geographical location constraints. In contrast, battery storage has a short construction period, simple and flexible site selection, strong adjustment ability, large or small volume, fast reaction speed, millisecond to second response, and flexible deployment in various application scenarios such as power supply, power grid and user side.

In recent years, the development of battery storage has been rapid. With the rapid decrease in costs, its installed capacity has grown significantly, and the proportion of installed capacity is constantly increasing. There are also a range of mandatory storage allocation and subsidy policies which have supported this trend. By the end of 2021, the installed capacity of pumped storage in China reached 37.6 GW, accounting for 87% of the total installed capacity, the installed capacity of battery storage reached 5.1 GW or 12% of installed storage capacity, and compressed air storage and flywheel energy storage accounted for less than 1%. Preliminary figures for 2023 are even more striking, suggesting China installed 8.63GW of non-hydro storage capacity between January and August 2023.

Figure 3: Storage capacity of China's power sector in 2010–2021[15]



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[15] CNESA (China Energy Storage Alliance), White Paper on Energy Storage Industry Research. 2023.

The electricity market

The National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the Guiding Opinions on Accelerating the Construction of a Nationally Unified Electricity Market System in January 2022, which specifies the completion by 2030 of a standard medium-to-long-term, spot and auxiliary service electricity market system adapted to the requirements of a new type of electric power system.

The mid-long-term market forms the backbone of power trading volume, facilitating multi-year, annual, quarterly, monthly and weekly transactions, including electric energy, interruptible loads and auxiliary services like voltage regulation. Currently, annual and monthly trading dominate this market. The main participants are coal power enterprises, industrial and commercial large-scale users, and power-selling companies. Part of the power is also from solar and wind, hydropower and nuclear power plants. The average market trading price of coal-fired generating units nationwide in 2022 was RMB 0.45/kWh.[16] CEC data shows that the total amount of electricity directly traded in the national mid-long-term market in 2022 amounted to 4,100bn kWh – a year-on-year increase of 36.2% – maintaining a share of over 90% of the total traded electricity.[17] Trading within provinces accounted for 96.9%, while trading between provinces was 3.1% of the market.

The spot market construction is advancing steadily. This market mainly carries out day-ahead, intra-day and real-time electric energy trading and auxiliary service trading, such as standby and frequency regulation. The first batch of eight power spot market pilots (Shanxi, Shandong, Guangdong, Gansu, Mengxi, Zhejiang, Fujian, Sichuan) has successfully completed extended trial operations, while the second batch of six pilots (Henan, Liaoning, Jiangsu, Anhui, Hubei, Shanghai) conducted simulation trial operation, establishing an initial pricing mechanism that reflects real-time power supply and demand. The participants are more diversified, with renewable energy (including 'virtual power plants' made up of networks of small producers), nuclear power, hydropower and other priority sources playing a significant role. Small-scale industrial and commercial users, distributed energy storage, distributed photovoltaic systems and electric vehicles are progressively entering the transactions. In 2022, the inter-provincial electricity spot market accumulated 27.8bn kWh of electricity traded throughout the year (2.7% of the total),[18] and the maximum power traded on a single day exceeded 19 GW.[19]

The trading of auxiliary services is a part of the long-term and spot markets, mainly including services such as peaking, frequency regulation and standby. By the end of 2022, China's power auxiliary services had achieved complete coverage of six regions and 33 provincial and district grids, leading to the establishment of a unified auxiliary service rule system. In addition to conventional power sources (i.e. fossil, nuclear, hydro, wind and solar), 18 provincial grid companies have promoted energy storage, virtual power plants and other new market players to participate in the auxiliary service market. In 2022, through the market-based mechanism of auxiliary services, the system regulation capacity of more than 90m KW has been tapped, and more than 100bn kWh of additional generation capacity from clean energy has been promoted.[20]

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[16] China Electricity Council, A brief overview of the national electricity market from January to December 2022. 2023. https://cec.org.cn/detail/index.html?3-317500

[17] China Electricity Council, China Power Industry Annual Development Report 2023 (Short Version), https://www.cec.org.cn/detail/index.html?3-322625

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[19] TMTPOST,China's inter-provincial electricity spot market traded 27.8 billion KWH of electricity last year. 2023. https://www.tmtpost.com/nictation/6481381.html

[20] National Development and Reform Commission, Make more green electricity available and well used. 2023. https://www.ndrc.gov.cn/fggz/hjyzy/tdftzh/202305/t20230504_1355444.html

1.3. Public sector and policy

The objectives of peaking carbon emissions and reaching carbon neutrality necessitate further decarbonisation of China's power sector. In this transformation process, government departments play an instrumental role, serving as one of the key driving forces in the promotion of low-carbon advancements within the electrical industry. Consistent with those targets, numerous policies have been enacted in recent years to bolster the shift towards a low-carbon trajectory within China's power sector.

Power market reform

For decades, China's power sector operated under complete regulation. However, it is now transitioning towards liberalisation. Since 1985, the country has launched reforms to address various issues at different stages within the power system. In 2015, the establishment of mid-long-term and spot markets and pricing reform were set out as main objectives in the Central Committee and State Council's Document No. 9, Several Opinions on Further Deepening the Reform of the Electricity System.

As of 2022, market-based transactions accounted for 60% of the total societal electricity consumption.[21] This reform of the power market plays a pivotal role in supporting the low-carbon transition of China's power generation mix.

Since the reform, the pricing equation for the electricity traded in the markets has evolved to:

Fixed prices + transmission and distribution tariff + government funds and surcharges = electricity price

In terms of the fixed prices, there are two main categories: one involves prices negotiated between power generation companies and large-scale electricity users, and the other prices set by the national government. In the second category, specific prices vary in different regions and power sources. China calculates the transmission and distribution tariff using a pre-set formula. Specifically, permitted revenue, which is determined by a fixed return rate on the asset base plus permitted costs, is divided by the pre-set volume for the subsequent three years.[22] Government funds and surcharges are incorporated as part of the electricity price, aiming to support various government funds, such as the renewable energy development fund. The electricity price here is the price that end users pay, or power suppliers sell to the customer. Prices for electricity not traded via the market are set by the Chinese government. In the UK market, the price is set by the marginal unit of supply, which is constantly changing. This can also be found in the Chinese spot market, in which only a few provinces operate and which are dominated by mid-long-term transactions.

Renewable Portfolio Standard (RPS)

In 2019, China's National Development and Reform Commission and National Energy Administration jointly issued Document No. 807, Notice on the Establishment and Improvement of the Renewable Energy Power Consumption Guarantee Mechanism. This document sets out the rules for the Renewable Portfolio Standards (RPS).

Under the RPS, the government mandates a specific percentage of the power mix to come from renewable energy sources. The targets are allocated to provinces in the forms of quotas, who comply with them. These quotas align with the government's five-year renewable energy targets, which are critical to China's transition towards a power generation mix with a larger share of renewables. The most recent goal is to increase the consumption of renewable electricity to 33% of total electricity consumption by 2025.[23] To ensure the consumption aligns with the established quotas, provinces can purchase green electricity and green certificates.

Green electricity trading

Despite its nascent stage, green electricity trading is poised to play a complementary role in promoting future renewable consumption. Green electricity is traded in the Chinese market voluntarily, encompassing electricity generated from wind and solar sources. The Green Electricity Consumption Certificate (GECC) is awarded to those who purchase this electricity.

Green electricity transactions primarily occur between power supply companies and power generation companies. These suppliers, knowing the demand from larger-scale users, bid for green power in the market on behalf of their clients. The first round of green electricity trading started in 2021, resulting in a total of 7.9bn kWh traded, with the clearing price exceeding that of long-term contracts by 0.03 to 0.05 RMB/(kWh).[24]

Emission Trading Scheme (ETS)

Prior to the establishment of the national ETS, pilot projects had already been initiated in various provinces. Beginning in 2013, cities and regions such as Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, Shenzhen, and Fujian ran trials of ETS within their respective jurisdictions. In 2017, the National Development and Reform Commission (NDRC) unveiled the National Carbon Emission Trading Market Construction Programme, specifically targeting the power generation sector. It wasn't until July 2021 that the national ETS market officially began operating. This involves more than 2,000 companies and covers around 4.5 Gt CO2 – or around 40% of China's energy sector CO2 emissions in 2020.[25] In 2022, the ETS saw the exchange of approximately 50.9m tonnes of carbon allowances, resulting in a substantial annual turnover of CNY 2.81bn. The average price per tonne traded was around CNY 55.3.[26]

However, quotas were allocated for free on the basis of intensity in the Chinese carbon market (i.e. no hard cap). Designed mainly to incentivise high efficiency and inhibit inefficient fossil fuel thermal power generators, the market's positive impact on renewable energy is currently quite limited.[27]

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2. A multi-model approach to modelling the power sector

China’s power sector reforms aim to address a multitude of objectives, reflecting the country’s ambition to create a modern, efficient and sustainable energy system. One key objective is market liberalisation, transitioning from a more planned system to a more competitive, market-based one, which involves encouraging private investment, promoting competition among energy providers, greater efficiency in resource allocation and reducing state control over pricing. The reforms also focus on efficiency improvements, operational optimisations and technology upgrades.

Another vital objective is the promotion of renewable energy, in line with China's commitment to reducing carbon emissions and tackling climate change. This includes incentives for renewables projects, as well as grid connections and consumption targets for renewables. The reforms also incorporate measures for environmental protection, such as stricter emission standards and the phasing out of outdated coal-fired power plants.

Ensuring energy security is a critical aim, which includes diversifying energy sources, enhancing grid resilience. Modernising the grid is another focus of the reforms, improving infrastructure and management, and incorporating smart grid technologies to handle the evolving energy mix and demand patterns. The reforms also focus on fostering regional integration, through inter-regional power trading and coordinated grid development, optimising resource allocation and risk sharing among regions.

Lastly, encouraging innovation and technological adoption is integral to the reforms, stimulating research and development, incentivising technology adoption and promoting the development of new energy technologies. Collectively, these objectives represent a comprehensive strategy to transform China's power sector into a more sustainable, efficient and resilient system.

To understand how to best support the objectives of China's power sector reform, this section introduces two different but complementary models of the power sector and wider economy. These are the Renewable Electricity Planning and Operation (REPO) model from the Tsinghua 3E group and the E3ME-FTT:Power model from the Exeter/Cambridge Econometrics groups.

The FTT:Power component is a dynamic, non-equilibrium model that simulates competition between various power generation technologies, taking into account factors such as cost, performance, technological learning and policy impacts. The model encompasses 71 regions, including China. It is coupled with the E3ME macroeconomic model, which integrates a range of social and environmental processes. The two-way linkages between the economy, wider society and the environment are a key feature of the model. E3ME is designed to address national and global economic and economy-environment policy challenges, but can be applied to other policy areas due to its in-built adaptability. The model has been used in policy areas as diverse as climate change, gender equality and the UK's exit from the EU.

The REPO model is a capacity expansion and dispatch model tailored specifically for China. It aims to minimise the total discounted cost of the power system, offering optimal capacity and power generation solutions for each technology, transmission capacities between provinces, and carbon emission levels.

Through the comparison of scenarios and results of both models, we hope to understand what these models are telling us about the likely pace of renewable deployment in China, the constraints to the balance of the power system, and the impact of different pricing mechanisms.

2.1. The REPO model

The REPO model is a computer-based model that calculates China's installed capacity, power mix, emissions, etc, at the minimum cost, and is typically used for evaluating the influence of China's low-carbon technologies and policies on its power system. The model provides a cost-optimisation approach to understanding the running and operation of China's power system and informing policy decisions.

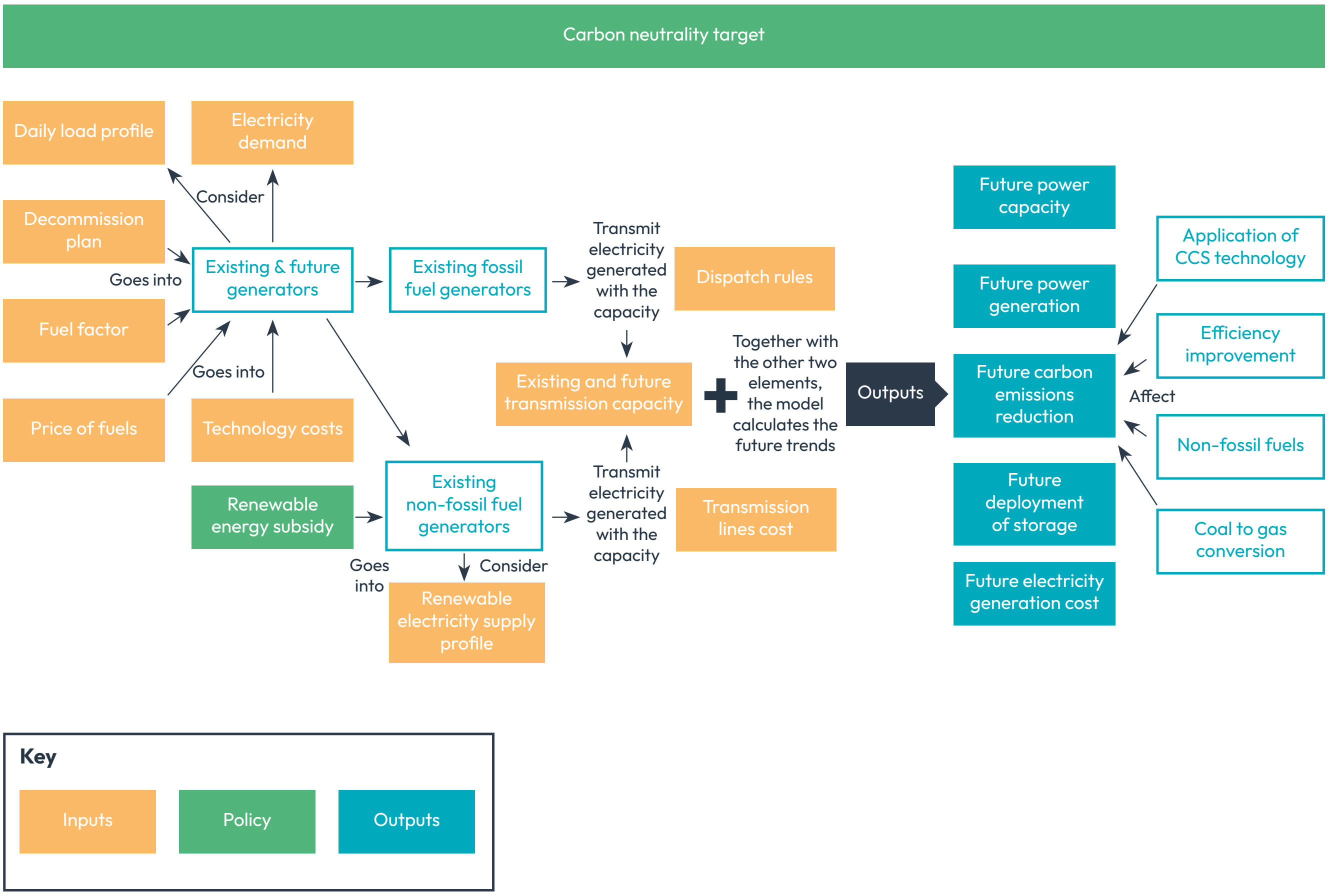
As REPO was built upon Balmorel and uses economic assumptions of the China-in-Global Energy Model (C-GEM), it is worth briefly describing these. Some of the principle assumptions of Balmorel and C-GEM are inherited by REPO.

As illustrated in Figure 4, the REPO model incorporates a set of parameters for both existing and future electricity generators. These encompass decommissioning plans, fuel attributes, fuel prices and technology costs for various energy sources including coal, natural gas, nuclear, biomass, hydro, wind and solar. In addition, the model factors in the daily load profile and electricity demand.

The electricity generated from both renewable and fossil fuel sources is modelled to be transmitted via the grid, taking into account the transmission capacity of existing and future transmission lines. By integrating dispatch rules and transmission line costs along with the previously mentioned factors, the model is capable of forecasting various future trends, including projected generation capacity, changes in the power generation mix, the deployment of energy storage technologies, reductions in carbon emissions, and future electricity generation costs.

The REPO model further identifies the key drivers contributing to reductions in carbon emissions. These include the adoption of Carbon Capture and Storage (CCS) technology, improvements in energy efficiency, the use of non-fossil fuels and the conversion from coal to natural gas.

Figure 4: The overall logic of the REPO model



C-GEM and Balmorel

C-GEM is a Computable General Equilibrium model that simulates the influence of energy and climate policy on economy, trade, energy and CO2 emissions.[28] Balmorel is a partial equilibrium model for long-term planning and operation of electricity and combined heat and power systems, finding the most cost-effective mix of electricity generation, transmission and consumption.[29][30]

Both C-GEM and Balmorel use the representation of equilibrium (general equilibrium and partial equilibrium) and perfect competition. In perfect competition, the market consists of many buyers and sellers and they are all price takers. The prices affect how much buyers and sellers purchase and produce. No single seller can either influence price or make consistently high profits.

REPO details

The REPO model is essentially the Chinese iteration of the Balmorel model. In other words, it was constructed based on the Balmorel model and tailored to align with Chinese characteristics. Unlike FTT:Power being integrated into E3ME, REPO operates independently from C-GEM, although it incorporates the economic assumptions derived from it. Additionally, the results adjustment process is not unidirectional; it's not solely REPO results adjusting C-GEM, but a reciprocal adjustment in which both REPO and C-GEM results can influence and modify each other to achieve the desired outcomes. REPO is a provincial power system planning model that reflects the operational characteristics and inter provincial differences of China's power system. REPO has been used for evaluating renewable energy development and CO2 emissions in China's power sector, and the impact of energy and carbon policy on China's power sector.[31][32]

As shown in Figure 5, the REPO model aims to minimise the discounted cost of the power system, and can obtain the installed capacity and power generation of each power generation technology and province during the simulated years. The model covers 32 power grid regions, representing almost all provinces of China. It does not cover Hong Kong, Macao and Taiwan (Inner Mongolia is divided into East Mongolia and West Mongolia according to the power grid structure). The model expresses electricity demand, resource potential, existing installed capacity and existing transmission capacity at the provincial level, and expresses the wind and solar resources in a more detailed regional space. The model takes 2020 as the base year, five years as the optimisation step, and can be optimised to 2060.

In each optimisation year, the model selects 12 typical days and 12 time periods for each typical day to represent the annual power operation situation for optimisation. It has covered conventional power generation technologies such as coal-fired power and gas-fired power, nuclear power, and various renewable technologies such as hydro, wind, solar and biomass. Coal-fired and gas-fired power technologies are divided into eight technologies and three technologies respectively, to better reflect thermal power in China. Pumped hydro storage technology, battery storage technology and compressed air storage technology are also considered.

The model characterises the resource potential and resource fluctuation of renewables such as wind and solar power. In addition, it considers the technological progress of future renewable energy generation. The constraints considered in the model mainly include power supply and demand balance constraints, inter-regional power transmission constraints, renewable energy output constraints, storage operation constraints, unit commitment constraints and policy constraints. The model can simulate the capacity expansion and power operation of the country and provinces under future policy constraints.

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[28] Zhang Xiliang, et al.(2022). Research on the Pathway and Policies for China's Energy and Economy Transformation toward Carbon Neutrality, Journal of Management World, 38 (01),35-III-14

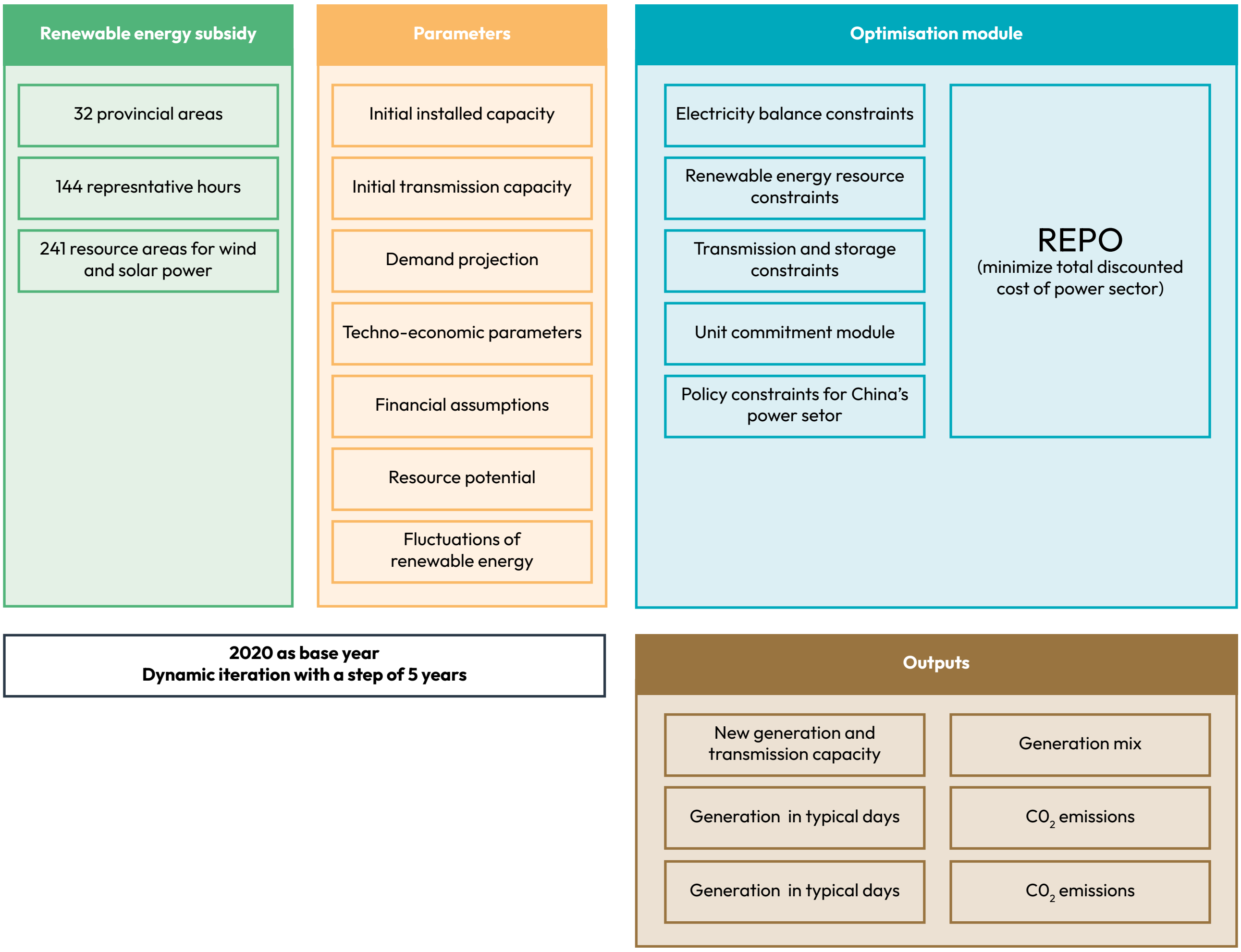
[29] Frauke Wiese, et al. (2018). Balmorel open source energy system model, Energy Strategy Reviews,Volume 20.26-34.

[30] Hans F. Ravn. (2001). The Balmorel Model: Theoretical Background. http://www.balmorel.com/images/downloads/the-balmorel-model-theoretical-background.pdf

[31] Yang, Y. et al, Regional power system modeling for evaluating renewable energy development and CO2 emissions reduction in China, Environmental Impact Assessment Review, 2018, 73, 142–151, https://doi.org/10.1016/j.eiar.2018.08.006.

[32] Zhang, H. et al, The role of output-based emission trading system in the decarbonization of China's power sector. 2023, 173, 113080. https://doi.org/10.1016/j.rser.2022.113080. Vol.47 No.2 Feb. 2023.

Figure 5: Structure of the REPO model



Key assumptions

Below are some of the key assumptions made before designing scenarios.

- Electricity demand: On electricity demand, historical data and C-GEM's projection were taken into consideration. National electricity demand growth rate would be slower than the past decade.[33] Provincial demand growth rates are assumed to be in line with the national growth rate after 2030.[34] Table 3 details precise demand assumptions.
- Load profile and renewable electricity supply profile: Daily load curves are assumed to stay the same within a month. The data of wind, solar and hydro electricity supply profile is an exogenous input to the model.
- Existing generators and decommission plan: Data from the CEC were used to determine the initial national and provincial capacity and generation mix.[35] [36] The capacities for each coal- and gas-fired power subcategory were verified using unit-level data.[37] Since the lifetime of hydro power and nuclear power can exceed 50 years, REPO assumes that all the hydro power, pumped hydro storage and nuclear power plants would be still operating by 2060.[38] The other existing generators would all be decommissioned before 2060.
- Existing transmission capacity: Electricity transmitted from province X to Y is not allowed to exceed the capacity of the transmission line in REPO.

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[33] Zhang Hongyu, (2022). Modelling the Effects of Carbon Market on the Decarbonization of China's Power System, Tsinghua University, Doctoral dissertation.

[34] Yuanzhe Yang, et al. (2018). Regional Power System Modelling for Evaluating Renewable Energy Development and CO2 Emissions Reduction in China, Environmental Impact Assessment Review, Volume 73.142-151.

[35] CEC, China Electricity Industry Development Annual Report 2016. 2016, Beijing.

[36] CEC, China Electricity Industry Development Annual Report 2021. 2021, Beijing.

[37] Zhang, H. et al, The role of output-based emission trading system in the decarbonization of China's power sector. 2023, 173, 113080. https://doi.org/10.1016/j.rser.2022.113080

[38] Yuanzhe Yang, et al. (2018). Regional Power System Modelling for Evaluating Renewable Energy Development and CO2 Emissions Reduction in China, Environmental Impact Assessment Review, Volume 73.142-151.

- **Dispatch rules:** In the model, dispatch was assumed to be partly planned in 2020, and economic dispatch after 2025. As a result of the political push and incentives to generate electricity from gas-fired generators, a minimum operating time of 2500 hours per year was assumed for gas-fired plants.
- **Renewable energy subsidy:** China's non-hydro renewable power (wind, solar, biomass) generation enjoys subsidies from the feed-in tariff. REPO calculates current average subsidy price of each technology and assumes the subsidy will gradually phase out.
- **Technology costs:** In REPO, technology costs consist of installed cost, and operation and maintenance costs (as detailed in Table 1). The technologies in REPO can be grouped into coal, natural gas, nuclear, biomass, hydro, wind and solar. Technology cost assumptions were based on several sources, including CEC data,[39] Cost of Electric Power Projects,[40] World Energy Outlook 2021,[41] China Power System Transformation4 and a National Renewable Energy Laboratory (NREL) study.[43] The operation and maintenance (O&M) costs for different technologies were adopted from the NREL report.[44] This study made the assumption that carbon capture and storage (CCS) technology allows for the capture of 92% of plant emissions. Efficiency loss of CCS-equipped plants was also considered.

Table 1: Cost assumptions for key technologies

	Capital costs			Variable O&M costs	Fixed O&M costs
	(CNY/W)			(CNY/MWh)	(CNY/kW-yr)
	2020	2035	2060	2020	2020
Coal	3.6	3.6	3.6	31	214
Coal with CCS	23.6	11.0	9.4	58	349
Gas	2.6	2.5	2.5	23	96
Gas with CCS	14.8	9.5	7.6	46	224
Biomass	10.8	10.8	10.8	35	712
Biomass with CCS	27.0	18.2	13.0	68	1052
Nuclear	15.6	15.0	15.0	14	629
Hydro	10	10	10	0	203-268
Wind onshore	7.0	4.4	4.2	0	170
Wind offshore	15.0	6.4	6.0	0	515
Solar PV	5.1	3.0	2.7	0	95
CSP	39.2	25.4	20.4	27	438
Pumped hydro	0.5	0.5	0.5	1	4.5
Battery	1.5	1.0	0.9	14	25
Compressed air	0.33	0.28	0.26	20	1.5

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[39] CEC, China Electricity Industry Development Annual Report 2016. 2016, Beijing.

[40] Electric Power Planning and Engineering Institute, China Renewable Energy Engineering Institute, Cost of Electric Power Projects during 12th Five Year Period. 2017, Beijing.

[41] IEA (International Energy Agency), World Energy Outlook 2021. 2021, Paris.l

[42] IEA, China Power System Transformation. 2019, Paris.l

[43] NREL, 2016 Annual Technology Baseline. 2016. https://data.nrel.gov/submissions/52

[44] NREL, 2016 Annual Technology Baseline. 2016. https://data.nrel.gov/submissions/52

Cost assumptions for transmission lines included installation and O&M costs. Set costs for constructing transmission lines between two regions included those related to capacity (CNY 1.5m per MW) and distance (CNY 1,000 per MW•km). O&M costs for transmission lines were set at 3% of the cost of installation.

- **Price of fuels:** There are four types of fuel in REPO: coal, natural gas, biomass and nuclear. In REPO, the price of fuels differs in each province. The regional coal prices for 2020 were based on data from the China Coal Transportation and Distribution Association, in which Xinjiang and Inner Mongolia had the lowest price. The regional gas prices for 2020 were based on the gate price for gas in China and on the IEA New Policies Scenario (NPS) full flex case in China Power System Transformation,[45] in which Xinjiang and Qinghai had the lowest gas price. As shown in Table 2, average annual fuel price growth followed the World Energy Outlook (WEO) STEPS[46] before 2035 and keep constant afterwards. The fuel price of biomass and nuclear are set at CNY 50/GJ and CNY 5.7/GJ respectively.
- **Fuel emission factor:** The model applied an average fuel factor for coal of 95kg CO2/GJ and 56.8kg CO2/GJ for gas for the analysed period, following IPCC's guidelines.[47]

Table 2: Average fuel price in China (CNY/GJ)

	2020	2025	2030	2035	2040	2045	2050	2055	2060
Coal	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.2
Gas	69.3	74.3	74.3	75.3	75.3	75.3	75.3	75.3	75.3

Scenario design

The REPO scenario presented here reflects China's ambitions of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. The parameters essential for simulating this scenario, including power demand, carbon prices and others, are sourced from C-GEM.

Under China's carbon neutrality goal, along with the growth in the national economy and the promotion of electricity substitution in industries and residential life, China's electrification rate (i.e. share of electrification in end-use energy consumption) would increase from less than 30% in 2020 to about 75% by 2060, and electricity consumption will continue to grow, from approximately 7500 TWh in 2020 to 15000 TWh in 2060.[48] At the same time, a carbon price was also needed to drive the decarbonisation. In this scenario, the electricity demand and carbon price assumptions are set as in Table 3.

Table 3: Electricity demand and carbon price assumptions

	2020	2025	2030	2035	2040	2045	2050	2055	2060
Electricity demand (TWh)	7521	9414	10881	12268	13042	13740	14392	14792	15003
Carbon price (yuan/ton CO2)	58	68	104	178	287	435	751	1363	2732

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[45] IEA, China Power System Transformation. 2019, Paris.

[46] IEA, World Energy Outlook 2021. 2021, Paris.

[47] Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2006. https://www.ipcc.ch/report/2006-ipcc-guidelinesfor-national-greenhouse-gas-inventories/

[48] Zhang, X. et al., Research on the Pathway and Policies for China's Energy and Economy Transformation toward Carbon Neutrality, Journal of Management World. 2022,38(01),35-66. https://www.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2022&filename=GLSJ202201003&uniplatform=OVERSEA&v=_fG3sk79BwBKwfDbeV6jJscnzbv1b24KvaGLYg19AiPkvCHxkbvcMGPNVtXZfsah

2.2. The E3ME-FTT:Power model

Description of E3ME

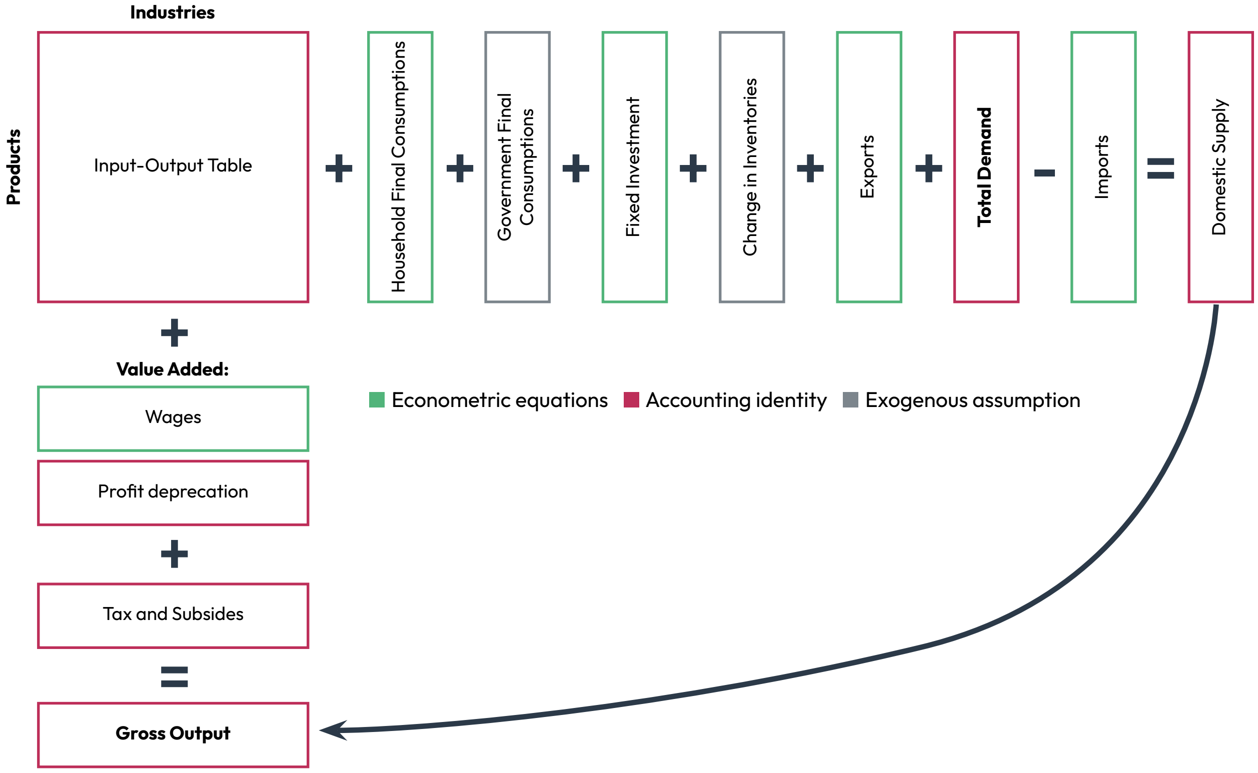
E3ME is a computer-based model of the world's economic and energy systems and the environment. Economic activity undertaken by individuals, households, organisations and other sections of society has effects on other groups (possibly after a time lag) and the effects may persist into future generations. But there are many actors, and the effects – both beneficial and damaging – accumulate in economic and physical stocks. A detailed description can be found online.[49]

The effects of economic transactions by economic agents are transmitted through the environment, the economy and the price and money system (via the markets for labour and commodities), and through global transport and information networks. The markets transmit effects in three main ways: through the level of activity creating demand for inputs of material, fuel and labour; through wages and prices affecting incomes; and through incomes leading in turn to further demands for goods and services. These interdependencies suggest that an E3 model should be comprehensive and include many linkages between different parts of the economic and energy systems – hence why E3ME was designed with a high geographical and sectoral resolution.

E3ME-FTT:Power is a global model of 71 regions with major economies represented individually and distinguishes 70 economic sectors in European countries and 43 in non-European countries. E3ME is a demand-led macro-econometric model. It determines the components of demand using time-series econometrics to solve components of final demand and various other indicators. See Figure 6. The econometric parameters represent past and current behaviour in response to shocks.

The energy domain is also determined by econometric relationships and builds on some of the accounting identities displayed above, but also includes responses to endogenous innovation and energy prices. The wholesale part of non-renewable energy prices is formed via a cost-supply curve approach which integrates an uncertainty parameter. Tax brackets are then added on top of that.

Figure 6: National accounts structure of E3ME



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[49] Cambridge Econometrics (2022). E3ME Model Manual. Available at: https://www.e3me.com/what/e3me/

The role of technology in the E3ME-FTT:Power model

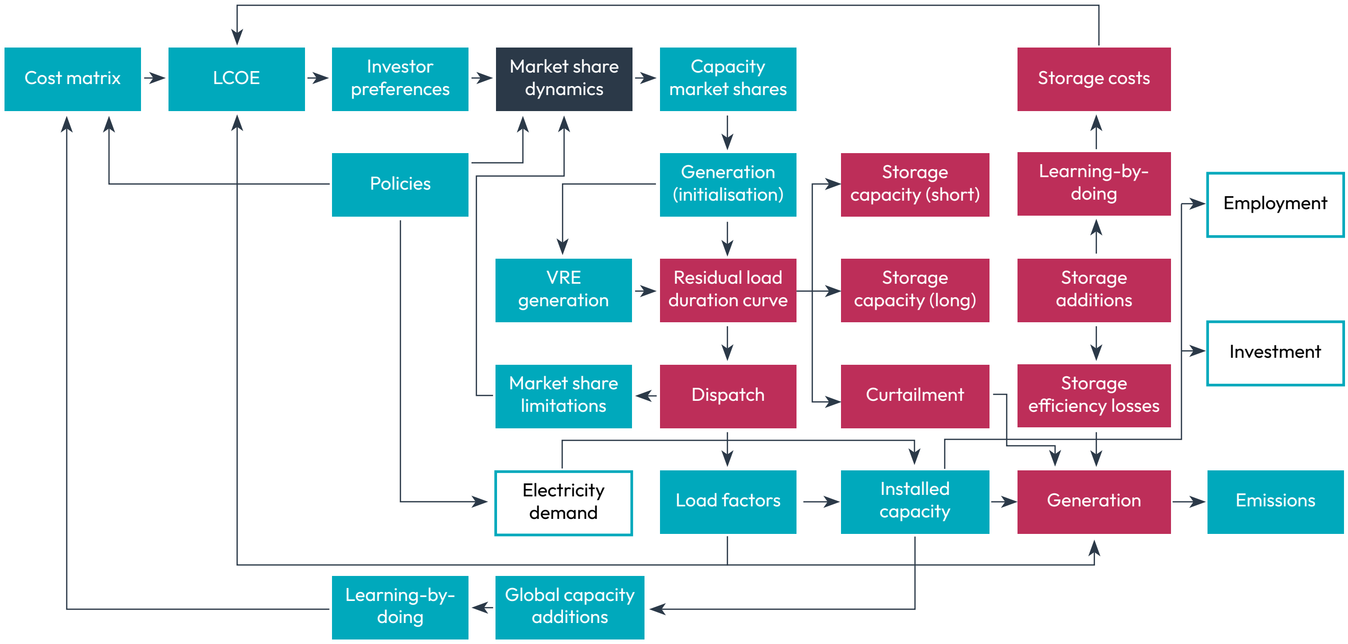
Understanding why and how economic agents pick technologies is important in questions surrounding decarbonisation of the economy. Time series econometric equations require a long track history in order to simulate the future. For novel technologies, such history does not exist and therefore econometric equations are not entirely suitable to address technology-induced transitions. This is where Future Technology Transformations (FTT) comes into play. FTT is a suite of models integrated with E3ME that describes technology decision making in the most emission- and energy-intensive industries, such as power generation,[50] iron and steel,[51] household heating[52] and passenger vehicles.[53]

FTT:Power follows evolutionary economics which dictates that socio-technical regimes (why something is done the way it is done) change due to internal (e.g. innovation) and external (e.g. shortages or policies) pressures, and such change is often irreversible and non-marginal. FTT:Power incorporates uncertainty in its input parameters which represents the heterogeneous character of economic agents as well as fundamental uncertainty.

FTT:Power determines the technology configuration to meet the demand which is determined elsewhere in E3ME-FTT. The core builds on the Lotka-Volterra replicator function, which compares all technologies on a pair-wise basis and takes investor preferences (determined as a binary logit), technology substitution frequencies and market shares of the previous year as inputs to determine market shares of the current year.[54] It includes positive feedback such as learning-by-doing based on global cumulative technology capacity additions, and negative feedback due to sectoral constraints such as VRE deployment in the power sector leading to supply-demand mismatches, or scrap availability being limited for recycling in the iron and steel sector.

Figure 7 illustrates the FTT:Power diagram, depicting the model's input flows and corresponding outcomes. One of the key elements of the FTT:Power model is the Levelised Cost of Electricity (LCOE). Within the model, LCOEs serve to construct binary logits, which effectively capture investor preferences for one technology over another. These preferences, when coupled with technology substitution rates – owing to differing lifespans of technologies – are integrated into logistic equations to simulate market dynamics within the power sector.

Figure 7: FTT:Power model logic (Blue: core of the model; Pink: the dispatching and storage side of the model; Grey: connection points to E3ME)



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[50] Mercure, J. F. (2012). FTT: Power: A global model of the power sector with induced technological change and natural resource depletion. Energy Policy 48: 799-811.

[51] Vercoulen, P. et al. (2018). Decarbonizing the East Asian steel industry in 2050. Meijo University Discussion Paper #0008.

[52] Knobloch, F. et al. (2021). FTT: Heat - A Simulation Model for Technological Change in the European Residential Heating Sector. Energy Policy 153: 112249

[53] Lam, A., and Mercure, J-F. (2015). The Effectiveness of Policy on Consumer Choices for Private Road Passenger Transport Emissions Reductions in Six Major Economies. Environmental Research Letters, 10(6): 064008

[54] Mercure, J-F. (2015). An Age Structured Demographic Theory of Technological Change. Journal of Evolutionary Economics, 25(4): 787-820.

It's notable that policies are not mere bystanders in the FTT:Power model; they exert a tangible influence on either the cost matrix or more directly via government procurement or regulations on the market share dynamics. These dynamics, in turn, dictate the allocation of capacity share and the generation of various technologies.

A core component of the FTT:Power model is residual load-duration curves (RLDCs). These curves delineate the frequency and duration for which generators must operate, once VRE generation has been factored in. Employing a third-degree polynomial, the model uses the generation shares of solar PV and wind power to yield a range of outputs, including six load band (LB) heights (baseload, lower mid-load, upper mid-load, peak-load and spare capacity load), storage capacity, storage costs, and curtailment.[55]

Furthermore, to ensure grid flexibility and reliability, the model uses a dispatching routine to mimic the dispatch of flexible capacity, thereby obtaining dynamic load factors for dispatchable generators.[56] In practise, when renewable capacity is high, fossil fuel plants need to run more flexibly, which reduces their capacity factor. Given that each technology has a minimum operational load factor, this informs decisions on installed capacity. Upon this foundation, the installed capacity determines generation mix. Consequently, this allows for the forecasting of employment, investment, and emissions.

The FTT:Power model also estimates short-term and long-term electricity storage capacities. Short-term storage is a direct output of the RLDCs, while long-term storage is estimated based on the disparity between residual peak load and firm power generation capacity. Based on the system configuration, the model obtains estimates for both short-term and long-term storage costs, which feed into the LCOE calculations. Notably, 'learning-by-doing' also takes place for storage costs, based on historical estimates for lithium-ion and vanadium-flow batteries (short-term storage) and hydrogen (long-term storage).

How does E3ME differ from other models?

E3ME is often compared to Computable General Equilibrium (CGE) or Dynamic Stochastic General Equilibrium (DSGE) models.[57] [58] In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, underlying this are important theoretical differences between their approaches. Models like E3ME build upon data and try to infer economic relationships from that. Most other macroeconomic or integrated assessment models (IAMs) try to build upon micro foundations and theory.

In a typical CGE or DSGE framework, optimising behaviour is assumed, output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used. In E3ME, the determination of output comes from the demand side of the economy and it is possible to have spare economic capacity. It is not assumed that prices always adjust to market-clearing levels.

The differences have important practical implications, because they mean that, in E3ME, regulation and other policies could potentially lead to increases in output, if they are able to draw upon the available spare economic capacity. The role of the financial sector is key.

The role of finance

E3ME is a Post-Keynesian model and within this school of thought money is endogenous – i.e. it can be created by banks through, for example, lending. This approach differs from that in many other models where the supply of money is fixed.[59] A fixed supply of money implies full crowding-out; endogenous supply of money does not, per se. E3ME is therefore agnostic on finance. The model tracks the investment needs of a given sector as a result of the econometric relationships or the FTT:Power outcomes, but it does not provide information on whether the demanded finance is accessible.

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[55] Yeliz Simsek, et al. (2023). FTT:Power 2.0: A global simulation model of power technology diffusion with learning-by-doing and renewables integration.

[56] Yeliz Simsek, et al. (2023). FTT:Power 2.0: A global simulation model of power technology diffusion with learning-by-doing and renewables integration.

[57] Mercure, J-F., et al. (2019). Modelling Innovation and the Macroeconomics of Low-Carbon Transitions: Theory, Perspectives and Practical Use. Climate Policy 19(8): 1019-1037.

[58] Lefevre, J., et al. (2022). Global Socio-Economic and Climate Change Mitigation Scenarios Through the Lens of Structural Change. Global Environmental Change 74: 102510.

[59] Mercure, J-F and Pollitt, H. (2018). The Role of Money and the Financial Sector in Energy-Economy Models used for Assessing Climate and Energy Policy. Climate Policy 18(2): 184-197.

Key assumptions

Below are some of the key assumptions made before designing scenarios.

- Electricity demand: Electricity demand follows from the energy domain of E3ME. It follows from a two-step approach. First, total energy demand is estimated based on the average energy price, economic activity, R&D and investment. Second, energy demand by individual energy carrier – including electricity – is estimated based on total energy demand, and the energy price relative to the average. The rationale is that total energy demand is likely more stable than the demand of individual components. It also allows for some substitutability between energy carriers.[60] Energy demand for passenger road transport, residential heating, steelmaking and power generation are solved by the respective FTT models.
- Load profile and renewable electricity supply profile: Load profiles are represented through parameterised residual load-duration curves (RLDC), which were originally developed for the REMIND model.[61] The RLDC takes the share of wind and solar in the generation profile as input and determines what that means in terms of curtailment, short-term storage needs, and five load band heights. The load band heights determine how much capacity is needed and for how long it has to run to meet demand. Then, long-term storage needs are based on the difference between peak demand estimates and firm capacity available in the system. Storage follows from VRE generation and it feeds back cost consequences, net curtailment effects on VRE profitability, and additional generation needed to cover round-trip efficiency losses due to storage.
- Existing generators and decommission plan: The historical generation profile is based on IEA's World Energy Balances. Due to the lack of publicly available sources on power generation capacities on a global scale, capacities are estimated via load factors estimates based on the above described RLDC framework and dispatching. Decommissioning of vintage capacity is included in the substitution frequencies and used within the market share dynamics.
- Existing transmission capacity: In the current formulation of FTT:Power the geographical resolution of the Chinese grid is coarse; it solves for the whole country rather than per region. Additionally, it is assumed that transmission and distribution co-evolve with the needs of the grid.
- Dispatch rules: The RLDC framework provides information on when firm capacity is required to meet demand.
- Renewable energy subsidy: The baseline of FTT:Power does not include information on specific policies currently in place. Instead, FTT:Power is calibrated to reflect current policies by aligning the market share increments of the last few years of history to the market share increments of the first few years of simulation. The LCOE estimates that dictate decision making are adjusted until alignment is found. Any policy applied is therefore implicitly added on top of or removed from the policies currently in place.
- Technology costs: FTT:Power requires similar technology cost inputs as the REPO model. Conversion efficiencies, O&M and investment cost factors are obtained from the IEA.[62] Technology learning rates are obtained from BNEF[63] and applied to investment cost factors. Finally, fuel costs are estimated using cost-supply curves in combination with tax brackets and conversion efficiencies.[64] In FTT:Power it is assumed that CCS captures 90% of the emissions at the cost of efficiency losses.
- Energy (resource) prices: In E3ME-FTT, cost-supply curves are used to estimate the wholesale prices of 12 energy resources. This includes four non-renewables – fissile material, coal, oil, and gas – and six renewable energy resources based on the potentials of hydro, geothermal, tidal, onshore wind, offshore wind and solar.[65] Renewable energy resources can affect the LCOE

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[60] Cambridge Econometrics (2022). E3ME Model Manual. Available at: https://www.e3me.com/what/e3me/

[61] Ueckerdt, F., Brecha, R., & Luderer, G. (2015). Analyzing major challenges of wind and solar variability in power systems. Renewable energy, 81, 1-10.

[62] IEA, Projected Costs of Generation Electricity. 2022. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

[63] BloombergNEF. 2H 2020 LCOE Data Viewer (2021).

[64] Mercure, Jean-François, and Pablo Salas. "On the global economic potentials and marginal costs of non-renewable resources and the price of energy commodities." Energy Policy 63 (2013): 469-483.

[65] Mercure, J. F., & Salas, P. (2012). An assessment of global energy resource economic potentials. Energy, 46(1), 322-336.

[66] Intergovernmental Panel on Climate Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2006. https://www.ipcc.ch/report/2006-ipcc-guidelinesfor-national-greenhouse-gas-inventories/

of relevant technologies via different mechanisms. It is expected that the next unit of geothermal or hydropower will have to be built in less convenient places, i.e. the need to drill deeper holes or build a hydropower dam in a less-accessible part of a river, which is represented as an increase in investment costs. Building the next wind turbine or solar PV installation will likely occur in a less windy or less sunny location than the previous unit. This effect is represented as a decrease of the load factor. In turn, electricity prices are estimated by FTT:Power.

- Fuel emission factor: Like REPO, emission factors by fuel are based on IPCC guidelines.[66]

Table 4: Cost assumptions for key technologies

	Initial capital costs	Initial fuel costs	O&M costs	Learning exponent	Electrical conversion efficiency
	$(2013)/kW	$(2013)/MWh	$(2013)/MWh	%	%
Nuclear	2428	10	13	-8.6	100
Oil	416	224	22	-1.4	45
Coal	777	26	15	-4.4	42
Coal + CCS	5010	22	26	-7.4	37
IGCC	1297	20	10	-4.4	42
IGCC + CCS	8367	20	7	-7.4	37
CCGT	544	66	14	-5.9	57
CCGT + CCS	2543	71	13	-7.4	47
Solid Biomass	3435	93	18	-7.4	42
S Biomass CCS	5092	93	19	-10.5	37
BIGCC	3283	93	10	-7.4	42
BIGCC + CCS	3876	93	13	-10.5	37
Biogas	3200	0	61	-7.4	57
Biogas + CCS	4383	0	61	-10.5	47
Tidal	2702	0	38	-2.0	100
Large Hydro	3348	0	14	-2.0	100
Onshore	1140	0	16	-19.4	100
Offshore	2199	0	21	-19.4	100
Solar PV	709	0	12	-31.9	100
CSP	5987	0	14	-19.4	20
Geothermal	6700	0	21	-7.4	100
Wave	4993	0	56	-21.8	100
Fuel Cells	4439	500	30	-23.4	80
CHP	1942	66	38	-4.4	80

E3ME-FTT:Power Scenario design

The changing landscape of power generation in China

The power generation landscape in China is undergoing a significant transformation. While coal has been the dominant power generation technology,[67] there is now rapid deployment of Variable Renewable Energy (VRE) technologies like solar and wind power. Over the last couple of years, VRE technologies have been deployed at a staggering rate globally, with China recently taking the lead in the deployment of offshore wind turbines. Between 2018 and 2021, solar PV and onshore wind power also nearly doubled in capacity in China.

As the costs of renewables continue to decline, as evidenced over the past decade, it is likely that the trend of VRE deployment will not only continue but possibly accelerate, especially given that these technologies are now outcompeting conventional technologies in terms of the LCOE in most regions of the world. However, on top of insufficient grid resilience, access to finance, lagging supply chains and resistance from declining industries,[68] another hurdle to VRE uptake could be how electricity markets are designed.

Pricing mechanisms: The Merit Order Approach (MOA) vs Weighted Average Levelised Cost (WALC)

In many liberalised markets, electricity prices are determined by the marginal costs of production, also known as marginal pricing or the 'Merit Order Approach' (MOA). Marginal pricing is effective in markets primarily powered by fossil fuels, where costs are mainly driven by fuel purchases.

However, VRE technologies, unlike fossil-fuel based ones, incur most costs upfront in capital investments (known as CAPEX). As VRE uptake rises, marginal pricing could result in VRE operators facing losses, especially on days with high wind or solar availability when their marginal costs are nearly zero, thereby setting the electricity price. With more renewable energy, this scenario could become more frequent, indicating marginal pricing might be unsuitable in a VRE-dominated future. Conversely, high fossil fuel prices could lead to windfall profits for VRE companies.

In contrast to MOA, some markets (such as India) rely on long-term contracts tied to the LCOE. Despite being less flexible than a day-ahead market, this approach of long-term contracts offers a pricing mechanism that doesn't suffer from the disadvantages of MOA, particularly in a VRE-heavy grid.

Generally speaking, the Chinese electricity market is dominated by mid-long-term transactions, with a minimal share in spot markets. Unlike India, in China, prices in the mid-long-term transactions consider power generation companies' profits. Therefore, the prices tend to be higher than just LCOE. MOA occurs in Chinese spot markets. However, in reality the clearing price under it is not necessarily always equal to marginal costs.

Exploring future scenarios for China

As VRE technologies continue to grow, there is an urgent need to reconsider existing market designs and pricing mechanisms, as well as different power generation technology mixes. To address this need, the E3ME-FTT:Power model explores various future scenarios for China's power system. These include scenarios where fossil fuel use remains high (HighFF) and others where VRE uptake is accelerated (HighVRE). We also examine the impact of different pricing mechanisms on these scenarios.

Specifically, the model looks at a technology diffusion scenario where VRE uptake is met by additional resistance beyond what current trajectories suggest and as a result fossil fuel use is higher (HighFF), and a set of technology diffusion scenarios where VRE could potentially be sped up by putting a cap on fossil fuel investments (HighVRE).

Finally, each scenario is exposed to two different pricing mechanisms: one that mimics MOA (as often is seen in liberalised markets); and the other a paradigm where electricity prices are formed as the weighted average levelised cost [of generation] (WALC) which serves as an indicative alternative pricing mechanism that builds upon lifetime costs rather than short-run marginal costs. FTT:Power accounts for the cost of storage and the effect of curtailment on the LCOE. See Table 5 for an overview of the scenarios.

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[67] IEA. (2019). World Energy Balances 2019. www.iea.org/statistics/

[68] Nijsse, F. J. M. M., et al. (2022). Is a Solar Future Inevitable? Global Systems Institute Working paper series number 2022/02. https://eeist.co.uk/journalpapers/

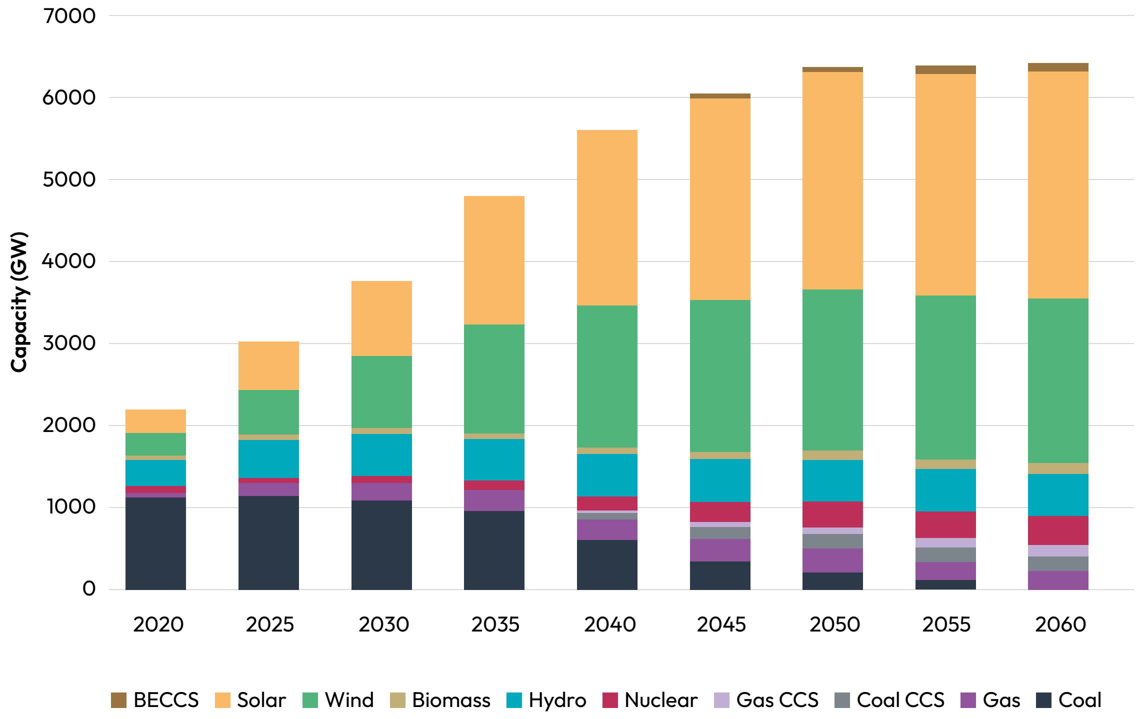
Table 5: Scenarios focused on the power systems in China using E3ME-FTT:Power

Scenario name	Diffusion assumption	Market design
REF-MOA	Diffusion of technologies follows its current trajectory	10
HighFF-MOA	Greater barriers to VRE uptake, expressed as reduced diffusion rates for VRE technologies	224
HighVRE-MOA	Fewer barriers to VRE uptake, expressed by a maximum capacity cap on FF technologies	26
REF-WALC	Diffusion of technologies follows its current trajectory	22
HighFF-WALC	Greater barriers to VRE uptake, expressed as reduced diffusion rates for VRE technologies	20
HighVRE-WALC	Fewer barriers to VRE uptake, expressed by a maximum capacity cap on FF technologies	20

2.3. REPO results – imagining a pathway for China's power sector

As described above, REPO has designed a carbon neutrality scenario and modelled renewable development, future CO2 emissions, and involvement of ETS in China's power system. Below are the results regarding power generation mix shift and corresponding CO2 emissions, and the role of storage in China's power system.

Figure 8: Power generation capacity in REPO for 2020-2060



Power capacity and generation

Total installed capacity

According to the REPO model, China's total installed power capacity is projected to increase from approximately 2,200 GW in 2020 to 3,750 GW by 2030, 4,800 GW by 2035, and further to 6,350 GW by 2050. Post-2050, the model anticipates a slowdown in growth, reaching about 6,400 GW by 2060 (See Figure 8).

Fossil fuel-based power capacity

The model suggest varying trends for different fossil fuel technologies:

- Coal-fired Power without CCS: A slight increase is expected until 2025, peaking at around 1,150 GW, followed by a gradual decline, to about 1100 GW by 2030, and then to about 970 GW by 2035, to about 200 GW by 2050, eventually phasing out by 2060.
- Gas-fired Power without CCS: The model foresees an initial increase, growing from about 100 GW in 2020 to 215 GW in 2030, to 235 GW in 2035, peaking at 300 GW in 2050, before declining to 240 GW by 2060.

Non-fossil fuel power capacity

The REPO model suggests a steady growth in non-fossil fuel power generation technologies. Nuclear, Hydropower, and Biomass: These are expected to see consistent growth, with specific numbers outlined in the model.

- The installed capacity of nuclear power increased from about 50 GW in 2020 to 93 GW in 2030, further increasing to 117 GW in 2035, 305 GW in 2050, and finally 350 GW in 2060.
- The installed capacity of hydropower increased from about 370 GW in 2020 to about 500

GW in 2030. Then the development speed of hydropower will slow down, and the installed capacity of hydropower will increase to about 530 GW by 2060.

- The installed capacity of biomass power generation will steadily increase, from 30 GW in 2020 to 50 GW in 2030, further increasing to 57 GW in 2035, reaching 100 GW in 2050, and further increasing to 120 GW in 2060.

According to the model, wind and solar power will be the main drivers of future installed capacity growth, with specific projections for each.

- The installed capacity of wind power will increase from 290 GW in 2020 to about 890 GW in 2030, to 1340 GW in 2035, and to about 1970 GW in 2050. Subsequently, the growth of installed capacity of wind power will slow down, with its capacity increasing to about 2000 GW in 2060.
- The installed capacity of solar power will increase from about 250 GW in 2020 to about 900 GW in 2030, to 1550 GW in 2035, and to about 2640 GW in 2050. Subsequently, the growth of installed capacity will also slow down, with its capacity increasing to about 2750 GW in 2060.

Carbon capture technologies

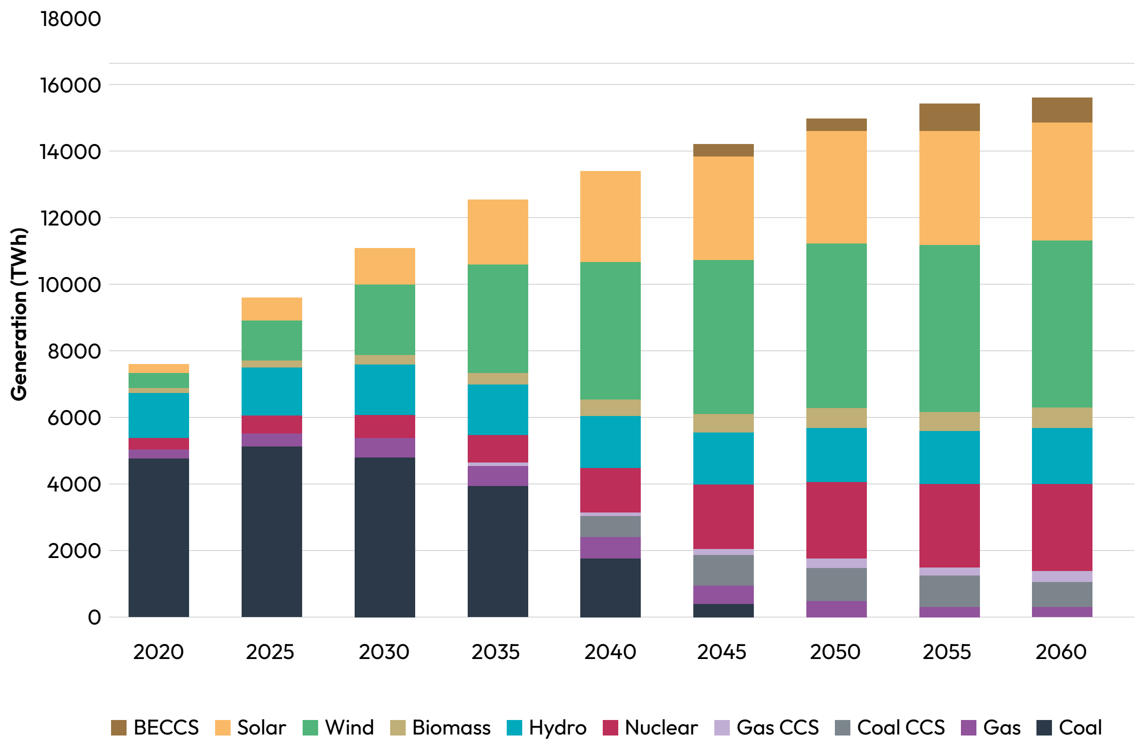
The model suggests that CCS technology will start being applied from 2035, with BECCS technology becoming prominent post-2045.

- CCS technology will be gradually applied from 2035, with a total installed capacity of approximately 10 GW for coal-fired and gas-fired power equipped CCS in 2035. This capacity will increase to about 250 GW by 2050, and further increase to about 300 GW by 2060.
- Biomass with CCS (BECCS) technology will be widely applied from 2045, with an installed capacity of 50 GW. By 2060, the installed capacity of BECCS will exceed 100 GW.

Decarbonisation trends

The REPO model suggests that China's power system can undergo significant decarbonisation, with the share of non-fossil fuel power in total installed capacity expected to exceed 90% by 2060. Wind and solar power capacity will become the mainstay of China's future power system installed capacity, reaching nearly 75% by 2060.

Figure 9: Electricity generation in 2020-2060



Electricity generation from fossil fuels

According to the REPO's results (Figure 9), coal-fired electricity generation is projected to peak at approximately 5100 TWh around 2025 before gradually decreasing. Similarly, the model forecasts that electricity generation from gas-fired units will follow a trend of first increasing and then decreasing.

- coal-fired power generation will peak at approximately 5100 TWh around 2025, gradually decreasing to about 4750 TWh by 2030 and further decreasing to about 3800 TWh by 2035. After 2050, the power generation from coal-fired power units without CCS can be basically ignored.
- According to the REPO's results, the peak time of electricity generation by gas is later than that of coal-fired power. The electricity generation from gas-fired power units will increase to about 600 TWh by 2030, and further increase to about 700 TWh by 2035. Subsequently, the electricity generation capacity will gradually decline, dropping back to 430 TWh by 2050 and further decreasing to 250 TWh by 2060.

Electricity generation from nuclear, hydropower, and biomass

The model also predicts a different trajectory for nuclear and hydropower energy sources.

- Electricity generated from nuclear power will increase from 366 TWh in 2020 to 710 TWh in 2030, further to 890 TWh in 2035, to 2300 TWh in 2050, and to 2640 TWh in 2060. The proportion of nuclear power in total electricity generation will gradually increase from 5% in 2020 to 17% in 2060.
- Hydropower generation will continue to increase in the future, increasing from 1355 TWh in 2020 to 1650 TWh in 2060. However, the proportion of hydropower in total electricity generation will continue to decline, gradually decreasing from 18% in 2020 to only 11% in 2060.
- The biomass electricity generation will gradually increase from 136 TWh in 2020 to 236 TWh in 2030, and further increase to 590 TWh in 2060. However, the proportion of biomass power generation in total electricity generation will be relatively limited, with only 4% by 2060.

Electricity generation from wind and solar

Wind and solar power are highlighted in the model as the main drivers of non-fossil fuel generation growth, particularly before 2040. Their rapid expansion will make them increasingly important in China's future electricity supply.

- According to the REPO's results, wind electricity generation will increase from 490 TWh in 2020 to 2140 TWh in 2030, further increasing to 3260 TWh in 2035, and 4950 TWh in 2050. After 2050, the growth of wind electricity generation will be significantly slower, and it will increase to 5050 TWh in 2060.
- Solar electricity generation will increase from 261 TWh in 2020 to 1100 TWh in 2030, further increase to 1930 TWh in 2035, and increase to 3400 TWh in 2050. After 2050, the growth of solar power generation will also be significantly slower, increasing to 3540 TWh in 2060.
- The proportion of wind and solar power in total electricity generation will increase from 9% in 2020 to about 30% in 2030, and exceed 40% by 2035. After 2040, this proportion will exceed 50%, and wind and solar electricity will become the absolute mainstay of China's electricity supply.

Units equipped with carbon capture and storage

Generation units equipped with Carbon Capture and Storage (CCS) technology are also projected by the REPO to play an increasingly important role in electricity generation. The model anticipates that by 2050, these units will contribute significantly to the overall electricity generation, although their share will slightly decrease by 2060.

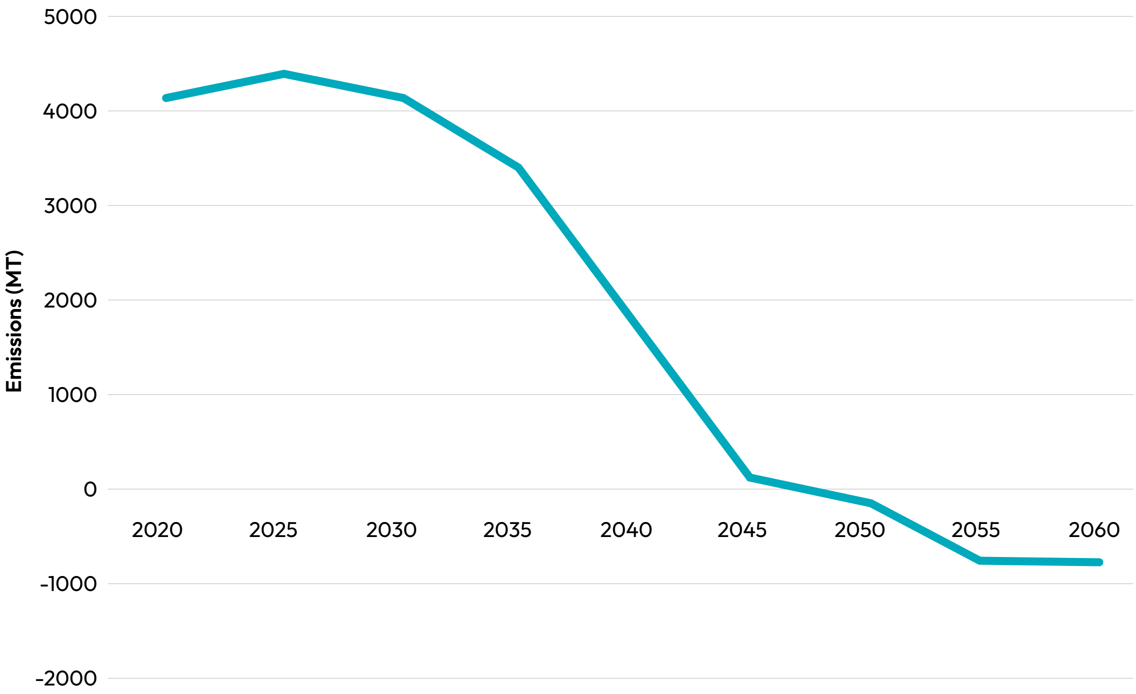
- Although coal- and gas-fired units with CCS equipped will be implemented in 2035, their electricity generation accounted for less than 1% at that time. Afterwards, the electricity generation of coal-fired and gas-fired units with CCS equipped will experience a trend of first increasing and then decreasing. By 2050, their total electricity generation will reach 1270 TWh, and will fall back to 1100 TWh by 2060. The proportion in the total electricity generation will also decrease from 9% in 2050 to 7% in 2060.
- Adding the electricity from gas-fired units without CCS, the electricity generated from fossil fuels will account for no more than 10% by 2060.
- For BECCS, its electricity generation will increase from 370 TWh in 2045 to 800 TWh in 2060, and the proportion of BECCS in total electricity generation will also increase to 5% by 2060.

Driving factors of the decarbonisation

Carbon emissions future trajectory

According to the REPO model, the carbon emissions trajectory for China's power sector is projected to peak around 2025 at approximately 4350 Mt (Figure 10). The model suggests a plateau period for total carbon emissions exceeding 4000 Mt until 2030, followed by a rapid decline post-2035, reaching near-zero levels by 2045. After 2050, with the further reduction of coal- and gas-fired power generation and the application of BECCS, the power sector will generally exhibit negative emissions, reaching a total carbon absorption of approximately 750 Mt by 2060.

Figure 10: CO_2 emission trajectory

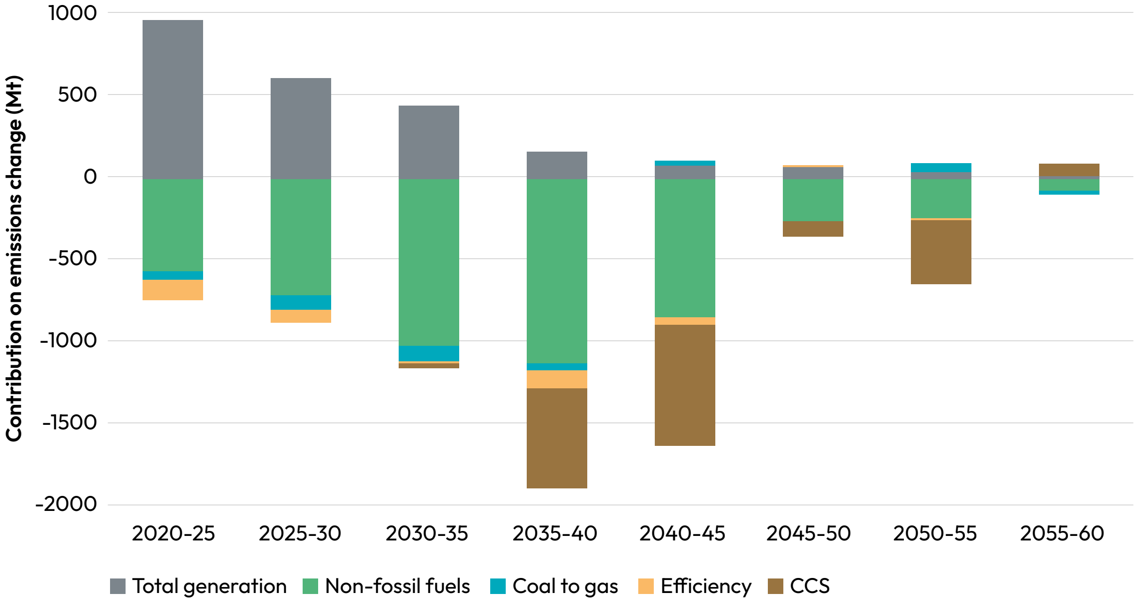


Contributing factors to emission reduction

The model also examines various contributing factors to these emission changes in China's power sector, including total electricity generation, non-fossil fuel adoption, coal-to-gas conversion, efficiency improvements, and the application of CCS technology (Figure 11).

- The model estimates that from 2020 to 2060, the increase in total electricity generation will bring about 2450 Mt of emission additions to the power sector. Non-fossil fuel adoption would bring 4930 Mt of emission reductions.
- Coal-to-gas conversion would bring 230 Mt of emission reductions.
- Efficiency improvements would bring 360 Mt of emission reductions.
- The application of CCS technology would bring 1800 Mt of emission reductions.

Figure 11: Contribution on emission change



Specifically, the model suggests that:

- The model shows that the total electricity generation would play a role in increasing carbon emissions in the power sector in the near term as it is expected to contribute approximately 1000 Mt of carbon emissions increase during 2020-2025. As the growth of future electricity demand slows down and the carbon emissions of the power sector decrease, the total electricity generation would have a limited impact post-2035. After 2035, the contribution of total electricity generation to the increase of carbon emissions in the power sector would not exceed 200 Mt in five years, and the contribution will be very limited after 2050.
- Efficiency improvements and coal-to-gas conversions would offer moderate emission reductions, a total of 100 Mt to 200 Mt every five years, until 2040.
- Non-fossil fuels will be the core driver for emission reductions, especially between 2035 and 2040. Non-fossil fuels will contribute about 570 Mt of emission reduction during the 2020-2025 period. With the further acceleration of non-fossil fuels development, the contribution of non-fossil fuels to the emission reduction of the power sector will further increase. Non-fossil fuels will contribute about 1150 Mt of emission reduction during the 2035-2040 period. After 2040, as the development of non-fossil fuels will gradually slow down, the contribution of non-fossil fuels to the emission reduction of the power sector will also decline.
- CCS technology will also contribute to reducing carbon emissions in the power sector as it will be applied post-2035, with its contribution exceeding 400 Mt until 2055. During the period from 2055 to 2060, the amount of CO2 captured by CCS will decrease, thus CCS technology will show an increasing effect on emissions.

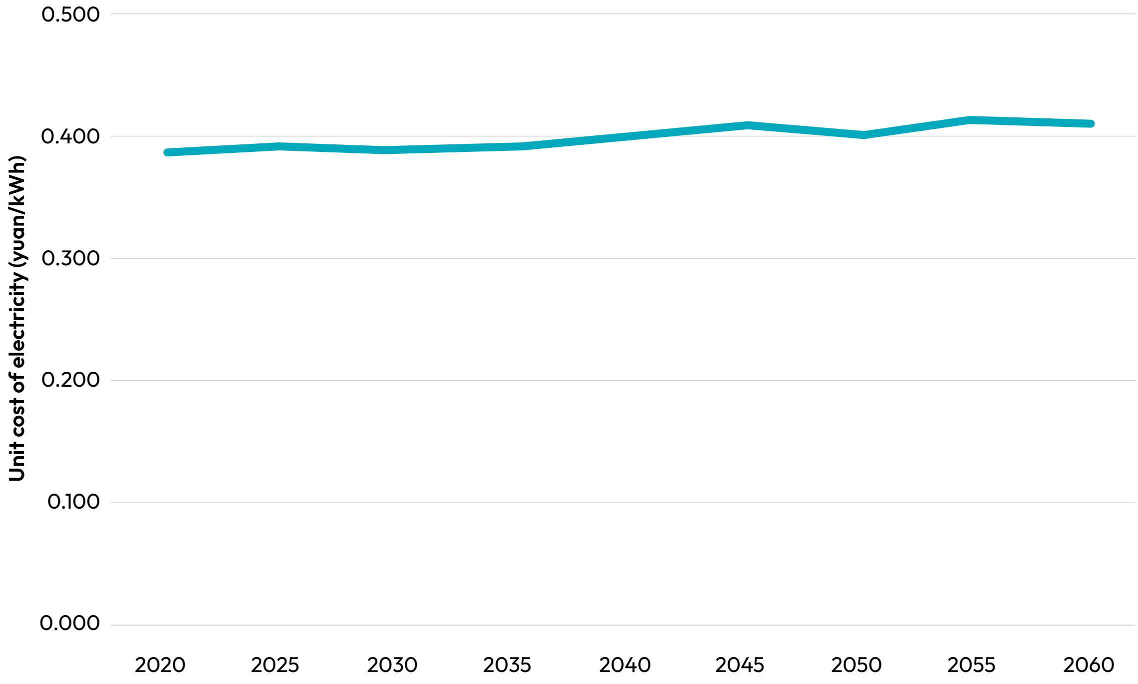
Electricity generation cost

According to the REPO model, the unit cost of electricity in China's power sector is projected to experience a gradual increase from 2020 to 2060 (Figure 12). The model estimates that by 2030, the unit cost will be 0.39 yuan/kWh, marking a 1% increase from 2020 levels. By 2050, the unit cost is expected to rise to 0.40 yuan/kWh, a 4% increase compared to 2020. Finally, by 2060, the model predicts a unit cost of 0.41 yuan/kWh, a 6% increase from 2020 levels.

The model also suggests that this cost increase is generally manageable for China's power sector. For renewable sources like wind and solar power, which are projected to become the main electricity suppliers in the long term, the capital costs are expected to significantly reduce. The generation cost of wind power and solar power per kilowatt hour will also be significantly lower than that of the traditional coal-fired power and gas-fired power. However, the model also indicates that due to the spatiotemporal mismatch between wind and solar power output and electricity demand, additional regulating facilities will be required. This is expected to result in an increase in system balance costs, which will offset the decrease in generation costs, leading to an overall increase in the unit cost of electricity.

The model also suggests that this cost increase is generally manageable for China's power sector. For renewable sources like wind and solar power, which are projected to become the main electricity suppliers in the long term, the capital costs are expected to significantly reduce. The generation cost of wind power and solar power per kilowatt hour will also be significantly lower than that of the traditional coal-fired power and gas-fired power. However, the model also indicates that due to the spatiotemporal mismatch between wind and solar power output and electricity demand, additional regulating facilities will be required. This is expected to result in an increase in system balance costs, which will offset the decrease in generation costs, leading to an overall increase in the unit cost of electricity.

Figure 12: Unit cost of electricity



The role of storage

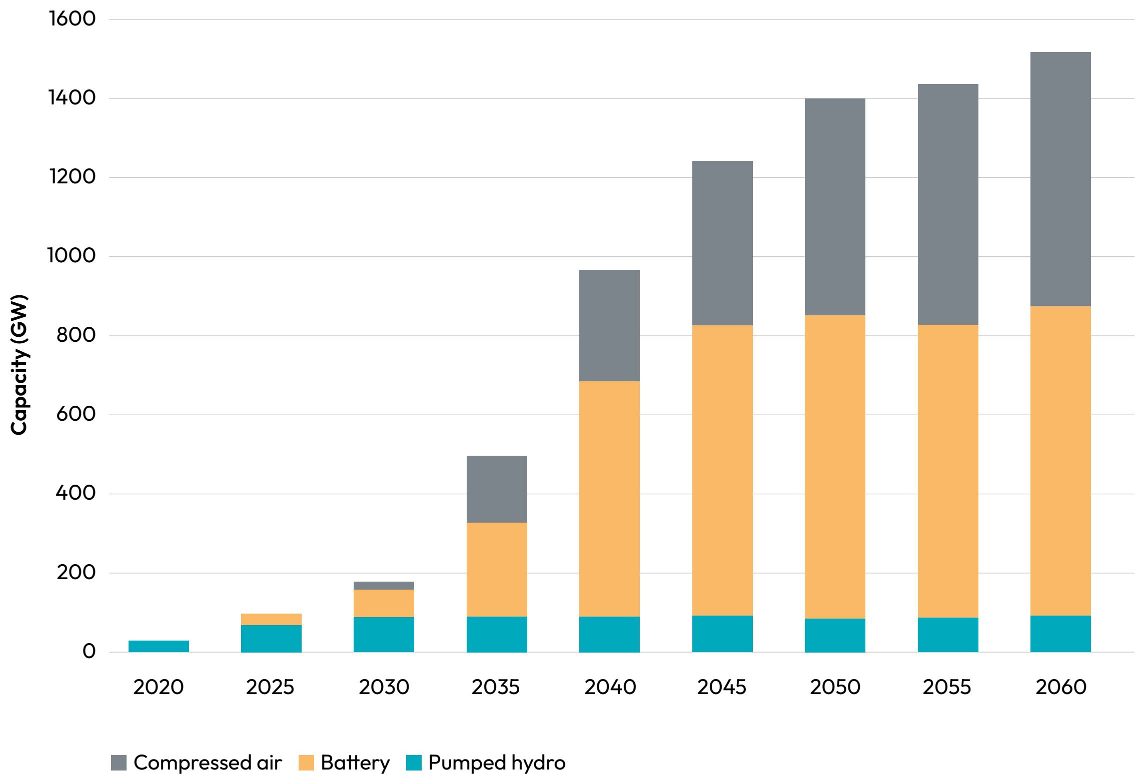
According to the REPO model, the future of energy storage in China's power sector is set for large-scale development (Figure 13). The model projects that:

- The installed capacity of energy storage will accelerate in the near term, particularly with the large-scale deployment of wind and solar power.
- Post-2040, as the growth of renewable energy slows, the model predicts a corresponding slowdown in the growth of energy storage capacity.
- After 2050, with the relatively stable power generation structure of China's power sector, the growth of energy storage installed capacity is relatively small.
- By 2060, the total installed capacity for energy storage is estimated to be around 1500 GW, approximately a quarter of the total installed power generation capacity projected for that year.

Specifically, the model suggests that:

- Pumped hydro storage technology will see a significant increase in the near term, growing from 32 GW in 2020 to 90 GW by 2030. However, its growth is expected to plateau post-2035 due to cost-competitiveness issues.
- Battery storage, benefiting from rapid cost reductions, is projected to reach an installed capacity of 70 GW by 2030 and 240 GW by 2035. Post-2045, the model estimates that battery storage capacity will stabilise around 750 GW in light of limited growth in wind and solar power capacity and power generation. The REPO model also indicates that battery storage would be used as daily electricity transfer and be more suitable for balancing daily wind and solar power generation with electricity demand because the battery storage has the characteristics of higher cycle efficiency and higher self-discharge rate.
- The model underscores the suitability of compressed air storage for inter-seasonal energy storage needs, attributing this to its low energy capacity cost and extended charging and discharging durations. As the proportion of conventional power sources is projected to decrease, the model anticipates a corresponding surge in the demand for cross-seasonal energy storage. This sets the stage for the large-scale deployment of compressed air storage systems, which are expected to commence in earnest by 2035. By that year, the installed capacity for this type of storage is projected to reach approximately 170 GW, and it is further expected to escalate to around 640 GW by 2060.

Figure 13: Storage capacity in 2020-2060



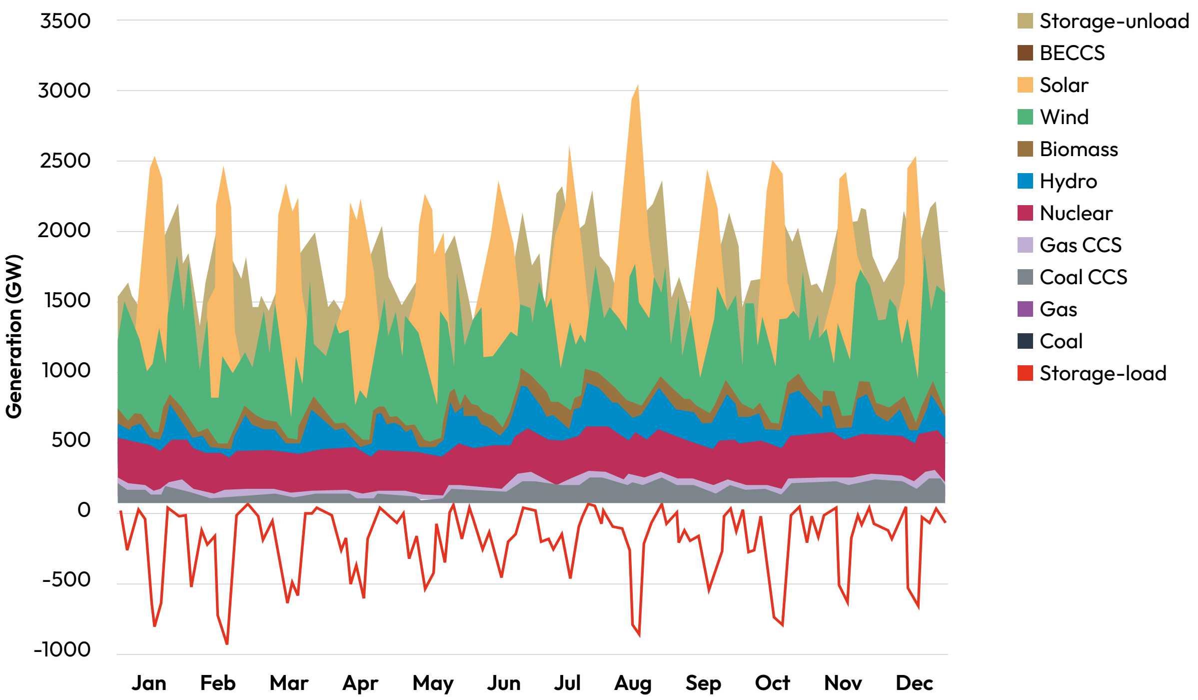
Role of storage in power balance

The REPO model's results of energy storage also provides insight for the role of storage in balancing China's power system in 2060. According to the model projections (Figure 14),

- Fossil fuel-based electricity generation is anticipated to be minimal throughout the year.
- Nuclear power is projected to serve as the system's base load, maintaining a stable output year-round.
- Wind and solar power will be the primary electricity suppliers, but there are differences in their output curves and electricity load fluctuations. For solar power generation, it has the characteristics of high output at noon and inability to output at night, which is significantly different from electricity load fluctuations.
- Hydropower is expected to play a significant regulatory role—generating less electricity during the day and more in the evening—it will not suffice to meet the peak demand requirements of China's 2060 power system.

In this context, the model underscores the critical role of energy storage in balancing electricity supply and demand. In the model, energy storage systems are projected to primarily store electricity at noon to balance the excess solar power generation during the day, and discharge it to the grid in the evening to balance the electricity shortage caused by the rapid decline in solar power generation. The model also indicates that the amplitude of energy storage charging and discharging will be greater during the winter and summer seasons compared to spring and autumn. Notably, the peak capacity for energy storage charging and discharging could exceed one-third of the total power generation at that time, emphasising the irreplaceable role of energy storage in maintaining power system balance.

Figure 14: Electricity balance in typical days in 2060



2.4. E3ME-FTT:Power results – the impact of different pricing approaches

The FTT:Power scenarios revolve around different pricing regimes in the power sector and different possible futures in terms of deployment of renewables. We now explore these scenarios in terms of outputs for power generation, electricity prices and macroeconomic impacts.

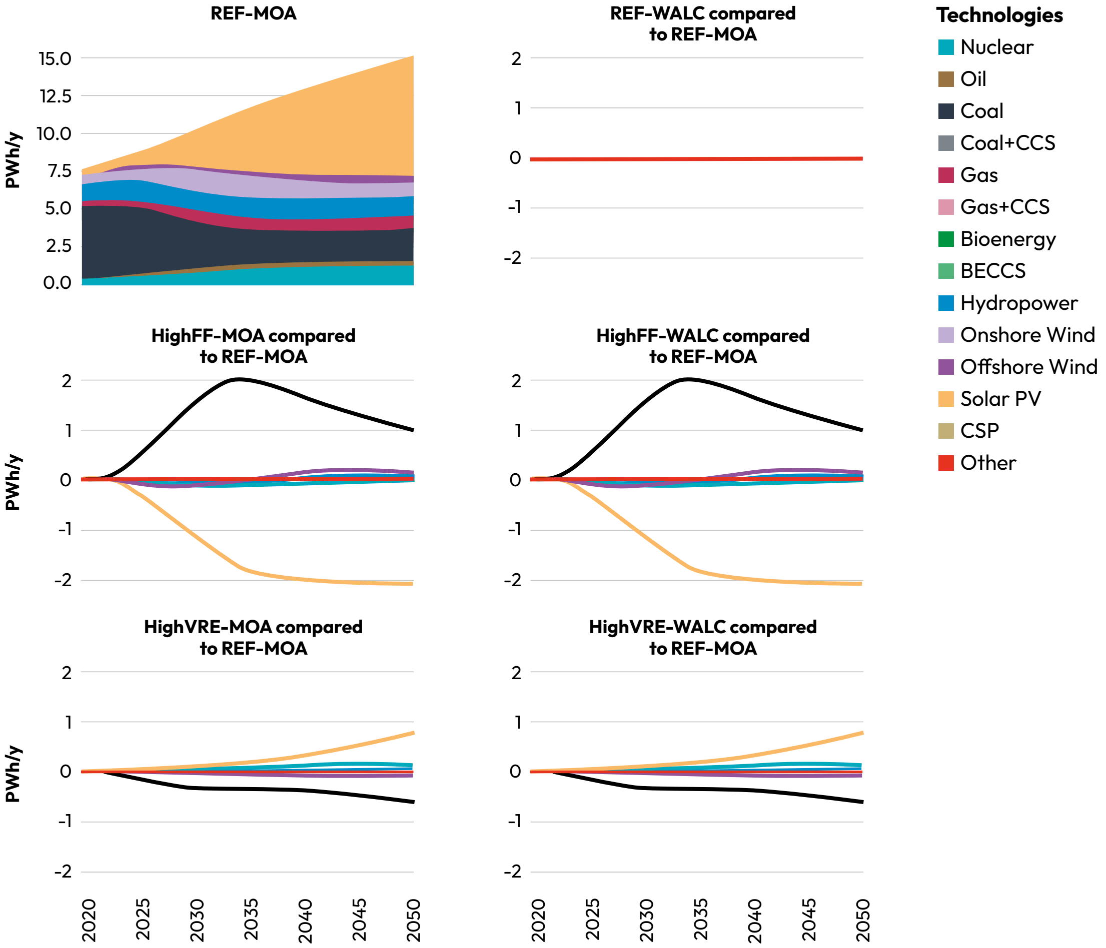
Power generation technology mix

FTT:Power simulates a continued diffusion trajectory of VRE technologies in the reference scenarios (REF-MOA and REF-WALC), in line with past diffusion dynamics and continued cost reductions (see Figure 15). Solar PV in particular gains momentum as costs continue to decline for the technology itself and for the storage technologies that facilitate VRE uptake. It is likely that solar PV will outcompete wind power or any other alternative in the near future. Due to an expansion in VRE capacity, fossil fuels are set to decline.

However, if VRE technologies run into additional barriers that prevent such a deployment (see Figure 15, HighFF-MOA and HighFF-WALC) then uptake of VRE is slightly slower, which benefits fossil-fuelled power generation. Solar energy starts with a small market share and the industry cannot grow as fast in absolute terms as wind when construction times are long. Less VRE also means less storage capacity is needed, which reduces electricity losses and therefore lowers the supply required to meet demand.

In the scenarios where VRE faces fewer obstacles and fossil-fuelled power generation is considered a less attractive investment, then – as expected – there is an increased uptake of VRE. The heightened reluctance to construct new fossil fuel plants creates space for VRE technologies.

Figure 15: Power generation by technology. Top left panel shows absolute levels of generation, while all subsequent panels show the differences in generation by technology compared to the REF-MOA scenario



Electricity prices

The scenario and market design play an important role in the electricity price. Figure 16 shows electricity prices in the various scenarios. Electricity prices are lower in the HighVRE scenarios compared to the HighFF counterparts, regardless of market design. This is due to the lower prices of renewables and storage compared to fossil fuels, depicted in Figure 17. It shows that solar PV is already cost competitive to fossil fuels on a levelised cost basis. Moreover, the cost of solar PV in the medium term is lowest in the HighFF scenario as these scenarios require relatively less storage. However, in the long term, learning effects on both solar PV and storage technologies overcome the cost of additional storage needs.

The price mechanism also plays a role, with the WALC outperforming the MOA. The MOA price mechanism typically leads to a higher electricity price, as it relies on marginal costs for fossil fuels and can lead to large profits for nuclear and VRE when marginal fossil fuel prices are high.

It is interesting to compare the REF-WALC and HighVRE-MOA scenarios. Both show lowered electricity prices, but for different reasons. The WALC price mechanism leads to lower prices than the MOA mechanism because the price is no longer determined by expensive marginal fossil fuel costs, and the HighVRE scenario shows lower prices due to the fact that variable renewables are cheaper than fossil fuels. Under the WALC price mechanism, VRE gains a larger weight in determining the electricity price compared to the MOA mechanism. In the HighVRE-MOA scenario, the increased deployment of VRE also leads to a greater weight of VRE in determining the electricity price, despite the MOA mechanism. The lowest electricity prices are achieved when these two effects are combined, in the HighVRE-WALC scenario.

Figure 16: Comparison of electricity prices, total employment and GDP of each scenario in percentage difference to the REF-MOA scenario

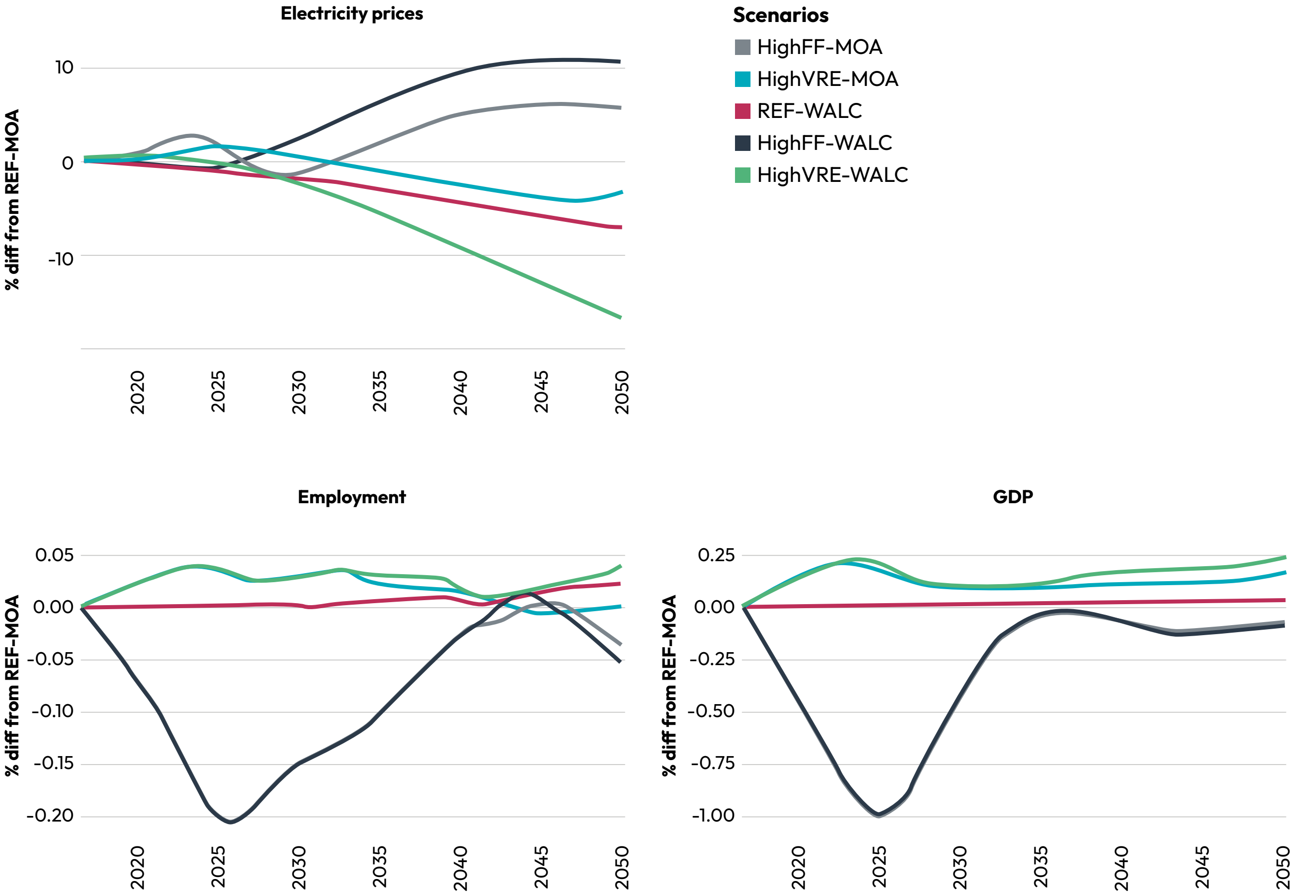
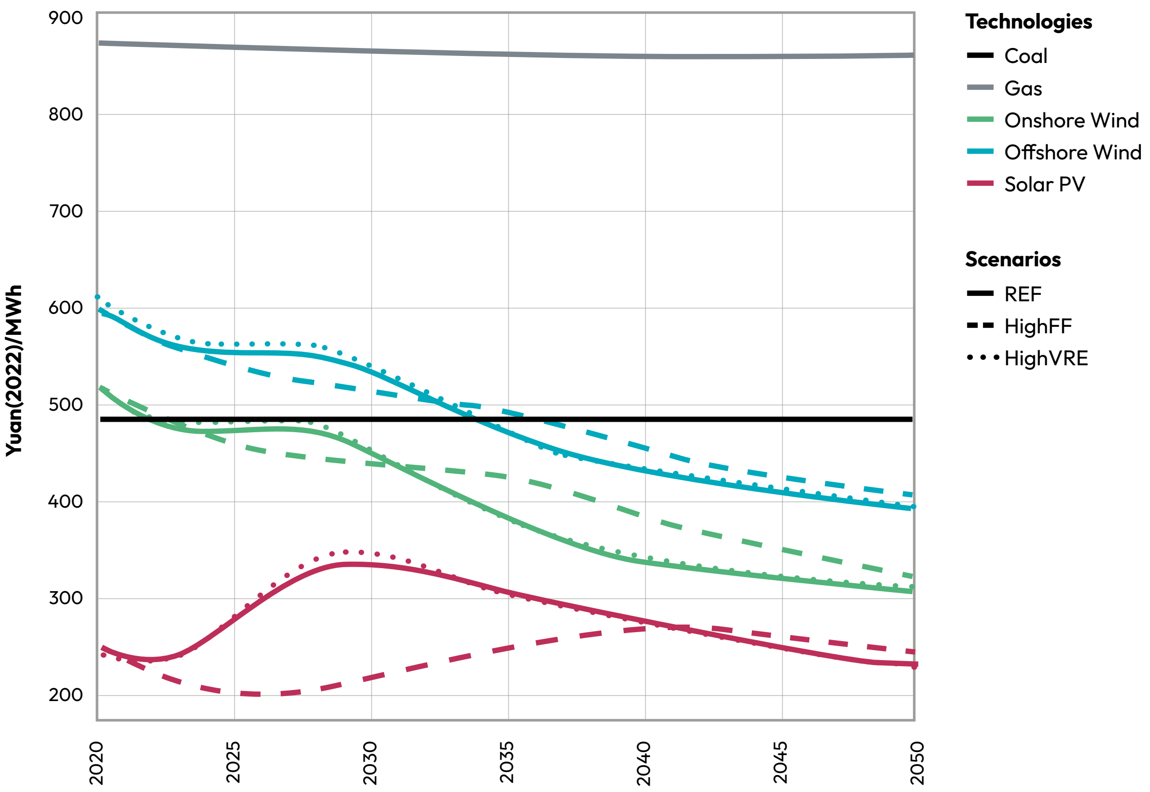


Figure 17: Comparison of levelised cost of a few selected technologies



Macroeconomic effects

Changes in electricity prices lead to knock-on effects on the rest of the economy. Lower electricity prices reduce energy bills, which unlocks consumer spending. Production costs are also reduced, again helping to increase consumer spending.

Most high fossil fuel scenarios show slightly negative GDP results compared to the reference case, because high electricity prices and high costs of industrial production constrain consumption in many sectors of the economy. The GDP losses occur early in the period due to a weakened construction sector from less VRE deployment. There is a positive effect on GDP in the high renewables scenarios, which arises due to the lower electricity price enabling higher consumption, and also due to the investment stimulus associated with increased uptake of VRE. This positive effect is greatest when high renewable deployment is combined with the WALC market design.

In the High-VRE scenarios and the WALC market design, we see increased employment in many sectors, and net gains overall. The job gains are on a par with the reference case. This is because job gains in the renewables industry are offset by job losses in the domestic fossil fuel extraction industry. Conversely, the employment outcomes are negative for scenarios with higher electricity prices, particularly the high fossil fuel scenarios. In these scenarios, higher electricity prices weaken the demand for services and lead to lower employment (Figure 18).

It is important to note that the model simulates employment outcomes within 43 sectors which include the coal, oil & gas and electricity sectors, but do not include the more detailed level within industries for the manufacture and installation of individual energy technologies, such as solar PV production by the electrical engineering sector. Consequently, the potential for additional jobs to be created by the development of new industries in China around the manufacturing of solar and wind technology is not represented, meanino.

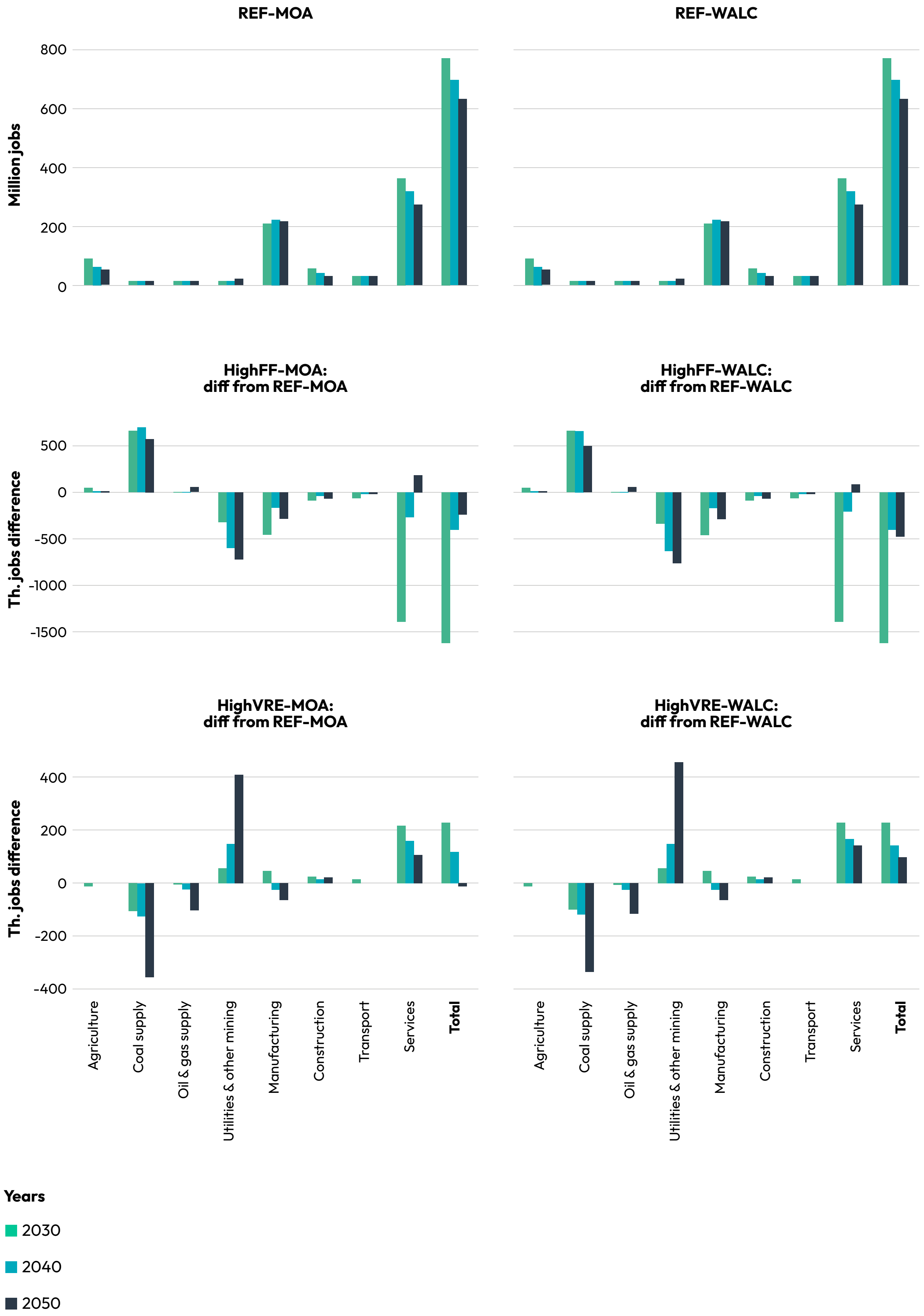
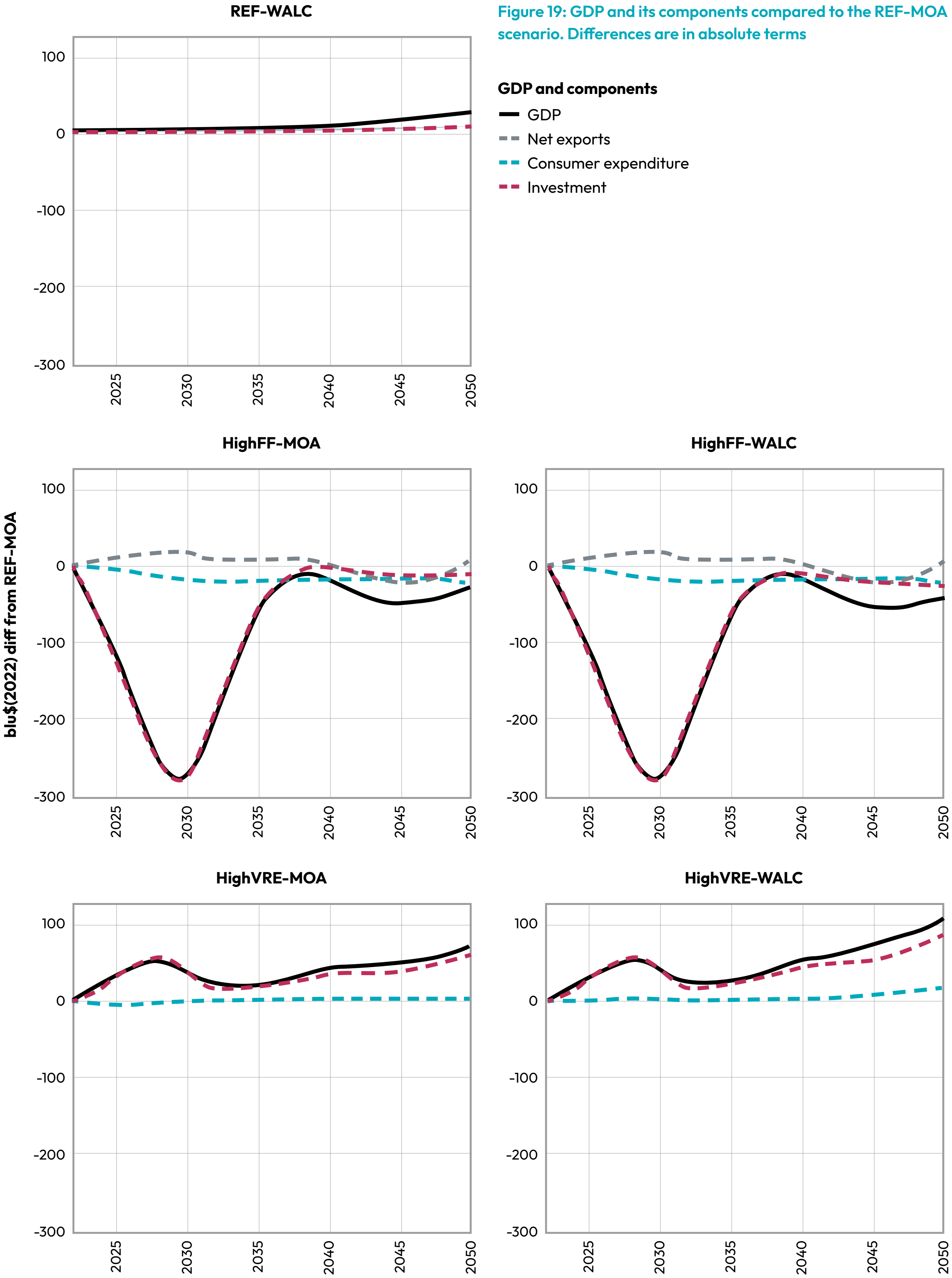


Figure 18: Sectoral job impacts compared to REF-MOA scenario. Differences are in absolute terms.

When tracking the components of GDP (see Figure 19), we find that positive results in the HighVRE scenarios are driven by capital investment in additional VRE capacity. The HighFF scenarios show GDP results that are either on-par or below baseline levels by 2050. In these scenarios the negative impacts come through via increased energy imports and depressed consumer spending due to high electricity prices.

Figure 19: GDP and its components compared to the REF-MOA scenario. Differences are in absolute terms



2.5. Comparison of REPO and E3ME-FTT:Power results

This section compares the results of the two models directly. First, we consider differences in underlying design principles, then scenarios and results. It’s crucial to understand that the REPO and FTT:Power models serve different purposes. The REPO model focuses on optimisation, aiming to find the best possible outcomes under given constraints, i.e. the carbon neutrality goal. On the other hand, the FTT:Power model is a simulation model, forecasting what is likely to happen under certain conditions, such as different policy or market design choices. An overview of the comparison is provided at the end of the section in Table 7.

Simulation and optimisation models

REPO is an optimisation model and E3ME-FTT:Power is a simulation model. This is a subtle but important distinction which is outlined in Table 6. Optimisation models aim to identify the optimal result (typically with regard to costs) within distinct scenarios. They integrate factors and constraints, and then obtain a viable optimal approach or recommend a precise strategy. They are frequently used to provide support to decisions around the distribution and utilisation of materials, products and other resources. REPO aims to identify the least-cost technology mix for electricity generation.

In contrast, simulation models help us understand system behaviours as they might actually occur, and evaluate what the outcomes of different policies or strategies are likely to be. This information can be useful for decision making, for example, by helping governments identify the policies best able to achieve a desired goal. Simulation experiments can evaluate multiple scenarios realistically, so that people have a deeper understanding of how the actual system works, rather than what might be ‘optimal’ in terms of one particular outcome. This approach is particularly suitable to simulate business processes, develop scenario plans and answer hypothetical questions about the likely effect of policies on different outcomes of interest. Simulation models do not seek to find the policy mix that gives a least-cost or ‘optimal’ system configuration.

The two types of models can be combined: optimisation models can be used to find a least-cost solution, using detailed technological constraints. Simulation models can then be used to find an effective mix of policies to achieve these solutions, and explore whether induced innovation can lead to further cost savings.

Table 6: Comparing optimisation and simulation models

	Optimisation models	Simulation models
Purpose	Model optimal scenarios given an objective (typically low costs) and constraints.	Model likely futures or the impacts of specific policies.
Strengths	Identifying optimal outcomes and thus supporting goal development.	Identifying likely outcomes and thus supporting forecasts and policy choices. Simulating policy that impacts the speed of innovation.
Weaknesses	Model cannot identify the policies that will be most effective in achieving the optimal outcome. Results can be perceived as forecasts, which they are not.	Model cannot help us find optimal path or outcomes.

Depth vs breadth in model scope and design

Beyond the overarching difference in model approach, there are further differences in the models which are important, but can be easily missed when focusing on results. These relate to differences in their detail and coverage.

REPO is a technology-focused model tailored to the unique complexities of the Chinese context. It is detailed in terms of representation of transmission, siting issues and operation constraints. In light of these attributes, it offers a high level of detail in representation. FTT:Power is not as detailed about the Chinese context. It provides a broader analysis of the energy transition and carbon neutrality, considering additional dimensions such as economic and social impacts that REPO does not.

There is no ‘right way’ to model the energy transition. These are differing and hopefully complementary ways of approaching the topic: REPO with more detail but less breadth and FTT:Power conversely with more breadth but less detail on the Chinese context.

Power generation

Figure 20 shows a direct comparison between the six FTT:Power scenarios and REPO for the power generation technology mix. While the scenario designs are significantly different, several themes emerge in the comparison. All of the FTT:Power scenarios are relatively similar to each other from a power generation technology mix perspective, when compared to REPO, which is substantially different.

The FTT scenarios all show a dominant role for solar PV, providing around 50% of total generation or more by 2060. In the REPO scenario, solar provides only 22% of generation by 2060. This difference arises due to the models’ different assumptions of technology costs. In FTT, the cost of renewables falls as a result of their increased deployment, following the historically observed Wright’s law relationship. This leads to faster cost reduction that is assumed by REPO, particularly in the High-VRE scenarios. The difference between the models is most pronounced for solar because solar has the steepest learning curve, with costs falling by 32% with each doubling of cumulative production, compared to 19% for wind (Figure 21).

Wind power shows a large difference in the opposite direction: it provides 32% of generation by 2060 in the REPO scenario, and only around 9% in the FTT scenarios. This is mainly because the high solar deployment in FTT constrains the space for wind deployment.

In REPO’s decarbonisation scenario, coal power is quickly and completely removed, whereas in FTT:Power’s pricing scenarios with varying degrees of VRE uptake it does not; in the REF and HighFF scenarios it even retains a large role. The sharp reduction of coal in REPO, and its combination with CCS at a later point, reflects REPO’s assumption of rising carbon prices.

Nuclear, hydropower and BECCS all play larger roles in REPO than in FTT. The difference is large for nuclear, which has 17% of generation from nuclear by 2060 in REPO, compared to around 9% in FTT. These differences arise because FTT assumes faster cost reduction and greater deployment of energy storage, as well as solar and wind, reducing the need for these forms of baseload generation. Oil-fired power generation plays a minimal role in FTT, and is not included in REPO due to its minimal presence.

The differences between REPO and FTT:Power are driven by scenario design, methodological difference and cost assumptions. Figure 21 shows the investment factors of a few selected technologies used in both models. Both models show good alignment for onshore wind, offshore wind and coal power, but they show significant differences for solar PV (about twice as low in FTT:Power) and gas power (about twice as high in FTT:Power).

Figure 20: Comparison of power generation for FTT:Power and REPO. Note: For FTT, onshore and offshore wind outputs have been combined, and CSP and 'other' sources, including CCS, have been removed for readability

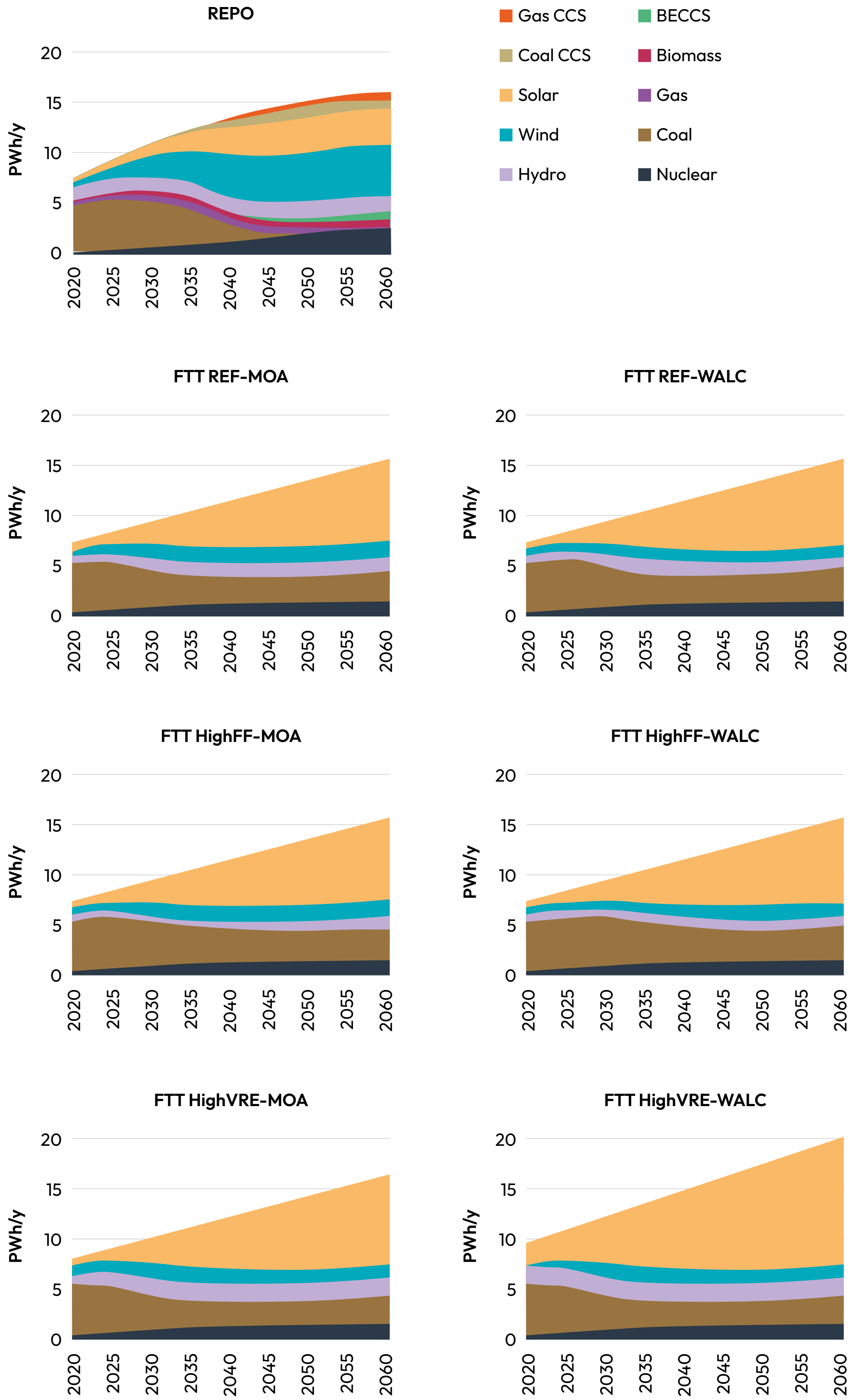
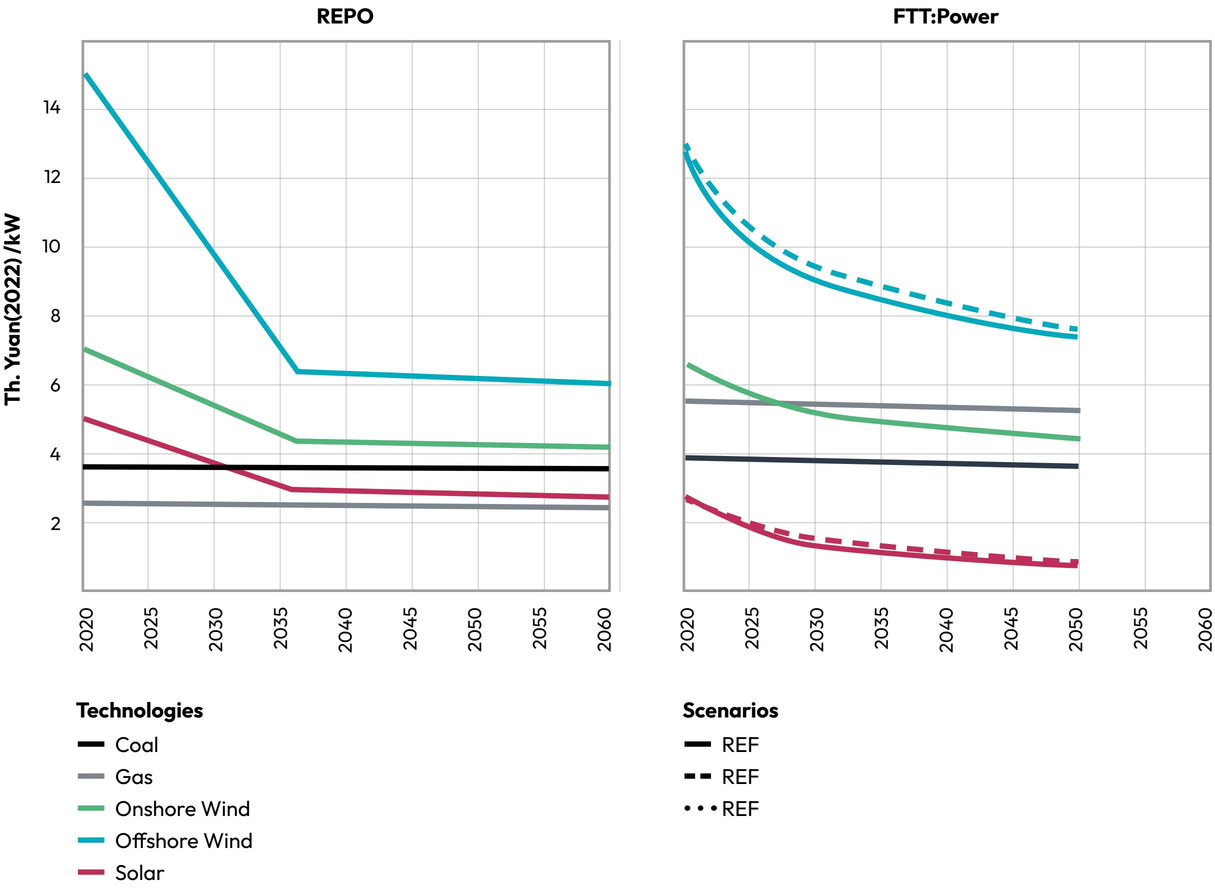


Figure 21: Comparison of technology investment factors in the REPO and FTT:Power models for a few selected technologies.

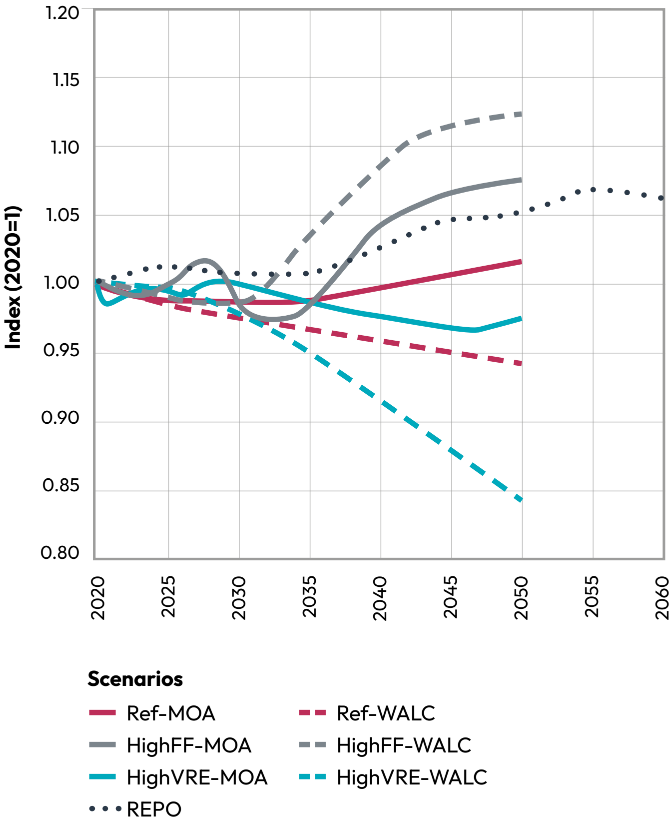


Electricity prices

While the REPO model focuses on electricity generation costs and the FTT:Power model centres on projecting electricity prices, a comparative analysis of these two sets of results is valuable. Often, electricity generation costs are embedded within electricity prices, and examining both can offer insights into the underlying similarities and differences, albeit at a high level.

Figure 22 plots the indexed electricity prices and generation costs from REPO and the various scenarios in FTT. When we consider the electricity price/cost trajectory of the two models, we see the difference the FTT:Power scenarios make (recall, they all looked similar in the generation comparison). REPO's trajectory falls between the REF-MOA scenario, and the HighFF scenarios, which have a steeper upward trajectory. The HighVRE and REF-WALC scenarios have a downward trajectory.

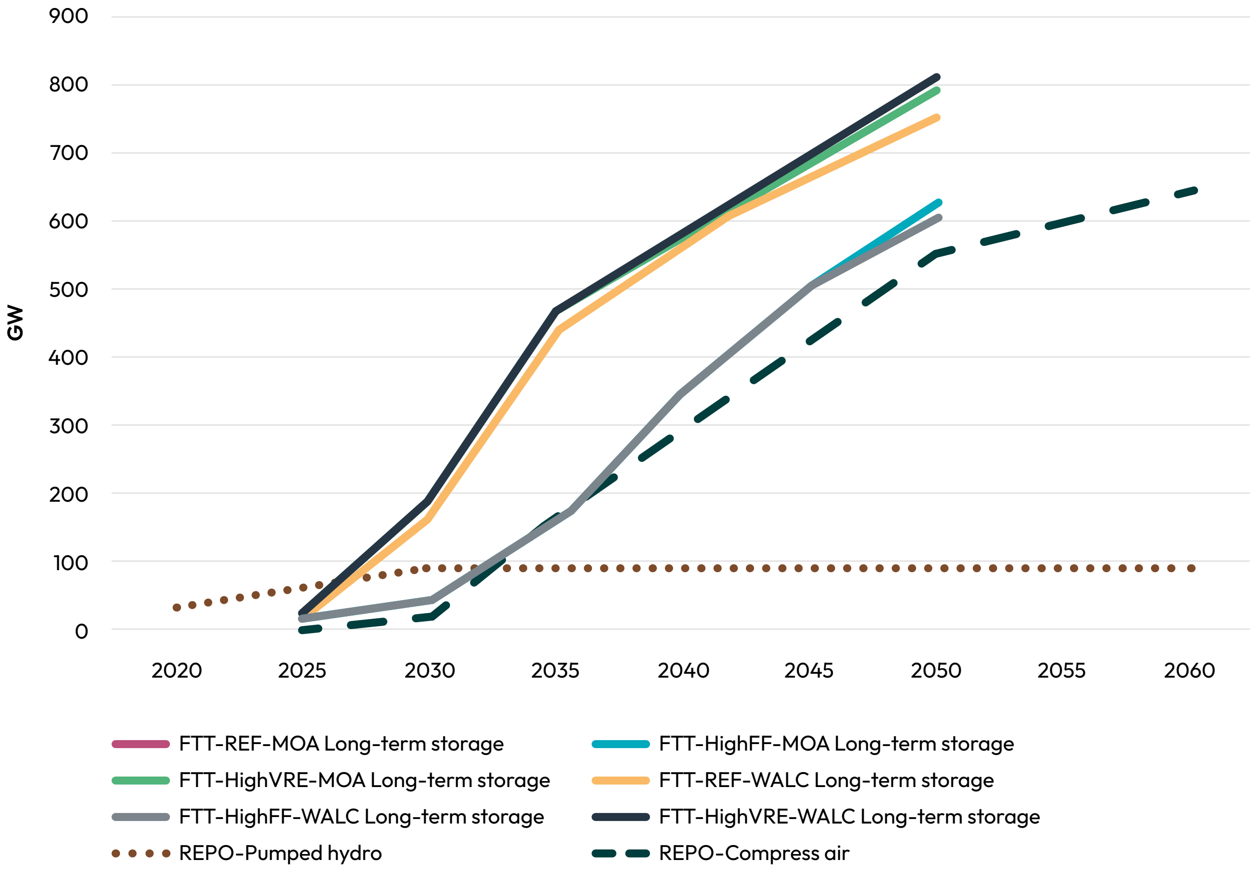
Figure 22: Electricity costs and prices in FTT:Power and REPO. Note: REPO does not calculate electricity prices directly but does calculate cost of generation, including transmission and storage costs, which we use here.



FTT:Power explores how different price mechanisms (MOA and WALC) and high fossil fuel or VRE scenarios can lead to varying electricity prices, reflecting a more complex and nuanced approach to understanding price dynamics. The MOA mechanism typically results in higher electricity prices because it's based on the marginal costs of fossil fuels. In contrast, the WALC mechanism lowers prices by moving away from reliance on expensive fossil fuel costs. The declining costs of solar and storage explain the declining prices where they are seen.

In the REPO model, the unit cost of electricity is calculated using the total discounted power system cost divided by total electricity generation. The total discounted power system cost includes annualised capital cost, O&M costs, transmission and balancing costs. The increasing development of storage for system balance purposes and the use of some high-cost generation technology under high carbon price drive the increase in unit cost of electricity.

Figure 23 FTT:Power and REPO storage deployment forecast (GW)



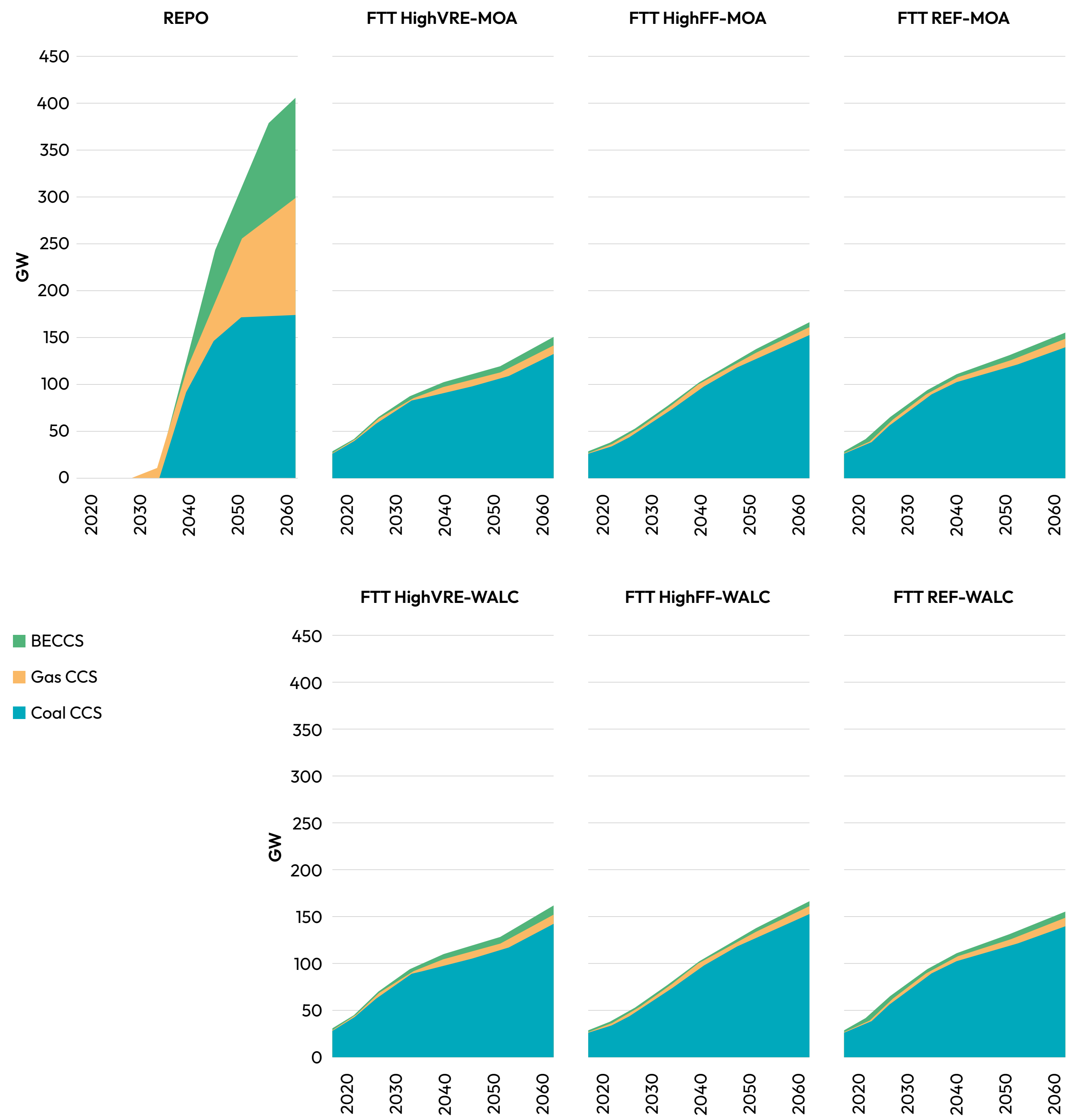
Storage beyond batteries

Both models concur that storage will hold an important position in China's future power mix, considering the substantial proportion of solar and wind indicated by these models. Although FTT:Power does not delineate the precise long-term technologies it encompasses, both models suggest a surge in long-term storage deployment starting around 2025 (Figure 23).

In REPO, long-term storage technologies include pumped-hydro and compressed air. A notable difference arises in the trajectory of pumped hydro, peaking approximately in 2035 and maintaining a consistent share thereafter in REPO. This divergence is attributed to REPO's assumption that the cost competitiveness of pumped hydro will diminish compared to batteries and air-compressed storage.

FTT HighVRE-MOA

Figure 24: FTT:Power and REPO forecast on CCS (GW)



CCS

REPO shows some role for CCS, but it is small, and even smaller in FTT scenarios. Figure 24 shows a bigger role for coal in combination with CCS, and a lesser role for gas and bioenergy combined with CSS. However, the higher proportion of gas combined with CCS and BECCS in the REPO stems from the scenario's assumption of stringent emissions constraints and the cost-optimisation principle that underpins the model. Additionally, CCS application in the REPO takes place at a later point as its scenario assumes that CCS becomes more cost-competitive once a specific level of carbon tax is reached.

Table 7: Model comparison summary

	Commonalities	Differences	Reasons for differences
Design and philosophy	● Both models include similar technologies and simulate technology mix and costs.	● FTT:Power is a simulation model. ● FTT:Power is a less detailed model, but has coverage of wider macroeconomic dynamics. ● REPO is an optimisation model. ● REPO is a detail technology-focused model, designed specifically for China.	● Design choices stemming from original model development, and FTT's connection to E3ME.
Scenarios		● REPO has one core scenario around China's carbon neutrality goal. ● FTT:Power explores six scenarios around market design and power mix assumptions. ● FTT:Power specifically explores two pricing mechanisms – WALC and MOA, whereas REPO focuses on the lowest total cost of the power sector.	● The analyses here serve different purposes. The REPO analysis seeks to understand the ideal transition to China's carbon neutrality goal, whereas the FTT:Power scenarios seek to understand the impact of different pricing mechanisms.
Power generation and technologies	● Solar and wind combined will be the dominant energy sources. ● Fossil fuel generation, particularly coal, will decrease.	● A larger role for wind in REPO. ● A larger role for nuclear power in REPO. ● A larger role for coal in FTT:Power. ● A bigger role for BECCS in REPO. ● REPO includes Coal CCS and Gas CCS, but does not include oil.	● The differences here mostly flow from the REPO scenario's more stringent assumption of a carbon price, and its closer representation of the Chinese power sector. ● The power mix in FTT:Power is dominated by the cost declines in solar, which outcompetes wind. ● A larger role for coal in the FTT:Power stems from its representation of imperfect decision-making. And none of the FTT:Power scenarios include climate mitigation policy.
Generation costs and electricity prices	● REPO and the HighFF and REF-MOA scenarios in FTT:Power suggest upward trajectory in costs/prices. ● Both models agree that renewables will be cost effective.	● The FTT:Power HighVRE scenarios, and REF-WALC scenario, anticipate a decline in electricity prices, driven by learning-by-doing effects on both generation technologies and storage technologies.	● Stringent emissions targets in the REPO scenario necessitates the application of high-cost technologies in the future, such as CCS and BECCS. ● Additionally, a significant investment in energy storage is required to complement the high proportion of wind and solar power generation. These bring the costs up in REPO.
Storage	● Both models show similar storage requirements. ● Long-term storage deployment follows an upward trajectory in both models.	● Pumped hydro in stagnation in REPO after 2035. ● Storage in FTT:Power is solved at a coarser granularity and remains agnostic of the type of storage technology. ● Decision making around storage capacity expansion is based on economic considerations for each individual technology in REPO, while it is part of the decision making for VRE expansion in FTT:Power.	● REPO assumes pumped hydro will fall short of the cost competitiveness of batteries and compressed-air storage technologies.
CCS	● Both models concur an upward trajectory in CCS deployment, especially coal combined with CCS.	● Larger roles for gas combined with CCS and BECCS in REPO. ● CCS application takes place at a later point in REPO.	● The cost-optimisation principle of REPO. ● Carbon tax consideration in the scenario.

3.1. Market reform of China's power sector

Both REPO and FTT:Power model agree that renewable technologies are more cost-effective in the power sector, and the FTT:Power model suggests that a high renewables power sector, with the right pricing mechanism, could reduce electricity prices.

The market reform of China's power sector is clearly of great significance for achieving the country's goal of addressing climate change. Reform is intended to promote efficient and low-cost utilisation of low-carbon resources. Among the various measures to be taken, economic dispatch (i.e. plants with the lowest costs get to operate and dispatch) is particularly important for the power sector to achieve low-cost emission reduction. At present, China's electricity dispatch and pricing mechanism still largely relies on administrative means, which has led to unreasonable protection for some inefficient units. This is because of the country's dispatch principle of transparency, impartiality and fairness,[69] which aims to ensure similar annual utilisation hours for coal-fired power units in the same region. This implies that inefficient coal-fired power units receive a certain level of protection. If placed under economically optimal scheduling, these inefficient units won't be able to operate as much.

At the same time, cost changes on the generation side are difficult to pass down to the user side, which to some extent restricts the application of emission reduction measures on the user side. However, China has begun to carry out this market reform, aimed at improving the role of market mechanisms. Pilot spot markets and auxiliary service markets have been carried out in many provinces and regions.

China also plans to establish a unified national power market system by 2025. After this, economic dispatch will fully leverage the role of market mechanisms, incorporating carbon costs into electricity dispatch decisions, incentivising power plants to operate flexibly based on their carbon emissions levels, thereby reducing the running hours of inefficient and high-emission units, and increasing the running hours of efficient and low-emission units.

For the overall power sector, economic dispatch should in theory help the sector find the optimal operating solution that meets emission constraints, helping it achieve the lowest cost in emission reduction. However, this is unlikely to happen without a range of policy support. Nonetheless, accelerating the market reform of the power sector will help achieve emission reduction targets at a low cost, while a slowdown in the process may affect the emission reduction of China's power sector due to the lock-in effect of the current large-scale coal-fired power units.

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[69] State Grid, Interim Measures on Promoting Transparency, Fairness, and Impartiality in Power Scheduling, January 2004, https://www.gov.cn/gongbao/content/2004/content_62904.htm

3.2. Emission Trading System (ETS)

The ETS is a key policy for China to achieve carbon neutrality. Although the cost of renewable energy power generation technologies such as wind and solar power and energy storage will continue to decline in the future, our modelling suggests it is still not enough to support China's power system to spontaneously complete the low-carbon transformation required by the carbon neutrality goal.

In FTT:Power a distribution of costs per technology is modelled. Thus, even if wind is cheaper than coal on average, there will be more expensive wind projects and cheaper coal projects, so that some investment will continue to go to coal, for example. As such, a carbon tax remains an important tool here. From a REPO perspective, the cost of renewable power generation and the cost of coal power should not be directly compared and contrasted. Because power supply and demand need to be balanced in real time, where the renewable energy output curve and power demand curve do not match, energy storage is needed. The costs of renewable energy paired with storage in some areas are not necessarily lower than the cost of coal power.

The low-carbon transformation of China's power system thus still needs to be supported by carbon prices. However, different ETS designs will have different impacts on the emission trajectory and transformation pathway of the power system, so ETS design needs to be adapted to the priority goals of power system transformation.

In the near term, unit efficiency remains one of the important emission-reduction measures in China's power sector. The priority goal of the ETS can be to improve the efficiency of fossil fuel power generation units. China's national ETS is currently applying an output-based mechanism, which focuses on encouraging unit efficiency. In the medium term, the power sector will need to deploy CCS technology to support further emission reduction. However, excessive deployment of CCS technology will significantly increase the cost of the power system. In addition, renewable energy generation will also need further development. Introducing partial auctions at this time can provide effective incentives for CCS technology, renewable energy and gas-fired power, promoting the diversified development of power generation structure. At the same time, the introduction of partial auctions in the ETS can also generate revenue that can be used in low-carbon technology research and development and other fields.

In the medium to long term, China's power system will need to ensure the achievement of absolute emission reduction targets as well as control the cost of power system transformation. At this time, a cap-and-trade based ETS will be more in line with the above goals. This will be more technologically neutral, providing a unified carbon price signal for different power generation technologies, incentivising the further development of the lowest-cost emission reduction technology, thereby improving the cost-effectiveness of power system emission reduction.

The design of the ETS also needs to be adapted to other mechanisms and policies of China's power system. In the early stage of the national ETS, the incentive effect on renewable energy is limited under the output-based ETS will free allocation, so it is necessary to cooperate with the implementation of renewable energy incentive policies. The introduction of partial auctions needs to be coordinated with the market reform of the power sector, otherwise the cost increase of coal-fired power units caused by allowance auctions will not be passed down to users, causing large-scale losses for coal-fired power units, which will bring risk to the safe and stable operation of the power system.

3.3. Public R&D

Technology research and development are crucial for achieving carbon neutrality at an affordable cost. The two models in this study have shown a variety of potential pathways in terms of the costs of generation and electricity. This variety hides that fact that both models assume, plausibly,[70] the costs of renewable energy, energy storage and CCS will continue to decline rapidly. At the same time, these technologies also need to be further developed and matured to be suitable for large-scale application in power systems. These all require social investment in funds and time for research and development. In addition, due to the time required for technological research and development, we need to plan ahead.

According to China's pathway to achieving carbon neutrality, recent technological research and development needs to focus on renewable energy and energy storage, further reducing the cost of this technology to a significantly lower level than traditional fossil fuel power generation, reducing the cost of new energy storage, and improving the safety of energy. In medium to long-term technology research and development, it is also worth considering a stronger focus on CCS technology to ensure its application before 2035, and to further improve efficiency in the long term while reducing costs.

For the power system, in addition to power generation and energy storage technologies, R&D in related supporting technologies is also very important. Due to fundamental changes in China's power sector to achieve carbon neutrality by 2060, adjustments will need to be made. These adjustments require the development of new technologies, such as sector coupling and demand response (for instance, charging EVs during the afternoon), scheduling and operation under the new power system, flexible transmission with large capacity, and an active distribution network.

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[70] Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. Joule, 6(9), 2057-2082.

3.2. Deployment of renewable energy and storage

Electricity is the core sector of modern energy systems and the main way to use renewable energy. In order to achieve China's carbon peak and carbon neutrality goals, both models make clear the future power system needs to vigorously deploy renewable energy, especially wind and solar. By 2030, the proportion of renewable electricity generation will reach nearly half of the total electricity generation in both models, and the proportion of wind and solar power in total electricity generation will need to reach nearly 30%. By 2060, the proportion of renewable electricity generation needs to reach roughly 70%, and both models agree that wind and solar power might need to supply more than half of the total electricity.

In order to achieve China's net-zero goals the average annual installed capacity of wind and solar power will exceed 150 GW in the near future. After 2040, although the growth of installed capacity of wind and solar power will slow down, considering that wind and solar power will also experience the retirement of large-scale existing power plants, the actual average annual newly built wind and solar power capacity will also exceed 150 GW. The large-scale increase in capacity will require the cooperation of the entire industry chain of wind and solar power, ensuring that they can support the development needs of wind and solar power generation from equipment production, installation, operation and maintenance to subsequent retirement management.

Energy storage will play a key role in the power system, with a high proportion of sustainable energy such as wind and solar. Therefore, in the power system that helps realise China's carbon neutrality goals, energy storage applications need to grow rapidly. Further development of energy storage itself is required to improve efficiency, enhance security and safety, and reduce costs. Additionally, it needs the cooperation of the energy storage industry and the market to improve the energy storage manufacturing capability. In particular, profit models and cost recovery mechanisms need to be designed to support the large-scale application of energy storage in the future.

EEIST

Economics of Energy Innovation and System Transition

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