EU-CHINA

Energy Cooperation Platform

中国 - 欧盟能源合作平台

Energy Modelling in the EU and China

November 2021

Funded by the European Union

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The EU-China Energy Cooperation Platform was launched on 15 May 2019 to strengthen EU-China cooperation on energy policies, and to support the implementation of activities announced in the 'Joint Statement on the Implementation of EU-China Energy Cooperation'. In line with the EU's Green Deal, Energy Union, the Clean Energy for All Europeans Package, the Paris Agreement on Climate Change and the EU's Global Strategy, this enhanced cooperation will help increase mutual trust and understanding between the EU and China and contribute to a global transition towards clean energy on the basis of a common vision of a sustainable, reliable and secure energy system. Phase II of ECECP is implemented by a consortium led by ICF, and with National Development and Reform Commission-Energy Research Institute. Policy steering is by the EU (DG ENER) and the China National Energy Administration.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report is about energy system modelling in the EU and China, under the auspices of the EU-China Energy Cooperation Platform (ECECP).

The capability requirements for energy system models have evolved during the last few decades. New challenges have arisen with the implementation of high shares of renewable energy sources (RES). The climate goals of the Paris Agreement and national GHG emission reduction strategies involve a restructuring of national energy systems. Adequate and appropriate models are required in order that these climate goals can be achieved.

The main objectives of the study are to describe the challenges and caveats relating to current modelling practices, and to provide recommendations for future energy system modelling in China and the EU. Improved models will pave the way for the integration of more renewables and other emerging technologies into energy systems, thereby reducing climate gas emissions, advancing the transition to clean energy and combating climate change.

The key recommendations for improving energy system modelling are:

- **Enhancing modelling of sector coupling:**
  To combat climate change, the synergies between the different energy sectors and networks, e.g. between hydrogen and transport, need to be utilised. Interactions take place when energy is converted between different energy carriers: the challenge is to provide services and to ensure that each is managed optimally.
  The costs of wind and solar are declining rapidly, providing strong motivation to integrate these power sources into other sectors and place them at the core of future energy systems.

- **Enhancing modelling approaches, with emphasis on variable renewables and storage:**
  The growing share of variable renewables (VRE) in power systems makes it increasingly important to model generation from wind and solar at a high resolution, taking into account the correlations between time and space. Additionally, the capability of models to represent the chronological aspects of storage and the interlinkage between storage and VRE need to be further enhanced.

- **As power systems become increasingly interconnected, the modelling footprint needs to be broadened – even for local analyses:**
  The growing number of transmission lines between model nodes (e.g. price

areas) and countries, along with rising prevalence of market coupling, make it necessary to increase the footprint of energy system models. The model area must include adjacent areas/countries, even when the focus is on more local issues.

- **Improved access to information to support international cooperation on energy issues, e.g. between China and the EU:** China could draw inspiration from the ENTSO-E Transparency Platform, which gives access to real-time as well as historical data. This presents an obvious potential for further collaboration.

- **Enhanced system modelling that takes into account market designs and reforms:** The development of future energy systems is increasingly driven by market design, which must therefore be a key boundary condition for system planning. Europe has accumulated considerable experience and can share more than 20 years of energy market liberalisation. With China's current energy market reforms, launched in March 2015, critical linkages are being created between market actions and planning decisions, and these need support from energy system modelling.

The EU and China have each made ambitious and firm commitments to moving away from fossil fuels and achieving climate neutrality near mid-century. This decade will be pivotal in bending the curve of global carbon emissions, thus putting the world on track to limiting the potential catastrophe of climate change and fulfilling the global commitments of the Paris Agreement. The EU and China together accounted for 37% of global emissions in 2019, according to IEA's World Energy Outlook 2020. Globally, the energy sector accounts for 41% of carbon emissions. As such, the energy transitions in both China and the EU are critical to global success in achieving net zero. Energy transition involves fundamental changes in the approach to energy supply and demand, energy technology development and deployment, and the institutional frameworks binding these together. It is imperative for the EU and China to collaborate in this effort.

Energy systems are complex, interlinked and connected to all important aspects of the economy and modern life. High quality energy modelling is needed to support the energy transition. Energy system modelling allows policy makers and stakeholders to make informed decisions when designing policies, making investments, and operating new energy systems. Europe and China have an obligation to demonstrate to the world that this can be done successfully and efficiently without adverse effects on the economy.

Note: Chapters 4 and 5 together give an overview of the Chinese power market development and planning process, which are also presented in the ENTSO-E Showcase for China report. These sections are included in both reports for completeness.

1. INTRODUCTION

This report on energy system modelling in the EU and China has been completed under the auspices of the EU-China Cooperation platform (ECECP). It builds on the research done in the ENTSO-E Grid Planning Modelling Showcase for China, ECECP.

The report's objective is to give an overview of present energy system models in China and the EU, and to advise on further development of these models. Any recommendations include a discussion of the potential benefits, challenges and limitations.

The report has been edited by Ea Energy Analyses, who also led the ENTSO-E Grid Planning Modelling Showcase for China report, hereafter referred to as the ENTSO-E Showcase for China report. The writing of the report has been facilitated by ICF, with input from the China Electricity Council (CEC), the Energy Research Institute under NDRC (ERI/CNREC) and State Grid Energy Research Institute (SGERI).

Chapter 2 provides an overview of present energy system models in China and the EU and offers suggestions for the future enhancement of modelling capabilities.

Chapter 3 provides a set of recommendations for improving energy system models in China and the EU.

Chapters 4-9 of this report present a detailed overview of the building blocks and background in China and Europe for performing energy system analyses and modelling, with a focus on power markets.

Chapter 4 describes the development of the power market in China and juxtaposes it with the power market in the EU.

Chapter 5 provides information about the present transmission planning process in China.

Chapter 6 describes the ENTSO-E European transmission planning approach.

Chapter 7 provides information on the Chinese scenarios for future energy supply and demand.

Chapter 8 gives a detailed description of two important models used for energy system planning: SGERI's internal model and ERI/CNREC's EDO model.

Chapter 9 gives background information on grid representation in SGERI's and ERI's model.

Chapter 10 summarises the report, and presents a set of recommendations for enhancing modelling capabilities in China and the EU.

Glossary

Term	Description
AC	Alternating Current
ACER	European Union Agency for the Cooperation of Energy Regulators
API	Application Programming Interface
bn	billion
bcm	billion cubic meter
BIPV	Building Integrated Photovoltaic Power
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CEC	China Electricity Council
CfD	Contract for Difference
CGE	Computable General Equilibrium
CNREC	China National Renewable Energy Centre
CREAM	China Renewable Energy Analysis Model
CREO	China Renewable Energy Outlook
CS	Consumer Surplus
CSG	China South Power Grid
CSP	Concentrated Solar Power
DC	Direct Current
DEA	Danish Energy Agency
DG	Distributed Generation
EC	European Commission
ECECP	EU-China Energy Cooperation Platform
EDO	Electricity and District Heating Optimisation (Model)
EENS	Expected Energy Not Served
ENS	Energy Not Served
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
ERI	Energy Research Institute under NDRC
EU	European Union
EUCS	EU Commission Scenario
EV	Electric Vehicle
FCA	Forward Capacity Allocation
FYP	Five Year Plan
GCA	Global Climate Action (Scenario)
GTC	Grid Transfer Capacity
GW	Giga Watt
G2P	Gas to Power
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine
ICF	Global Consulting and technology services company
IDC	Internet Date Centre
IEA	International Energy Agency
KPI	Key Performance Index

Term	Description
kV	kilo Volt
kW	kilo Watt
LCOE	Levelized Cost of Energy
LEAP	Long-range Energy Alternatives Planning system
LOLE	Loss of Load Expectancy
MWh	Mega Watt hour
NAIC	Normal Annual Investment Calculation
NEA	National Energy Administration
NDRC	National Development and Reform Commission
NPV	Net Present Value
NTA	Non-Transmission Alternatives
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational Expenditure
OPF	Optimal Power Flow
O&M	Operation and Maintenance
PCI	Project of Common Interest
PINT	Put IN One at a TIME
Prosumer	an individual who both consumes and produces energy
PS	Producer Surplus
PV	Photo Voltaic
PX	Power Exchange
P2G	Power to Gas
P2X	Power to X
RAB	Regulatory Asset Base
RE	Renewable Energy
RES	Renewable Energy Sources
RMB	Yuan (Chinese currency)
SEW	Socio Economic Welfare
SERC	State Electricity Regulatory Commission
SGCC	State Grid Corporation of China
SGERI	State Grid Energy Research Institute
SoS	Security of Supply
SPCC	State Power Corporation of China
ST	Sustainable Transition (Scenario)
tce	ton of coal equivalent (1 tce= 29.307 GJ)
TOOT	Take One Out at a Time
TPA	Third Party Access
TS	Transmission System
TSO	Transmission System Operator
TWh	Tera Watt hour
TYNDP	Ten Year Network Development Plan (ENTSO-E)
T&D	Transmission and Distribution
UHV	Ultra High Voltage
UHVDC	Ultra High Voltage Direct Current
USPV	Utility Scale Photo Voltaic
VALCOE	Value Adjusted LCOE
VIU	Vertically Integrated Utility
VRE	Variable Renewable Energy
V2G	Vehicle to Grid
Wh	Watt hour

2. ENHANCING ENERGY MODELLING CAPABILITIES IN CHINA AND EU - RECOMMENDATIONS

2.1 Summary

This chapter builds on the work of the ENTSO-E Grid Planning Modelling Showcase for China, an ECECP flagship project. It provides an overview of present energy system models in China and the EU, describing the benefits, challenges, and limitations relating to the development of energy system models, as well as recommendations for how to enhance modelling in China and the EU.

Awareness of the challenges involved in the development of energy system models will help to improve development in China and the EU; the recommendations in this chapter aim to achieve better models and improved energy investments, thereby supporting the transition to clean energy.

2.2 Present energy system models in China and the EU

2.2.1 Introduction

Decisions about energy systems need to be based on robust analyses and modelling. Energy system models are computational models that simulate how energy is produced, transformed, and consumed, taking into account socio-economic behaviours and physical constraints.

The models generate insights regarding a range of issues, including energy supply and demand, climate change mitigation pathways and the impact of energy, environmental and economic policies.

Modelling the energy system is difficult because of the immense complexity of system components, economy-wide interconnections between sectors, and the behaviour of consumers and producers. In recent years, the development of VRE, distributed energy, electrification, and flexible demand has made modelling increasingly difficult.

Assumptions about political decisions, economic incentives and social behaviour can have a significant impact on results, particularly in long-term predictions. Often, such uncertainties are addressed by using different future scenarios, which form the basis for the modelling exercise.

2.2.2. China energy system models

A variety of economic models have been developed in China over the past three decades, but sophisticated energy system-specific models are relatively few and have only appeared in recent years. The development is described in CREO 2018 (CNREC, 2018)[1].

The earliest energy system models in China were developed in the 1980s. Most of these were simple models which guided forecasts of energy demand.

It was not until the 1990s that more advanced energy system models started to be developed in China. In collaboration with the OECD Development Centre, the NDRC devised China's first computable general equilibrium (CGE) model in 1997.

In 1999, the Institute of Quantitative and Technical Economics of the Chinese Academy of Social Sciences (IQTE) developed a CGE model in collaboration with Monash University, and the ERI started building the Integrated Policy Assessment Model for China (IPAC) in collaboration with Japan's National Institute for Environmental Studies, based on the Asian-Pacific Integrated Model.

In the 2000s, modelling practices started to blossom in China. A MARKAL model was developed by a research team from Tsinghua University in 2001 and has since been adopted and incorporated into the energy system planning of several regions, including Beijing and Shanghai.

In 2004, the same Tsinghua team integrated a top-down MACRO model with the bottom-up MARKAL model to create a MARKAL-MACRO China model for the study of carbon mitigation strategies and their impact on the energy system. This was complemented by an energy-economy-environment model built by Shanghai University of Finance and Economics for the analysis of 'green GDP' in Shanghai's industrial sector.

The most important energy system models currently used to analyse China's energy system are summarised below in Table 2.1 (CNREC, 2018).

The table does not constitute a comprehensive list: many models in China, such as those used by CEPRI and SGERI, are confidential, and no public documentation or studies are available. Models are also used in academic settings which have not been widely applied by decision-making bodies.

2.2.3 EU energy system models

Numerous models exist at the European level. Obtaining a comprehensive overview of these models and their scope is a difcult task, and it makes model comparison

1 CNREC. (2018). China Renewable Energy Outlook 2018. CNREC.

Table 2.1: Important energy system models currently used in China.

Model	Full name	Type	Geographic Resolution	Planning Horizon	Primary User
MRIO	multiregional input output model	top-down input/ output	regional	short-term	Chinese Academy of Sciences
EPPEI Planning Model	EPPEI generation planning model	bottom-up optimisation	national	Medium- to long-term	Electric Power Planning & Engineering Institute, EPPEI
EPS	energy policy solutions/ simulator	system dynamics	national	long-term	National Center for Climate Change Strategy and International Cooperation, NDRC ERI
IPAC-ERI	integrated policy assessment model	hybrid	national, regional, provincial	long-term	NDRC ERI
CREAM (CGE, LEAP, EDO)	China renewable energy analysis model	hybrid	national	long-term	NDRC ERI/CNREC
CGE-NCEPU	computable general equilibrium model	top-down CGE	national	short-term	North China Electric Power University, NCEPU
GCAM-China	global integrated assessment model	market equilibrium	national	long-term	Pacific Northwest National Laboratory, PNNL
MSCGE	multisector computable generation equilibrium model	top-down CGE	national	medium-term	State Council Development Research Centre, DRC
GESP	generation electricity system planning model	bottom-up optimisation	national, regional	medium- to long-term	State Grid Energy Research Institute, SGERI
DCGE-SIC	dynamic computable general equilibrium model	top-down CGE	provincial	short-term	State Information Center, SIC
China TIMES	integrated MARKAL-EFOM system model for China	bottom-up optimisation	national	long-term	Tsinghua University
MARKAL-MACRO China	market allocation model and macroeconomic model	hybrid	national	long-term	Tsinghua University

Tsinghua-MARKAL	market allocation model	bottom-up optimisation	regional	long-term	Tsinghua University
SWITCH -China	solar and wind energy integrated with transmission and conventional sources - China	bottom-up optimisation	national	medium- to long-term	UC Berkeley, Stony Brook University
MES-SAGE	model for energy supply strategy alternatives and their general environmental impact	bottom-up optimisation	national	long-term	University of the Chinese Academy of Sciences, UCAS

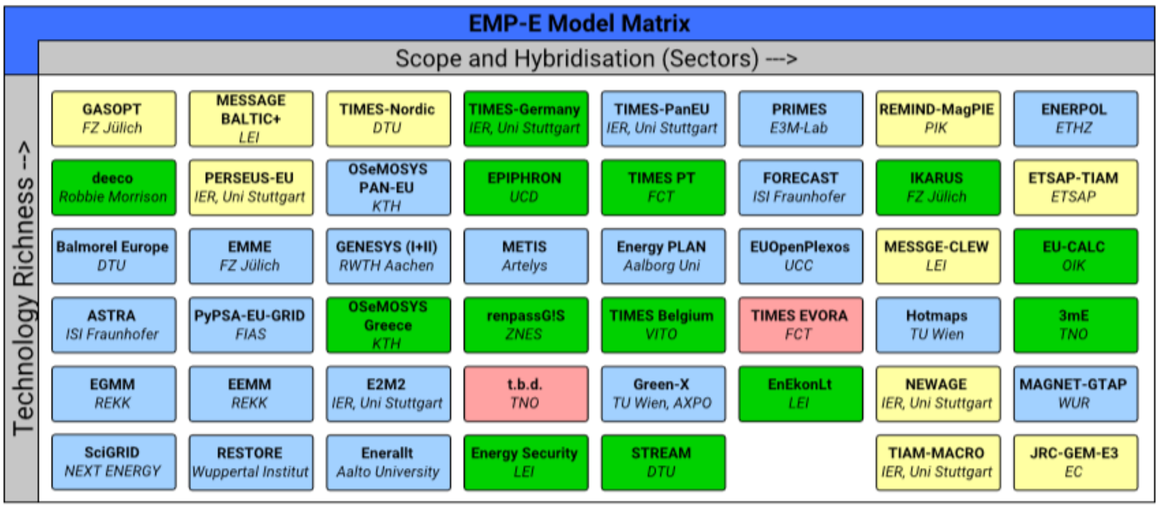
exercises resource-intensive.

Since the first attempts to summarise, categorise and compare energy system models, such as Huntington, H G, 1982[2], there have been many studies in the field that have taken different approaches to this task.

In 2017, the EU made important progress towards describing and categorising energy system models with the formation of the Energy Modelling Platform for Europe (EMP-E). This platform, established as part of the Horizon 2020 Research and Innovation Programme, facilitates cooperation between modelers and decision-makers in order to provide a peer-reviewed digest of models and policy insights for European energy scenario projects.

At the inaugural 2017 EMP-E meeting, 47 different energy system models were described and categorised as shown in Figure 2.1 along with model names and primary users /developers (research institutions/universities).

Figure 2.1: EMP-E model matrix: blue - EU, green - national, red - regional, yellow - other) (Müller, Gardumi, & Hülk, 2017)[3].



2 Huntington, H.G. (1982). Modelling for insights not numbers; the experiences of of the energy modelling forum, Omega.
3 Müller, B., Gardumi, F., & Hülk, L. (2017). Comprehensive representation of models for energy system analyses- Insights from EMP-E. Energy Strategy Reviews.

The models are categorised according to three characteristics: 1) technology richness, 2) scope and hybridisation (from single sector to multi-sectoral analysis), and 3) geographic focus: as follows:

- Colour indicates geographic focus: blue for 'EU', green for 'national', yellow for 'other'.

- The x-axis of the model matrix displays the scope and hybridisations of the models, starting from left (one sector) to right (multiple sectors). From the perspective of energy system modelling, final energy sectors (electricity, heat, liquid fuels, gas) and demand sectors (households, industry, commercial/retail, transportation/mobility) are often differentiated. However, at the 2017 EMP-E meeting, models including other sectors such as ecology, land use, health, and behaviours were featured. Therefore, no breakdown into sectors was suggested on the axis, nor a scale with the number of sectors, leaving the interpretation to the modelers.

- The y-axis indicates the richness in technology. On the bottom, models with aggregated representation of technologies (such as economy-wide models) are featured. On the top, models with high technology resolution are listed, such as bottom-up models. As a result of the variety of models in the matrix and the broad definition of the term technology, no scale of technology richness has been given.

The EMP-E is set to provide a continuous space for interaction between modelers and for engagement with key players in the energy sector.

2.2.4 Summary

In both China and the EU there remains a wide scope of applications for energy system models. The models are widely used to gain a better understanding of the energy system, its potential evolution and its optimal configuration. They can also be used for purposes such as evaluating the optimal penetration of technologies or assessing the possible impact of specific measures.

Given the multitude of uses for these models, it is important for the ECECP to support current and future model capabilities in the EU and China.

2.3 Development of energy system models

The requirements for energy system models have changed during the last few decades. New challenges have arisen with the implementation of higher proportions of RES. Along with the climate goals of the Paris Agreement, the national GHG strategies involve a restructuring of national energy systems. To achieve these climate goals, adequate and appropriate models are required.

Summarising the evolution of energy system models[4], their latest development corresponds to current and future research questions. In order to respond to these diverging questions, models need to be more flexible and transparent.

Open source and open access information, as well as data transparency, represent a major trend in energy systems modelling that will improve future model development.

In order to extrapolate current trends and consider future challenges, models will require an increased computing effort. Due to higher shares of RES, emerging cross-sectoral technologies, energy storage needs and growing international energy markets, model complexity will intensify. There are additional significant uncertainties, such as the technological properties, the costs of alternative future technologies, and future weather conditions. Moreover, further interconnections between countries will serve to increase the size of the model footprint and the problem's complexity.

Conventional optimisation and integrated assessment models are used extensively to develop policy-led transformation scenarios for the future, often involving the transition of energy systems from fossil to green technologies.

These models can help policymakers understand how to achieve long-term decarbonisation targets. The targets can be met by choosing combinations of low carbon energy technologies whilst minimising total cost. The models frequently[5] include a single decision-maker that has perfect foresight[6] about future trends in costs and prices. Some models are able to run with imperfect foresight which limits information about the future.

2.4 Developing a common understanding of modelling approaches and objectives

2.4.1 Categories of models

There are two approaches for modelling of energy systems: top-down models, and bottom-up models.

Top-down models are typically adopted by economists and public administrations. The models focus on connecting the energy system to other macro-economic sectors.

They are usually characterised by a simplified representation of the components and complexity of the energy system and are therefore not appropriate for use when identifying sector-specific policies.

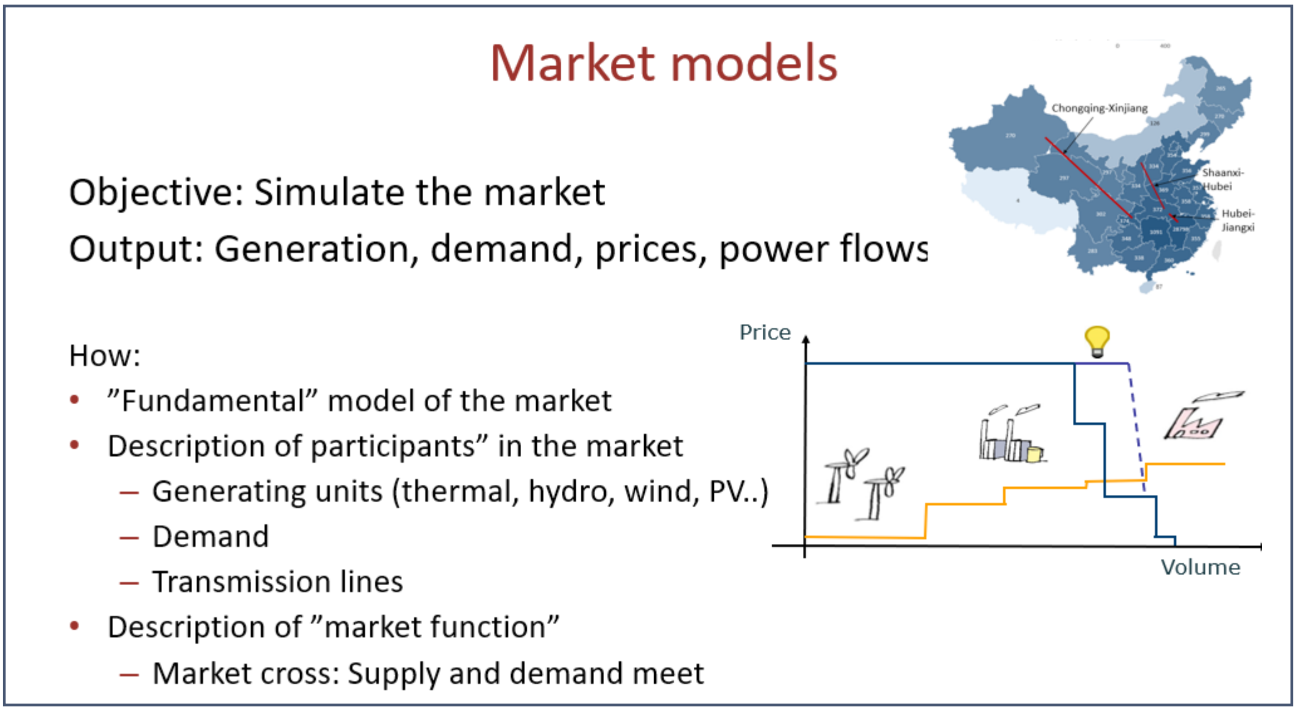
4 Lopion, P. et al. (2018). A review of current challenges and trends in energy systems modelling. Renewable and sustainable energy reviews 96, 156-166.
5 Hanna, Richard et al. (2021). How do energy system models and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity? Implications for policy and practitioners. Energy Policy 149, 111984.
6 Model perfect foresight means that the 'model' knows what is going to happen to the exogenous parameters in the whole model horizon.

They are used to evaluate the impact of energy and climate policies on socio-economic sectors such as social growth, employment etc.

Bottom-up models can provide in-depth analysis of the components and interconnections between the different energy sectors. From a techno-economic standpoint, these detailed models allow the user to compare the impact of different technologies on the energy system. However, the bottom-up approach does not take into account the connections between the energy system and the macro-economic sectors, and so neglects the impact on these sectors.

Figure 2.2 shows a simplistic sketch of a bottom-up dispatch model with objective, input/output, and description of the market 'players': generation, demand, and transmission lines etc.

Figure 2.2: Outline (simplistic) of a fundamental bottom-up market dispatch model (source: Ea Energy Analyses).



The main categories of methodology are as follows:
(This list is not exhaustive)

Econometric models
Econometric models use derived, statistical relationships from past behaviour to model future behaviour. Econometric models can be derived either from deterministic or stochastic economic models.

Macro-economic models
Macro-economic models focus on the entire economy, of which energy is only a part. Specific technical information is not included, and use of the models often require a high level of expertise.

Economic equilibrium models
Economic equilibrium methodologies focus on long-term growth paths and are used to study the complete economic system, of which the energy sector is part. Focus is placed on the interrelation between economic sectors. The models can be classified into either general equilibrium (simultaneous equilibrium in all sectors) or partial equilibrium (equilibrium in parts of the market).

Optimisation models
Mathematical optimisation can be used to find an optimal mix of technologies, given certain constraints, and can be used in both top-down and bottom-up approaches. First, an objective function has to be defined in order to be minimised; this function could involve aspects such as cost, fuel usage, emissions, or even maximum investment returns. Optimisation models are useful for finding least-cost solutions. They are typically data-intense and complex. A key benefit is that their purpose can be adapted to suit the user's need: e.g. a model's objective function could be to maximise socio-economic welfare rather than to minimise cost.

Simulation models
These models simulate the behaviour of energy producers and consumers in response to prices, income, and other signals. The models describe a logical representation of a system and attempt to reproduce its operation. They can simulate the uptake of technologies better than optimisation models as they can be run more efficiently with higher resolution.

Backcasting models
This methodology identifies desirable future outcomes and uses expert knowledge to define the path and policies that will lead to these results.

Multi-criteria models
A multiple-criteria decision analysis (MCDA) evaluates a set of possible courses of action. Multi-criteria models include a wide set of measures, economic and otherwise.

2.4.2 Context of the ENTSO-E Grid Planning Modelling Showcase for China project

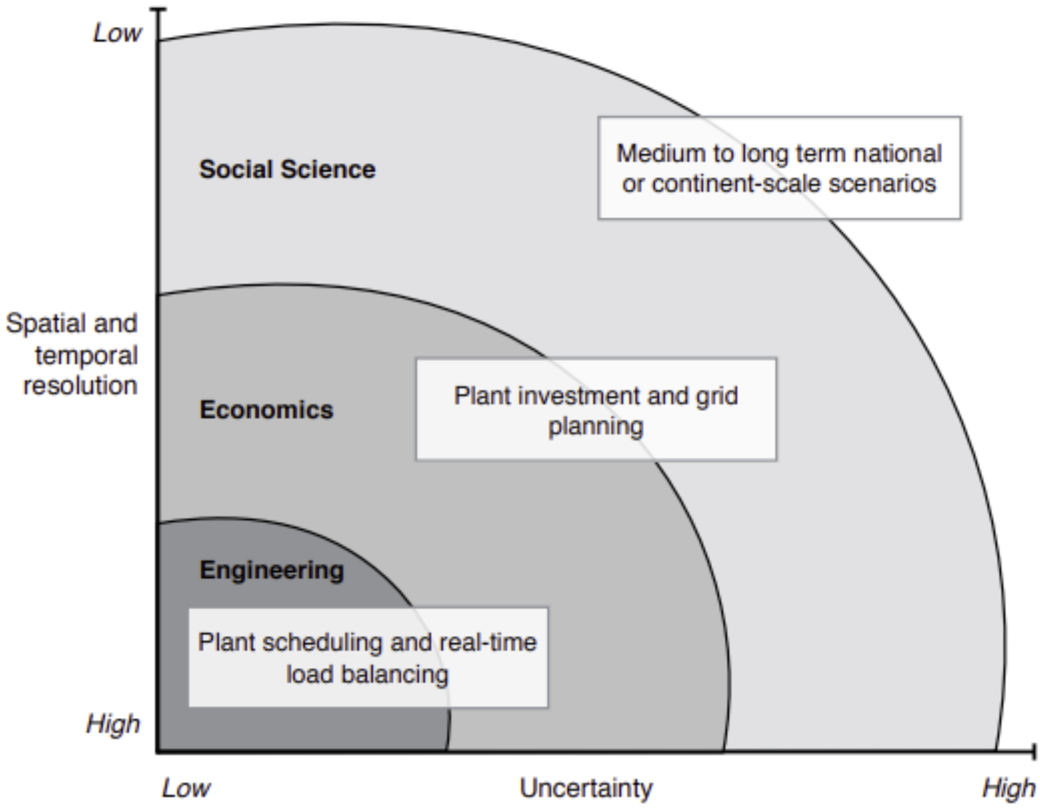
The aim of the ENTSO-E Grid Planning Modelling Showcase for China project was to demonstrate the ENTSO-E transmission system planning process for China. Its objectives were clear and consisted of three steps: defining scenarios, screening of potential new transmission assets, and demonstrating the advanced EU/ENTSO-E CBA methodology for China (see Chapters 5 and 6).

In order to make decisions using models, the concept of resolution has to be considered. This encompasses resolution in time, space, techno-economic detail and sector-coupling. These main fields can be divided into different levels of resolution: low, medium, and high. Using low resolution introduces errors into the modelling, while high resolution creates challenges regarding size of model and computation time. In practice, the choice of resolution will require compromise and awareness of the study's objectives.

As well as resolution, scale is also an important factor, i.e. moving from the scale of per-second balancing of power supply and demand to that of designing infrastructure with decades of lifetime and long-term path dependency (see Figure 2.2). Rather than simply increasing temporal resolution, an alternative approach could be to consider different time scales with varying levels of detail.

Models often do this by including a planning step and an operational step. At the planning time scale, decisions are made about how much capacity to install. At the operational time scale, decisions are made how to operate the available system to satisfy a given energy demand. Such a model could be called a two-scale model. It can be extended to several scales. For example, on a continent-wide electricity grid, sensible scales might be local (the generation profile of individual solar or wind sites), national (the characteristics of the national energy system and aggregated demand it needs to match), and international (the capacity for long-range transmission and the additional balancing possibilities this introduces).

Figure 2.3: Illustration of model with different time scales with different level of detail.[7]



The selected model for the ENTSO-E Showcase for China report includes a planning module and an operational dispatch model (see section 2.4.3).

7 Pfenninger, S. et al. Energy systems modelling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews, 33, pp. 74-86. DOI: 10.1016/j.rser.2014.02.003.

2.4.3 Selected model approach in ENTSO-E Grid Planning Modelling Showcase for China

The ENTSO-E team decided on a bottom-up approach for the modelling of power transmission system development. This type of model enables a detailed description of power systems and linked district heating systems with technical and economical parameters and constraints. This is also the approach currently being applied in both China and the EU for transmission system planning.

The ERI/CNREC's EDO model was selected for the ENTSO-E Showcase for China report project. EDO is a combination of a capacity expansion model and an optimal unit commitment and economic dispatch model. Essentially, the model finds the optimal cost solution for the power and district heating sectors by minimising costs, including capital, operation and maintenance, and fuel costs, subject to constraints imposed on the solution such as specific targets or policies that must be achieved.

Key modules of EDO model

The EDO model operates according to the following power system modelling concepts, using user settings and input data:

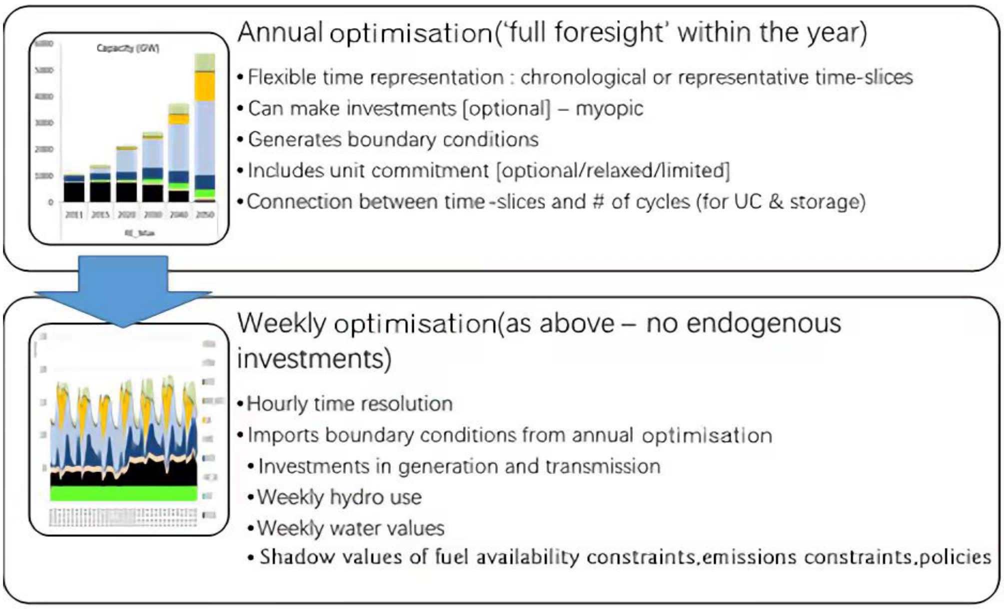
- Economic dispatch optimisation – finding the optimal level of generation from each unit to satisfy demand in each area of a grid, subject to power grid limitations, technical constraints, and other limitations in each time step.

- Unit commitment – using the economic dispatch optimisation with the added complexity of deciding which units should be started and stopped, and when. This adds complexity to the cost and technical representation of units, as start-ups and shutdowns are costly operations and discrete decisions.

- Capacity expansion – allows for capacities to be endogenously determined by the model. As a result, the model can be used to make investments in generation, transmission and storage based on the needs and economics of the system.

The model runs in two different modes which can interact (see Figure 2.4). The first mode looks at one year, and the user can configure the time resolution. For computational reasons, this will be less than full hourly resolution. The second mode looks at one week at a time at hourly resolution. The model therefore runs 52 times, simulating each week of the year. Each of these modes can be run for successive years, creating a pathway for development of the power and district heating systems. If the user allows investing in the annual model, the capacity installed by the model in one year is available in subsequent years until the end of its technical lifetime.

Figure 2.4: Flow diagram of EDO operation - 2 scale model encompassing a capacity expansion (planning) model and a dispatch (operational) model.



2.5 Power system modelling and planning in a market context

2.5.1 General about market modelling approach

The overall objective of the ENTSO-E Grid Planning Modelling Showcase for China project is to support the modernisation of top-level grid planning in China. The project draws on existing scenarios and modelling frameworks for China and Europe, with emphasis on market modelling and CBA in grid planning processes. This showcases the critical connection between grid planning and power market reform: the market prices determine the supply and demand of power and are therefore an important driver for new transmission lines or extension of existing ones.

This choice to focus on market-driven grid planning has been made for this project. The ENTSO-E Showcase for China report will be of great value to China in demonstrating the potential applications of these concepts.

The selected CBA parameters for market modelling in China are:

- SEW (socio-economic welfare)
- Costs for fuel
- CO_2-reduction
- RES integration: reduction in curtailment (GWh/y)
- CAPEX for the investment in question
- OPEX for the investment in question

Figures 2.5 and 2.6 in Box 1 show some important features in estimating socio-economic welfare:

BOX 1:

Calculation of SEW

A central parameter in most European projects is B1 (SEW). In the European TYNDP this parameter is often the most important when providing evidence for a proposed infrastructure expansion. The calculation of B1 is conducted through market modelling of the European system with and without the project in question. In the model, the future fully implemented Chinese day ahead market is emulated in each hour over the year in each scenario.

Figure 2.5 demonstrates the increase in B1 when connecting two bidding areas with a transmission line with capacity C. The optimal scheduling is to transport the amount C from the low-price area to the high price area. This will increase the price in the low-price area and decrease it in the high price area; congestion constraint on the interconnector will cause different prices in the two zones.

Also shown is the change in consumer and producer surplus in the two price areas. The net increase in surpluses is indicated by the dark purple triangles. The light purple area is the congestion rent.

Figure 2.5: Optimal flow between two market zones in the market model.

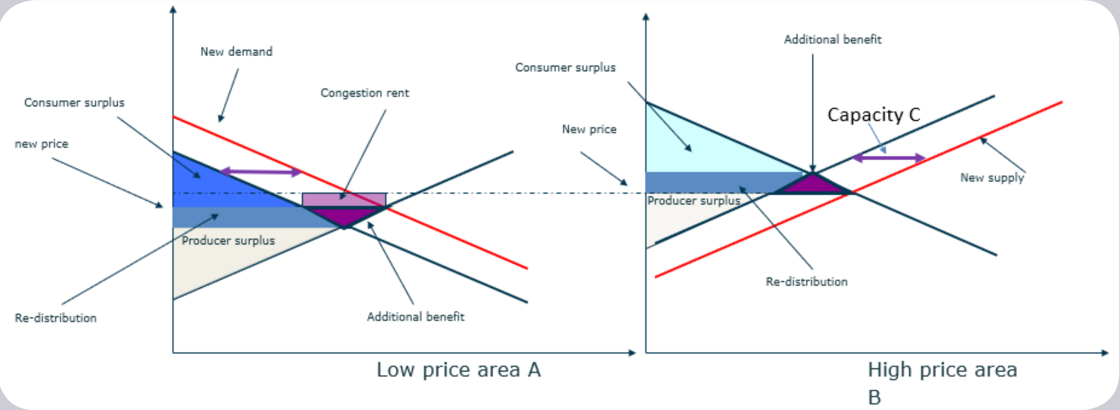
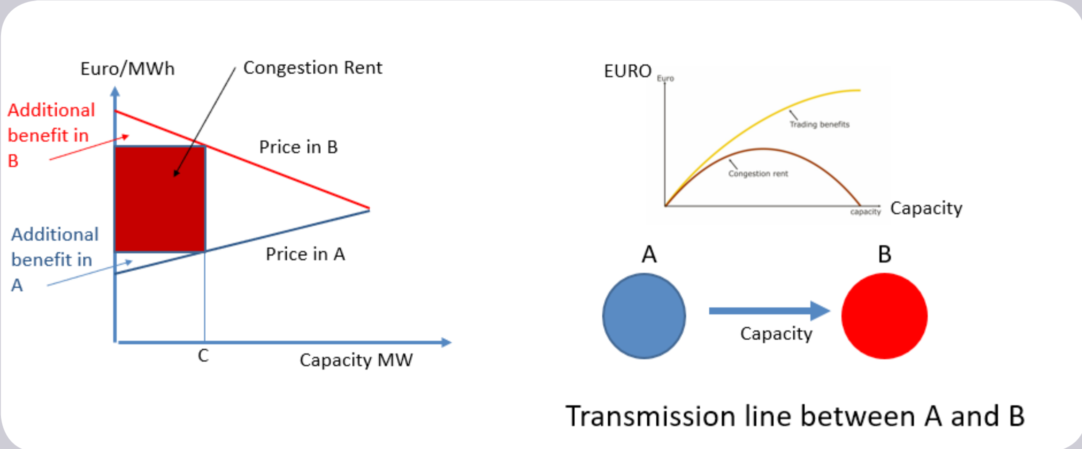


Figure 2.6 demonstrates the prices, congestion rent and B1 increases in areas A and B as the capacity between areas increases.

The red and yellow curves show the variations in congestion rent and total trading benefit, respectively.

Figure 2.6: Congestion rent and SEW as a function of transmission capacity.



(Source: Ea Energy Analyses)

In the market model, the total gain in SEW is calculated for all price areas, including net increase in all congestion rents for the power system when adding a given project. This is done for each hour over the year in all scenarios.

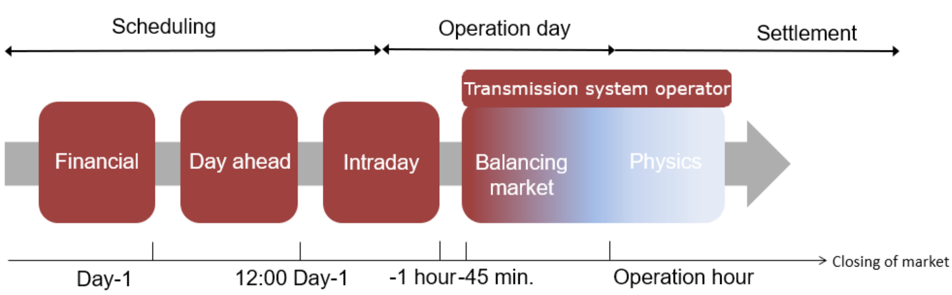
The changes in SEW, CO_2 emissions and curtailment of renewables (wind and solar) are all results of the market modelling.

2.5.2 Model representation of markets and their shortcomings

The electricity market is not just one market but a suite of markets: financial, day-ahead, intraday markets, and the balancing power market. Figure 2.7 indicates the timeline of activation for different markets.

The representation of the markets in the context of the ENTSO-E Showcase for China report has been confined to the day-ahead market. This is the largest and most important market for price formation.

Figure 2.7: The electricity market is not just one market, but a suite of markets. (Illustration of European market design).



In most power systems analyses, only the day-ahead market is modelled due to the size and complexity of the modelling. Intraday markets, balancing markets and reserve markets are normally accounted for separately.

When limiting the approach to day-ahead market modelling, a perfect foresight and deterministic conditions are assumed. This is a major shortcoming of the model as VRE generation cannot be predicted with certainty. The uncertainty regarding demand and VRE generation for the coming days are the main reasons for the use of intraday and balancing markets.

The ENTSO-E Showcase for China report has assumed perfect market conditions, i.e. that generators are bidding into the market with their short-term marginal costs and/or opportunity costs. Any consideration of market power, where some market participants are able to manipulate the market price through strategic bidding, is not included. It is also assumed that large consumers bid into the market with realistic demand.

In most cases, the potential exercising of market power is analysed through specific customised models simulating strategic bidding and applying game theory.

2.6 Model challenges and caveats

2.6.1 Access to data

For modelers in all regions of the world, access to sufficiently accurate and transparent data is a challenge. In many respects, the amount of available data is increasing, both in China and the EU, especially with the sharing of resources over the Internet. Public institutions increasingly make data available that has been collected and compiled under their jurisdiction. By opening these data vaults they have created a public resource. Commercial data providers can provide value through the collection, organisation, and provision of access to data for those who require it. Transparency has become widespread in public, commercial and academic spaces, and transparency is now a necessary condition for data to be considered trustworthy and usable.

In the energy sector specifically, market reforms drive more transparency, as market participants need access to information in order to have trust in the market processes and to operate efficiently in the market space. Regulators need access to data to ensure a level playing field in the market. These characteristics of energy markets serve to elicit data from public monopolies such as grid operators, as well as proprietary information from market participants.

There are reasonable limitations on the move towards transparency. Commercial secrets are not shared, and there are concerns about cybersecurity when increasing data transparency.

In practice, access to data for modelling is not solely connected to commercial sensitivity. For modelers, it is also a question of convenience regarding the formats in which data is available. Flexible platforms with the option to query data and link datasets help to improve data availability and applicability. These are increasingly provided with open application program interfaces (APIs). These provide a convenient means of access using common programming languages, which allow the user to run their own code to select, organise and update data according to the specific needs. Nevertheless, compilation of sound and accurate data for modelling purposes remains one of the most resource-intensive elements of applied energy system modelling.

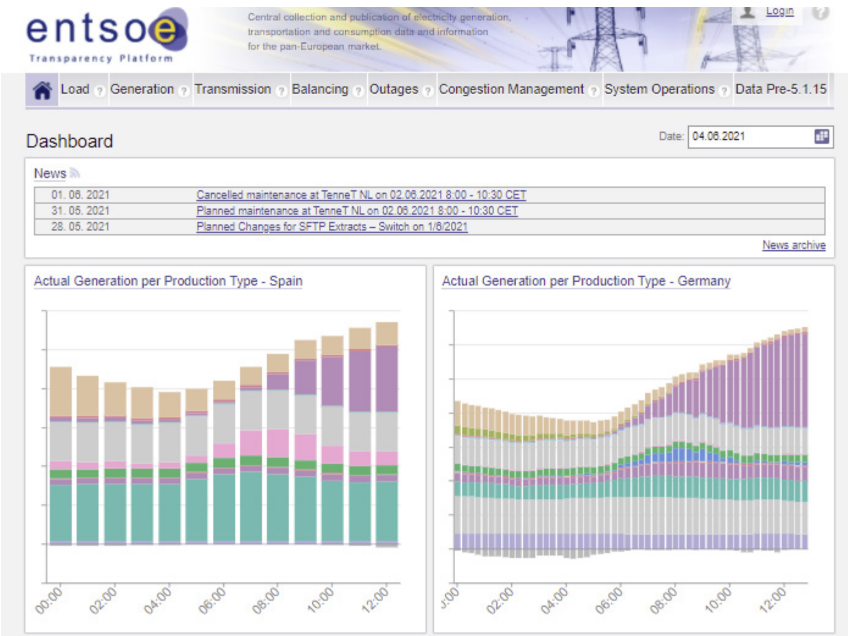
The data requirements for models are also increasing. With more powerful models, computational power and increasingly detailed demands placed on models, the need for data access is rising.

Europe
The ENTSO-E Transparency Platform[8] is a central publishing centre for electricity market information about load, power generation, transmission, balancing, outages, congestion management, system operations, and prices of electricity on a pan-European level. The Transparency Platform has been established in line with EU transparency regulation 543/2013 for electricity markets and is maintained by ENTSO-E. The data on the Transparency Platform are publicly available.

The Transparency Platform has an open API by means of which the data on the platform can easily be collected to be used in other applications. The API is suitable for users that want to request limited volumes of data near to real time. Transparency data can also be downloaded through the web interface.

Figure 2.8 shows an example extract of the transparency platform dashboard for 4 June 2021.

Figure 2.8: Extract of the transparency platform dashboard for 4 June 2021.



8 http://transparency.entsoe.eu

For Europe there exists a similar transparency platform for gas[9]. It is maintained by the European Network of Transmission System Operators for Gas (ENTSO-G).

China
China does not have an equivalent transparency platform. In general, access to data is more limited and most Chinese data is treated as confidential for a variety of reasons. However, the trend is for an increasing amount of information about energy systems to be available in China. The energy market reforms are likely to strengthen this trend as they are carried to fruition. This improvement in transparency will support increased international cooperation on energy issues, particularly between China and the EU. If China were to develop a transparency platform similar to that commissioned by the EU, with data near to real time along with historical data, the potential for further collaboration could grow.

2.6.2 Emphasis on sharing methodology approach and assumptions on key results

In energy system modelling projects, the parties may often be tempted to focus on key model results which support preliminary expectations. Results can often be presented as fact rather than sophisticated modelling.

More emphasis should be placed on interpreting model results with caution, highlighting methodological uncertainties and caveats. A model will always be an abstraction of the real world. In general, more weight should be put on discussing assumptions, developing more scenarios, conducting sensitivity analyses etc. Such an approach would improve overall trust in energy systems models.

2.7 Representation of high variable RE penetration

The increasing share of VRE in power systems makes it increasingly important to model generation from wind and PV with high resolution in both time and space, considering correlations from timestep to timestep and from node to node.

It is currently standard practice to use generation data based on several years' of simultaneously recorded data for wind and PV for each node and timestep in the model. This approach guarantees use of correct correlations in both space and time in the model studies. Where wind and solar are important generation sources, a timestep of one hour is usually sufficient. When there are only a limited number of recordings available, virtual time series can be constructed. These series are generated with the same statistical properties and correlations as the observations, and can later be used as input for the model.

The size and location of nodes is also an important issue. In market models, a practical approach could be to identify individual nodes with price areas. When price areas are too large for computation, a subdivision of price areas could be identified as nodes.

9 https://transparency.entsog.eu/

Figure 2.9: Example of how to categorise bottom-up models according to resolutions in time, space, techno-economic detail and sector coupling.[10]

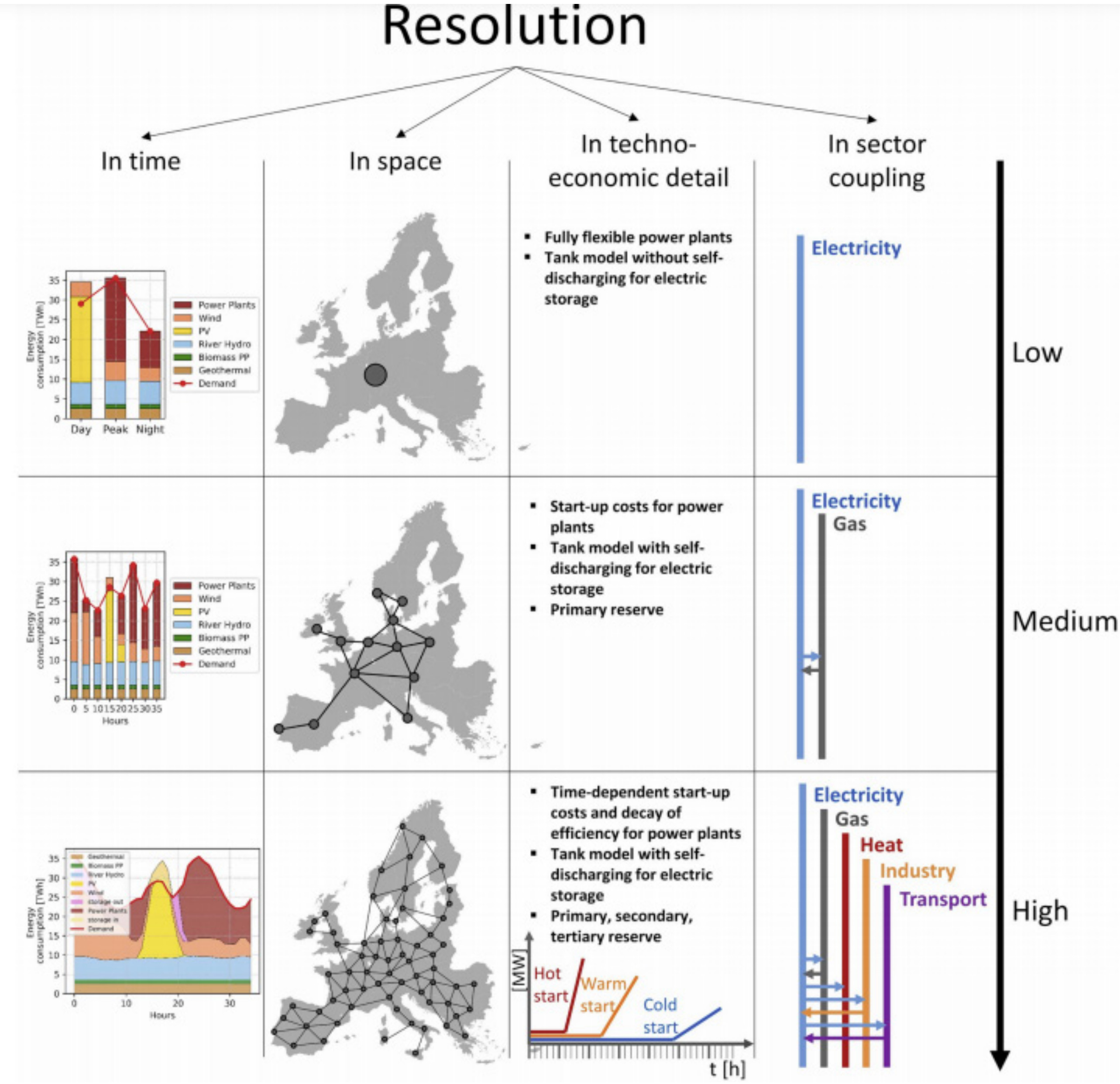


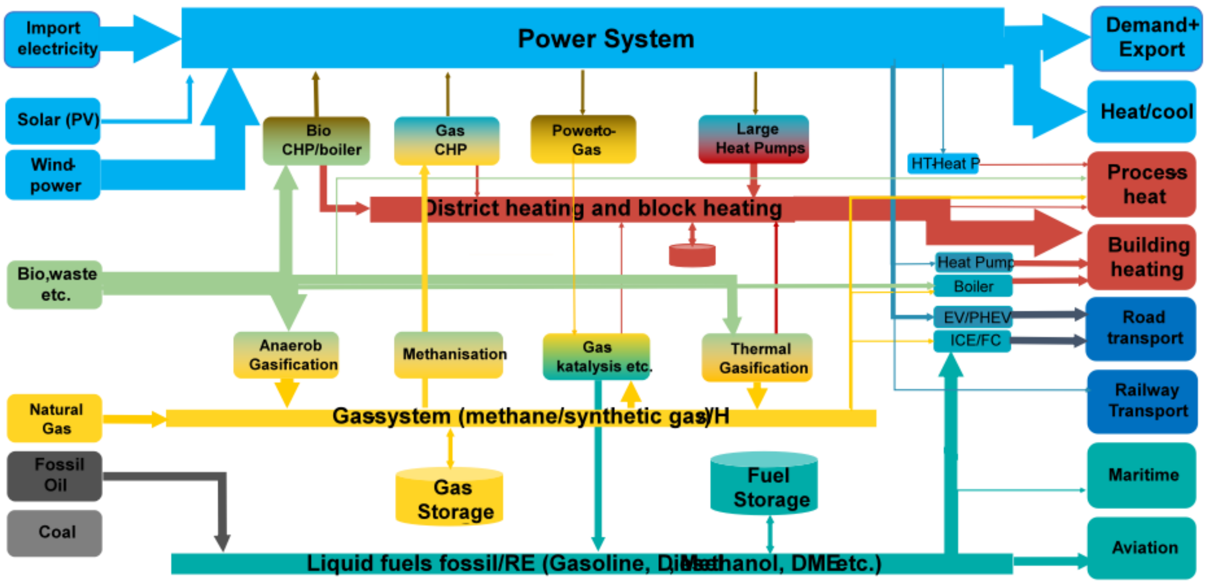
Figure 2.9 shows an example of how to categorise bottom-up models according to resolutions in time, space, techno-economic detail and sector coupling.

In transmission system planning studies, a medium to high resolution in space should be selected in order to conduct the transmission system simulation with a reasonable and satisfying resolution. In the ENTSO-E Showcase for China report, the level of resolution was selected for Chinese provinces.

10 Prina, Matteo Giacomo et.al. , Classification and challenges of bottom-up energy system models- A review, Renewable and Sustainable Energy Reviews, 129 (2020).

Modelling of sector coupling has become increasingly relevant with the decarbonisation of energy sectors through electrification based on renewables. Figure 2.10 shows a 2035 scenario for Denmark, where the energy system is based on renewables and there is a high degree of sector coupling for power, heat, gas, and mobility.

Figure 2.10: Scenario (2035) illustrating sector coupling in Denmark[11].



11 Eriksen, P. B. Energy system flexibility and integration.
- precondition for large scale integration of VRE (wind) in the Danish power system. Presentation at iiESI, Imperial College, 2017.

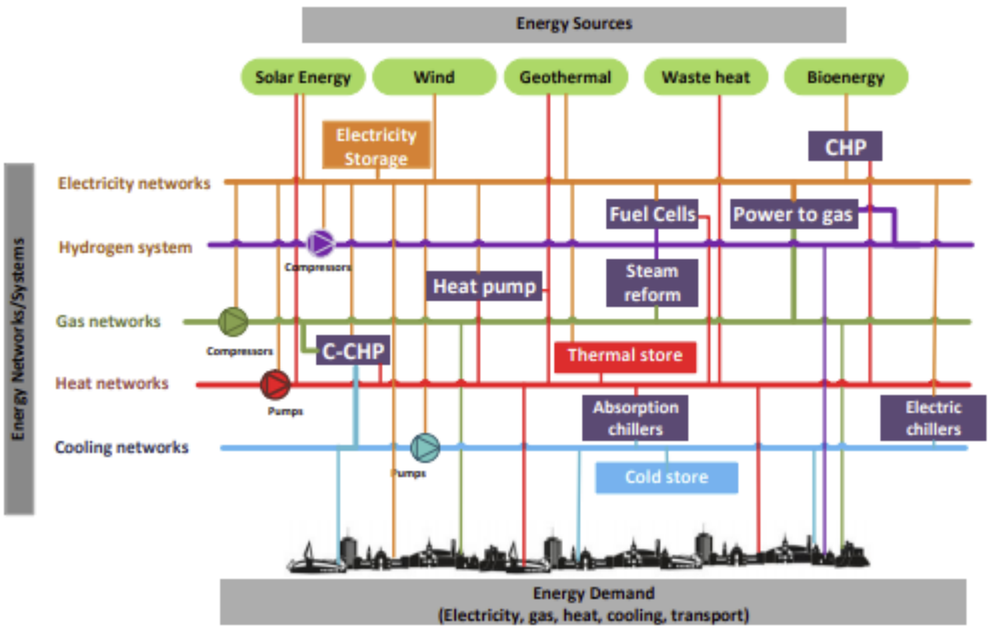
3. RECOMMENDATIONS FOR FUTURE MODELLING IN CHINA AND THE EU

3.1 Enhancing modelling of sector coupling

Traditionally, the different energy systems i.e. electricity, gas, district heating/cooling and hydrogen have had relatively few interactions. They were originally designed and operated independently of each other. However, there is increasing interest in exploring the synergies between energy sectors and networks.

Interactions takes place through the conversion of energy between different energy carriers and related storage in order to provide services and ensure that each is managed optimally. The numerous possible interactions between the various energy systems are illustrated in Figure 3.1.

Figure 3.1: Illustration of energy sector coupling[12].



Some of the most important drivers for studying the integration of energy sectors are:

- Carbon emissions and the increasing generation and utilisation of wind and solar power

12 Abeysekera M. et al. Integrated energy systems: An overview of benefits, analysis methods, research gaps and opportunities. HubNet Position Paper Series, 2016, www.hubnet.org,uk.

Wind and solar power are steadily decreasing in cost. There is therefore a strong motivation to use these power sources in sectors such as heat, transport or industrial processes. This will be an important measure for reducing CO_2 emissions.

- Reducing the use of primary energy
  This can be done by using CHP plants and integrating power and heat networks.

- Providing cost-effective flexibility in the electrical power system
  Coupling the power and heat/gas sectors will provide storage opportunities for heat and gas, thereby increasing flexibility options for a power sector that will increasingly be dominated by variable renewables.

ENTSO-E and ENTSO-G have been assessing their power and gas systems for a long time, in collaboration with the European regulator ACER and the European Commission. According to EU Regulation No. 347/2013, the ENTSOs must develop a 'consistent and interlinked electricity and gas market and network model including both electricity and gas transmission infrastructure'.

The ENTSOs initially delivered an interlinked model that focussed on common scenario building, but ACER took the view that several additional aspects should be investigated in more detail. This would make it possible to include interlinkage issues in the cost benefit calculations for power and gas projects in the TYNDP.

Figure 3.2: Illustration of interlinkage between power and gas systems. A: separate system approach. B: Interlinked systems.

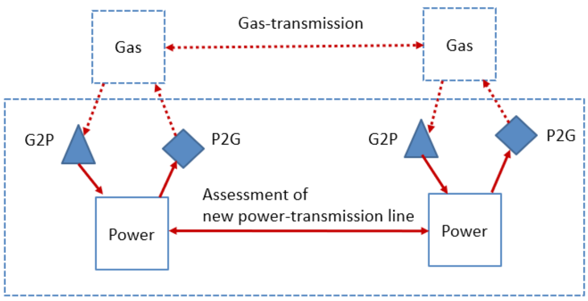


Figure A : CBA for power system

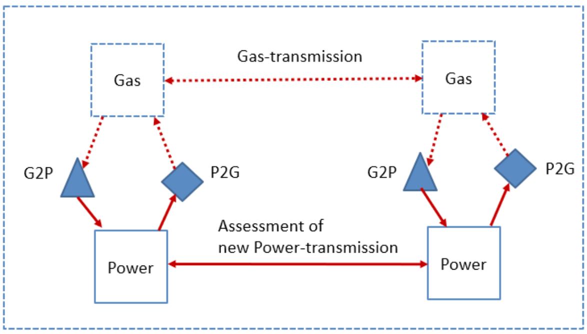


Figure B: CBA for interlinked power and gas system

(Source: Ea Energy Analyses)

In Figure 3.2, the links between the gas and power system are illustrated by 'gas to power' (G2P) and 'power to gas' (P2G). The latter is predicted to be important for the future production of green gases and green liquid fuels as a substitution for fossil fuels, in the pursuit of climate neutral energy targets. There are many connections between the two systems. For the sake of simplicity, Figure 3.2 only describes G2P and P2G.

It is clear from Figure 3.2 (A) that if the sole consideration is the impact on the power system, this is a flawed approach when, for example, assessing a new power line. A new power line may also have an important impact on the gas system with respect to gas supply to power stations, the level of green gas production and the amount of gas in the gas transmission lines . See Figure 3.2 (B).

Gas is expected to play an important role in the coming years in China as coal is phased out. It would therefore be beneficial to enhance China's power system models, such as the ERI's EDO model, with a gas module. This would significantly enhance the energy system modelling capability.

3.2 Enhancing modelling approaches with an emphasis on variable renewables and storage

With the increasing shares of VRE in the power systems, it is becoming increasingly important to model generation from wind and solar with a high resolution in both time and space.

It would be useful to enhance the model capabilities of storage and the interlinkage between storage and VRE. Battery storage is expected to play a growing role in the future as a flexibility measure to integrate more VRE. This is because investment costs for electric storage are declining – a trend that is expected to continue.

Storage in hydroelectric reservoirs is also an important element to include in the modelling, as well as virtual storage in district heating systems and gas systems – especially when considering sector coupling. These will be a growing focus as they are important as flexibility measures for the power system.

3.3 Increasingly interconnected power systems require broadening of modelling footprint – even for local analyses

The increasing number of transmission lines between model nodes (e.g. price areas) and countries make it necessary to extend the footprint of energy system models. The model area must include more and more adjacent areas/countries, even when the focus is on more local issues; interlinkages grow stronger between areas when transmission lines grow in number and capacity.

- A useful example is Denmark: when performing energy system studies for Denmark, the modelling footprint has extended from one where Denmark was considered on its own, with a quantitative description of boundary conditions to neighbours, to a footprint that includes the Nordic countries, Germany, and the Baltics. The model used for Denmark now consists of a model of Northern Europe including the Nordics, Germany, the Baltics, Poland, UK, France, the Netherlands, and Belgium.

This general development in the necessary model footprint should be borne in mind in future energy system modelling.

A growing trend towards market coupling is taking place in parallel with the increased physical connection between energy systems. In practical terms, Europe is one coupled day-ahead market area, where market clearing is done simultaneously for each hour of the coming day for the whole of Europe. The prices, generation, and power exchanges for the whole of Europe are calculated in the same algorithm (Euphemia). Work is ongoing with respect to integrating national and regional intraday and balancing markets into Europe-wide platforms.

A parallel development of integration of markets in China is planned.

3.4 Access to data

China does not have an equivalent transparency platform to the European platform described in Section 2.6. In general, access to data is more limited and most Chinese data is treated as confidential for a variety of reasons. However, the trend is for an increasing amount of information about energy systems to be available in China. The energy market reforms are likely to strengthen this trend as they are carried to fruition. This improvement in transparency will support increased international cooperation on energy issues, particularly between China and the EU. If China were to develop a transparency platform similar to that commissioned by the EU, with data near to real time along with historical data, the potential for further collaboration could grow.

4. MARKET DEVELOPMENT IN CHINA AND THE EU

4.1 Power market development in China

By 2019, the power sector in China had developed from one with a critical shortage of power supply to one with a fully interconnected national power system with a capacity of 2 010 GW, an RES share in total generation (including hydro) of 26.37%, and 14 UHVDC transmission lines. This history of development is central to a review of the process of market-oriented reforms in the power sector to promote sustainable development of power industry, as well as the systematic and gradual implementation of the transition to clean energy.

China has experienced a long process of market-oriented reform in the power sector since last century, marked by three directives from the national government. The directives have clearly divided the process into three stages.

4.1.1 Stage 1 (1985-2001)

'Directive 1985/72 Resolution for Multi-Channel Funds Raising for Power Development and Multiple Electricity Pricing' issued by the state council of the People's Republic of China (hereafter Directive 72) guided the process.

Before the early 1980s the power sector was owned and vertically operated by both national and local government. For some time, China had experienced serious shortages in power supply and investment which were having a critical impact on the development of the national economy. Directive 72 widened the investment channels and made some changes to government ownership.

The main points of Directive 72 are:

- encouraging foreign investors, local governments, enterprises and even individuals to invest in power projects with cost plus pricing.
- using a double track electricity pricing system including cost+ based and electricity rationing.
- withdrawing government control over vertically integrated utilities; setting up a power dispatching hierarchy.

After the implementation of Directive 72, power generating capacity developed rapidly and the provincial power systems were interconnected to form six regional systems. A level pricing system was introduced for each power plant. However, this system of 'one price for one plant' distorted the electricity price. The State Power Corporation of China (SPCC), a vertically integrated utility, was founded in 1997, introducing full separation between government and power enterprises.

4.1.2. Stage 2 (2002-2014)

'Directive 2002/5, The Resolution of Power Sector Reform in China' (hereafter Directive 5) guided the process.

The process built on the reforms introduced by Directive 72. The main points of Directive 5 are:

- unbundling generation from the VIU-SPCC.
- establishing an independent regulator, State Electricity Regulatory Commission (SERC).
- starting market-oriented competition on generation.
- divestiture of non-T&D regulatory asset base (RAB).
- development of cross regional power transmission.

In the process, SPCC was separated into two TSOs - SGCC (State Grid Corporation of China) and CSG (China South Power Grid) - and five generating groups, comprising 50% of total power generation capacity in China. Since that time, many generating companies have emerged which have broken the monopoly and provided competition. Major adjustments were made to the 'one price, one plant' electricity pricing structure. A benchmark price was implemented for coal-fired power plants based on fuel cost in each province, resulting in a single price for coal fired power plants in each province. These were all interim steps on the way to market competition. In line with the terms of Directive 5, SERC issued a series of rules for tariff reforms, network codes, operation, ancillary services and so on.

A pilot of annual and monthly generation competition in the northeast region extended to 80% of total generation with a single buyer model. It was intended that the findings from this pilot would be used to inform the introduction of further market competition. However, significant issues remained, and the momentum towards a more market-oriented system stalled. SERC became part of the National Energy Administration (NEA) in 2013.

4.1.3 Stage 3 (2015-present)

'Directive 2015/9, The Resolution for Deepening Power Sector Reform' (hereafter Directive 9) formed the basis for further development of the power sector.

Directive 9 was issued in 2015, and draws on the experiences and lessons learned in the previous two stages of development, whilst taking on the additional challenges of the transition to clean energy.

The main points are:

- further deregulation of the generation and consumption tariff and schedule.
- retail business opening.
- full implementation of third-party access (TPA) in transmission and distribution.
- establishing independent power exchanges (PX).
- opening new distribution businesses to public investment.

- enhancement of power development planning, regulation, safe operation, security of supply.

Directive 9 introduced guidelines and rules relating to transmission and distribution tariffs, establishment of power exchanges, market design, market-oriented scheduling for generation and consumption, inter-provincial and inter-regional power trading, retail, and new distribution businesses opening for public investment, embedded generation, renewable energy and so on.

Beijing's PX is responsible for cross-provincial and regional power trading in the SGCC service area; Guangzhou PX deals in cross provincial power trading in the CSG service area; while the provincial PXs oversee power trading in their own provinces.

Transmission and distribution tariffs designed using a cost plus methodology for the provinces have been approved by local governments, but transmission and distribution businesses have not yet become independent entities. Directive 9 has played an important role in promoting market development. Market trading of electricity represented 38.22% of total electricity generation in 2019.

A feed-in tariff was selected for variable RES, with regulated prices, but in some provinces with a high production of variable RES, the regulated price for a set volume of variable RES was reduced. Most coal-fired power generation businesses have been exposed to the market and are subject to a +10% price ceiling and -15% price floor as introduced by the NDRC's Document No. 1658 .

4.1.4 The development of long- and medium-term power trading, inter-provincial and regional power trading and the spot market.

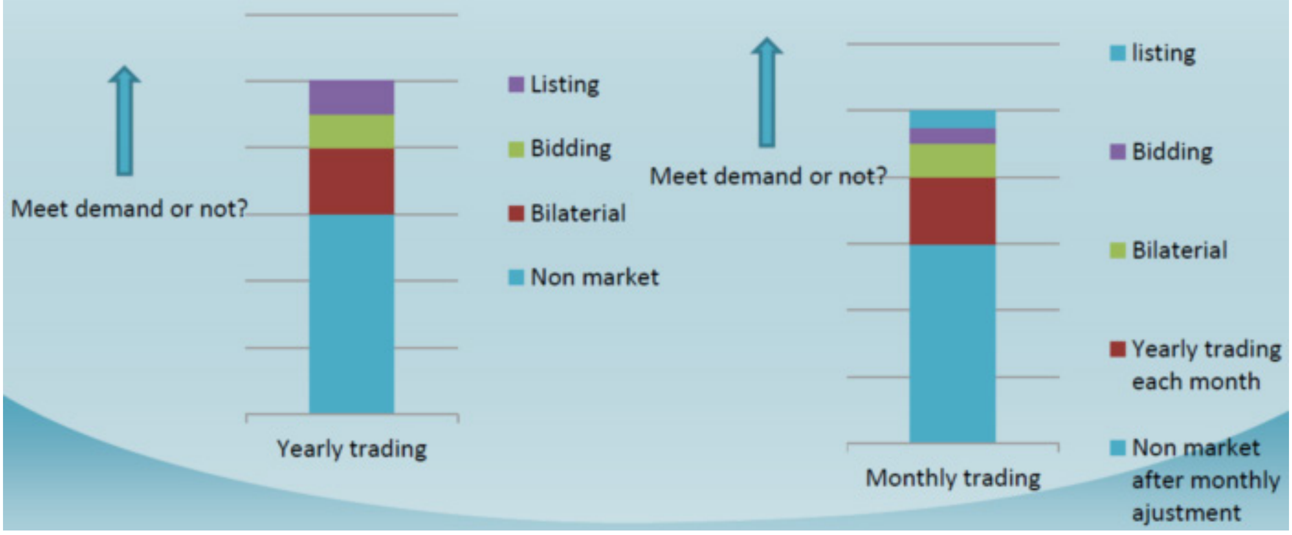
Annual and monthly power trading in the provinces
The annual generation schedules of the non-market part are organised and then allocated to each month, while residual electricity is traded on the market until demand is met.

Monthly power trading follows the same process once the annual power trading has been allocated. Both annual and monthly power contracts are traded once or twice before delivery. It is not a continuous process.

Inter-provincial and regional power trading
In China, demand is concentrated in the east, while the coal mine deposits and RES are predominantly in the west. It is now common to see long distance and high-volume energy transmission being used to optimise allocation of energy resources. Total cross-regional transmission capacity stood at 136.15 GW in 2018. Some basic rules for annual and monthly inter-provincial or inter-regional trading are as follows:

- Contract path principle.
- Wheeling charges with stamp methodology.
  Provincial charges (220kV and below at most, only if the generators are connected to the provincial grid).
  Regional charges (500kV and above, with power trading using the regional

Figure 4.1: Annual and monthly trading.

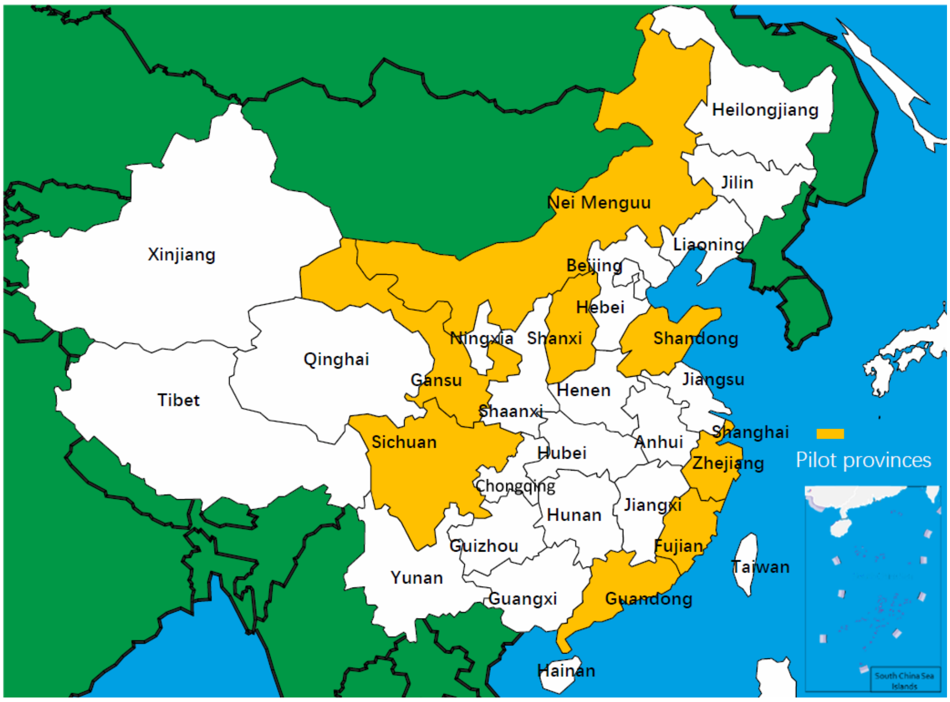


grids, based on the contract path).
Charges for the use of inter-regional transmission lines (mostly HVDCs).

- A sequence of annual and monthly power trading, coordination with non-market sector.

The spot market
After annual and monthly trading, residual demand is handled in the spot market. The NEA has designated eight provinces as pilot spot markets (Figure 4.2). These eight provincial systems have selected two different models for their local spot markets.

Figure 4.2: The eight provinces with pilot spot markets.



Model 1: Annual and monthly power trades are physical contracts and residual demand after the annual and monthly power trading is handled in the spot market. Suppliers and large consumers may participate in the spot market and trade with generators directly.

Model 2: Annual and monthly power trades are governed by Contract for Difference (CFD) financial contracts. The full volume of generation is traded on the spot market and the annual and monthly trades are settled by CFD contracts in each trading period.

4.1.5 Recent progress in power market development

Power market reform has seen significant progress following the publication of two documents by NDRC and NEA jointly in the first half of 2020:

- 'The basic rules for medium and long-term power trading revised'.
- 'The notification of promoting continuous trial operation with financial settlement for the pilot power spot markets'.

Outlines of 'the notification of promoting continuous trial operation with financial settlement for the pilot power spot markets' and recent progress.

The national government issued this document in March 2020 to guide the financial settlement process.

Its main points are as follows:
The pilot spot markets represent an important step in power sector reform. They will help to build a fair and competitive market environment by: strengthening guidance in the initial stages; improving the connections between spot market and long/medium power trading; reinforcing management of the financial settlement process in the spot power markets; maintaining the neutrality of power market operators; preventing the risks of market distortions and so on.

Recent progress
In accordance with the quarterly monitoring reports of power market reform published by CEC, some of the pilot provincial markets have begun a continuous trial operation with financial settlement. For example, Fujian provincial power market has started a continuous trial operation with financial settlement for two months. Others are preparing to begin the process.

With the deepening of electric power market reform, new problems have emerged in the power spot market operation, such as the linkages between inter-provincial and intra-provincial markets, and in medium and long term and spot markets, etc. Agencies that lead the market construction across the country are constantly optimising market rules to promote the long-term operation of power spot market. Coordination between market and non-market trading, long/medium and spot market, provincial and cross-provincial trading needs to be carefully handled.

Outlines of 'the basic rules of medium and long-term power trading revised', and recent progress.

This revised version of the basic rules for medium and long-term power trading summarises the operational experiences of medium and long-term power trading over recent years. Some of the important points are: more trading products relating to years, year, season, month, and week and distinguished as peak and off-peak; additions and improvements to regulations for market participation, trading products, pricing, trade scheduling, non-market and market trading coordination, imbalance treatment, security checks, market supervision, ancillary services, partial VRE participation, continuous trading in the trading period and so on.

Recent progress
Most provinces have drawn up their own provincial rules based on the national rules and the process bears some resemblance to elements of the EU's 2009 Third Energy Package – a legislative package that aimed to further open up the gas and electricity markets in the European Union.

In 2021, 'the rules of medium and long-term cross provincial power trading in East China region' were announced by the regional regulator. This represents an important instance of provincial power markets coupling in one region and will add to an accumulation of experience of market coupling in regional systems at a national level.

4.2 Comparison with development and status in Europe

The development of the power market and transmission systems in China and Europe have some similarities, such as large, interconnected power systems, a step-by-step process of market development, three directives in China and three energy packages in Europe, RES targets and carbon emission reduction targets.

The power sector in Europe has experienced unbundling transmission from VIUs, regulated Third Party Access (TPA), T&D tariff, independent regulators, retail business opening, market coupling, and cross border trading guided by the three energy packages issued by the European Commission between 1996 and 2018.

The power sector in China has taken a similar road map. It has introduced double track electricity pricing, levelised cost plus pricing for generators, benchmark pricing for coal fired generation, unbundling generation from vertically integrated undertakings (VIU), regulated third party access, T&D tariff, independent regulator, retail business opening, and a competitive market, as directed by the three directives between 1978 and 2021.

The key features in Europe and China are explained as follows:

- **Unbundling**
  China: The competitive part, generation, was separated from the monopoly part, transmission and distribution, after unbundling.

Europe: The monopoly part, transmission, was separated from the VIUs and VIUs own competitive part, generation and supply, and monopoly part, distribution legally separated after unbundling.

- **Independent regulation**
  China: The independent regulator, SERC, was founded in 2003 and became part of the NEA in 2013.
  Europe: The independent regulators were established following the issue of the Third Energy Package by the European Commission.

- **Power exchanges (PX)**
  China: The PXs are relatively independent to a certain extent and TSOs hold shares in the PXs.
  Europe: The PXs for long and medium-term trading (financial trading) are independent and the PXs for the spot market are owned by TSOs.

- **Long and medium-term trading**
  China: Energy-only trading is not separated into peak and off-peak trading. The trading process is not continuous: trades may occur one or more times prior to delivery.
  Europe: Energy trading is separated into peak and off-peak periods and the trading process is continuous. Trading can take place during the trading period with no limit on frequency.

- **Power dispatching**
  China: SGCC and CSG have set up highly hierarchical power dispatching structures and these have played important roles in ensuring the safe and stable operation of the transmission systems.
  Europe: A pan-European power coordinating centre is under consideration. Some regional power coordinating centres already exist, in countries that are already closely interconnected.

- **Transmission capacity allocation**
  China: HVDC transmission lines now transmit a large amount of power from energy resource rich provinces to distant regions with a high concentration of load centres, and interconnect all the regional systems countrywide. All the transmission assets are owned by SGCC and CSG and transmission capacity is efficiently allocated and utilised.
  Europe: The Forward Capacity Allocation guideline (FCA) lays down detailed rules on cross-zonal capacity allocation in the forward markets and on the establishment of a common methodology to determine long-term cross-zonal capacity, as well as the establishment of a single allocation platform at European level offering long-term transmission rights. The allocation of transmission capacities between bidding areas in the spot market in Europe is determined implicitly in the European market optimisation algorithm.

Summary

On many issues, China and Europe have to some extent followed parallel paths in market development.

5. TRANSMISSION PLANNING PROCESS IN CHINA TODAY

5.1 Chinese power system planning

5.1.1 Chinese power planning process

Power planning consists mainly of national power planning and provincial power planning. The national power plan is prepared and issued by the NEA after having been approved by the NDRC. The provincial-level power plan is prepared by the provincial energy authority and is reported to the provincial government for approval and publication after being reported to NEA. The national power plan guides the provincial power plan. The provincial power plan complies with the national power plan and the provincial energy development plan.

The Electric Power Planning and Engineering Institute (EPPEI) is the main unit responsible for electric power planning research work. It is tasked by the NEA and the provincial energy authority to carry out specialist and comprehensive research on electric power planning.

Electric power enterprises implement and ensure the safety of electric power planning. They are responsible for providing basic planning data, undertaking research topics for electric power planning, making planning recommendations, cooperating with planning, and preparing business cases in accordance with approved national and provincial power plans. Relevant units such as power industry federations and other industry associations, societies, scientific research institutions, and universities are required actively to coordinate power planning work and make research recommendations to the competent energy department.

NEA and provincial energy authorities carry out power planning two years in advance. Power planning in China consists of five steps: research and preparation; compilation and connection; review and release; implementation and adjustment; evaluation and supervision.

(1) Research and Preparation
Power planning research includes planning recommendation, special topic research and comprehensive research. Power planning recommendations are put forward by power companies, power industry associations, research institutions and universities. These recommendations form the basis for power planning. The specialist research is related to power planning and involves power demand, structure and layout, system security, economic evaluation, environmental evaluation, scientific and technological progress, and system reform. The remit of the comprehensive research is to offer extensive and systematic power planning by means of a comprehensive selection and balance. The comprehensive research report forms the basis of preparations for national and provincial power planning.

(2) Compilation and Connection
Power planning should be incorporated into the comprehensive research results of power planning, fully absorb the power planning recommendations, and put forward the guiding ideology, basic principles, development goals, key tasks and safety measures for power development.

National power planning needs to focus on: large-scale hydropower (including pumped storage); nuclear power scale and project construction arrangements (including commissioning and start-up); wind power; photovoltaic, CSP, and other new energy power generation large-scale construction projects; large-scale coal generation projects; inter-provincial and inter-regional power grid project construction arrangements (including commissioning and start-up); provincial power grid project construction arrangements for projects of 500 kV and above (including commissioning and start-up); and the province's own coal and gas power over the five-year planning period.

Provincial power planning should focus on clarifying the construction arrangements (including commissioning and start-up) of large and medium-sized hydropower (including pumped storage), coal, gas, and nuclear power projects in its region, and further clarifying the scale and layout of new energy generation. It will also include proposals for 110 (66) kV and above power grid project construction arrangements (including commissioning and start-up) and 35 kV and below power grid construction projects.

Provincial power planning is subordinate to national power planning and provincial energy planning, and the national power planning and provincial power planning are connected as follows:

- After the start of planning, the provincial energy authorities study and submit the first draft of the provincial power plan and submit it to the NEA.
- After NEA has organised a summary balance of the first draft of the provincial planning, it initially defines the main objectives of the national plan, the overall framework and the boundary conditions of the provincial plans and submits written feedback to the provincial energy authorities.
- The provincial energy authorities prepare provincial power plans (including an environmental impact assessment) based on feedback and submit them to NEA.
- NEA integrates and balances the provincial power planning and provides written feedback. The provincial energy authorities revise and improve the provincial power planning in line with the feedback.

(3) Review and release
National electric power plans are generally submitted to the NDRC for approval by the NEA before the end of May of the first year of the Five-Year Plan and are then publicly released by the NEA. Provincial power planning is generally prepared by the provincial

energy authority before the end of June of the first year of the Five-Year Plan, and is published once it has been agreed by the NEA.

(4) Implementation and adjustment

After the approval of the power plan, the energy authorities and power companies at all levels have to implement in full the tasks specified in the plan. Power companies are required to formulate their development plans in accordance with the approved electric power plans. The annual scale of new energy generation approved by the provincial energy authority may not exceed the target for the year in question, as determined by the annual development plan. Unapproved power projects cannot enter the power market for trading, cannot be included in the permitted cost of the power grid, and cannot enjoy support policies such as electricity price subsidies and tax reductions.

While the plan is being implemented, it can be adjusted to reflect the actual situation. Two to three years after the release of the power plan, the NEA and the provincial energy authority may adjust the Five-Year Plan based on economic development and implementation of the plan. For power planning adjustments, special research work should be organised in the second year of power plan implementation, and adjustment plans should be prepared in the third year, when the adjustment plan should be reviewed, approved, and issued.

(5) Evaluation and supervision

The NEA and the provincial energy authority should entrust intermediaries to carry out mid-term assessments of national and provincial power planning and draw up a 'Mid-term Assessment Report on the Implementation of Power Planning' two years after the implementation of the plan and a 'Power Planning Implementation Evaluation Report' after the end of the Five-Year Plan. The NEA's agencies have to prepare and publish a 'Supervision Report on the Implementation of the Mid-term Power Plan' and a 'Supervision Report on the Implementation of the Five-Year Power Plan' accordingly. These act as important reference points for future planning preparation and adjustment.

5.1.2 Power planning content

The power plan is synchronised with the national economic and social development plan. The preparation cycle is generally five years. The research and preparation of the power plan looks at power development trends 10-15 years ahead. Considerations include load forecasting, power generation planning and power grid planning.

(1) Load forecasting

A prediction is made for each region's load demand, taking into account key factors such as economic development, industrial structure adjustment, the urbanisation process, and electric energy substitution. These factors together yield the future power demand and load curves of various provinces, regions and countries. Usually, three load forecast prediction scenarios are prepared (high, medium and low), of which one is recommended.

(2) Power generation planning
A power balance analysis takes account of the demand level and characteristics of the local electricity market. It makes a reasonable assessment of the scale of renewable energy generation and gives priority to renewable energy, so reaching a decision on the installed capacity, structure and layout of power generation. Combined with load characteristics, a system peak shaving balance analysis is carried out to determine the construction scale and scheme selection of the peak shaving power source. The analysis also formulates a number of alternative construction options, conducts technical and economic comparisons, and proposes a reasonable annual construction scale and investment estimates.

(3) Power grid planning
Power grid planning takes into account factors such as load development, power supply layout, and power transmission and receiving scheme, after which the necessary electrical calculation and analysis are carried out to estimate power flow, stability, reactive power, short-circuit current and so on, so that the project can be incorporated into the target grid scheme of 220kV and above. The planning process also develops a number of alternative construction options, conducts technical and economic comparisons, proposes recommended solutions, power transmission and distribution projects and makes estimates of the investment required. Other factors include consideration of urban and rural economic and social development and the urbanisation process, and preparing distribution network planning and smart grid planning.

5.2 Chinese transmission planning practice

5.2.1 Power grid planning mechanism of SGCC

In 2019, the SGCC established the Power Grid Planning Management Committee and the Power Grid Planning Expert Advisory Committee.

Responsibilities of the Power Grid Planning Management Committee
To study power grid development strategy, development direction and development ideas, examine work plan and priorities of power grid planning; coordinate the safety, quality, and efficiency of power grids, consider major issues of power grid development, the reconstruction of backbone grids and major project construction schemes, and examine the overall planning report of the State Grid.

Responsibilities of the Power Grid Planning Expert Advisory Committee
To provide advice and suggestions on major boundary conditions, technical standards, and basic principles of power grid planning, and provide technical support for the decisions of Management Committee.

- **The headquarters** is responsible for the overall planning of the State Grid and oversees regional power grid planning.
- **The regional division** is responsible for regional power grid planning and oversees provincial power grid planning (high voltage grid).
- **The provincial division** is responsible for provincial-level power grid planning and oversees municipal grid planning.

- **The municipal division** is responsible for power grid planning of 110 (66) kV and below.

5.2.2 Basic principles of grid planning

China’s power grid planning follows the basic principles of safe, green, efficient, coordinated and shared development.

Safe development. Grid planners should: encourage bottom-line thinking (where outcomes can be measured more quickly and easily); deepen research on the characteristics of large power grids; improve the structure of the power grid; rationally stratify and partition; solve the problems of ‘strong DC and weak AC’, short-circuit current exceeding the standard, and heavy load of the current; and avoid dense transmission channels as much as possible. Key users and areas should be equipped with certain emergency self-provided power supplies and ‘black start’ power supplies. Key cities should construct important networked channels as ‘security’ lines. Grid planners should encourage continued improvement of the ‘three lines of defence’ to prevent the risk of large-scale blackouts.

Green development. Grid planners should: actively develop non-fossil powered energy; promote the clean and efficient use of coal power, and achieve full control over coal consumption; strengthen the regulation capacity of the power system; promote the unified planning of source-grid-charge-reservoir; accelerate the flexible adjustment of power supply construction; and meet the need for large-scale development of new energy. Grid planners should also propose a reasonable development scale and layout for new energy, in line with the target for a new energy utilisation rate of not less than 95%. The aim should be to improve the grid-connected performance of new energy grid-connected units and improve the tolerance level and support capacity of new energy.

Efficient development. Grid planners should: make good use of resources, make optimal increments, and actively improve the overall efficiency of the power system. In the planning stages, they should give full consideration to demand response, backup sharing, peak load and valley filling at 5% of the maximum load, and put more emphasis on power balance. Plans should prioritise scientific, steady, and precise investment. Plans should implement the central government's deployment of price and fee reductions, tap all potential to increase efficiency, reduce and cut costs, and continuously improve the quality and efficiency of development.

Coordinated development. Grid planners should: optimise the power structure and layout according to the local balance principle; give priority to the power supply in the receiving area, and support clean and efficient coal power at the load centre. Gas-fired power stations will be arranged in the Yangtze River Delta and the Beijing-Tianjin-Hebei region where gas sources are guaranteed, and electricity more affordable.

While making effective use of existing channels, the plan is for new cross-regional transmission channels to be built. In accordance with the principle of integration of wind, PV, coal storage and transmission, the power supply at the dispatch end, the corridor along the way and the end market will be coordinated. New cross-regional connectors should adhere first to market orientation and agreement, and the governments and relevant companies who are contracting to sell or buy power should sign long-term agreements to clarify transmission and pricing principles.

5.2.3 Chinese transmission planning process

China's power grid planning follows the basic principles of safe, green, efficient, coordinated and shared development. It includes four steps: research on major issues, determination of planning boundary conditions, comparison of options, and preparation of planning reports.

(1) Research on major issues
Power demand forecasting and load characteristics research
Tasks: Study and evaluate the medium and long-term economic development trends, consider the development of new kinetic energy, and make projections for the total amount, structure and layout of electricity demand. Consider the impact of distributed power, energy storage, and electricity price policies on load characteristics, analyse the peak and off-peak consumption differential and evaluate the demand-side management potential and implementation measures.

Research on power supply structure and development layout
Tasks: Implement the national energy development strategy, analyse the medium and long-term development paths of various power sources, focus on clean development and construction scale and layout of coal power, peak shaving performance, flexibility reform and policies relating to coal power units, and put forward proposals for coal power development. Combine new energy development policies, technological progress, market factors, and so on, to evaluate the scale and timing of distributed and offshore wind power development in central and eastern China. Research and make proposals for new energy development and layout. Analyse peak capacity and peak demand in power grids, and make proposals for pumped storage power stations, energy storage, and gas. The recommendation is to make flexible adjustments to the construction scale and layout of power generation, in order to make the system easier to regulate.

New energy consumption research
Tasks: Calculate the contribution of new energy to the power balance in actual operation. Analyse the impact of new energy output characteristics and unit performance on the safe operation of the power system. Combine the system with peak and frequency modulation performance. Research and propose new energy consumption capacity and development scale recommendations.

Power grid security research
Tasks: Identify and evaluate the weak links that might impact the nation's power grid security. Analyse the profound changes in power grid characteristics brought about by the large-scale connection of new energy sources and multiple DC feeds. Study and make proposals to optimise the power grid structure. Enhance the frequency, voltage support and anti-disturbance capability of the system.

Grid economic research
Following the increase in electricity consumption, a rolling analysis of the power grid's capacity will be a boundary condition for new power grid project arrangements. Research will need to focus on two key factors - reducing the cost of social energy consumption and achieving sustainable development of power. This will involve improving efficiency and preventing risks, deepening the research of grid investment strategies, clarifying the investment direction, structure, scale and timing, improving grid efficiency, and enhancing the operating efficiency of grid companies.

(2) Determination of boundary conditions
Major boundary conditions such as power demand forecast, power supply installation scale and layout, and cross-provincial and cross-regional power flow, represent the prerequisites and foundations of grid planning. Reaching a reasonable determination of boundary conditions is key to ensuring the accuracy of power grid planning. Grid companies need to take the initiative to communicate with the government's energy authority in order to clarify the boundary condition plan as a basis for grid planning. On the basis of previous major studies, recommendations for grid planning boundary conditions have been put forward:

- Provinces to research and present recommendations for boundary conditions such as power demand, installed power, and cross-regional power and capacity arrangements.

- Research will include carrying out load characteristic analysis, uniform adoption of production simulation procedures, power supply and demand balance analysis by province and region, and a study of the scale, occurrence period and duration of electricity and power profit and loss.

- The aim will be to coordinate the development of power supply bases, the consumption market, and the construction of delivery channels, optimise the adjustment of existing power flows, and propose new cross-provincial and inter-regional power flows.

- Provincial companies will report the power supply and demand situation and the proposed layout of power sources to provincial energy authorities and clarify the power demand forecast and power construction plan for each province.

- The State Grid Development Department takes the lead and actively participates in the work of the NEA's power planning working group to promote the clarification of major boundary conditions such as national power demand forecasting, power supply scale and layout, and inter-provincial and inter-regional power flows.

(3) Comparison of options
Grid companies need to study solutions and measures based on the needs of grid development, combined with actual operational problems. They should strengthen the calculation and analysis of grid planning simulation and consolidate the planning

foundation. The grid plan proposes that the grid company planning unit needs to carry out a comprehensive technical and economic comparison and selection of multiple schemes, and propose recommended schemes to improve the scientific level and authority of the planning.

- Through the grid planning simulation calculation platform provided by the State Grid Simulation Centre, unified calculation data for the entire network is available. The current grid uses measured values, and the planning grid uses typical parameters.

- According to the actual development and operation of the power grid, a variety of power grid schemes are constructed, and comprehensive technical and economic comparisons are proposed for individual schemes to ensure that the scheme is technically feasible, economically reasonable, and practicable.

- Suggestions relating to the construction of major projects will be used as the basis for the annual operation mode arrangement.

- Planners need to ensure that the production and operation departments are involved throughout the process and that their opinions are sought on power grid and engineering construction plans.

- Grid planning can include not only projects and investment, but can also include an analysis of investment capacity and electricity prices. It must be linked to operating indicators such as asset-liability ratios and the performance of provincial companies.

(4) Preparation of planning reports
The **grid development planning report** is a guiding document for SGCC's grid planning at all levels, the basis for scheduling of grid projects, and the ultimate expression of the results of grid planning.

The SGCC draws up a 'three-level' grid planning report for the headquarters, the six regions, and the 27 provincial grids. Planning reports at all levels include a general report, two special reports (a special report on power supply and demand analysis, and one on grid planning simulation calculations), as well as additional special reports as required by the characteristics and issues of the individual province. The planning report should include power grid development assessment, power supply and demand and balance analysis, target grid planning, grid construction focus, investment estimates and benefit evaluation, policy recommendations and safety measures.

5.2.4 Key factors in transmission planning

For high-voltage (especially DC) transmission, the need for resource allocation and the complementary and mutually beneficial functions among different regions are crucial. In such cases, more communication is required between the various stakeholders (power generation and power grids, different provinces, national and local governments). Such plans are likely to be somewhat controversial. The final construction depends on the outcome of discussions between the stakeholders and the attitude of the national government.

For low-voltage transmission, the main issue is to ensure the safety and stability of power system operation and the reliability of power supply. In such cases, the planning scheme is based more on objective laws and actual physical needs, which do not tend to be controversial. The viability of construction mainly depends on local requirements for power supply reliability and the investment situation of grid companies.

5.2.5 Outlook for transmission planning in a market environment in China

Intermediate steps in the planning process
Firstly, greater value needs to be given to the question of whether power generation companies and power grid companies are willing to invest in power plants and power grids. In a market environment, the construction of certain power sources and transmission lines is not determined by national or local government. Therefore, a viable planning scheme needs to consider the attitude of the relevant power companies.

Secondly, incentives are set to play an increasingly important role in grid planning. Currently, transmission planning focuses on specific transmission projects, because the decision on whether to proceed with construction or not is cleared at the top level of government. However, future transmission projects need to feature proposals to encourage companies to invest in the projects.

Thirdly, a market operation simulation is necessary. The CBA process needs to be changed so that in future, experts and planners in China think about the profitability of certain projects based on a market operation simulation. The operation hours and transmission profit per kWh should form part of the planning stages.

Changes when dispatch of power generation becomes more market based
The long-distance transmission lines that are designed to transmit a certain mix of new energy generation and thermal power generation are set to be planned in a different way.

Currently, a number of long-distance transmission lines are planned that will transmit energy resources from the resource centres in the western part to the load centres in the eastern part in China. New energy resources such as wind and solar are taken into consideration, together with coal power, and this mix offers stability to the power transmission system.

In a market environment, the generation mix may be different from this approach. Planners should be ready for transmission lines that focus on delivering new energy generation.

Additionally, the location of power sources with lower costs will be a crucial factor in transmission planning. More transmission capacity is necessary to meet the requirements of power plants that are likely to be built in future. Therefore, the planning process for transmission projects will need to consider the location of various power plants and rank them accordingly.

Changes when power prices are established in each province based on market principles

A more cautious approach will be taken towards transmission lines that connect different provinces. Since power prices are established in each province based on market principles, power price trends are different in each province. Therefore, an economic evaluation of cross-province transmission lines is both more critical and more challenging. A simulation of market operation in the relevant provinces is necessary, rather than the current practice of calculating the fixed power price difference.

6. TRANSMISSION SYSTEM PLANNING IN EUROPE

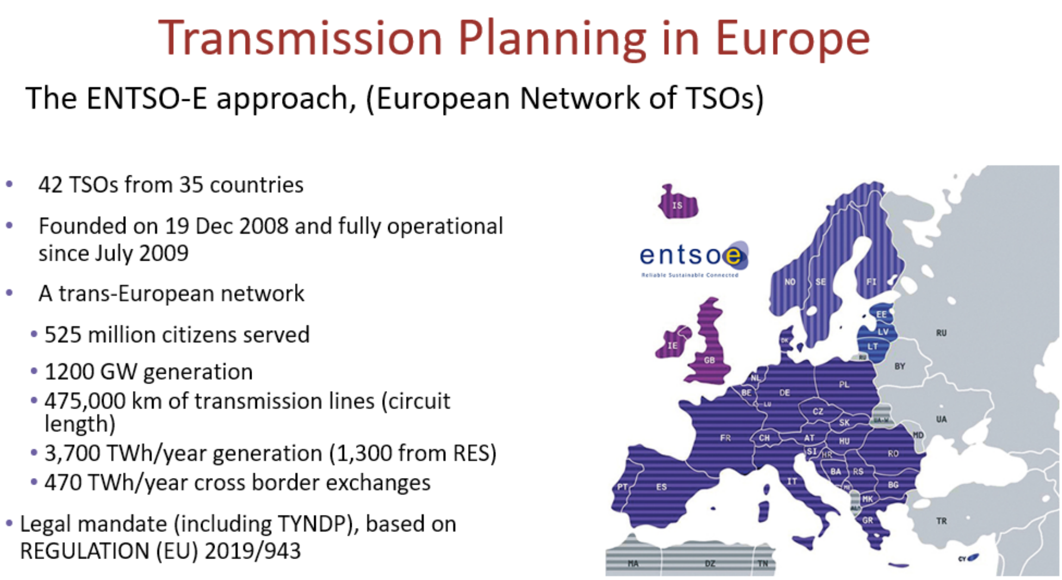
6.1 ENTSO-E overview

ENTSO-E promotes closer cooperation across Europe's TSOs to support the implementation of EU energy policy and achieve Europe's energy and climate policy objectives, which are changing the very nature of the power system. The main objectives of the ENTSO-E centre on the integration of renewable energy sources (RES) such as wind and solar power into the power system, and the competition of the internal energy market (IEM). This is central to meeting the EU's energy policy objectives of affordability, sustainability and security of supply. ENTSO-E aims to be the focal point for all technical, market and policy issues relating to TSOs and the European network, interfacing with power system users, EU institutions, regulators and national governments.

With the establishment of ENTSO-E, the European TSOs have been given important tasks and thereby substantial influence on the development of the European power market and transmission system. Key information about ENTSO-E is shown in Figure 6.1.

One of the main tasks of ENTSO-E is to create a non-binding community-wide Ten Year Network Development Plan (TYNDP) every other year. Grid development is a vital instrument in achieving European energy objectives, such as security of electricity supply across Europe, and sustainable development of the energy system with RES integration and affordable energy for European consumers through market integration. As a community-wide report, the TYNDP contributes to these goals and provides a central reference point for European electricity grid development.

Figure 6.1: ENTSO-E key figures.



Besides proposing an EU-wide TYNDP, ENTSO-E has a mandate to:

- Propose network codes.
- Ensure EU-wide market integration.
- Support research and development.
- Analyse the European Resource Adequacy Assessment (5-15 year horizon).
- Provide an integrated network modelling framework at the European level.

6.2 ENTSO-E TYNDP - overview

As mentioned above, the mainstay for TSO planning is the TYNDP which is carried out under EU regulation 714/2009. While the plan is non-binding; the TYNDP is an important pan-European planning tool which is published every two years. The TYNDP 2018 consists of a package of documents[13], including the following:

- A scenario report describing future European scenarios that form the basis for the TYNDP. The scenarios are developed in cooperation with European stakeholders including regulators. For the first time, the same scenarios are used both for power and gas (ENTSO-G is the corresponding cooperation for gas-TSOs, and draws up a parallel TYNDP for European gas transmission). Therefore, TYNDP-Electricity and TYNDP-Gas use the same data describing future energy systems for 2025, 2030 and 2040.

- For the first time a pan-European 'system need' report has been introduced. The report describes future power system needs with a focus on new or reinforced transmission capacity in the main European transport corridors. The results are based on long term pan-European market- and grid-analyses extending to the year 2040.

- The idea is to compare the power system with a 'frozen' transmission grid (corresponding to the 2020 grid) with a system with sufficient grid development for 2040, to illustrate the benefits of a proper grid development.

- Regional investment plans address system and transmission needs at a regional level. For planning purposes, Europe has been divided into six regions.

- The TYNDP 2018 main report makes transmission development its focus, by means of a socio-economic cost benefit analysis of a number of concrete projects. Most projects have been nominated by the TSOs based on national and regional planning and on the work carried out based on 'system need' (see above).

- In addition to the TSOs' project proposals, third-party projects (typically commercial investor projects) are addressed in the TYNDP. Third party

13 https://tyndp.entsoe.eu/tyndp2018/:

projects must meet the same criteria for inclusion in the TYNDP as TSOs' projects.

- Alongside the TYNDP main report, a number of insight reports are published that focus specifically on key regional or European subjects that are important for the future development of the power system (e.g. transition of the power system into a green system).

6.3 TYNDP results – overview

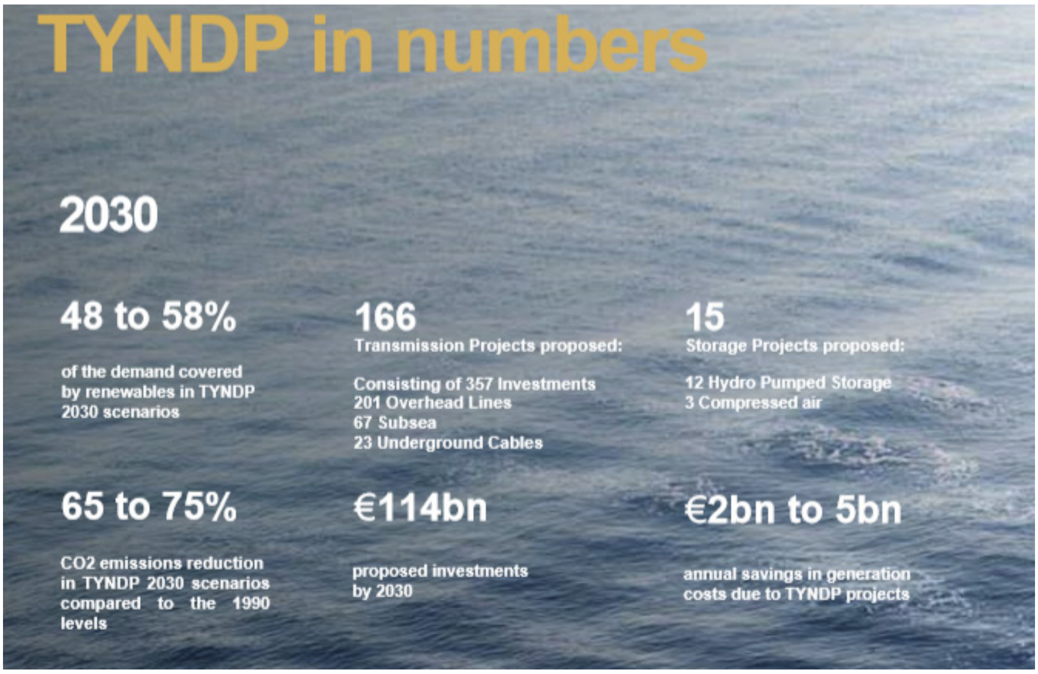
The 2018 TYNDP plan includes a description of 166 transmission projects and 15 storage projects, all scheduled to be commissioned before 2030. For each project, cost-benefit evaluations were conducted in four European scenarios. The total investment in TYNDP 2018 has been estimated at EUR 114 billion. The projects will lead to savings of EUR 2.5 billion/yr in generation costs. The plan also illustrates a decline in wholesale prices as the transmission projects allow for the cheapest generation resources to be shared across Europe.

Investment in more grid connections is a precondition for further RE integration (wind and PV). According to the 2030 scenarios, RE will account for between 40% and 58%, while CO_2 emissions will reduce by between 65% and 75 % in the 2030 scenarios.

In addition, the TYNDP projects in general will help to ensure improved security of supply, because they are helping to relieve existing bottlenecks in the system.

Main results from TYNDP 2018 are shown in Figure 6.2.

Figure 6.2: Brief overview of TYNDP 2018 results.



6.4 Project of Common Interest (PCI)

Every second year the European Commission updates a list of projects of high European importance, the so-called PCI list. This list is taken from the most recent TYNDP. The latest list was published in November 2019.

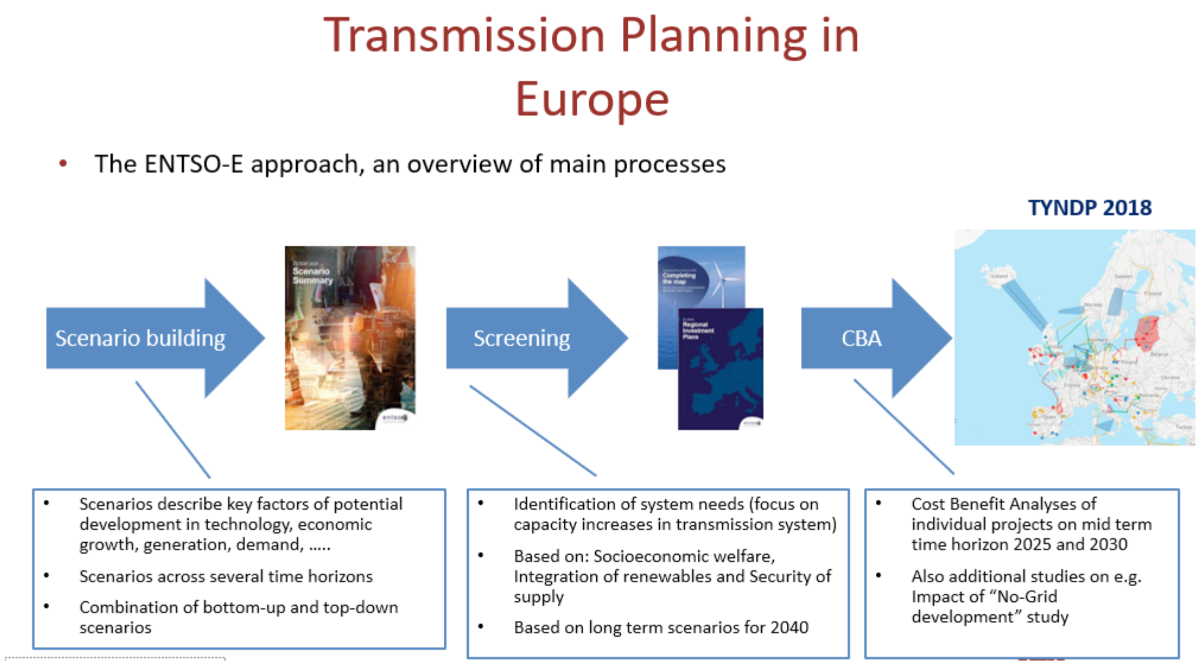
PCI projects have to comply with certain rules with regard to transparency and involvement of stakeholders. However, in return the PCI projects can anticipate more rapid authorisation and financial support from EU.

6.5 ENTSO-E planning process

General
ENTSO-E uses a coordinated and comprehensive transmission grid planning approach, which includes sharing of data, development of scenarios, coordinated market modelling and grid stability modelling, combined cost benefit analysis, stakeholder engagement, and so on. The aim is to ensure system stability, guarantee power supply and integrate more RE at the lowest possible cost.

In general, the ENTSO-E approach ensures that pan-European grid planning is optimised for the common good and addresses the different interests at stake. A key aspect of the ENTSO-E methodology is the recognition from the transmission grid planning perspective that the market will determine the use of the grid. The main processes in the ENTSO-E approach are scenario building, screening, and CBA (see Figure 6.3).

Figure 6.3: ENTSO-E TYNDP planning process.

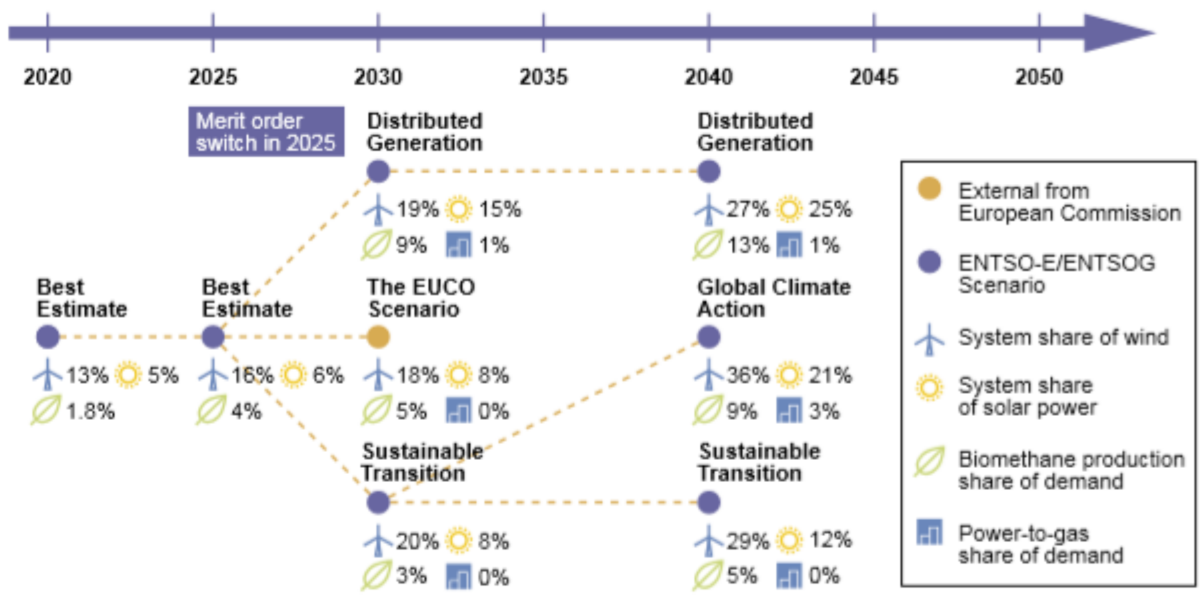


Step 1- develop scenarios for the future
To identify what Europe needs in terms of electricity transmission infrastructure, it is first necessary to analyse how the energy landscape will evolve. Some political objectives have been set for 2030/2040, but many uncertainties remain regarding generation investments, demand evolution and market developments, to name but a few. The TYNDP scenario development is about framing uncertainties. It is not about predicting the future. Stakeholders are strongly encouraged to participate in the scenario building.

Figure 6.4 shows the scenarios in the 2018 TYNDP.

The TYNDP scenarios include a 'best estimate' scenario for the short and medium term (including a merit order sensitivity between coal and gas in 2025), but three narratives regarding the longer term reflect increasing uncertainties. However, they are all on track to meet the 2030 decarbonisation targets set by the EU. The scenario pathways from 2020 to 2040 can be seen in Figure 6.4.

Figure 6.4: TYNDP 2018 scenarios.



To give an idea of the spread in narratives of scenarios, we have listed narratives for three of the scenarios 2030/2040 (ref ENTSO-E TYNDP 2018 scenario report):

- Sustainable Transition (ST) seeks a quick and economically sustainable CO_2 reduction by replacing coal and lignite in the power sector with gas. Gas also displaces some oil usage in heavy transport and shipping. The electrification of heat and transport develops at a slower pace than in other scenarios. In this scenario, reaching the EU goal (80%-95% CO_2 reduction by 2050) requires rapid development during the 2040s by means of increased technological adoption or evolution.

- Distributed Generation (DG) places prosumers at its centre. It represents a more decentralised development with a focus on end user technologies. Smart technology and dual fuel appliances such as hybrid heat pumps allow consumers to switch energy depending on market conditions. Electric vehicles see their highest penetration with PV and batteries widespread in buildings. These developments lead to high levels of demand side response. Biomethane growth is strong as connections to distribution systems grow, utilising local feedstocks

- Global Climate Action (GCA) represents a global effort towards full speed decarbonisation. The emphasis is on large-scale renewables and even nuclear in the power sector. Residential and commercial heat become more electrified, leading to a steady decline in gas demand in this sector. Decarbonisation of transportation is achieved through both electric and gas vehicle growth. Energy efficiency measures affect all sectors. Power-to-gas production sees its strongest development within this scenario.

Step 2 – Screening of needs for infrastructure expansion

The TYNDP normally offers three or four scenarios for the development of the power system. Some set high targets for RE, some envisage a more decentralised power system, and some envisage a strong European framework. Based on these scenarios, experts representing the 41 TSOs in 34 European countries carry out joint planning studies.

Using common methodologies and tools, the experts look at how power will flow in Europe in 2030/2040, taking into account the different scenarios. This allows them to see where bottlenecks will be and how much transmission capacity is needed at borders to manage these flows.

The screening studies result in a series of infrastructure projects. These are only one feature of the entire TYNDP. Other features are made up of projects from third party investors (non-ENTSO-E members) that meet the European Commission's criteria for inclusion in the TYNDP.

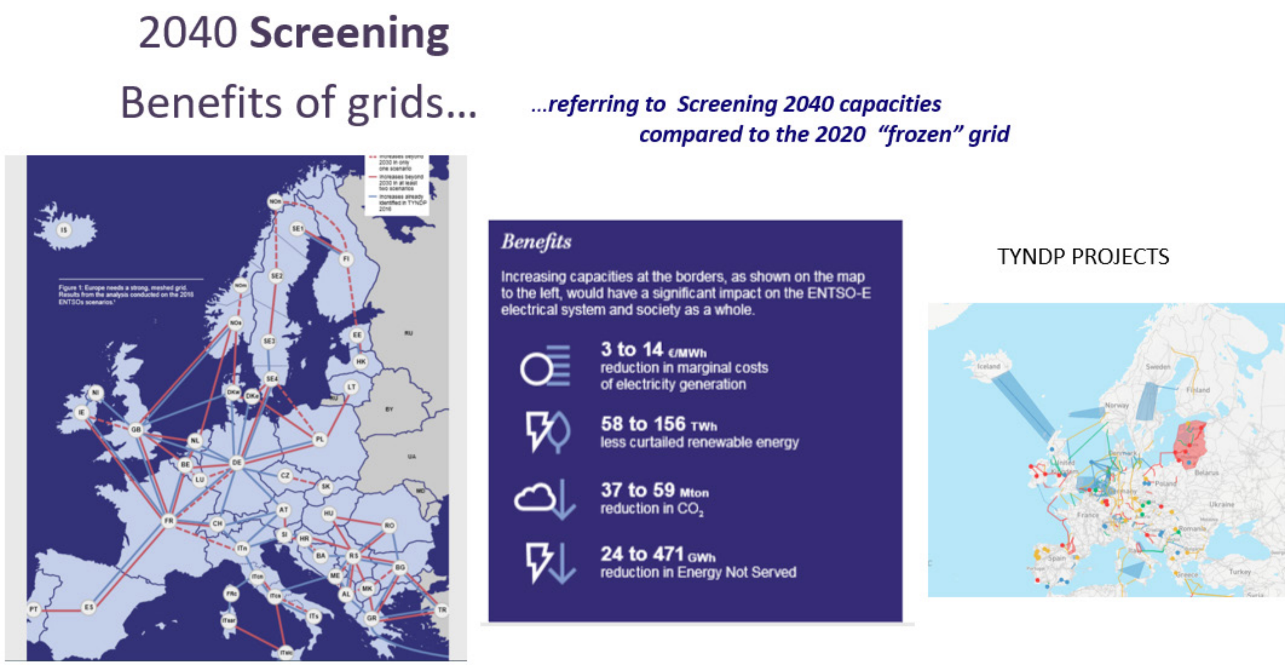
The list of projects is open to public consultation before being finalised.

Figure 6.5 shows an example of the results of these screening studies in the TYNDP 2018 process. The results are based on market modelling for Europe as an integrated system. The market model emulates the European spot market in the future scenarios. In an iterative process, the capacities at the borders between market areas are successively increased, and borders with highest socio-economic benefits compared to investment costs of expansion are selected for further assessment.

Figure 6.5 also shows a comparison between the 2020 'frozen' grid and an expanded 2040 grid. It follows that the expansion of the grid as proposed in the screening will cut the marginal costs of generation, limit curtailment of renewables, and reduce CO_2 emissions.

In addition, a reduction of expected energy not served (EENS) is evident.

Figure 6.5: Example of screening results for selecting potential projects for the TYNDP 2018.



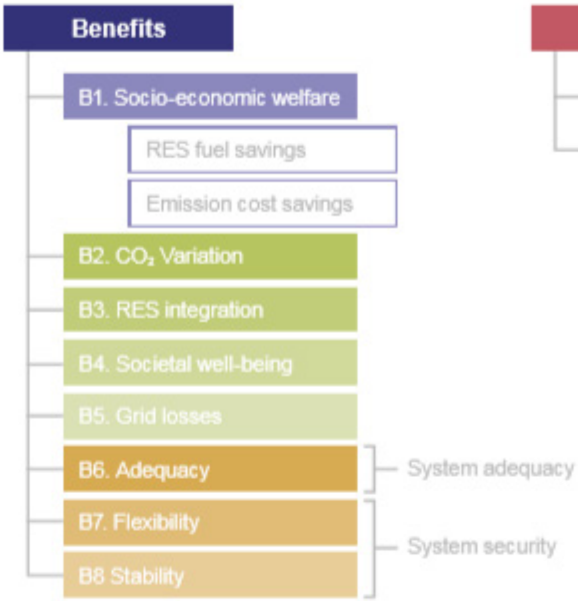
Step 3 – Project assessments
The final phase of the TYNDP planning process is the assessment of projects. This is done using a European-approved methodology to assess the costs and benefits of projects. This is not purely an economic assessment. It also takes into account how projects support the environment, welfare in Europe, the security of supply, and other factors. The results of these cost and benefit assessments form the core of the TYNDP report.

The TYNDP report illustrates the value of each infrastructure project. It provides decision-makers with a robust and detailed analysis of transmission infrastructure projects on which to base their decisions. TYNDP projects and the accompanying assessments are used in a European Commission-led process for updating the PCI list of projects.

6.6 ENTSO-E system-wide CBA Analysis-method

General
All new transmission project candidates in the TYNDP planning process are assessed according to the same system-wide cost-benefit methodology developed by ENTSO-E (ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects) and approved by the European Commission. The assessment includes the categories outlined in Figure 6.6.

Figure 6.6: Categories of cost benefit assessment parameters, TYNDP 2018.

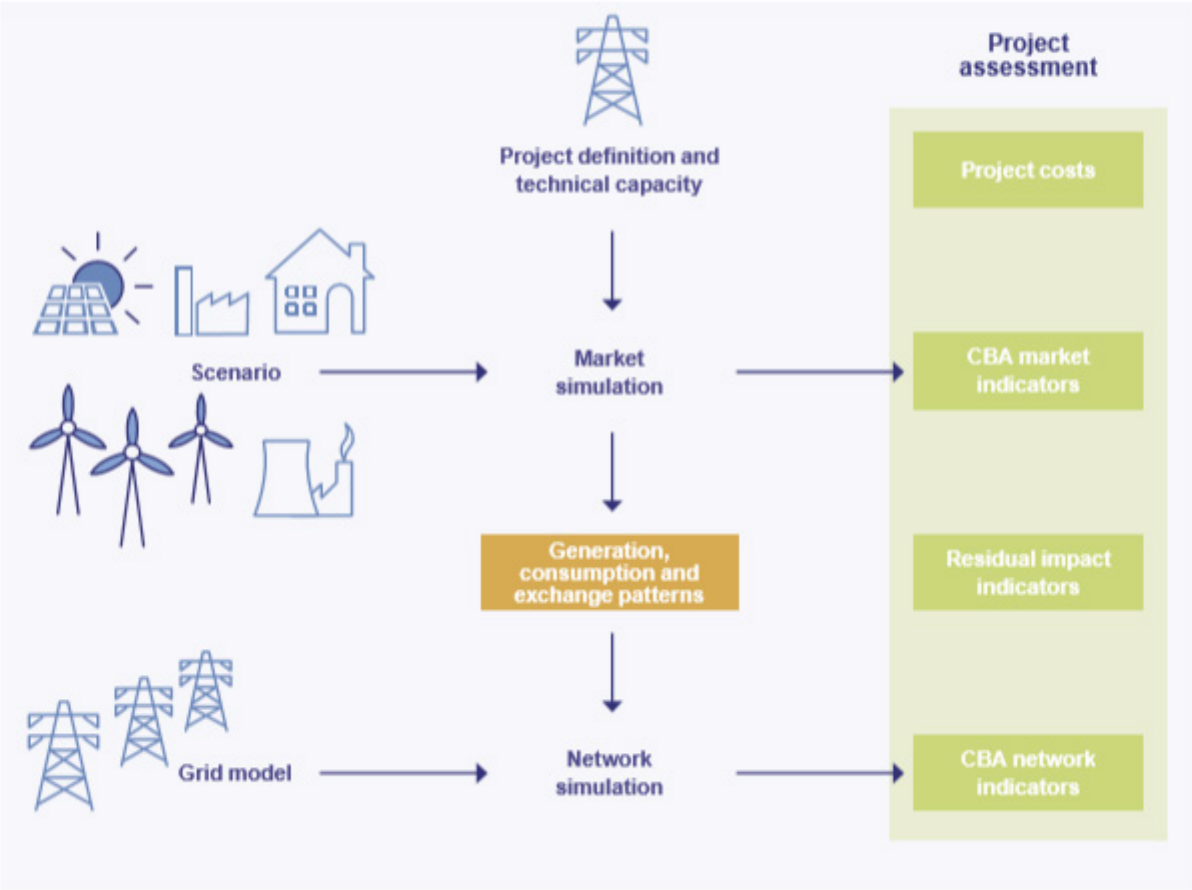


The elements analysed in the CBA are:

- Grid Transfer Capacity (GTC) in MW. This is estimated by grid analysis.
- Security of supply is Expected Energy Not Served (EENS) or Loss of Load Expectancy (LOLE).
- Socio-economic welfare (SEW) is defined as the sum of producer surplus, consumer surplus and congestion rents. SEW includes implicitly monetised values for CO_2 and RES integration (e.g. improved value of RES generation by reducing curtailment of wind).
- Monetised values for CO_2 and RES integration (e.g. improved value of RES generation by reducing curtailment of wind).
- Losses are transmission losses (change in losses for the whole system).
- Costs are project costs and changes in other costs incurred by the project (except for losses).
- Technical resilience/system safety is the ability of the system to withstand increasingly extreme system conditions (exceptional contingencies). Semi-quantitative estimate is based on key performance indices (KPI) scores.
- Flexibility/robustness is the ability of the proposed reinforcement project to be adequate in different possible future development paths or scenarios. Semi-quantitative estimate is based on KPI scores.

The assessment framework is shown in Figure 6.7 with market and network indicators resulting from market and network modelling, respectively.

Figure 6.7: 'CBA market' and 'CBA network indicators' are the direct outcome of market and network studies, respectively. 'Project costs' and 'residual impacts' are obtained without the use of simulations.



Reference grid

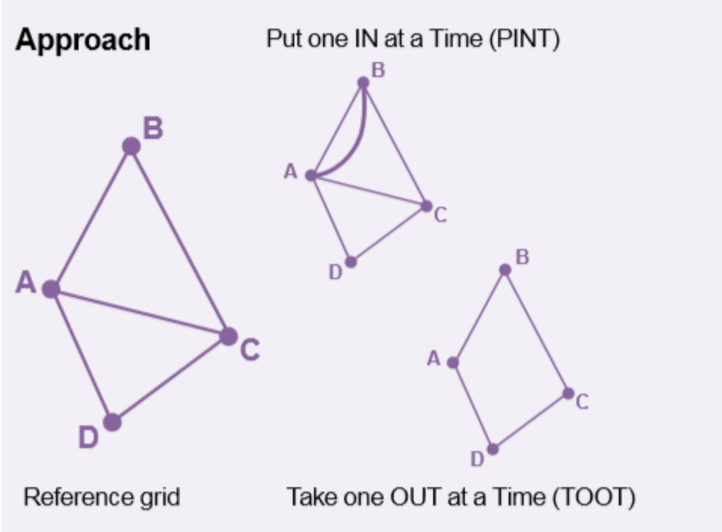
Project benefits are calculated as the difference between a simulation which does include the project and a simulation which does not include the project. The two proposed methods for project assessment are as follows (see Figure 6.8):

- TOOT (Take Out One at a Time) method, where the reference case reflects a future target grid situation in which all additional network capacity is presumed to be realised (compared to the starting situation) and projects under assessment are removed from the projected network structure (one at a time) to evaluate the changes to the load flow and other indicators.

- PINT (Put IN one at a Time) method, where the reference case reflects an initial state of the grid without the projects under assessment, and projects under assessment are added to this reference case (one at a time) to evaluate the changes to the load flow and other indicators.

Given that the selection of the reference case has a significant impact on the outcome of an individual project assessment, a clear explanation of it must be given. This should include an explanation of the initial state of the grid, in which none of the projects under assessment in the relevant study is included. The reference network is then built up including the most mature projects that are a) in the construction phase or b) in the 'permitting' or 'planned but not yet permitting' phase, where their timely realisation is most likely i.e. when the country-specific legal requirements have been met and the need for these projects has been acknowledged.

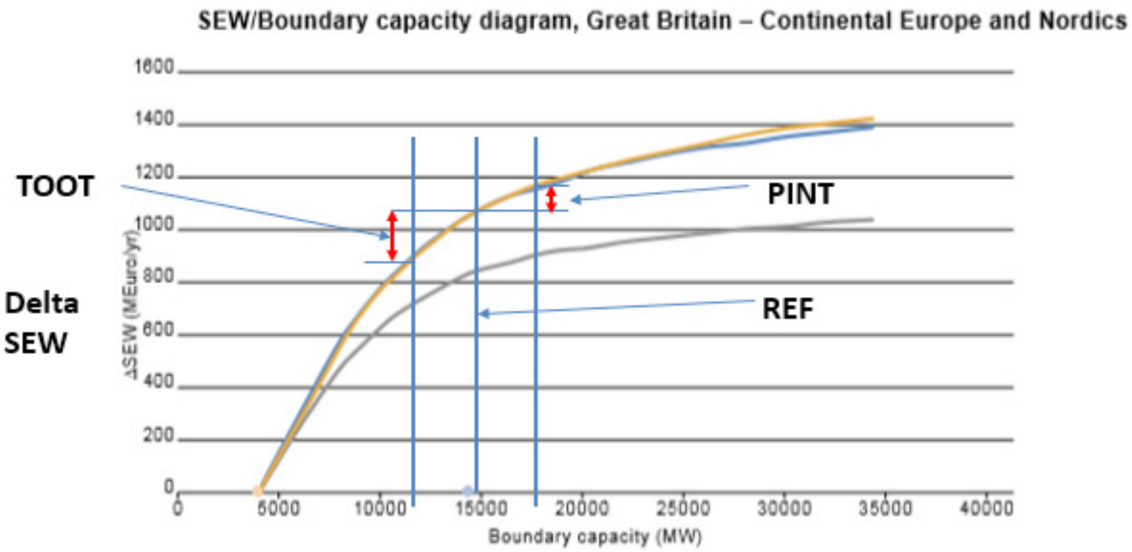
Figure 6.8: Reference grid and definition of TOOT and PINT.



Projects in the 'under consideration' phase are seen as non-mature and are therefore generally excluded from the reference grid, leading to an assessment using the PINT approach.

Figure 6.9 illustrates the assessment of a capacity investment at a boundary with decreasing marginal expansion benefit. It follows that TOOT and PINT will yield different results.

Figure 6.9: Assessment of capacity expansion across a border according to TOOT and PINT.



Specific description of CBA parameters, overview

Benefit categories are defined as follows:

B1: Socio-economic welfare

SEW, or market integration, is characterised by the ability of a project to reduce congestion. It thus provides an increase in transmission capacity that makes it possible to increase commercial exchanges, so that electricity markets can trade power in a more economically efficient manner.

BOX 1: Illustration of socio-economic welfare (B1)

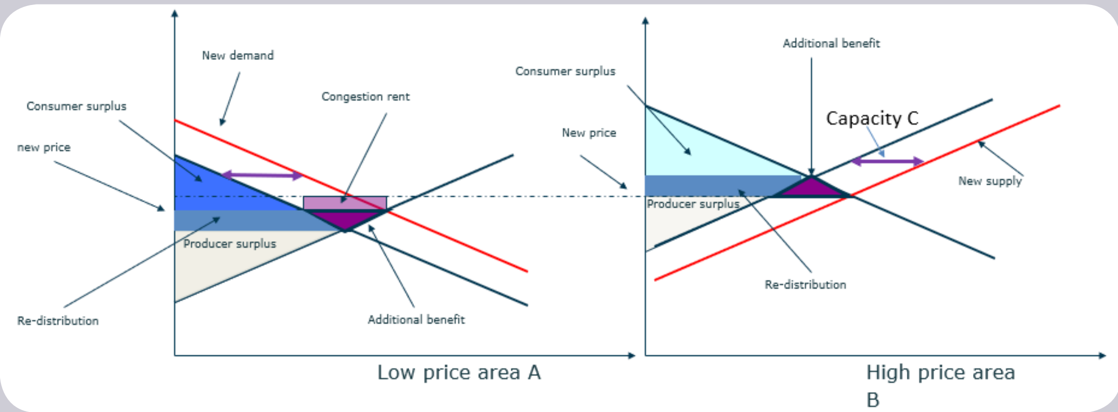
Principles of calculation of SEW

A central parameter in most European projects is SEW (socio-economic welfare) – referred to here as B1. In the European TYNDP this parameter is often the most important source of evidence for a proposed infrastructure expansion. The calculation of B1 is conducted via market modelling of the European system in two cases: with and without the project in question. In the model the European day ahead market is emulated in each hour over the year in each scenario.

The principle is illustrated in Figure 6.10, showing the gain in B1 when connecting two bidding areas (zonal price design) by a transmission line with capacity 'C'. The optimal scheduling is to transport the amount 'C' from the low-price area to the high price area. Thereby the price will increase in the low-price area and decrease in the high price area, as shown in Figure 4.10. The prices in the two zones will in this case end up being different, due to congestion constraints on the interconnector.

The figure shows the change in consumer and producer surplus in the two price areas. The net increase in surpluses is indicated by the dark purple triangles. The light purple area is the congestion rent.

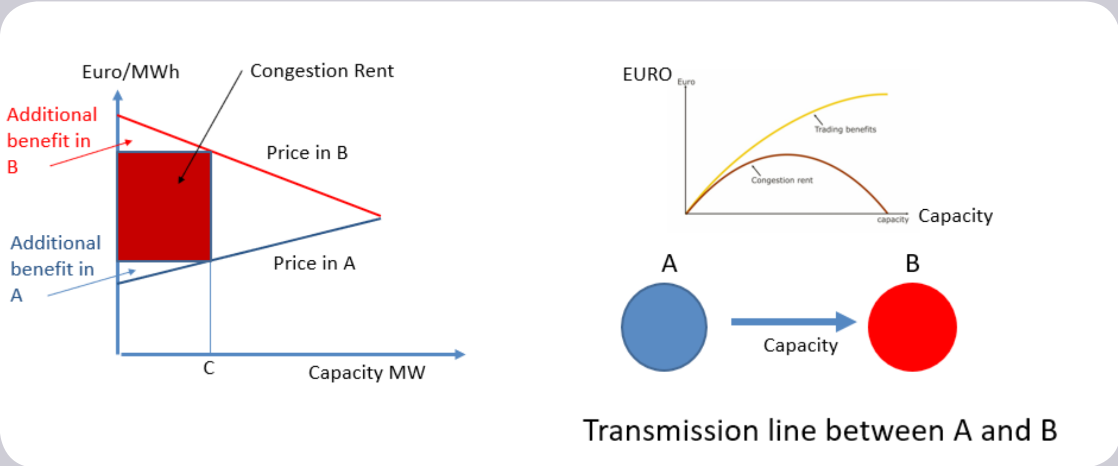
Figure 6.10: Optimal flow between two market zones in the market model.



The situation is further illustrated in Figure 6.11. This shows the prices in area A and area B when the capacity between areas increases, together with congestion rent and gains in B1 in the two areas (on the left hand side of Figure 6.11).

The illustration also shows the variation in congestion rent (lower red curve in right part of the figure) and total trading benefit (SEW) (the upper yellow curve in right part of the figure).

Figure 6.11: Congestion rent and SEW as a function of transmission capacity.



(Source: Ea Energy Analyses)

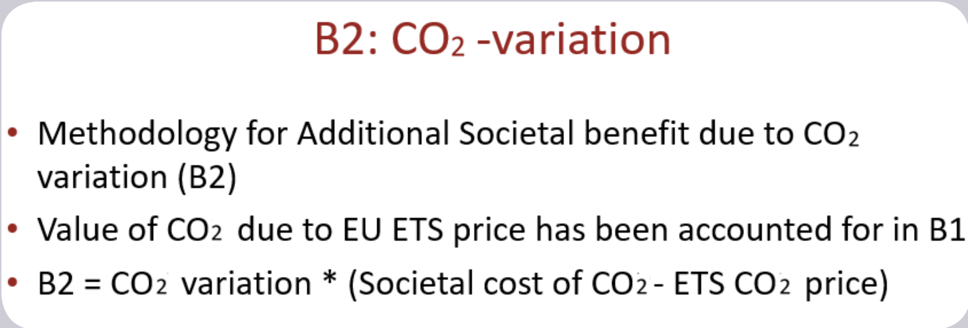
In the market model the total gains in SEW are calculated for all price areas including total net increase in all congestion rents for the whole European system when adding a given project. This is done for each hour over the year in all scenarios.

In addition to the changes in SEW, the changes in CO_2 and in the curtailment of renewables (wind and solar) are evident in the market modelling.

B2: CO_2 variation

The calculation of the additional societal benefit due to CO_2 variation represents the change in CO_2 emissions in the power system due to the project. It is a consequence of changes in generation dispatch and unlocking renewable potential. The EU has defined its climate policy goals by announcing that it plans to reduce GHG emissions by at least 40% by 2030 compared to 1990 levels. As CO_2 is the main greenhouse gas for which the electricity sector is responsible, it is displayed as a separate indicator. This indicator takes into account the additional societal costs of CO_2 emissions compared to the assumed future EU ETS price, which is already included in B1.

BOX 2: Illustration of CO_2 variation (B2)



B3: RES integration

Contribution to RES integration is defined as the ability of the system to allow new RES generation to connect to the grid, unlock existing and future renewable generation, and minimise curtailment of electricity produced from RES. RES integration is one of the EU's targets. The monetary value of improved RES integration is included in B1.

B4. Variation in societal well-being

Variation in societal well-being as a result of variation in CO_2 emissions and RES integration is defined as the increase in societal well-being beyond the economic effects that are captured in B1.

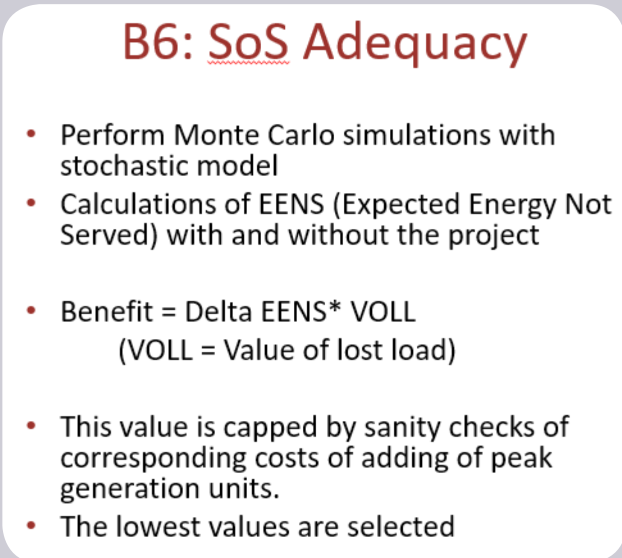
B5: Variation in grid losses

Variation in grid losses in the transmission grid is the cost of compensating for thermal losses in the power system due to the project. It is an indicator of energy efficiency.

B6: Security of supply (SoS)

Adequacy to meet demand characterises the project's impact on the ability of a power system to provide an adequate supply of electricity to meet demand over an extended period of time. Variability of climatic effects on demand and renewable energy sources production is taken into account.

BOX 3: Illustration of SoS adequacy (B6)



B7: Security of supply: System flexibility
System flexibility characterises the impact of the project on the capacity of an electric system to accommodate rapid and far-reaching changes in net demand in the context of high penetration levels of non-dispatchable electricity generation.

B8: Security of supply: System stability
System stability characterises the project's impact on the ability of a power system to provide a secure supply of electricity.

Residual impact is defined as follows:
S1. Residual environmental impact characterises the (residual) project impact as assessed through preliminary studies and aims to give a calculation of the environmental sensitivity associated with the project.

S2. Residual social impact characterises the (residual) project impact on the (local) population affected by the project as assessed through preliminary studies and aims to make a calculation of the social sensitivity associated with the project.

S3. Other impacts include an indicator to capture all other impacts of a project.

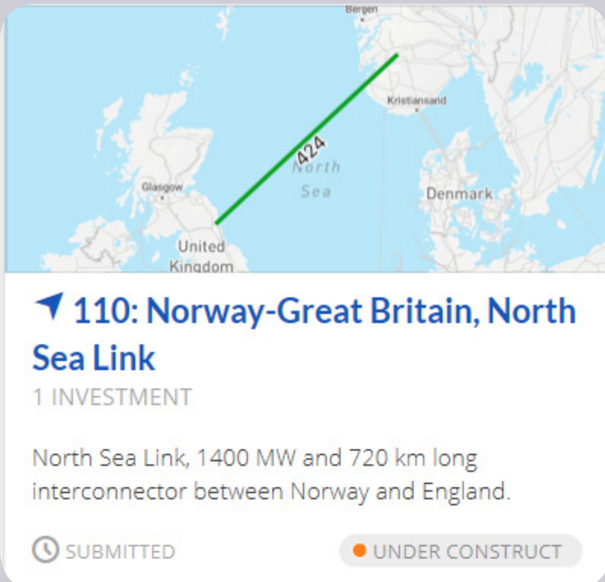
Costs are defined as follows:
C1. Capital expenditure (CAPEX). This indicator reports the capital expenditure of a project, which includes elements such as the cost of obtaining permits, conducting feasibility studies, obtaining rights of way, land, preparatory work, designing, dismantling, equipment purchases and installation. CAPEX is calculated using analogous estimates (based on information from prior projects that are similar to the current project) and parametric estimates (based on public information about the cost of similar projects).

C2. Operating expenditure (OPEX). These expenses relate to project operating and maintenance costs. The calculation of the OPEX for all projects must be based on the costs for the year of study (e.g. for TYNDP 2018 the costs should relate to 2018).

Box 4 is an example from TYNDP 2018, showing results for changes in SEW, RES integration and CO_2 due to a 1 400 MW interconnector between Norway and Great Britain.

BOX 4: Case study from TYNDP 2018

1 400 MW interconnector between Norway and Great Britain.



Euco is a scenario developed by the European Commission

7. SCENARIOS

7.1 Introduction

This chapter describes Chinese scenarios for the future. Section 7.2 sets out the SGERI scenarios, while section 7.3 outlines the ERI/CNREC scenarios.

At the initial project meeting in March 2020, it was decided that both the SGERI scenarios and the ERI/CNREC scenarios should be used during the present study, where ENTSO-E methodologies are applied to China's transmission planning. The SGERI scenarios were to be applied to SGERI's model and ERI/CNREC's scenarios were to be applied to ERI/CNREC's model.

However, it was later concluded that the resolution on SGERI's model was too low to be applied (simulation is based on regions instead of provinces). Instead, only ERI/CNREC's model and scenarios have been used for screening and CBA simulations.

Nevertheless, SGERI's scenarios are also described in this chapter (section 7.2) for completeness.

7.2 SGERI scenarios

This section aims to describe the path for China's future energy development by setting up different energy transition scenarios.

Taking into account China's national energy security strategy and global carbon emissions reduction target, China's energy transition involves the exploitation and utilisation of clean energy on a massive scale while also increasing the share of electricity in final energy consumption. A two-pronged approach, involving 'increased electrification' and 'decarbonised power generation', will help to build a modern energy system centred upon electricity and usher in a new phase of development based on 're-electrification'.

Given that 'accelerated electrification + new-generation power systems' will be an important impetus for the energy transition towards a clean and low-carbon future, this description is based on the new trend of high-quality economic growth and the modern model of energy transformation and development. With enhancements in energy efficiency and adjustments to energy structure, the description constructs future development scenarios by focusing on developments in electrification and clean energy as well as describing the role and influence of electricity in China's energy transition process.

This section sets up two representative transition scenarios: The Conventional

Transition Scenario and the Accelerated Electrification Scenario. In the Conventional Transition Scenario, the implementation of various transition measures is relatively balanced, while in the case of the Accelerated Electrification Scenario, the level of electrification increases much faster, and the scale of clean energy development is more significant.

Conventional Transition Scenario

Here, the energy efficiency of conventional technology increases at a slowing rate, while electrification increases steadily. Natural gas consumption rises rapidly as coal consumption decreases, whereas petroleum consumption remains relatively stable. Steady improvements can be seen in the final energy consumption structure, alongside improvements to end-use energy efficiency. New energy makes up an increasing proportion of final energy consumption, while coordinated ‘source-grid-load-storage’ development gradually takes shape.

Accelerated Electrification Scenario

In this scenario, improvements to the energy efficiency of conventional technology slow gradually, while newer technologies such as electric boilers, electric kilns, heat pumps, smart homes and electric vehicles expand their range of application. As a result, the level of electrification across society progresses at a rapid pace, accelerating the replacement of coal and oil in final energy consumption. In addition, there are rapid improvements to the final energy consumption structure, promoting the continuous and swift advancement of end-use energy efficiency.

Growth in natural gas consumption in the Accelerated Electrification Scenario is lower than that in the Conventional Transition Scenario. New energy develops rapidly, and the smart development and regulation capacity of power grids makes further advances, pushing the power system towards greater, coordinated ‘source-grid-load-storage’ development.

In both the Conventional Transition and Accelerated Electrification Scenarios, the effective demand for end-use energy, as determined by economic and social development standards, needs to be broadly consistent. Differences in end-use energy demand are reflected mainly in the energy efficiency gap caused by end-use energy-consuming technologies. For example, opinions differ as to whether to choose conventional fuel cars or electric cars for the same commute, whether to choose coal heating, gas heating or heat pumps to meet the same heating demand, or whether to smelt ores or process recycled metals to produce the same amount of steel and aluminium.

In the Accelerated Electrification Scenario, the future disruptive effects of ‘transport-sharing’ may unleash greater effective demand for end-use energy in the transportation sector after 2030, while somewhat reducing the energy-consuming production of upstream products, such as steel, copper, and aluminium.

Differences in main parameters between the two scenarios are shown in Table 7.1.

Table 7.1: Setting of main scenario parameters.

	Conventional Transition Scenario	Accelerated Electrification Scenario
Economic environment	There have been setbacks to global trade liberalisation on the international landscape. Sino-US trade frictions have impacted China's economic development. Domestically speaking, China's socio-economic situation remains stable. Economic growth has gradually slowed, economic structures are being optimised and adjusted, and growth momentum is shifting from traditional manufacturing sectors to tertiary and high-end manufacturing industries. Over the 14th and 15th Five-Year Plans, GDP is likely to grow at 5.5% and 5.0%, respectively. From 2030 to 2040 and 2040 to 2050, GDP growth rates will respectively be 4.2% and 3.2%. China's population will show a trend of slowing growth. In 2050, total population is estimated to be 1.4 billion.[14]	
Electrification levels	Electrification levels in various energy consumption fields will rise gradually. For example, the proportion of electric furnace steel in the iron and steel industry in 2020, 2035 and 2050 will reach 10%, 20% and 32% respectively. EV numbers in 2020, 2035 and 2050 will respectively reach 4 million, 92 million and 240 million. Accordingly, small sections of urban short-distance freight services will become electrified.	Electrification levels in various energy consumption fields will be higher than that in the Conventional Transition Scenario. For example, the proportion of electric furnace steel in the iron and steel industry in 2020, 2035 and 2050 will reach 15%, 35% and 54% respectively. EV numbers in 2020, 2035 and 2050 will respectively reach 5 million, 140 million and 350 million. Accordingly, urban short-distance freight services will become electrified.
End-use energy structure	According to the principle of 'choosing to use electricity, gas or coal in accordance with realities', electricity substitution will be promoted steadily, the use of natural gas will grow at a slightly higher pace, coal and combustion fuels will be gradually replaced, and there will be some scope for hydrogen energy applications.	Natural gas substitution will be lower than that in the Conventional Transition Scenario due to supply constraints. As such, the substitution of coal and combustion fuels with electricity will be higher than that in the Conventional Transition Scenario, and there is reason to be optimistic about the popularisation of hydrogen energy applications.
End-use energy efficiency	The energy efficiency of major industrial products was either at or close to internationally advanced levels in 2020, and China will become a global leader in energy efficiency by 2035. Global energy intensity in 2020 was 15% lower than the 2015 level and will reach the global average in 2030. The rate of decline in end-use energy consumption intensity will slow down gradually, with greater energy efficiency brought about by the replacement of coal and combustion fuels by natural gas and electricity.	Based on the Conventional Transition Scenario, the popularisation and integration of more efficient technologies for electricity utilisation, such as regenerative metal smelting and heat pump technology, will be higher than that of the Conventional Transition Scenario. The breadth, depth and speed of electricity substitution will be higher than that in the Conventional Transition Scenario, which will significantly increase energy efficiency.

14 Refers to forecast data from the State Information Centre.

New-energy power generation cost[15]	The installation costs of onshore wind power in 2035 and 2050 will decrease to CNY 5 000/kW and 4 700/kW respectively. The installation costs of offshore wind power in 2035 and 2050 will decrease to CNY 10 000/KW and CNY 8 600/kW respectively. The installation costs of PV power in 2035 and 2050 will decrease to CNY 2 800/kW and CNY 2 300/kW respectively. The installation costs of photothermal power in 2035 and 2050 will decrease to CNY 9 700/kW and CNY 4 500/kW, respectively.	The installation costs of onshore wind power in 2035 and 2050 will decrease to CNY 4 500/kW and CNY 4 000/kW respectively. The installation costs of offshore wind power in 2035 and 2050 will decrease to CNY 9 000/kW and CNY 7 400/kW respectively. The installation costs of PV power in 2035 and 2050 will decrease to CNY 2 300/kW and CNY1 900/kW respectively. The installation costs of photothermal power in 2035 and 2050 will decrease to CNY 7600/kW and CNY 3 200/kW, respectively.
Carbon emissions cost	Gradual increase from 20 CNY/tonne in 2020 to 200 CNY/tonne by 2050.	Gradual increase from 30 CNY/tonne in 2020 to 300 CNY/tonne by 2050.
Change in degree of coal power flexibility	Peak-shaving depth of co-generation units will reach 30% and 40% in 2035 and 2050, respectively. Peak-shaving depth of non-cogeneration units will reach 60% and 70% in 2035 and 2050, respectively.	Peak-shaving depth of co-generation units will reach 40% and 50% in 2035 and 2050, respectively. Peak-shaving depth of non-cogeneration units will reach 70% and 80% in 2035 and 2050, respectively.
Participation of cross-regional transmission in peak-shaving	50% of transmission capacity.	80% of transmission capacity.
Demand response potential	6% to 8% and 10% to 12% of the maximum load in 2035 and 2050, respectively.	7% to 9% and 15% to 18% of the maximum load in 2035 and 2050, respectively.
Energy storage costs[16]	Fixed investment costs in 2035 and 2050 will decrease to CNY 3 000/kW and CNY 2 000/kW, respectively.	Fixed investment costs in 2035 and 2050 will decrease to CNY 2 000/kW and CNY 1 000/kW, respectively.

15 The yearly cost forecast curve is formed according to the forecast of international authority institutions such as International Energy Agency, International Renewable Energy Agency, Bloomberg Finance L.P., etc. Due to space limitations, only the values of key years and the national average are shown, and the differentiated handling of each region is not shown. All prices in the report and model are based on the current price level, monetary value changes are not considered.

16 The yearly cost forecast curve is plotted in accordance with forecasts from authoritative domestic and foreign institutions such as the International Energy Agency, Bloomberg Finance L.P. and the China Energy Storage Alliance. Due to space limitations, only the values of key years are shown.

7.3 ERI/CNREC scenarios

China Renewable Energy Outlook 2019 uses scenarios to analyse how renewable energy can be used in the Chinese energy system. The scenarios provide a clear and consistent vision for long-term development as a basis for short-term decisions. Two scenarios are defined: The Stated Policies Scenario expresses the impact of a firm implementation of announced polices, while the Below 2°C Scenario shows a pathway for China to achieve its ambitious vision for an ecological civilisation to fulfil the terms of the Paris Agreement.

The scenarios are modelled in detailed bottom-up models for the end-use sectors and for the power sector. Specific assumptions for macroeconomic indicators, demographic indicators and targets or restrictions to the scenarios' energy systems are used as input to the models to steer the development trends in the intended direction and to ensure fulfilment of the goals for energy system development. Within these boundaries, the power sector model is driven by an overall cost-optimisation to ensure cost-efficient energy system transformation.

The scenarios are designed to:

- Provide a clear long-term vision. The energy system composition of this vision will be presented as well as the reasoning behind it.
- Establish a clear view of the current situation, trends, market and policy direction, and project this into the future.
- The forecasted trends and long-term vision are forced to converge and form a connected story as a complete energy system scenario.

7.3.1 Two main scenarios

Stated Policies Scenario
The scenario assumes full and firm implementation of energy sector and related policies expressed in the 13th Five-Year Plan and the 19th Party Congress announcements. The central priority is to build a clean, low-carbon, safe and efficient energy supply. The scenario also includes the NDC climate target to peak in emissions before 2030, the effects of the Blue-Sky Protection Plan, aspects of the Energy Production and Consumption Revolution Strategy, and the National ETS.

Policy trends are extrapolated to set the longer-term policy drivers.

Below 2°C Scenario
The Below 2°C Scenario shows a road for China to achieve its ambitious vision for an ecological civilisation and to fulfil the terms of the Paris Agreement. The main driver is a hard target for energy-related CO_2 emissions by means of a strategy that has renewable electricity, electrification, and sectoral transformation at its core. The target is for a total of 200 million tons of energy related CO_2 emissions between 2018 and 2050.

7.3.2 Key assumptions

Macroeconomics and population
Between 2021 and 2035, China will be in the middle and later stages of industrialisation and urbanisation. It will have the world's largest manufacturing sector, service industries, urban agglomerations, and middle- and high-income groups. The mode of economic growth is undergoing major changes. After 2035, China will start to build a modern and prosperous country, and its per capita GDP will reach about USD 40 000 by 2050.

Table 7.2: Assumptions related to macroeconomics and population.

	Stated Policies Scenario	Below 2°C Scenario
Population	Population will grow in the next 10 years and then drop. The population will be around 1.38 bn in 2050.	
Economic development	Economic growth from RMB 90 trillion in 2018 to RMB 380 trillion by 2050.	
Urbanisation rate	The process of urbanisation in China will continue to be an important factor. Urbanisation will increase from 59.6% in 2018 to 70% by 2030. According to ERI assumptions, 78% of citizens will be living in an urban environment by 2050	

Energy volume and structure
A green, low-carbon, safe, and efficient modern energy system is the future development direction of China's energy system. The medium- and long-term energy development goals adopted by China are listed below, along with the assumptions made to achieve these targets.

Table 7.3 Assumptions related to energy sector.

	Stated Policies Scenario	Below 2°C Scenario
Primary energy consumption limit	Growth in primary energy consumption should be controlled. By 2020, primary energy consumption was set to remain below 5 bn tce based on the 13th Five-Year Plan. By 2030, primary energy consumption should be below 6 billion tce, in line with the Energy Production and Consumption Revolution Strategy. The vision for 2050 states that primary energy consumption should stabilise between 2030 and 2050.	
Limit coal consumption	In 2020, coal consumption in 2020 was set to account for less than 58% of the primary energy consumption, according to the 13th Five-Year Plan. The scenarios restrict coal consumption to 1 billion tons of coal by 2050, according to an ERI assessment of the boundaries for an environmentally sustainable energy system for China.	

<table>
<tr><td>Security of supply</td><td colspan="2">The energy supply should be diverse and dependence on imported fuels should be reduced significantly.</td></tr>
<tr><td>Energy intensity per unit of GDP</td><td colspan="2">The 13th Five-Year Plan sets a target to reduce energy consumption intensity by 15% in 2020 relative to 2015. In the scenarios, the energy intensity should be reduced by 85% relative to 2018 (base-year).</td></tr>
<tr><td>Non-fossil proportion of Primary energy supply</td><td colspan="2">The 13th Five-Year Plan aimed for non-fossil fuels to make up 15% of primary energy supply in 2020 and 20% in 2030. The Energy Production and Consumption Revolution Strategy states that by 2050, more than 50% of primary energy supply should come from non-fossil sources.
To achieve emission reduction targets and successfully develop an ecological civilisation, the scenarios assert that non-fossil energy must account for at least two thirds of primary energy supply by 2050 in both scenarios.</td></tr>
<tr><td rowspan="2">Natural gas targets</td><td colspan="2">The 13th Five-Year Plan established a target to increase the proportion of natural gas proportion in the primary energy supply to 10% by 2020. The Energy Production and Consumption Revolution Strategy aims for natural gas to account for 15% of the energy mix by 2030.
Natural gas will further expand in the short-term but is required to peak in 2040 in both scenarios, and subsequently recede to be replaced by non-fossil sources.
Due to the difference in primary energy consumption in the scenarios, the absolute levels of natural gas consumption differ, and boundaries are set on absolute terms in each scenario.</td></tr>
<tr><td>The peak in 2040 is in the range 630-650 bcm</td><td>The peak in 2040 is in the range 580-600 bcm</td></tr>
<tr><td rowspan="2">Electrification rate</td><td colspan="2">The 13th Five-Year Plan aimed for a 27% electrification rate by 2020.
As a core pillar of the energy transition strategy, electrification is set to increase significantly.</td></tr>
<tr><td>>50%</td><td>>60%</td></tr>
</table>

Environment and resource potential

The energy transition needs to consider ecological and environmental protection as well as energy resource conditions. It also needs to take into account international commitments on carbon emissions. China has rich coal resources, but its oil and gas supplies are likely to rely on both long-term domestic and international resources for a long time to come. In the future, renewable energy, such as hydropower, wind power, solar energy, and biomass resources need to be further developed.

Table 7.4 : Assumptions related to environment and resource potential.

	Stated Policies Scenario	Below 2°C scenario
Carbon emission constraint	China's official target in the NDC and other policy documents is for carbon intensity to decrease by 40%-45% and 60%-65% by 2020 and 2030, respectively, relative to 2005.	Based on the carbon emissions limit set by the simulation results of the IPCC database, a 66% confidence rate can keep the temperature rise below two degrees. Cumulative emissions between 2018-2050 should be limited below 200 billion tons, and 2050 emissions should be less than 2 500 million tons.
Resource potential	In light of safety issues, only coastal sites are considered for nuclear power development. A total capacity of 100-110 GW capacity is envisaged in the long term (capacity in 2021 stood at 47.5 GW). Hydro power is well developed in China with future development planned, mostly in the areas of Sichuan, Yunnan, Tibet, and Qinghai. In total 530 GW of hydro power will be developed in the period to 2050. The technically and economically feasible resource potential for wind power and solar PV is modelled for different provinces. The overall potential for onshore wind is 4 900 GW, of which less than 2 000 GW can be developed in the form of distributed wind. The potential for offshore wind is 217 GW (mainly nearshore). The resource potential for solar power is 2 537 GW for utility-scale PV plants, and 1 633 GW for different types of distributed PV including BIPV and roof-top PV.	

End-use sector development

The energy transition begins with transformation in the way energy is used. The key indicators guiding the development of the scenarios' end-use consumption, are provided below.

Table 7.5: End use sector guidance.

	Stated Policies Scenario	Below 2°C Scenario
Industry	Phase out excess capacity: by 2050, steel output of steel decrease by 27%; cement output falls by 50%.	
	Resource recycling: Share of scrap-based steel will reach 50 % by 2050; share of recycled aluminium will reach 45% by 2050.	Share of scrap-based steel will reach 65% by 2050; share of recycled aluminium will reach 58% by 2050.

<table>
<tr><td rowspan="6">Transportation</td><td colspan="2">Per capita ownership for private cars will increase by 60% by 2035 and by 120% by 2050.</td></tr>
<tr><td>A ban on internal combustion engines (ICE) in passenger light-duty vehicles will be introduced by 2050.</td><td>An ICE ban on passenger light-duty vehicles will be introduced by 2035.</td></tr>
<tr><td colspan="2">Non-road passenger transport turnover increases by 30% by 2050. Passenger transport by rail and air will rise 200% and 180%, respectively, by 2050.</td></tr>
<tr><td colspan="2">Freight transport turnover increase by 80 % before 2035, and 115% before 2050, relative to 2018. The proportion of freight transport by -road, rail, and sea shifts from 48%, 20% and 32% in 2021 to 32%, 30% and 38% by 2050.</td></tr>
<tr><td>New energy vehicle (NEV) market share of light trucks is set to reach 12% by 2035 and 24% by 2050.</td><td>NEV market share of light trucks is set to reach 67% by 2035 and 100% by 2050.</td></tr>
<tr><td>NEV market share of medium and heavy trucks is set to reach 12% by 2035 and 20% by 2050.</td><td>NEV market share of medium and heavy trucks is set to reach 42% by 2035 and 75 % by 2050.</td></tr>
<tr><td rowspan="6">Buildings</td><td colspan="2">The total floor area occupied by buildings increases by 48% before 2035, and 70 % before 2050. The proportion of urban residential, rural residential, and commercial buildings shifts from 41%, 34% and 25% in 2021 to 55%, 17% and 28%, respectively.</td></tr>
<tr><td colspan="2">Internet Date Centre (IDC) floor area increases five-fold by 2035, and nine-fold by 2050</td></tr>
<tr><td colspan="2">By 2035, heating intensity is set to fall between 15and 35% for urban residential buildings and between 30% and 50% for rural residential buildings.</td></tr>
<tr><td colspan="2">Heating service saturation for urban residential buildings reaches 100% in 2035 in all areas.</td></tr>
<tr><td colspan="2">Increase of cooling intensity is set to rise between 15% and 35% for urban residential buildings and 28% for rural residential buildings by 2035.</td></tr>
<tr><td colspan="2">Cooling service saturation for urban residential buildings reaches 100% in 2035 in all areas.</td></tr>
</table>

Power sector development

Both scenarios posit that the development of non-fossil fuel and renewable energy must be at the foundation of the energy system transformation. This is implemented primarily through the power sector. The key indicators underpinning this scenario strategy are listed below.

Table 7.6: Power sector assumptions.

<table>
<tr><th></th><th>Stated Policies Scenario</th><th>Below 2°C Scenario</th></tr>
<tr><td>Non-fossil proportion of electricity</td><td colspan="2">In the power generation mix, a minimum target of 50% non-fossil electricity by 2030 is applied in both scenarios, based on the guidance set in the Energy Production and Consumption Revolution Strategy.</td></tr>
<tr><td>Energy resource potential and long-term targets</td><td colspan="2">In light of safety issues, only coastal sites are considered for nuclear power developments. A total capacity of 100-110 GW is envisaged in the long term (capacity in 2021 stood at 47.5 GW).

Hydro power is well developed in China: further resources are planned, mostly concentrated in Sichuan, Yunnan, Tibet, and Qinghai. In total, 530 GW hydro power will be developed in the period to 2050.

The technically and economically feasible resource potential for wind power and solar PV is modelled for different provinces. The overall potential for onshore wind is 4 900 GW, of which less than 2 000 GW can be developed in the form of distributed wind. The potential of offshore wind is 217 GW (mainly nearshore). The resource potential for solar PV is 2 537 GW for utility-scale PV plants, and 1 633 GW for different types of distributed PV including BIPV and roof-top PV.</td></tr>
<tr><td>RE subsidies</td><td colspan="2">By 2020, wind was set to be competitive with coal fired generation and solar was set to be competitive with grid electricity. Additionally, distributed solar was to be competitive with the grid price.</td></tr>
<tr><td>Carbon pricing</td><td>The price of CO_2 in the power sector rises from CNY 50/ton in 2020 to CNY 100/ton in 2030.</td><td>By 2030, the CO_2 emission cost to the power industry will increase to between CNY 160/ton and CNY 180/ton, and by 2040 will increase to about CNY 200/ton.</td></tr>
<tr><td rowspan="2">Power generation cost</td><td colspan="2">The energy generation costs from solar and wind are projected to decline rapidly, making these power sources more competitive. Fossil generation costs will increase due to fuel costs, pricing of emissions and reduced full load operating hours. Consequently, RE can be developed at a lower price than coal-fired power in the short-term. With the further decline of energy costs and integration costs, the scale of transformation will accelerate on a system cost basis.</td></tr>
<tr><td colspan="2">The initial investment cost (including unit, construction, taxes, etc.) of onshore wind power in 2035 and 2050 decreases to CNY 6 200 /kW and CNY 5 950/kW, respectively. Offshore wind power in 2035 and 2050 decreases to CNY 8 900/kW and CNY 7 800/kW or less. Costs for utility scale photovoltaic power generation in 2035 and 2050 fall to CNY 2 870/kW and CNY 2 460/kW, respectively.</td></tr>
<tr><td>Electricity demand and electrification</td><td>Electricity demand reaches 6 800 TWh by 2020, 9 000 TWh in 2035, and 11 700 TWh in 2050, when the electrification level will be 46%.</td><td>Electricity demand reaches 7 000 TWh by 2020, 11 400 TWh in 2035, and 14 000 TWh in 2050, when the electrification level will be 63%.</td></tr>
</table>

Demand response	It is assumed that, by 2030, demand response (DR) technology will be widely used. By 2030, industrial demand response provides up to 8 GW of flexibility. By 2050, this rises to 14 GW.	By 2030, industrial demand response provides up to 41 GW of flexibility. By 2050, this rises to 69 GW.
	Additionally, aluminium smelters provide 5 GW of DR flexible capacity in 2025, falling to 4 GW and 3 GW by 2035 and 2050, respectively. By 2030, 100% of electric vehicles will have smart charging. Vehicle to Gas (V2G) is introduced from 2030 and by 2050 50% of electric vehicles deliver power to the grid when needed.	
Developing well-functioning spot markets	Generation rights will be introduced, such as rights awarded to generators based on a perceived fair principle of allocation between market participants and generation assets. Designed full-load operating hours according to technology types will be gradually removed and replaced by economic dispatch, so that power generation is scheduled on the basis of economic merit order. Interprovincial transmission scheduling will be introduced, in which flow schedules are adopted initially by setting constant levels of flow for day time and night time. These fixed schedules will be further relaxed by mobilising the flexibility among regions to achieve a larger-scale balancing. The provincial markets were introduced before 2020. The first cross-provincial unified power markets are set to emerge in 2022. Regional power markets based on regional power grids are to be formed by 2035. A unified national market is to be established from 2040.	

Table 7.7 : Cost reduction of typical emerging technologies.

Year		Wind			PV		Chemical storage
		On-shore	DG*	Off-shore	Utility scale	DG	
2020	Investment	6 900	8 250	15 000	3 600	3 420	Investment cost is CNY 1.5/Wh, and the life cycle is 4 000 rounds.
	O&M	145	154	290	68.4	85.5	
2025	Investment	6 500	7 700	12 800	3 300	3 135	Investment cost is CNY 1.2/Wh, and the cost of 'DG+storage' is competitive for commercial users.
	O&M	142	150	285	67.2	84.5	
2035	Investment	6 200	7 250	8 900	2 870	2 640	Investment cost is CNY 1/Wh. The life cycle is more than 10 000 rounds.
	O&M	139	144	277	65.5	87.8	
2050	Investment	5 950	6 830	7 800	2 460	2 265	Investment cost is CNY 0.5/Wh. Applications to provide flexibility to grid are cost competitive.
	O&M	135	140	270	63.7	88.3	

** DG refers to distributed generation*

Figure 7.1: Timeline of regional spot power market establishment.

In addition to dispatching existing sources, assumptions are made about new flexible sources. The projections in both scenarios assume market signals that enable participation of end-users in balancing power markets, including:

- Demand-side flexibility, such as reducing air conditioning loads or shifting industrial processes.
- Smart charging of electric vehicles to times with low system marginal costs and correspondingly low market prices, so avoiding times with high market prices.

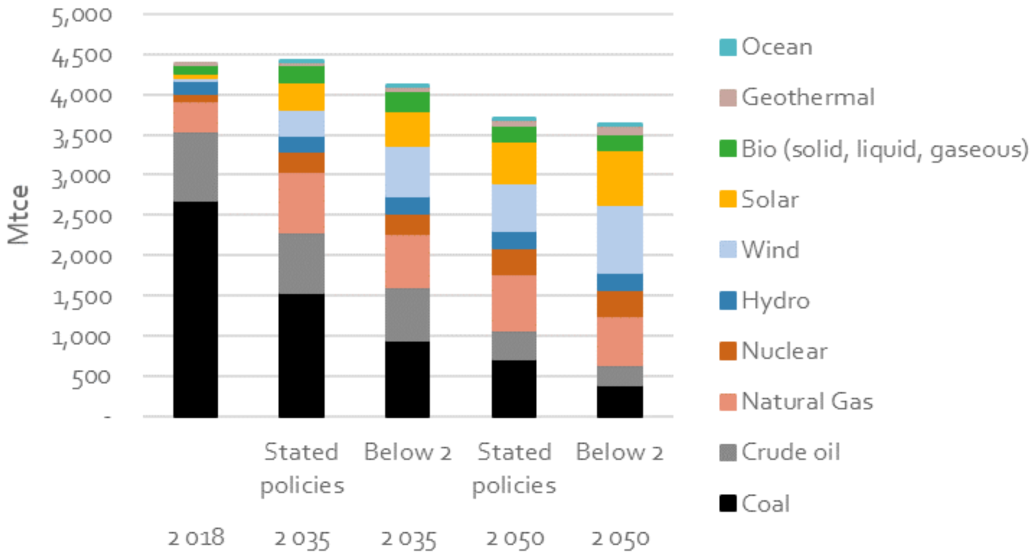
7.3.3 Key results

Primary energy consumption mix is diversified as low-carbon sources replace coal

By 2035, coal's contribution towards primary energy consumption is reduced by 51% in the Stated Policies Scenario and 62% in the Below 2°C Scenario. By 2050, coal consumption in the Stated Policies Scenario reduces further to 73% of 2018 levels, while in the Below 2°C Scenario the figure is 82%. In this way, coal, which accounted for approximately 61% of primary energy supply in 2018, accounts for 30%/23% in the Stated Policies Scenario and Below 2°C Scenario respectively in 2035 and 16%/11% in 2050. These shares are calculated using the physical energy content method.

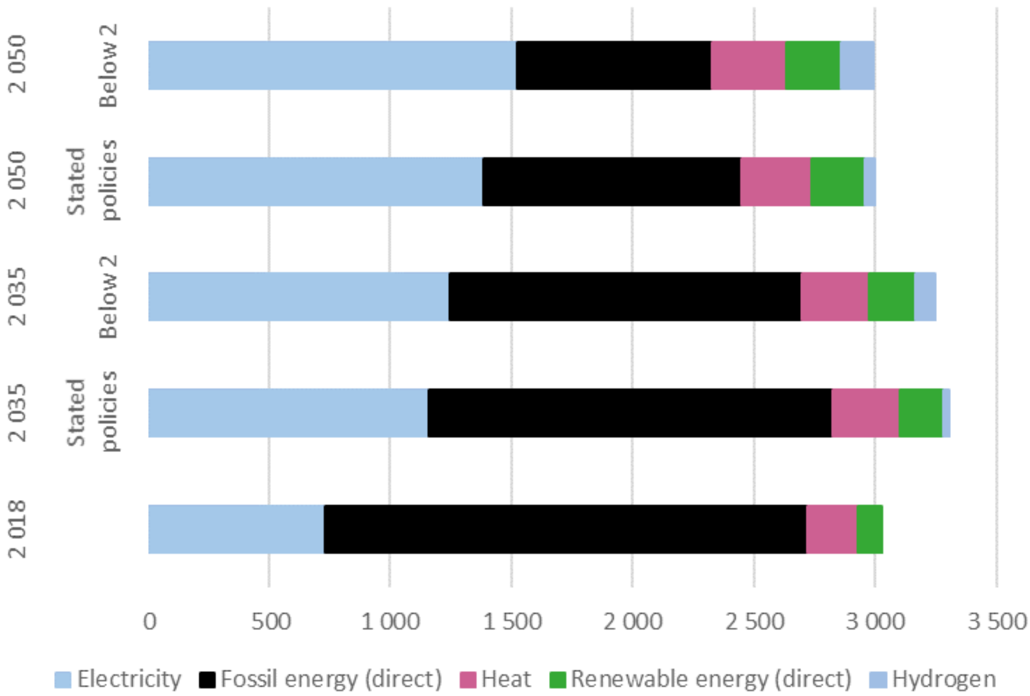
Using the physical energy content method, the non-fossil energy consumption share expands to 32% by 2035 in the Stated Policies Scenario and 42% in the Below 2°C Scenario. Using the coal substitution method of primary energy accounting that is commonly used in Chinese energy statistics and policy targets, increases the non-fossil energy proportion to 47% and 59% in the two scenarios respectively for the same year. Thus, by 2035 the non-fossil energy proportion will far exceed the official policy target of 20% by 2030. It is clear that the 2030 target needs to be raised.

Figure 7.2: Primary energy consumption in 2035 and 2050 compared to 2018 (Mtce).



Final energy consumption stabilises at current levels
Energy savings, together with economic restructuring, enable total final energy consumption in 2050 to be on a par with 2018, around 3 160 Mtce/yr. In the period to 2035, final energy consumption increases by approximately 10% to around 3 460 Mtce/yr in the Stated Policies Scenario and to around 3 350 Mtce/yr in the Below 2°C Scenario, before returning to its previous level (slightly below previous level in the Below 2°C Scenario).

Figure 7.3: Final energy consumption in 2035 and 2050 compared to 2018 (Mtce).



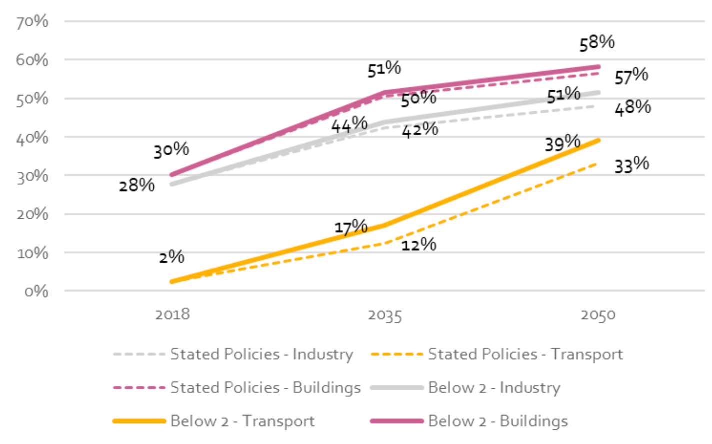
The energy transition is thereby able to achieve the targeted economic expansion with similar levels of final energy consumption by means of changes in the economic structure, improvements in energy efficiency of devices and production measures, as well as shifting away from direct use and combustion of fossil-fuels and towards consumption of electricity.

Along with the inter- and inner structural changes, China continues its economic growth while driving down its energy demand. The end result is a more balanced structure. Future energy growth is centred around the transportation and building sectors (both residential and commercial). By 2050, final energy use in the industrial, transport and building sectors changes from the current 54%:14%:25% to 44%:18%:34% by 2035 and then to 41%:26%:38% by 2050. The steady decline of industrial energy consumption benefits from this on-going industrial upgrade, which reins in the current energy-intensive and polluting activities and boost energy efficiency. A widespread electrification of transport offsets and limits the incremental energy demand brought about by burgeoning car ownership . Strong demand growth in the buildings sector is anticipated due to continuing economic growth, urbanisation, and higher standards of housing.

Electrification will enhance the reach of decarbonised electricity supply
In the World Energy Outlook 2018[17], the IEA states that 'A doubling of electricity demand in developing economies puts cleaner, universally available and affordable electricity at the centre of strategies for economic development and emissions reductions.' Due to the cost reductions in renewable electricity supply sources, electricity is becoming an increasingly cost-competitive energy carrier and thereby a means to replace direct consumption of fossil fuels.

The Stated Policies Scenario foresees an increase in electrification rate from approximately 26% in 2018 to 43% by 2035. In the Below 2°C scenario, it is predicted to rise to 48%[18]. By 2050, electrification is set to expand to 54% in the Stated Policies Scenario and 66% in the Below 2°C Scenario.

Figure 7.4: Development of electrification in transport, industry, and buildings.



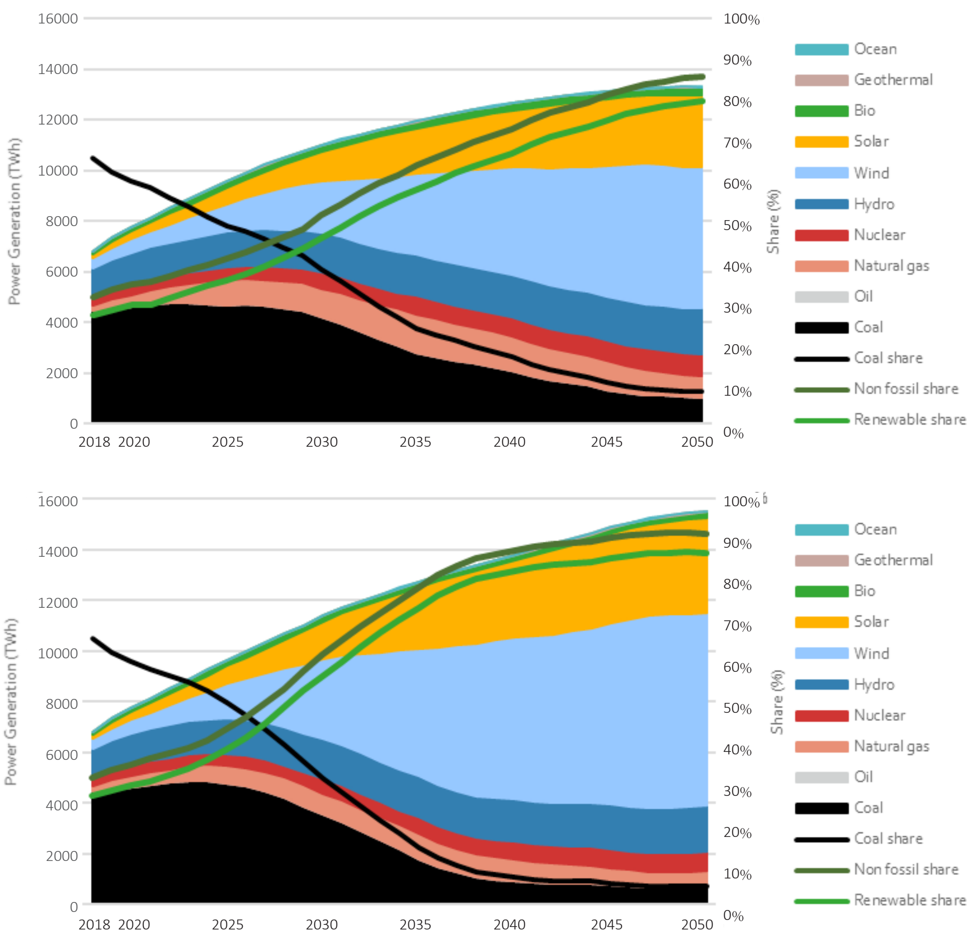
17 International Energy Agency. 'World Energy Outlook.' Paris (2018). https://webstore.iea.org/world-energy-outlook-2018
18 The electrification rate is defined as the electricity generation / final energy consumption (including power plants own consumption).

By 2050, the transport sector has reached 39% electrification in the Below 2°C Scenario, from 2% in 2018. Electrification in industry rises from 28% to 51% and in the buildings sector from 30% to 58%.

Electricity is decarbonised through expansion of non-fossil electricity sources
By 2035, the Stated Policies Scenario sees the non-fossil share of electricity supply more than double to 64% from about 31% in 2018. The Below 2°C Scenario goes even further, achieving 78% non-fossil supply by 2035. By 2050, the non-fossil electricity supply is 86% in the Stated Policies Scenario and 91% in the Below 2°C Scenario. Both development pathways presuppose firm implementation of key policies including the ongoing power market reform which will ensure a competitive level playing field for renewable electricity. This involves fossil fuels bearing an increasing proportion of the societal costs of their emissions e.g. through further development of the emissions trading system which is currently being deployed.

Electricity from wind and solar account for the majority of this transition, with 42% of the electricity supply coming from wind and solar by 2035 in the Stated Policies Scenario. This development is enhanced in the Below 2°C Scenario, with 58% of the total electricity generation coming from wind and solar in 2035. By 2050, wind and solar electricity accounts for 63% and 73% in the Stated Policies Scenario and Below 2°C Scenario, respectively.

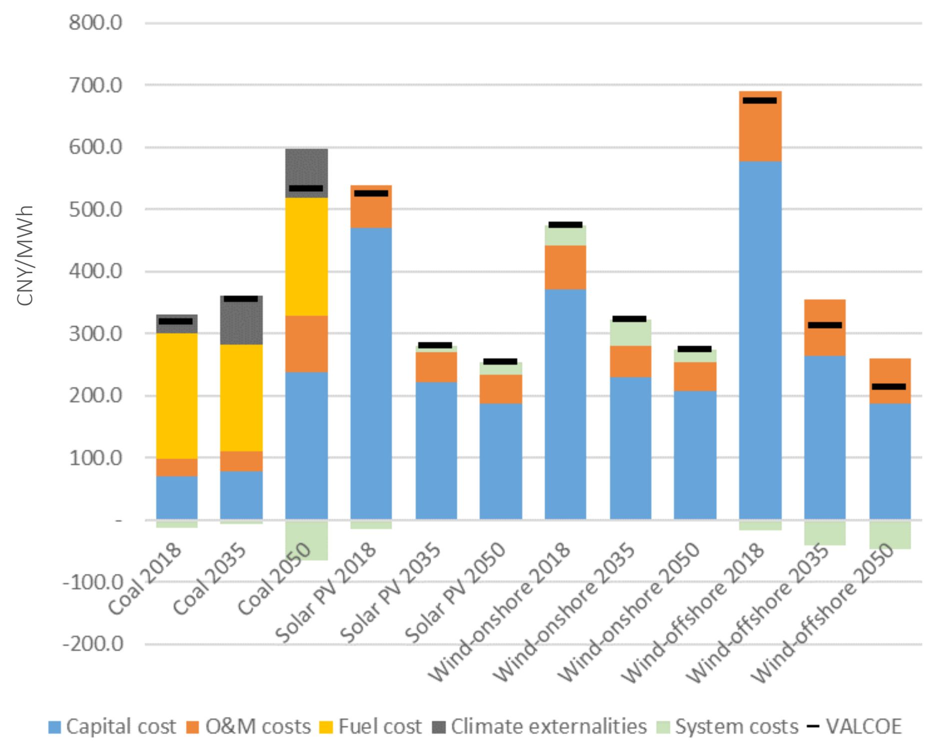
Figure 7.5: Generation by technology through to 2050 in the Stated Policies Scenario (top) and Below 2°C Scenario (bottom).



Cost of wind and solar is a key driver of a financially viable energy transition, but successful system integration is key
The primary driver for this massive expansion of wind and solar is the cost-competitiveness of their electricity supply. While today wind and solar for the most part remain slightly more expensive than coal power, cost reductions are on track to end this. Wind and solar will be on a par with coal during the 14th Five-Year Plan period and afterwards will drop below the price of coal power. This is crucially important for the planning of the energy transition: the combined political aspirations of decarbonisation, clean air policy and future fossil fuel independence depend on it.

The competitiveness of new coal power is reduced significantly in the medium- and long-term. The role of coal power changes from providing baseload electricity supply, to providing support for the power system as the renewable penetration share is increased.

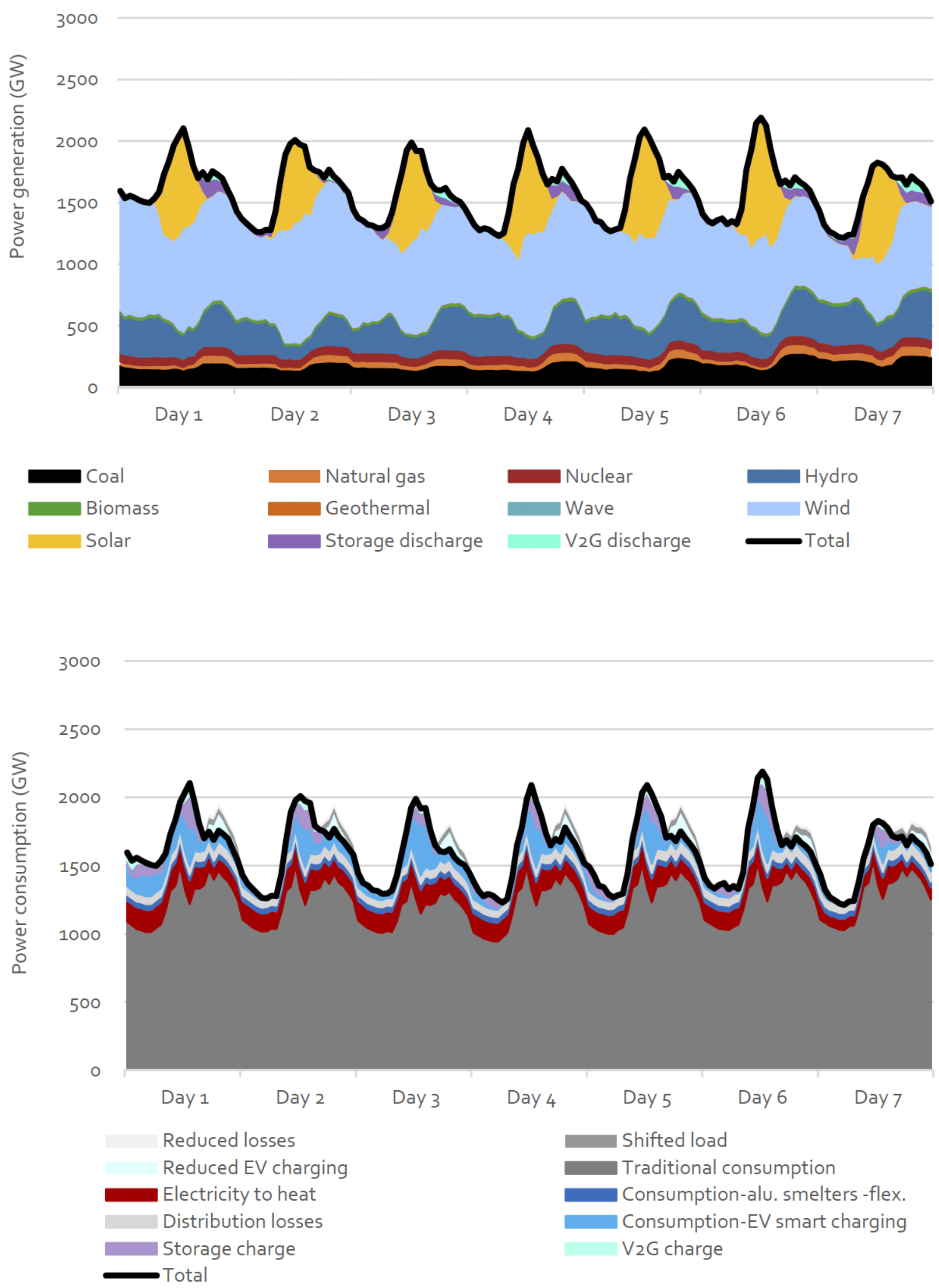
Figure 7.6: Levelised cost of electricity from new coal, wind and solar (utility scale PV) including value adjustments (system costs) and average operating hours from the Stated Policies Scenario.



Note: For 2018, average full-load hours (FLHs) for the technology are used in the calculations; for 2035 and 2050, the average FLHs for the respective technologies in the Stated Policies Scenario are used. The system costs reflect the difference between the specific technology's average system value of generation and the average overall technologies in the Stated Policies Scenario for that year. In a market setting, this reflects the higher (or lower) energy price that can be captured by the technology compared to the average. Two key factors determine this for the technologies averaged over all of China, namely the timing and location of generation vs. the needs in the system.

Cost efficient system integration is a central challenge of energy transition
VRE provides the lowest cost electricity and constitutes one of the lowest-cost options for replacing utility-scale fossil energy consumption. The transition is made cost-efficient in both scenarios by utilising all available cost-effective sources. This includes a host of technical messages, both on the power generation side and the consumption side. Various flexible sources, including storage, V2G, industrial load shifting, and smart EV charging, are mobilised to accommodate the power system fluctuation caused by the high share of VREs. The system is set to include new technologies as well as retrofitting and designing thermal plants for flexible operation, using the flexibility of hydro reservoirs, while expanding and utilising the power transmission grid efficiently.

Figure 7.7: Profiles for power generation (top) and consumption (bottom) in China in winter 2050 (Below 2°C Scenario).



Interprovincial transmission expansion and flexible operation is crucial for the integration of high penetration of renewable generation
Interprovincial grid expansion is critical to provide stability and balancing support, especially when the grid needs to integrate a high penetration of variable renewable sources. In the model, transmission grid expansion is planned according to least-cost principles to transfer electricity efficiently and ensure system security. In the short term, it is assumed that all lines currently planned or under construction will be completed. After 2020, new lines are added to support electricity demand growth and integrate more renewables in the power system.

From 2020 to 2050, total interprovincial grid capacity within different regions is expanded to 682 GW (amounting to an 89% increase) in the Stated Policies Scenario and 781 GW (amounting to a 116% increase) in the Below 2°C Scenario, from 361 GW in 2020. Interregional grid capacity and power transmission show similar trends as within the regions the growth is even sharper. In the Below 2°C Scenario, interregional grid capacity is expanded from 411 GW in 2020 to 506 GW in 2025, amounting to a 23% increase. The corresponding growth is less steep in the Stated Policies Scenario, with a 16% increase. The capacity expansion accelerates later on. Overall capacity in 2050 is more than doubled in the Below 2°C Scenario and in the Stated Policies Scenario, compared to 2020.

Figure 7.8: Power transmission between regions in 2020.

Figure 7.9: Power transmission between regions in 2050.

8. MODELS

8.1 Introduction

This chapter provides an overview of the various possible models that could be applied in the ENTSO-E Showcase for China report and explains how the models are selected.

8.2 Model candidates and selection of models to be applied

At the online launch of the project on 17-19 March 2020, SGERI and ERI/CNREC each presented their planning and market models.

It was decided that both models should be applied to demonstrate the outcomes from ENTSO-E methodologies on China transmission planning. The SGERI model should be used with the SGERI scenarios and the ERI/CNREC model with the ERI/CNREC scenarios, respectively.

However, it was later concluded that the resolution on SGERI's model was too low (simulation based on regions instead of provinces). Instead, only ERI/CNREC's model has been used for screening scenarios and CBA simulations.

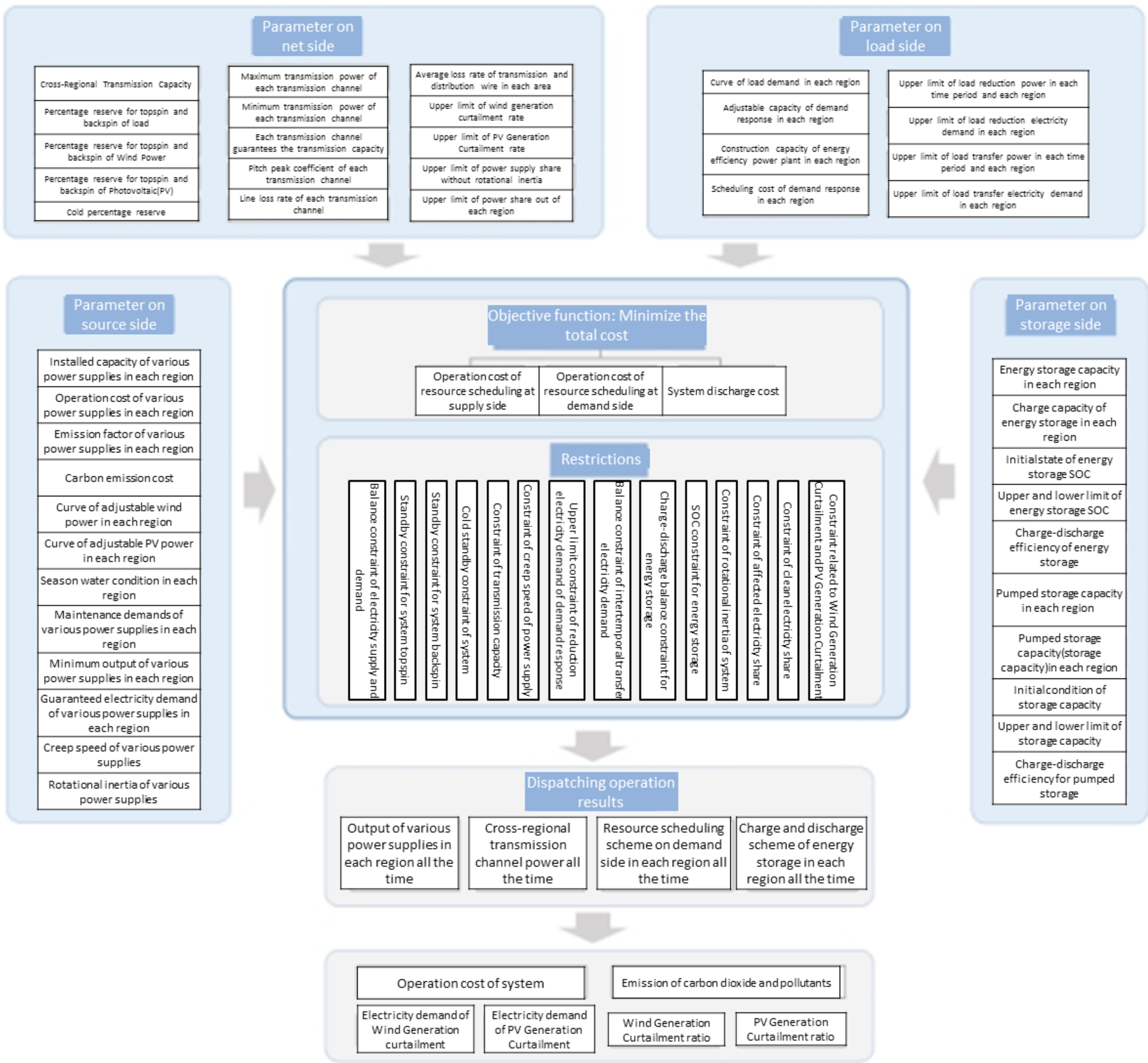
Nevertheless, SGERI's model is also described in this chapter (section 8.3) for the sake of completeness.

8.3 Short description of main features of SGERI model

The model is called a multi-regional coordinated source-grid-load-storage operation simulation of power system. It is utilised for optimisation and simulation of system operation status based on the planning outcomes for China's power system. Firstly, the source-grid-load-storage coordination planning in the main target year is verified. An operation method for China's power system in the main target year is then proposed. This allows for an optimal solution to be found synchronously that addresses: power outputs; transmission power of cross-regional transmission channels; DR and storage capacity on a typical day within the power grid simulation period of seven regions in China.

When applying the model to China's regional case study, the model program included over 36 000 formulae, about 160 000 exogenous variables and about 32 000 endogenous variables. A schematic diagram of the model principle is shown below in Figure 8.1.

Figure 8.1: Schematic diagram of source-grid-load-storage coordination-operation simulation model of power system.



Mathematical formulas in the model

As a mathematical optimisation issue, the model consists of an objective function and constraints. The objective is to minimise the overall costs including the generation cost, DR cost and carbon emission cost.

$$\min\ F=\sum_{t=1}^{H}\sum_{r=1}^{R}\sum_{i=1}^{N}\left(P_{i,t}\cdot FC_i\right)+\sum_{r=1}^{R}\sum_{t=1}^{H}\left(DRC_t\cdot Eh_t\right)+Pr_C\cdot\sum_{t=1}^{H}\sum_{r=1}^{R}\sum_{i=1}^{N}\left(e_i\cdot P_{i,t}\cdot I_{i,t}\right)$$

The model includes the following 19 constraints. The impacts of PV and wind power on up-and-down spinning reserves have been considered in order to ensure that the system reserve capacity can cope with the variability of new energy generation.

(1) Constraint on power balance.

$$\sum_{i=1}^{N}\left(P_{r,i,t}\right)-\sum_{g\in\Omega_{r1v}}Pt_{g,t}+\sum_{g\in\Omega_{v1r}}Pt_{g,t}\cdot\left(1-l_{g}\right)+DRC_{r,t}+DRSo_{r,t}-DRSi_{r,t}+Cc_{r,t}=Load_{r,t}$$
$$\left(r=1,2,\ldots,R;\quad t=1,2,\ldots,H\right)$$

(2) Constraint on up spinning reserve.

$$\sum_{i=1}^{N}\left(P_{r,i,t,\max}-P_{r,i,t}\right)\cdot I_{r,i,t}+DRC_{r,t,\max}-DRC_{r,t}+DRSo_{r,t,\max}-DRSo_{r,t}+DRSi_{r,t}$$
$$+Cc_{r,t,\max}-Cc_{r,t}\geq a_{1}\cdot Load_{r,t}+b_{1}\cdot Pw_{r,t}+c_{1}\cdot Pp_{r,t}$$
$$\left(r=1,2,\ldots,R;\quad t=1,2,\ldots,H\right)$$

(3) Constraint on down spinning reserve.

$$\sum_{i=1}^{N}\left(P_{r,i,t}-P_{r,i,t,\min}\right)\cdot I_{r,i,t}+DRC_{r,t}+DRSo_{r,t}+DRSi_{r,t,\max}-DRSi_{r,t}$$
$$+Cc_{r,t}-Cc_{r,t,\min}\geq a_{2}\cdot Load_{r,t}+b_{2}\cdot Pw_{r,t}+c_{2}\cdot Pp_{r,t}$$
$$\left(r=1,2,\ldots,R;\quad t=1,2,\ldots,H\right)$$

(4) Constraint on non-spinning reserve.

$$\sum_{i=1}^{N}\left[P_{r,i,t,\max}\cdot\left(1-I_{r,i,t}\right)\right]\geq a_{3}\cdot Load_{r,t}\qquad\left(r=1,2,\ldots,R;\quad t=1,2,\ldots,H\right)$$

(5) Constraint on the output range of power sources.

$$P_{i,\min}\cdot I_{i,t}\leq P_{r,i,t}\cdot I_{r,i,t}\leq P_{i,\max}\cdot I_{i,t}$$

(6) Constraint on the ramp-up rates of power sources.

$$-Rd_{i}\leq\frac{P_{r,i,t}-P_{r,i,t-1}}{P_{r,i,t-1}}\leq Ru_{i}$$

(7) Constraint on available wind power.

$$Pw_{r,t}\leq W_{r,t}\cdot Cw_{r}$$

(8) Constraint on available PV power.

$$Pp_{r,t}\leq S_{r,t}\cdot Cp_{r}$$

(9) Constraint on DR load curtailment.

$$DRC_{r,t} \le DRC_{r,t\,\max} \qquad (r = 1,2,\ldots,R; \quad t = 1,2,\ldots,H)$$

(10) Constraint on DR load shift out.

$$DRSo_{r,t} \le DRSo_{r,t\,\max} \qquad (r = 1,2,\ldots,R; \quad t = 1,2,\ldots,H)$$

(11) Constraint on DR load shift in.

$$DRSi_{r,t} \le DRSi_{r,t\,\max} \qquad (r = 1,2,\ldots,R; \quad t = 1,2,\ldots,H)$$

(12) Constraint on DR load shift balance.

$$\sum_{t=1}^{H} DRSo_{r,t} = \sum_{t=1}^{H} DRSi_{r,t} \qquad (r = 1,2,\ldots,R)$$

(13) Constraint on charge & discharge balance.

$$\sum_{t=1}^{H}\left[\max(Cc_{r,t},0)\right] = \sum_{t=1}^{H}\left[-\min(Cc_{r,t},0)\right] \qquad (r = 1,2,\ldots,R)$$

(14) Constraint on State of Charge of energy storage facilities.

$$SOC_{r\min} \le \frac{Sci_r + \sum_{t=1}^{t}\left[-\min(Cc_{r,t},0)\right]\cdot(1-\eta_c) - \sum_{t=1}^{t}\left[\max(Cc_{r,t},0)\right]}{Ec_r} \le SOC_{r\max}$$

$$(r = 1,2,\ldots,R; \quad t = 1,2,\ldots,H)$$

(15) Constraint on the share of power sources with no inertia.

$$\frac{Pw_{r,t} + Pp_{r,t}}{\sum_{i=1}^{N}\left(P_{r,i,t}\right) + Pw_{r,t} + Pp_{r,t}} \le VP_{\max} \qquad (r = 1,2,\ldots,R; \quad t = 1,2,\ldots,H)$$

(16)Constraint on the share of power import.

$$\frac{\sum_{g\in\Omega_{r1i}} Pt_{g,t}\cdot\left(1-l_g\right)}{Load_{r,t}} \le IP_{\max} \qquad (r = 1,2,\ldots,R; \quad t = 1,2,\ldots,H)$$

(17) Constraint on the share of power export.

$$\frac{\sum_{t=1}^{H}\sum_{i\in\Omega_{cr}}\left(P_{r,i,t}\right)}{\sum_{t=1}^{H}\sum_{i=1}^{N}\left(P_{r,i,t}\right)} \ge Rcp_r \qquad (r = 1,2,\ldots,R)$$

(18) Constraint on wind power curtailment rate.

$$\frac{\sum_{t=1}^{H}\left(W_{rt}\cdot Cw_r - Pw_{rt}\right)}{\sum_{t=1}^{H}\left(W_{rt}\cdot Cw_r\right)} \leq Rwc_r \quad \left(r = 1,2,\ldots,R\right)$$

(19) Constraint on PV power curtailment rate.

$$\frac{\sum_{t=1}^{H}\left(S_{rt}\cdot Cp_r - Pp_{rt}\right)}{\sum_{t=1}^{H}\left(S_{rt}\cdot Cp_r\right)} \leq Rpc_r \quad \left(r = 1,2,\ldots,R\right)$$

Inputs and outputs of the model

(1) Inputs:

- The capacity of various power sources, cross-regional transmission, demand response and energy storage facilities in each region in the target year to be simulated.
- The load demand curve in each region.
- The available resource curve of PV and wind power in each region.
- The maximum and minimum output coefficients, ramp-up rate, and fuel cost of each power source in each region.
- The maximum and minimum output coefficients of each transmission channel.
- The upper limits on the capacity and electricity of load curtailment and load shift, and the cost of DR.
- The efficiency and state of charge (SOC) limits of pumped storage and other energy storage facilities.
- The reserve rate coefficients considering the impacts of PV, wind power and load demand variability.
- Acceptable maximum curtailment rate of PV and wind generation.
- The upper limit on the share of power export/import in each region.
- The upper limit on the share of power sources with no inertia.

(2) Outputs:

- output of various power sources in various regions at each hour.
- the power transmission of each cross-region channel at each hour.
- the operation status of demand response and energy storage in various regions at each hour.
- the indicators on system cost and emissions.

8.4 Short description of the ERI/CNREC (EDO) model

The scenario development in CREO is supported by the ERI's energy system modelling tool, consisting of interlinked models, and covering the energy sector of mainland China.

8.4.1 Modelling structure

Since its establishment in 2011, the ERI has focused on developing comprehensive modelling tools to analyse the energy and socio-economic impact of development and integration of renewable energy in the Chinese energy system.

Final energy demands are directed in the END-USE model
The END-USE model, based on the Long-range Energy Alternatives Planning system (LEAP), represents bottom-up modelling of end-use demand and shows how this demand can be satisfied. End-uses are driven by assumed developments in key activity levels in the economy. These include projections for production relating to key energy intensive products such as steel, cement, and chemicals, and the economic value added for other industries.

These drivers translate to energy consumption when combined with assumptions such as industrial output changes, floor area development, energy efficiency improvement, device and fuel shifting (mainly in the industrial and transport sectors), as well as adjustments for end-use behavioural features.

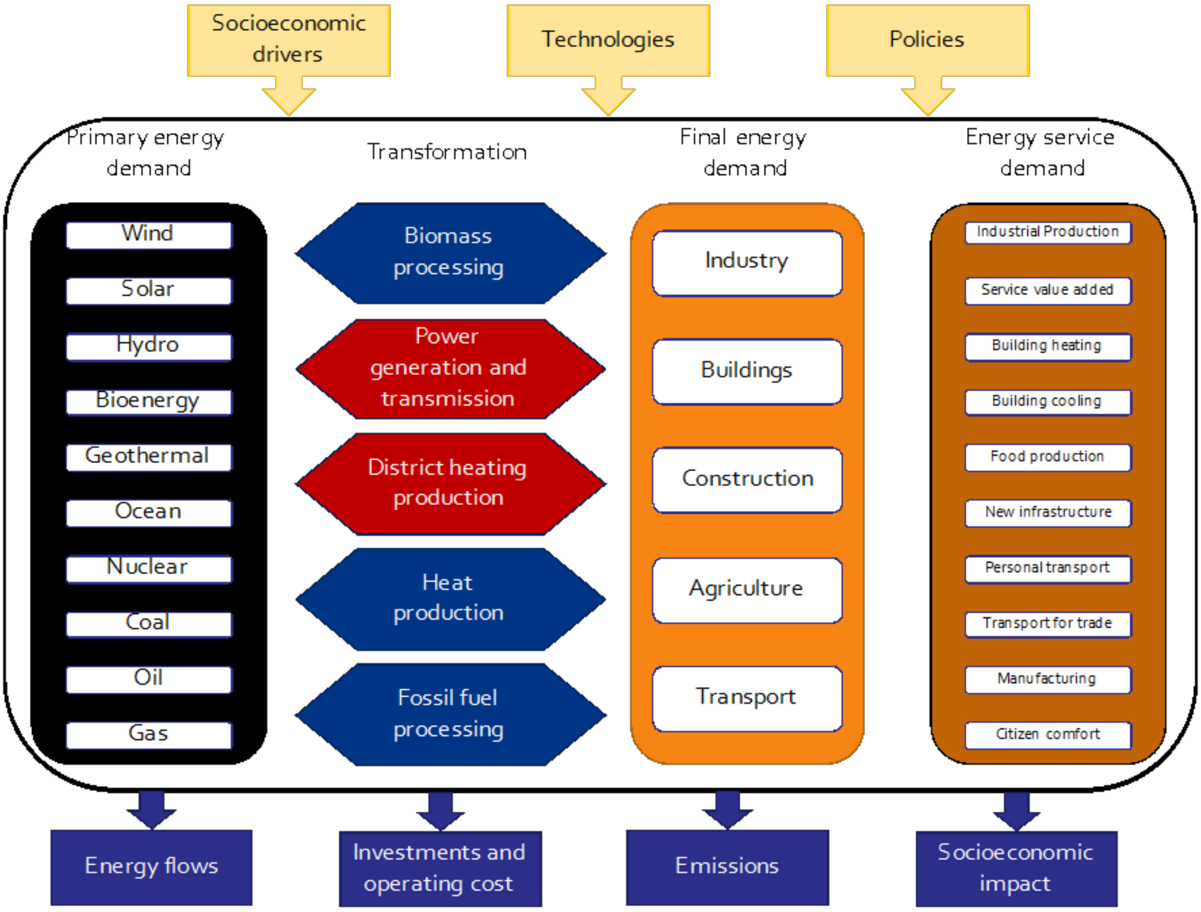
LEAP also covers transformation activities aside from district heating and power. These include upstream refinery activity, such as hydrogen production from the electrolysis process, biofuel production via different technical routines, and oil refining.

Power and district heating sectors are modelled in EDO
The EDO model is a model of power and district heating systems designed using the Balmorel model. The power system is represented at a provincial level, taking into account the interprovincial grid constraints and expansion options. The model includes all relevant production units: thermal (including CHP), wind, solar (including CSP), hydro, power storage, heat boilers, heat storages, and heat pumps. It also incorporates options for demand-side flexibility from industry, smart charging of electric vehicles, and the option of a fully integrated coupling with the district heating sector.

The model can represent the current dispatch in the Chinese power system on an hourly basis with limitations on the thermal power plants and interprovincial exchange of power. It can also represent the dispatch in a provincial, regional, or national power market based on the least-cost marginal price optimisation. Key characteristics relate to the detailed representation of the variability of load and supply (e.g. from VRE sources) as well as flexibility and flexibility potentials, which can operate optimally and be deployed efficiently in capacity expansion mode. As the Balmorel model is open source, flexible customisation and enhancements are possible, including core features and 'add-ons' to tailor the model for application to China, and for interaction with the CNREC suite of models. EDO was introduced in 2012 and has since been continuously used and enhanced, including in the production of earlier CREO reports.

Combined summary tool
Quantitative results from the SGERI and ERI/CNREC models are combined in an integrated Excel-based tool which provides an overall view of the energy system, e.g. combining fuel consumption from the power and heating systems from EDO with direct consumption in end-use sectors and consumption in other transformation sectors from LEAP.

Figure 8.2: The energy system using CNREC modelling tools.



8.4.2 EDO (Electricity and District Heating Optimisation) model

Scenario consistency in the power and district heating sector is ensured using the EDO model. EDO is both a capacity expansion model and an optimal unit commitment and economic dispatch model. Essentially, the model finds the cost-optimal solution for the power and district heating sectors by minimising total costs including fuel costs, capital, operation and maintenance, subject to constraints imposed on the solution such as specific targets or policies that must be achieved. Policy and scenario assumptions are then implemented to guide the model results towards the scenario narrative, rather than allowing the least-cost algorithm solely to determine the capacity mix which achieves the overarching objectives of the scenarios.

Key modules of EDO model

The CREAM-EDO model operates according to the following well-known power system modelling concepts using user settings and input data:

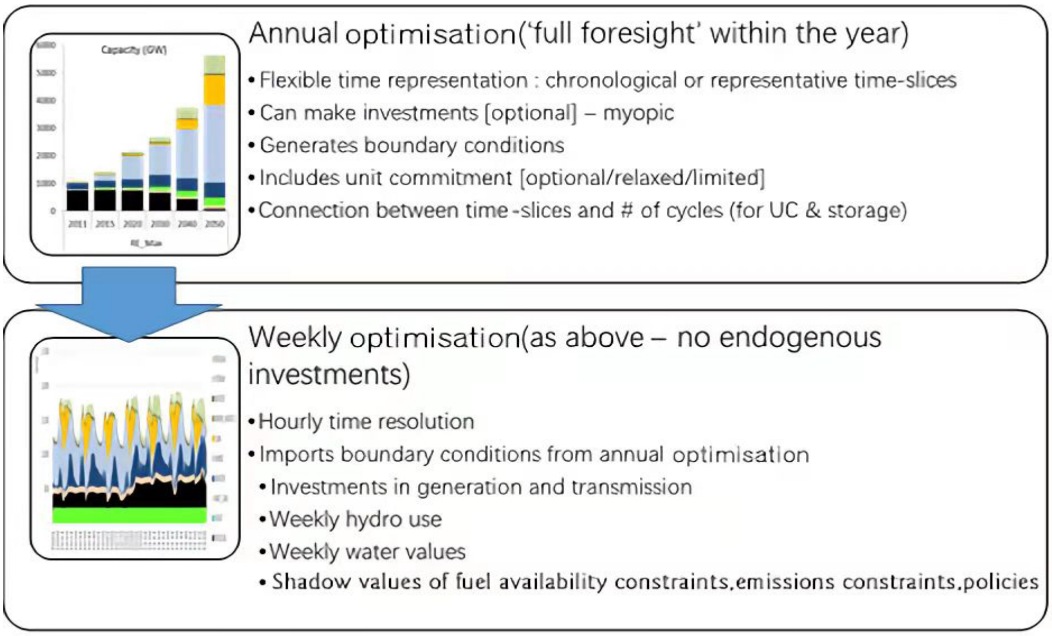
- Economic dispatch optimisation – finding the optimal level of generation from each unit to satisfy demand in each area of a grid, at each step subject to power grid limitations, technical constraints and other limitations.

- Unit commitment – similar to economic dispatch optimisation but with the added complexity of deciding when, and which, units should be started and stopped. This adds complexity to the cost and technical representation of units as start-ups and shutdowns are costly operations and discrete decisions, which affect subsequent decisions.

- Capacity expansion – provides for capacities to be endogenously determined by the model. Thereby the model can be allowed to make investments in generation, transmission and storage based on the needs and economics of the system.

Fundamentally, the model generates a series of linear optimisation programs (or mixed-integer linear programs), each covering either a week or a year. Standard commercial optimisation algorithms solve these mathematical problems.

Figure 8.3: Flow diagram of EDO operation.



A model run consists of one or more linear programs solved either in parallel or sequentially. In general, each year is solved sequentially without reference to future years.

The model runs in two different modes which can interact. The first mode looks at a full year. In this mode, the user configures the time resolution. Normally, for computational reasons, this will be less than full hourly resolution. The second mode looks at a full week at hourly resolution. The model therefore runs 52 times - once for each week of the year simulated. Each of these modes can be run for successive years, creating a pathway for development of the power and district heating systems. If the user allows investment in the annual model, the capacity installed by the model in one year will be available in subsequent years until the end of technical lifetime.

Inputs and outputs

CREAM-EDO contains input data describing the capacities and capabilities of the current system. These include the following:

- **Technologies,** defined as either individual units, unit types or aggregations of units. These are associated with technical and economic characteristics, e.g. capacities for production and/or storage, efficiencies, fixed and variable costs and associated fuels.

- **Fuels,** which are defined with associated characteristics: emission coefficients, renewable content, and prices.

- **Resource potentials or minimum fuel usage requirements,** which can be defined at various levels, from single plants to entire countries. Seasonal and hourly variations in availability (e.g. wind and hydro) need to be specified.

- **Electricity and heat demand** projections are input at regional and area levels.

- **Power transmission capacities** for each country (or at sub-country level) and for cross-border interconnections, as well as import/export with other countries. Capacities, losses, and costs of transmission are defined over a pair of adjacent regions.

- **Taxes and subsidies** include national taxes and subsidies on production, consumption or fuel inputs. These are dependent on geography, fuel types and technology types.

- **Environmental restrictions or penalties** on emission types (CO_2, SO_2, NOx). Regional policies can factored in using add-on modules, including current and future policies that may influence deployment or operations.

An EDO calculation yields results in terms of setting values for quantities and prices (shadow costs) for millions of variables. To analyse these results, data must be pivoted, filtered and/or aggregated to provide meaningful insights into the problem. At its core, the data output can be characterised as follows:

- **Generation of electricity** and heat associated with units in geographical locations and each simulation time step.

- **Consumption of electricity, heat, and primary energy (fuels)** distinguished by geography, units of fuel, and simulation time steps.

- **Transmission of electricity** between connected regions.

- **Prices of electricity** can be extracted, with differentiation according to both region and time steps in the simulation. Similarly, a fair market value of other limited resources such as fuels or CO_2-emission permits can be extracted.

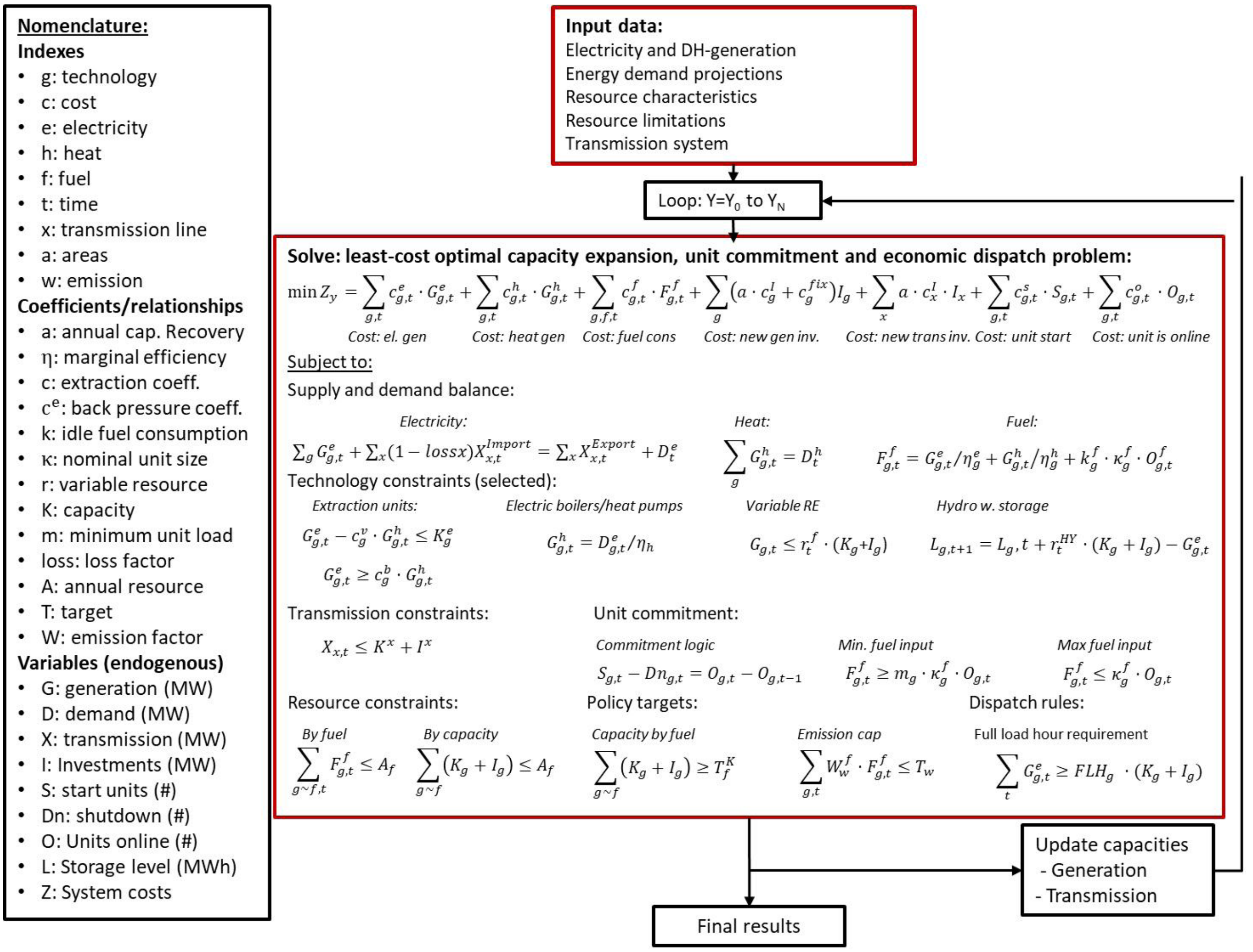
- **Investments** in electricity and heat generation capacity, transmission and storage capacity can be extracted as endogenous variables when running the capacity expansion model version. Economic rent from location limitations (e.g. for wind), transmission capacity and other capacity scarcity can be similarly evaluated using shadow prices.

- **Emissions** from the generation of electricity and district heat as distinguished by geography, units, and time steps.

Covering regions
CREAM-EDO is configured to cover 31 provinces in mainland China including the four provincial level municipalities. Inner Mongolia is divided into its eastern and western parts, creating a total of 32 distinct geographical regions in the model. Within each region, the model calculates generation, consumption and storage operations for power and district heating units and calculates the transmission of power between provinces. In association with these activities, the model calculates fuel consumption, emissions, and the economic costs of operating this system. The model provides these values for each time-step in the simulation. This is important, as power must be generated at the same rate that it is consumed and therefore in each time step, the balance between supply and demand must be maintained at each point in the system. The time resolution is customised but can go down to an hourly level.

Regional grids can also be used as input in the EDO model. According to the current grid area, these areas are Northeast, North, East, Central, South and Northwest China.

Figure 6.5: Representation of model optimisation problem.



9. GRID REPRESENTATION IN MODELS

9.1 Introduction

Transmission project benefits are calculated as the difference between a simulation which does include the project and a simulation which does not include the project. In section 6.6 and Figure 6.8 two proposed methods for project assessment are described: TOOT and PINT.

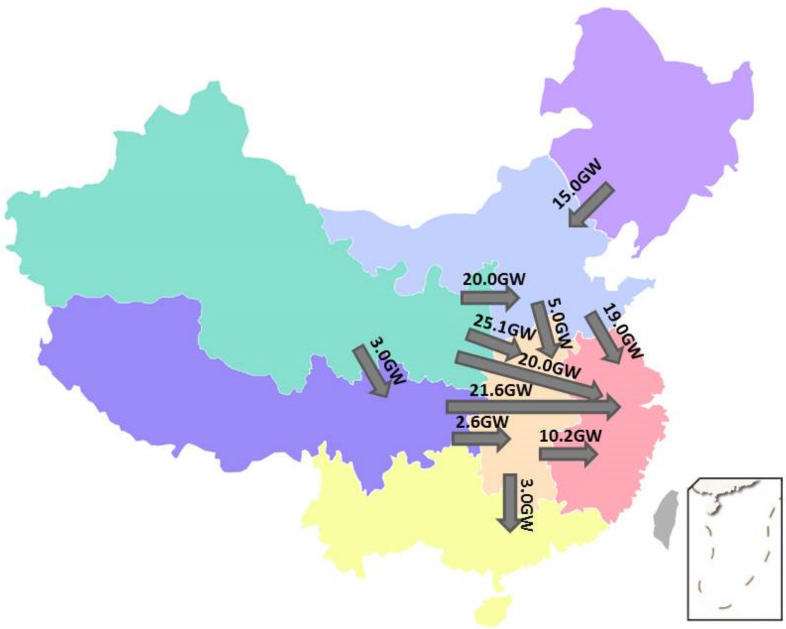
In both cases, it is important to define the initial state of the grid as a base case, that is, the case of no potential transmission projects being implemented. Here we will define the initial state of the grid as the grid in 2020.

Sections 9.2 and 9.3 show the initial grid representation in the SGERI and ERI/CNREC models in 2020.

9.2 SGERI initial state of grid

Figure 9.1 shows the SGERI model footprint and 2020 capacities of transmission lines between model areas. The model resolution corresponds to China's seven power system regions.

Figure 9.1: SGERI model footprint and capacities between model areas (regions), 2020.



9.3 ERI/CNREC initial state of grid

As described in Chapter 8, the electricity grid in the ERI/CNREC model for China is represented at a provincial level (see section 8.4). Each province is treated as a node in the network with its own specific generation capacity portfolio and electricity demand. It is assumed that there is no congestion within a province. Regional grids are built on top of provincial grids.

- The first layer represents the regional grids, where policies and targets are formulated within regional borders. According to the current grid area, these areas are Northeast, North, East, Central, South and Northwest China.

- The second layer is the provincial level, and here the electrical system and transmission are defined. In the model, they are defined as regions, as they can diverge from actual administrative boundaries. For example, Inner Mongolia is subdivided into two regions. Regions are seen as 'copper plates' and are modelled without congestion regarding electricity generation and demand.

These entities can be abstract or can be given specific names according to the geographical area represented. This flexibility means that the modelling and the structure of the power and district heating systems can be customised to any application, enabling the evaluation of specific areas.

The geographical subdivision provides flexibility when defining large areas and the data associated with them, and choosing large areas to be include in a particular simulation.

Figure 9.2: Provincial grid areas assumed in EDO.

Figure 9.3: Grid structure in 2020.

Table 9.1: Inter-regional capacity (GW) in 2020 and 2025

		Centre	East	North	Northeast	Northwest	South
2020	Centre	79					
	East	27	158				
	North	9	18	195			
	Northeast	-	10	46	48		
	Northwest	26	18	37	-	123	
	South	13	1	-	-	-	118
2025 SP	Centre	102					
	East	27	158				
	North	13	23	197			
	Northeast	-	10	46	48		
	Northwest	50	18	37	-	140	
	South	13	1	-	-	-	124
2025 B2	Centre	110					
	East	30	158				
	North	21	25	231			
	Northeast	-	10	46	48		
	Northwest	51	18	37	-	140	
	South	13	1	-	-	-	127

Table 9.2: Inter-regional power transmission (TWh) in 2020 and 2025.

		Centre	East	North	Northeast	Northwest	South
2020	Centre	162					
	East	12	109				
	North	40	144	424			
	Northeast	-	86	81	118		
	Northwest	191	149	180	-	347	
	South	58	10	-	-	-	361
2025 SP	Centre	370					
	East	21	107				
	North	97	185	521			
	Northeast	-	86	135	154		
	Northwest	375	149	58	-	405	
	South	84	10	-	-	-	363
2025 B2	Centre	424					
	East	7	115				
	North	157	205	640			
	Northeast	-	86	149	155		
	Northwest	406	149	56	-	405	
	South	82	10	-	-	-	417

10. CONCLUSION

The EU and China have each made ambitious and firm commitments to moving away from fossil fuels and achieving climate neutrality near mid-century. This decade will be pivotal in bending the curve of global carbon emissions, thus putting the world on track to limiting the potential catastrophe of climate change and fulfilling the global commitment of the Paris Agreement. The EU and China together accounted for 37% of global emissions in 2019, according to IEA's World Energy Outlook 2020. The energy sector accounts for 41% of carbon emissions globally. As such, the energy transitions in both China and the EU are critical for global success in achieving net zero. Energy transition involves fundamental changes in the approach to energy supply and demand, energy technology development and deployment, and the institutional frameworks binding these together. It is imperative that the EU and China collaborate in this effort.

Energy systems are complex, interlinked and intrinsic to all important aspects of the economy and modern life. High quality energy modelling is needed to support the energy transition. Energy system modelling allows policy makers and stakeholders to make informed decisions when designing policies, making investments, and operating new energy systems. Europe and China must demonstrate to the world that this can be done successfully and efficiently without adverse effects on the economy.

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EU-China Energy Cooperation Platform Project is funded by the European Union