Danish Energy Agency

Hainan Clean Energy Island
Power sector transformation pathways

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1. Executive summary

Hainan Province is composed of Hainan and other islands in the South China Sea. Its economy and population are growing rapidly and consequently, so is energy demand. Electricity demand could grow three-fold by 2035 by some estimates. Hainan currently relies mainly on non-renewable energy sources like coal and nuclear electricity.

In May 2019, the government of China issued "The *Implementation Plan* of *the National Ecological Civilization Experimental Zone (Hainan*)"[1] therethrough planning to build a demonstration zone of clean energy development by 2030.

The clean energy development for Hainan is closely related to the overall strategy for China to build a clean, low-carbon, safe and efficient energy system[2] as part of constructing the Ecological Civilisation and linked to, China's ongoing power market reform[3]. The clean energy transition for China has been analysed by the China National Renewable Energy Centre (CNREC) in its annual China Renewable Energy Outlook (CREO) Reports, which gives a detailed picture of the main development scenarios for the Chinese energy system based on comprehensive energy system modelling.

Using the modelling tools and scenarios from CREO, this report analyses viable pathways for achieving Hainan's clean energy development goal by 2030, by addressing the questions:

How can the power sector on Hainan transition and contribute towards the Clean Energy Island policy target?

Subsequently, what is the least cost-approach and what are the alternates?

[1] http://www.gov.cn/zhengce/2019-05/12/content_5390904.htm

[2] As stated China's 13th five-year plan for economic and social development of the People's Republic of China, https://en.ndrc.gov.cn/policyrelease_8233/201612/P020191101482242850325.pdf

[3] The current round of power market reform in China was launched the with the issuance of "Several Opinions of the CPC Central Committee and the State Council on Further Deepening the Reform of the Electric Power System" (Document No.9) in March of 2015

The main finding from the analysis are:

- A clean energy development pathway can be implemented by reducing exports and increasing generation from renewable sources, which will remove coal from the electricity generation mix.
- A clean energy development pathway will just have a 2% higher annual cost compared to business-as-usual.
- Solar and wind power provide the least cost path to displacing coal consumption.

The analysis reveals that, for Hainan's Clean Energy Island (CEI) policy to have a genuine impact on the broader energy system, there must be policy coordination and market design coordination with neighbouring provinces.

The key recommendations for future steps are:

- Conduct a local power system analysis with a broader regional context.
- Prepare comprehensive and systematic analyses to ensure efficient balancing resources and cost-efficient energy transition.
- Analyse how policy mechanisms supporting the CEI target can be efficiently coordinated with electricity market reforms.
- Conduct a more in-depth energy systems analysis to meet the short-term target of 50% primary energy consumption in Hainan from non-fossil energy by 2025.

1.1. Scenario methodology and power system modelling

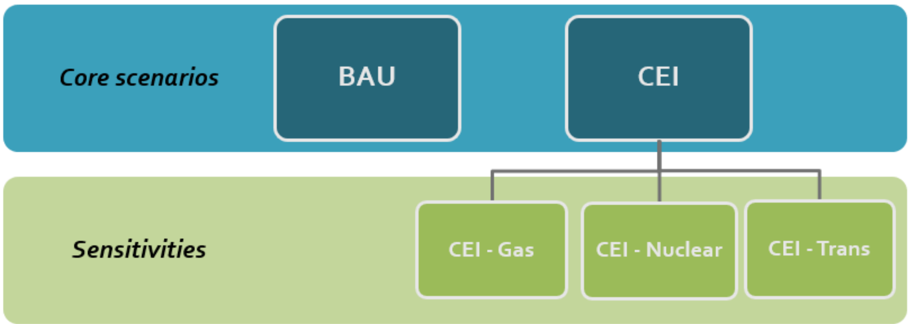
The analysis has been carried out using the electricity and district heating optimisation model (EDO) of the China National Renewable Energy Centre (CNREC). The model finds the cost-optimal investment in existing and planned generation and transmission capacity, subject to targets and policy constraints. The China Renewable Energy Outlook (CREO) 2019 provides the starting point, with key assumptions and data foundation originating with CREO's Stated Policies scenario.

Two core scenarios are analysed:

- Business-as-usual (BAU): Expresses the evolution of the energy system if current policies are maintained.
- Clean Energy Island (CEI): Sets conditions based on Hainan's plan to reduce production from coal by 2030 and increase low-carbon energy technologies.

Three variations are also made to the CEI scenario to explore potential alternative pathways to achieve the targets set, looking at the consequence of more natural gas, nuclear or transmission capacity.

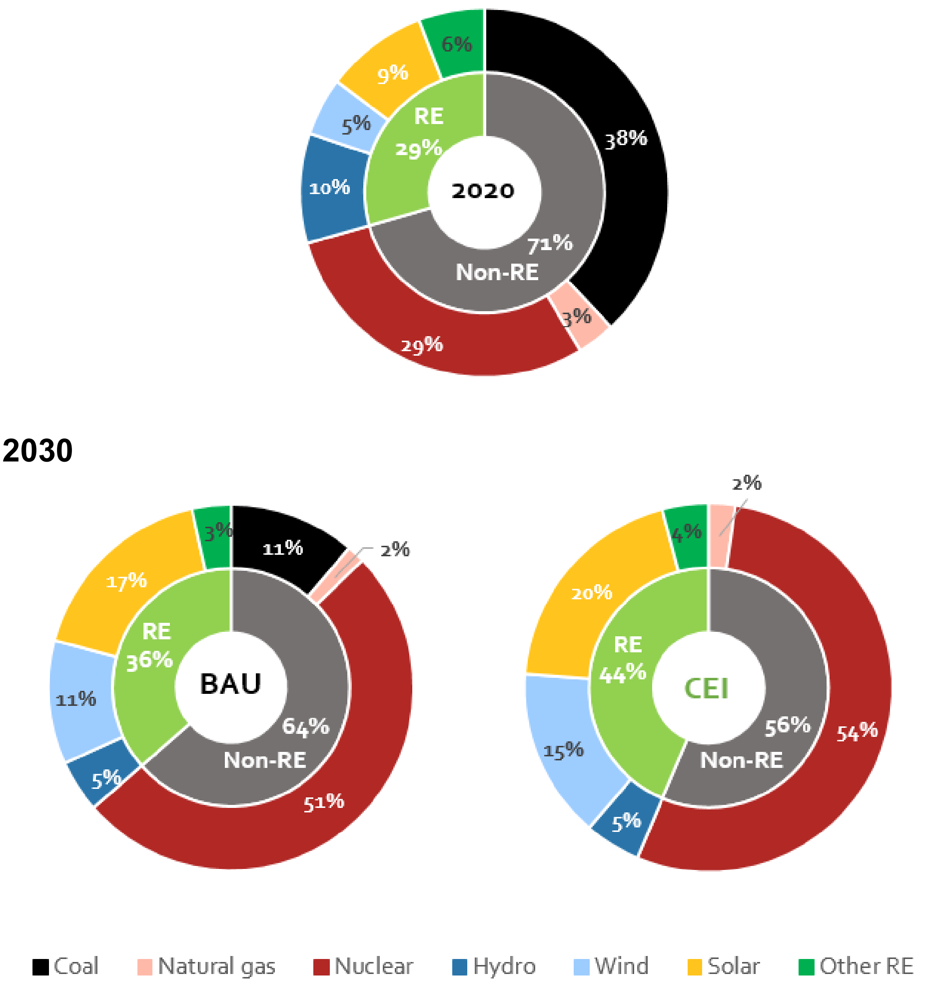
Figure 1-1: Overview of scenarios and sensitivities



1.2. Key results and analysis

In the BAU scenario, nuclear takes up 51% of Hainan's electricity generation mix by 2030, because of the ongoing development of nuclear power capacity. Wind and solar account for 11% and 17% of the electricity generation mix respectively in 2030. The expansion of nuclear capacity in particularly has the effect of reversing average transmission flows, from imports from Guangdong in 2020 to net-exports of 4.3 TWh in 2030.

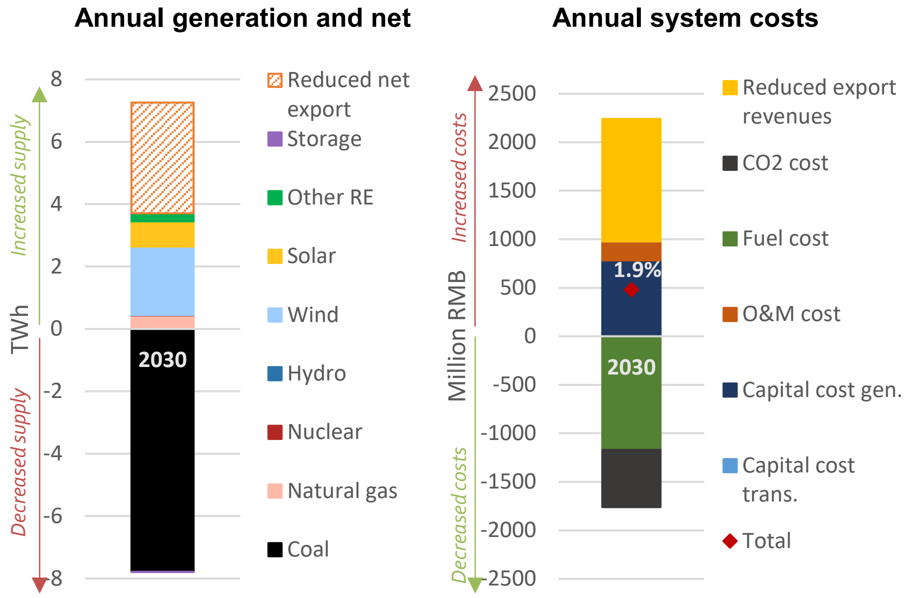
Figure 1-2: Electricity generation mix in 2020 and 2030 for Hainan, comparison between the BAU and CEI scenario.



Hainan's CEI target increases the 2030 RE percentage from 36% in the BAU to 44%.

In the CEI scenario, the coal-fired generation is completely removed in 2030 as compared to the BAU scenario. Coal is replaced by increased generation from wind and solar, and the export of power is reduced. Nuclear generation share increases because the total generation on Hainan is reduced due the decrease in net-export. Additional hydro has not been considered as part of this analysis; hence, the hydro share and generation are the same in both scenarios.

Figure 1-3: Impact of the CEI Target on the annual generation and export (TWh), and the annual system costs (Mill. RMB) in Hainan in 2030. Comparison of the CEI to the BAU scenario.



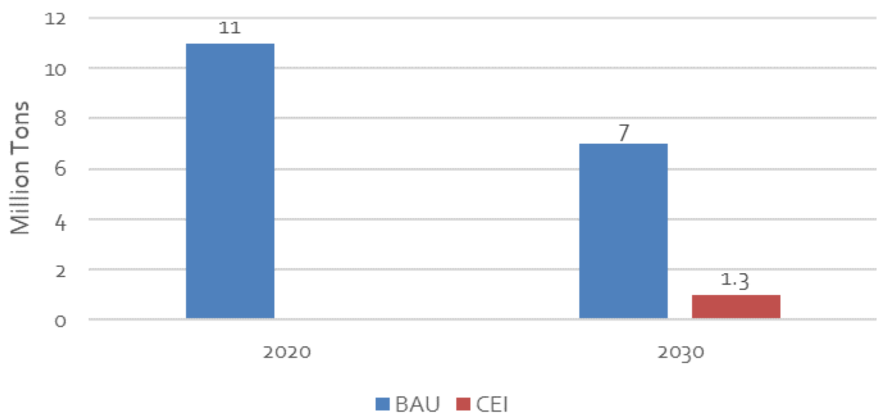
Note: Positive numbers indicate higher generation and lower exports in the CEI scenario relative to the BAU scenario.

The additional cost to the power sector of achieving Hainan's clean energy target, amounts to around 400 million RMB annually in the 2030-2035 period. If attributed per ton of CO_2 abatement, this additional cost amounts to around 50-60 RMB/ ton in 2030, which is low. The additional cost is attributed to additional investments in solar capacity, battery storage and transmission.

Hainan's clean and low-carbon energy system by 2030, would reduce the annual CO_2 emissions from the power sector from 7.0 million tons in the BAU scenario to 1.3 million tons in the CEI scenario. This is a 91% reduction of emissions between 2020-2030 compared with 36% in the BAU scenario.

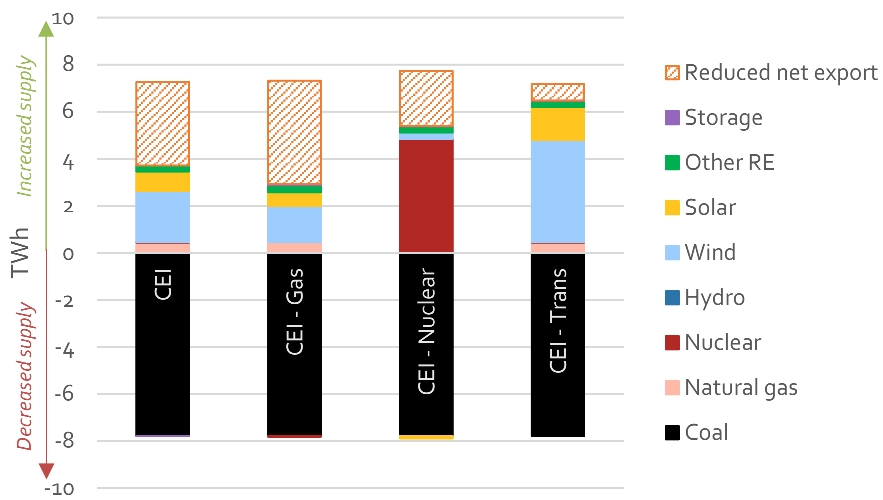
While the BAU scenario reduces Hainan's power sector carbon emissions by 36%, the CEI scenario converge on 100%, relative to 2020.

Figure 1-4: Power sector CO_2 emissions in Hainan in the BAU and CEI scenarios, Mill. tons.



The sensitivity scenarios all change the composition of power generation and export/import balance in Hainan. In the analysis, when more natural gas is used and when a larger transmission capacity is installed, there is a change in the amount of renewable electricity that is exported from Hainan to Guangdong and the amount of renewable electricity that is produced in China Southern Power Grid outside of Hainan. The scenario with more nuclear exchanges renewable generation in Hainan with nuclear generation. None of these displacements impact the CO_2 emissions, neither in the China Southern Power Grid region nor in Hainan.

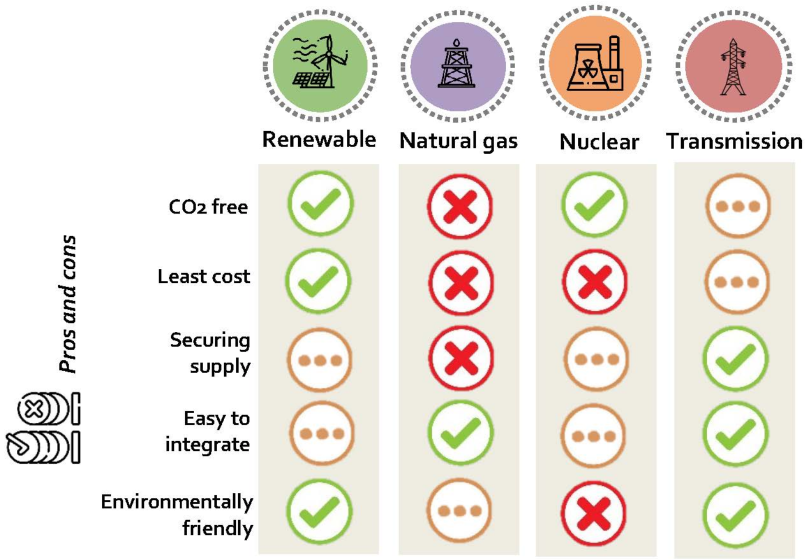
Figure 1-5: Impact of the CEI target on the annual generation and import in Hainan, comparison of the CEI and sensitivities to the BAU scenario for 2030, TWh



Note: Positive numbers indicate higher generation/net imports in the CEI scenario relative to BAU. The positive numbers for import here represent a decrease in annual exports from Hainan to Guangdong.

This analysis shows that amongst alternative pathways to meet the target of reducing coal consumption, wind and solar provide the least cost path. Natural gas, is expensive, must be imported and is not free of carbon. Nuclear is clean and carbon free, but with a price tag. Transmission with the mainland will be important but can be overbuilt, requires continued analysis, and does not ensure that the energy imported is emission free.

Figure 1-6: Alternative pathways for achieving Hainan's Clean Energy Island.



The figure provides a simple indication of each technological pathway's performance according to selected imperatives. The symbols indicate either a 'pro' or an 'con' or somewhere in-between.

1.3. Hainan as a pilot for energy reform

Despite an estimated growth in energy demand, the presented analysis shows that Hainan has the potential to shift to a more renewable energy mix, by leveraging its rich availability in renewable energy resources for electricity generation, like wind and solar. Moreover, Hainan can set an example for such necessary energy reforms and, in doing so, it can become a pilot case for China's energy revolution.

1.4. Hainan reform in a regional context

The CEI scenario invokes a critical reminder that, as Hainan's electricity generation mix is cleaned, a regional view must be considered while evaluating policy measures. Coal use on Hainan is reduced in the CEI scenario, but it is offset by generation on the mainland especially in the short term. For Hainan's CEI pathway to be a net positive, there must be policy links between the limitations set on the island province, and the trading systems for electricity and renewable electricity consumption in the region. This reflects the priorities of the Hainan

Comprehensive Energy Reform Plan, and has emphasis on the development of a unified, open, and orderly competitive market.

Abbreviations

BAU	Business-As-Usual
CEI	Clean Energy Island
CNREC	China National Renewable Energy Centre
CREAM	China Renewable Energy Analysis Model
CREO	China Renewable Energy Outlook
CSG	China Southern Power Grid
DEA	Danish Energy Agency
EPPEI	Electric Power Planning Engineering Institute
ERI	Energy Research Institute
ETS	Emissions Trading System
EV	Electric Vehicle
FYP	Five-Year Plan
NDC	Nationally Determined Contribution
NDRC	National Development and Research Commission
PV	Photovoltaics
RE	Renewable Energy
TSO	Transmission System Operator
V2G	Vehicle-to-Grid

2. Introduction

2.1. Current situation in Hainan

Hainan Province is composed of islands in the South China Sea. It has a land area of 35.4 thousand square kilometres.

The population of Hainan Province is steadily increasing. Hainan reached a resident population of 9.45 million in 2019 (of which 59% was urban population). This was an increase of 140 thousand from the previous year. It is estimated that in 2030 the population of Hainan will be 12.48 million.

The province is a popular destination for tourism, due to its numerous beaches and warm climate. In April 2018, Hainan Province was established as the pilot zone for several important reform tasks which planned to develop modern service industry and marine economy, promote tourism and improve agriculture.

Due to such reforms, the economy of Hainan is flourishing. According to the 13th Five-Year Plan (FYO) for Economic and Social Development of Hainan Province, it is expected that by the end of 2020 Hainan's GDP will grow at an average annual rate of 8.5%, more than doubling of GDP from 2010. In the 14th FYP (2021-2025), it is expected that Hainan's GDP will grow rapidly with an average annual growth rate of 12%.

2.2. Energy development in Hainan

The growing economy and population in Hainan province significantly affect the energy demand. In 2018, the total energy consumption was 22 million tce, a 4% increase compared to the previous year, while the energy consumption per capita was 2.4 tce. Electricity consumption was 32.7 TWh, with an annual average growth of 6.4% from 2015 to 2018. In 2035, the total electricity consumption in Hainan province is estimated to be 105 TWh, while the annual growth rate of total electricity consumption will be of 5.2% between 2026 and 2035[4]. In this study Hainan, electricity demand is assumed to be more moderate, based on analysis from the Electric Power Planning Engineering Institute (EPPEI). Annual electricity demand in 2030 is assumed 58 TWh and 72 TWh in 2035. Average annual growth between 2020 and 2035 is 4.2%

The energy demand of Hainan is increasing yearly.

[4] China Southern Power Grid, *Current Situation Of Energy Development In Hainan*, Workshop presentation, Beijing 2019

Hainan currently relies mainly on coal and nuclear electricity. Hainan had 9,130 MW of installed capacity in 2018, with an increase of 35% compared to 2015. Of this installed capacity, 38% is coal, 14% is nuclear, 13% is photovoltaic, 9% is hydro power and 8% is natural gas. The total energy production in Hainan Province was 4.06 million tce in 2018, growing of 5.8% over the year before. The production of crude oil and natural gas was about 0.43 million tce and 0.13 million tce respectively, and the total production of hydro power and wind power was 3.5 million tce.

2.3. Hainan energy development outlook: Hainan Clean Energy Island

An ambitious plan has been set for Hainan to become a Clean Energy Island (CEI) by 2030, reducing the dependence on coal in favour of low-carbon technologies. In April 2018, the government document "*Guiding Opinions on Supporting Hainan's Comprehensive Deepening of Reform and Opening-up*"[5] proposed to support Hainan in carrying out comprehensive energy reform, focused on the institutional reform of the electricity and gas.

The plan promotes the development of a clean, low-carbon, safe, and efficient energy system in Hainan Province. In March 2019, Hainan Province released its Clean Energy Vehicle Development Plan (2019-2030) announcing official targets for a shift to all clean energy vehicles, by banning petrol-driven vehicle sales by 2030 and with consequent rise of electric vehicles[6]. In May 2019, the government document "The *Implementation Plan* of *the National Ecological Civilization Experimental Zone (Hainan*)"[7] proposed to build a demonstration zone of clean energy development where to increase renewable energy generation, leverage demand response and enhance energy efficiency.

In July 2020, the Hainan comprehensive energy reform plan was issued (海南能源综合改革方案)[8], setting among other measures the target that 50% of Hainan's primary supply shall come from clean energy sources by 2025, and the transformation to a clean, low-carbon safe and efficient energy system shall be completed by 2035.

[5] http://www.gov.cn/zhengce/2018-04/14/content_5282456.htm

[6] https://theicct.org/sites/default/files/publications/Hainan_Clean_Energy_Vehicle_Dev_20190426.pdf

[7] http://www.gov.cn/zhengce/2019-05/12/content_5390904.htm

[8] https://mp.weixin.qq.com/s/6n88ySSkFBp5_Nmfo4vckg

2.4. Challenges in Hainan's energy development

In order to become a CEI and cope with the increasing energy demand, Hainan Province has to address some concerns related to its energy system. Concerns are both economic and operational.

Hainan's energy infrastructure needs to be strengthened. The power supply security in Hainan is relatively low, with the customers' average annual power outage duration of 15.7 hours.

Hainan suffers high energy supply costs. At present, Hainan ranks the second in the electricity supply costs across the whole nation, just after Shanghai. The general concern is that a clean energy transformation may further push up the costs of energy consumption, restricting Hainan's economic and industrial development.

Hainan has not yet established the mature energy market mechanism. In November 2018, Hainan launched its first power transaction participated only by 4 power plants and 11 power consumers. With few participants in the electricity market, it was difficult to achieve effective competition.

The pace of electric energy replacement needs to be accelerated in Hainan. Hainan has put forward the plan of accelerating the promotion of green vehicles and energy-saving and environmentally friendly vehicles, prohibiting the sale of petrol-driven vehicles by 2030. In order to meet such ambitions, it is fundamental to speed up the development of electric vehicles as well as the construction of their supporting infrastructure.

Hainan has not established the mechanism to remunerate the costs of peak load regulation auxiliary service. Due to the high share of nuclear power, Hainan has to construct peak load regulation generators and transmission lines to meet the arising shortage of peak load regulation resources, including pumped storage, natural gas power generation, and submarine cables connected to the mainland. However, an effective mechanism in Hainan is still absent to recover the investment of these peak load regulation resources.

To become a Clean Energy Island and cope with the increasing energy demand, Hainan Province needs to address some economic and operational concerns related to its energy system.

3. Possibilities for Hainan's future energy development

It is crucial for Hainan Province to investigate all possible solutions and opportunities to develop a clean, low-carbon, safe, and efficient energy system.

3.1. Exploring potential of clean energy generation from gas, renewable energy and nuclear

Hainan may exploit its availability in oil & gas, although these resources are mainly located in the South China Sea. Hainan lays claim to proven geological reserves of oil of about 16.3 billion tons, those of natural gas are about 32 trillion cubic meters, and those of natural gas hydrates are about 64.3 billion tons of oil equivalent. Currently, Hainan Province mainly depends on overseas imports, and natural gas is mainly imported from other provinces.

Hainan Province may leverage its rich availability in renewable energy resources for energy production. In terms of wind power, the technical potential of offshore wind in Hainan Province is estimated to be about 4250 MW, that of onshore wind is about 1300 MW, and exploiting these wind resources requires an area of 638 square kilometres. In terms of solar energy, Hainan Province belongs to the rich or medium-rich area of solar energy resources. The theoretical installed capacity is 25250 MW. Hainan Province is also rich in biomass energy, tidal energy and geothermal energy resources. In addition, the theoretical reserves of hydropower resources in Hainan Province are 1039 MW. Although renewables projects are currently raising concerns due to the environmental impact and coastal area usage, which may impact the tourism sector, promoting eco-tourism and carrying out environmental impact assessments could address these concerns.

Hainan might further expand its nuclear energy capacity. Two new nuclear reactors will start the operation in 2025 and 2026. However, due to the poor endowment of uranium resource in China[9], higher dependence on nuclear will affect China's energy independence, as China's foreign dependence on uranium is estimated to be more than oil. Moreover, the high environmental impact and investment cost shall be considered when further discussing nuclear development in the province.

3.2. Leveraging local demand-side management

Besides investigating the potential of energy generation, Hainan might focus on exploiting flexible energy consumption. With the introduction of digitalisation and smart grids, energy demand could be made to adapt according to the intermittent energy generation from renewables, supporting cost-effective and environmentally sustainable balancing. Large

[9] https://dl.acm.org/doi/pdf/10.1145/3070617.3070639

industrial loads as well as residential consumers can be equipped with smart meters, to increase awareness about their consumption. Individual controllers can track the dynamic electricity price and schedule the consumption when it is economically convenient, respecting a certain level of comfort. Moreover, with the increasing number of electric vehicles in Hainan, parked vehicles will constitute a significant source of flexibility, if dynamic charging/discharging of the batteries is implemented.

3.3. Focusing on green energy interprovincial trading

Leveraging the cross-border interconnection is also a possibility for Hainan Province. The province is connected to the transmission system operator (TSO) China Southern Power Grid (CSG), connecting Hainan to Guangdong, Yunnan, Guizhou and Guangxi. Specifically, Hainan's power system is connected to Guangdong's electric network through a submarine cable.

Yunnan's exploitable hydropower resources rank third in China, which might be exported to Hainan Province. Leveraging cross-border interconnection might support Hainan in reaching its green energy targets, by exploiting cost-effective green energy. However, Yunnan's hydropower generation is currently affected by significant curtailment (31.2 TWh, i.e., 13.7% of the hydropower generation in 2016) due to inadequate transmission capacity between Yunnan and Guangdong and lacking adequate policy framework to achieve a well-functioning interprovincial market. Such conditions limit the export of power between neighbouring provinces.

4. Long-term energy scenarios

4.1. Role and contributions of long-term energy scenarios

Energy system scenarios are an effective tool for supporting decision makers to take a long view in a world of great uncertainty by describing hypothetical possible futures and their corresponding pathways. Beyond the commonality of describing possible futures and pathways, in the context of energy scenarios it is relevant to divide them into three categories: predictive, explorative, and anticipative.

Predictive scenarios aim to describe the plausible futures, utilising the current context and observed trends. Predictive energy scenarios are often used when describing the expected evolution of an energy system if current policies are maintained, in what is called a "business-as-usual" (BAU) scenario.

Explorative scenarios not only consider the current context but aim to explore possible uncertain futures based on different assumptions, usually based on a qualitative assessment of different driving factors. An example can be exploring the effects of different possible policy measures in the evolution of the energy system and its climate impacts.

Anticipative scenarios (also called "normative"), work in the reverse direction: by establishing a future definitive vision and working backwards to identify pathways that can connect the existing context with the future vision. In this way they do not identify the effects of specific decisions today but provide information on which decisions need to be taken to achieve a specific future state. In the field of energy, one of the most typical uses is to identify which policies are needed to achieve specific targets, for example limiting global warming below 1.5 °C temperature increase.

The objective of long-term energy planning models is mainly to deliver support for strategic, operational, and political decisions for the future energy systems. In this manner, the effects of existing policies can be analysed, the effects of introducing new policies can be estimated, or new policies can be created to achieve a specific target.

4.2. Contributions from CREO scenarios and modelling

In a Chinese context, the Energy Research Institute (ERI) as part of the National Development and Reform Commission (NDRC) has developed an energy system scenario tool and scenario methodology since 2011 and published the results of the scenario analyses for China in several reports, including the annual China Renewable Energy Outlook report (CREO).

CREO's methodology focuses on developing two main scenarios, a predictive *Stated Policies scenario* which expresses the impact of a firm implementation of announced polices, and an anticipative *Below 2 °C scenario* which shows a pathway for China to achieve the ambitions vision for an ecological civilisation and the role China could take in the fulfilment of the Paris agreement.

The scenarios are designed to achieve the following:

- Provide a consistent and logical framework for the future development of the different energy sectors including the mutual relationships between sectors.
- Provide a clear quantitative long-term vision. The energy system composition of this vision is 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 national scenarios are set-up to illustrate China's success in the transformation to a clean, low-carbon, safe and efficient energy system and the development of the modern socialist economy. More specifically, three overall goals are identified:

- Securing the energy supply at reasonable cost to support China's sustainable economic development. GDP per capita of 30000 US dollars (US dollar as per the year 2005) by the year 2050 forms the economic target applied,
- Securing energy environment with not only temporary solutions but a fundamental solution, removing the air pollution problem of PM2.5 and meeting the PM2.5 emission criteria set by the World Health Organization;
- Securing the low energy climate impact, to implement China's commitment to the Paris Agreement, to follow a low-carbon development pathway by the end of the 21st century, to contribute to the global warming target of below 2 °C and striving for below 1.5 °C.

The CREO scenarios are thereby a suitable framework for regional and provincial studies on green energy futures.

4.3. Scaling modelling from a national to provincial level

In the regionally focused analyses, the National CREO scenarios can be applied as a framework and boundary conditions for more detailed local analysis. Boundary conditions in this case include power flows to and from the focus region and that region's contribution towards meeting national policy objectives and the bounds set in the scenarios' energy transition strategy. By focusing on a small region, more detail can be added to the local model simulations, more variants can be carried out and results more easily interpreted.
The interdependence between the focus region and the surrounding system is stable across simulations.

National scenarios provide anchoring for regional deep dives.

Using national CREO 2019 scenario results as a starting point, boundary conditions are set up, serving as input to the regional analysis of CSG in this study. These boundary conditions may include: 1) trade dynamics with neighbouring regions outside the deep dive region, 2) allotted share of the deep dive region in fulfilling national strategies or requirements.

National strategies or requirements implemented in the CREO scenario remain effective in the deep-dive analysis. In the CREO scenario, the contribution to the requirement by the system outside the focus region is determined. This contribution is then adopted in the deep dive simulation, converting the national requirement into a local one applied to the focus region.

By limiting the geographical scope, reducing computational complexity, regional deep dive simulations offer advantages in terms of increased computation speed and/or possibilities for elevating the level of detail: simulations with increased time resolution or more granular representation of the power system. Regional deep-dive modelling is well-suited for analyses requiring many simulation variants.

For this study, the CSG scenarios are anchored in the CREO, *Stated Policies scenario. A Pre-run* covering Mainland China is made. Results of this simulations are used to set the boundary conditions in terms of electricity transmission between CSG and its neighbouring regions.

Boundary conditions for the CSG power system consist of the transmission to and from external regions and external contribution to national policies. The resulting import and export figures from the *Pre-run* are applied as a fixed transmission profile. The net annual exports can be seen in Table 4-1.

Table 4-1: Annual net exports from regions within CSG to the rest of China, TWh.

From	To	2020	2025	2030	2035
Yunnan	**Sichuan**	13	13	8	12
	Zhejiang	10	10	5	8
Guizhou	**Hunan**	33	40	36	33
Guangdong	**Hubei**	25	12	1	0.3
	Hunan	3	20	4	4
Total		**85**	**95**	**54**	**57**

5. Long-term energy scenario modelling

5.1. Introduction to scenario analysis with EDO

The analysis has been carried out using the electricity and district heating optimisation model (EDO) of the China National Renewable Energy Centre (CNREC). EDO is an important part of the China Renewable Energy Analysis Model (CREAM) and determines how electricity and district heating demands (from the CREAM END-USE model) are met and balanced.

EDO is based on the Balmorel model[10], which is an open source economic/technical partial equilibrium model that simulates a power system and market. The model runs by solving linear programming problems, optimising the combined power and district heating systems. It is a combination of a capacity expansion model and a unit commitment and economic dispatch model.

Simultaneously optimized investment, unit commitment, and dispatch.

The model optimises the generation at existing and planned generation units. It can also allow for additional investments in generation and transmission capacity, as well as refurbishment of existing generation technologies.

Essentially, the model finds the cost-optimal solution for the power and district heating sectors by minimizing total costs including capital, operation and maintenance, and fuel costs, subject to constraints imposed on the solution such as specific targets or polices that must be achieved.

Cost-optimized solution for the power and district heating sectors.

5.2. Key assumptions

The CREO 2019 scenarios are applied here as a framework and boundary conditions for analysing Hainan in conjunction with the CSG footprint towards 2035. In the next 15 years from now to 2035, China will be in the middle and later stages of industrialization and urbanization. It will have the world's largest manufacturing, service industries, urban agglomerations, and middle- and high-income groups. The mode of economic growth is undergoing major changes, thereby framing Hainan’s journey towards a clean energy island in context of other national policy priorities.

[10] www.balmorel.com

For this study, CREO 2019's Stated Policies Scenario is the starting point.

Stated Policies Scenario expresses firm implementation of announced policies

The Stated Policies Scenario assumes full and firm implementation of energy sector and related policies expressed in the *13th FYP* and in the *19th Party Congress announcements*. Central priorities are the efforts to build a clean, low-carbon, safe and efficient energy supply. The scenario also includes the Nationally Determined Contribution (*NDC)* climate target to peak in carbon emissions before 2030, the effects of the *Blue-Sky Protection Plan*, aspects of the *Energy Production and Consumption Revolution Strategy*, and the *National Emissions Trading scheme*.

For more details on the CREO 2019 scenarios, refer to the Appendix (Sections 8.1-8.3) and the CREO 2019 report.

Electricity demand projections

The electricity demand projection for Mainland China is based on the demand-side modelling carried out as part of the CREO 2019 – Stated Policies Scenario. Herein, the electricity demand reaches 7700 TWh by 2020, 11900 TWh in 2035, and 13200 TWh in 2050, when the electrification level will be 54%. This includes grid losses and own consumption from power generation.

The whole society's electricity demand is composed of the exogenously provided end-use electricity demand (based on the LEAP model), plus the grid losses, own consumption in power generation (including storage losses) and endogenous consumption from power to heat. Electricity demand from end-use is shown in Table 5-1.

Hainan power demand is updated based on input from EPPEI, relative to the regional demand distribution in CREO 2019.

Table 5-1: Electricity demand projection (excluding grid losses and own consumption from power generation), TWh.

	Mainland China	China Southern Power Grid				
		Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	6010	29	147	150	130	555
2020	6796	41	169	170	154	617
2025	8469	47	214	222	195	743
2030	9822	61	251	2714	231	833
2035	10762	75	277	306	256	890

Interprovincial transmission constraints

To simulate the economic dispatch of generation capacity in a power system, the model considers the most important transmission constraints in the power system. This has been configured to the transmission limitations between the 5 provinces under the CSG footprint. Transmission constraints represent the maximum amount of electricity that can flow between regions and is defined by a capacity in MW.

The transmission constraints between provinces in the model by 2020 are listed in MW in Table 5-2.

Table 5-2: Transmission constraints included in the model (capacity from "row name" to "column name") 2020, GW.

	To Region				
From Region	**Guangdong**	**Guangxi**	**Guizhou**	**Hainan**	**Yunnan**
Guangdong	-	14.4	7.4	1.2	25.3
Guangxi	14.4	-	8.0	-	3.8
Guizhou	7.4	8.0	-	-	-
Hainan	1.2	-	-	-	-
Yunnan	25.3	3.8	-	-	-

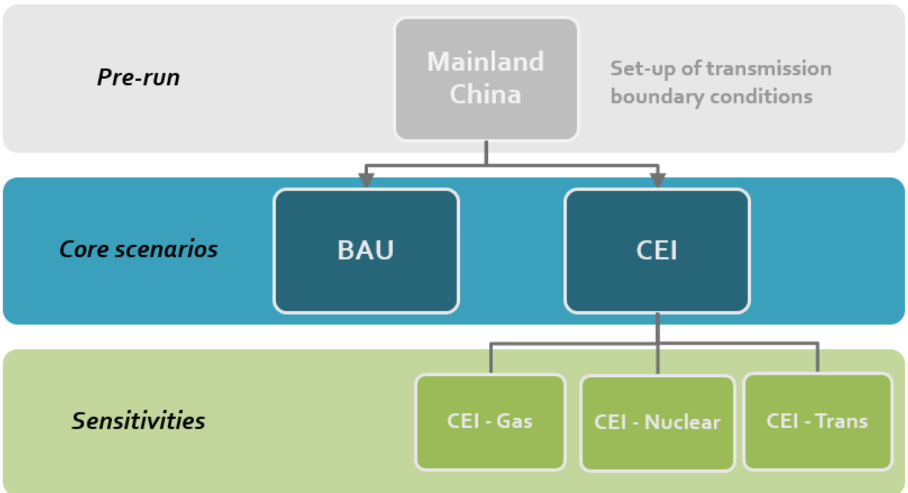
A significant proportion of interprovincial transmission capacity in the CSG area, comes from national key projects, including DC connections from Yunnan to Guangdong. These include the Yunnan-Guangzhou line completed in 2009, the Nuozadu-Guangdong line completed in 2013 and the Yunnan-Northwest Guangdong (Shenzhen) line completed in 2017 – all ±800 kV UHVDC. The Hainan-Guangdong interconnector capacity was updated compared to the CREO scenarios with current capacity (CSG).

Figure 5-1: Ultra-High Voltage infrastructure of China Southern Power Grid[11].

5.3. Scenario set-up

The scenario set-up in this analysis is used to quantify the impact that Hainan's CEI target has on Hainan Province and CSG in the near to mid-term future. CEI scenarios, representing the implication of the CEI target on the power sector, are established and compared to a reference, or BAU scenario, without a target. The central and optimized CEI scenario is further qualified by scenario variants representing alternative approaches, with emphasis on natural gas, nuclear and transmission interconnection.

Figure 5-2: Overview of scenarios in the analysis.



[11] Peter Fairley (2016), Why Southern China Broke Up Its Power Grid, https://spectrum.ieee.org/energy/the-smarter-grid/why-southern-china-broke-up-its-power-grid, Accessed 08-06-2020

Geographical focus

The geographical focus for this analysis is the CSG footprint, as this is deemed sufficient to represent the developments on Hainan as well as the relevant interactions and feedbacks a Hainan CEI policy might have vis-à-vis neighbouring provinces. This reduced geographical scope (compared to modelling mainland China) allows for an increased temporal resolution (i.e. reduced time aggregation) which will increase the accuracy of results of the analysis.

In order to represent CSG's interactions with the rest China, a *Pre-run* is made covering mainland China (as described in Section 4.3). Results of this simulations are used in the *Core scenarios* to set the boundary conditions in terms of electricity transmission between CSG and its neighbouring regions, etc.

Temporal scope and resolution

The simulations are carried out for the near to mid-term future, with the simulated years: 2020, 2025, 2030 and 2035, corresponding to three five-year plans. This year, 2020, is the concluding year of the 13th FYP period and marks the outset for the analysis. Presently, the deliberations about the elements of the 14th FYP (2021-2025) are ongoing. In context of the present analyses, the 2025 milestone, therefore, constitutes the important touchstone on the path towards 2030. The year 2030 represents the next critical milestone and the target year for CEI objective. It is also the year of the medium-term energy transition target of 20% non-fossil energy, and the year before which China's carbon emissions should peak, according to official policy including China's NDC. It is also the terminal year of China's *Energy Production and Consumption revolution* strategy, which among other elements, sets a goal of 50% non-fossil energy in power generation. 2035 marks the halfway mark towards the 2050 (2049) target of developing "great modern socialist country" that is "prosperous, strong, democratic, culturally advanced, harmonious and beautiful", before which China shall have realized a socialist modernization by 2035.

5.4. Core scenarios

The analysis describes two main scenarios to study the impact of Hainan becoming a CEI by 2030, as was proposed in the government document *The Implantation Plan of National Ecological Civilization Experimental Zone (*May 2019*)* in order to accelerate the green energy transition.

1. **BAU:** The BAU scenario illustrates a future where no steps are taken to reduce the fuel consumption from polluting fuels in Hainan beyond planned policies. This scenario can be viewed as the Stated Policies scenario from CREO 2019, with a focused geographical scope: limited to only CSG's footprint.

2. **CEI:** The CEI scenario reduces Hainan's coal consumption until 2030, where no coal use is permitted any longer. The coal consumption decline is linear between 2020 (where coal consumption is permitted at the same level as in the BAU scenario: 112.5 PJ) and 2030.
   The reduction in Hainan based coal consumption and thereby coal produced electricity should not be replaced by imports of electricity produced from fossil fuels. To prevent a counteracting increase in fossil fuel generated electricity in the rest of the CSG, the consumption of coal, natural gas and nuclear is restricted to not surpass the levels from the BAU scenario. In other words, Hainan is not allowed to satisfy its target through imports of electricity from fossil fuels.

Two core scenarios. A BAU reference and a Clean Energy Island alternative.

Both scenarios have identical boundary conditions, representing the transmission between CSG and the neighbouring regions. This setup provides a framework for comparison of two plausible pathways for Hainan, in context of the evolution of the energy system, and the overall system costs of achieving the target.

5.5. Sensitivities

The reduction in coal consumption in Hainan Province creates a deficit in generation which can be compensated for in four ways:

1) Increased renewable electricity generation,
2) Increased natural gas-fired electricity generation,
3) Increased nuclear electricity generation, and
4) Increased electricity import or reduced export (from the rest of CSG).

The main CEI scenario demonstrates an optimized approach based on cost-minimization, but potentially influenced by other policy constraints. For a more thorough investigation of the alternatives and balance between them, sensitivity analyses are carried out.

Three alternative scenarios highlight the alternative pathways.

In the sensitivity analyses, three out of those variants are compared directly to the CEI scenario through an exogenous capacity addition:

- **CEI – Gas:** 650 MW additional gas capacity comes online in 2030.
- **CEI – Nuclear:** 650 MW additional nuclear capacity comes online in 2030.
- **CEI – Import:** 650 MW additional transmission capacity to Guangdong comes online in 2030.

6. Long-term energy scenario results

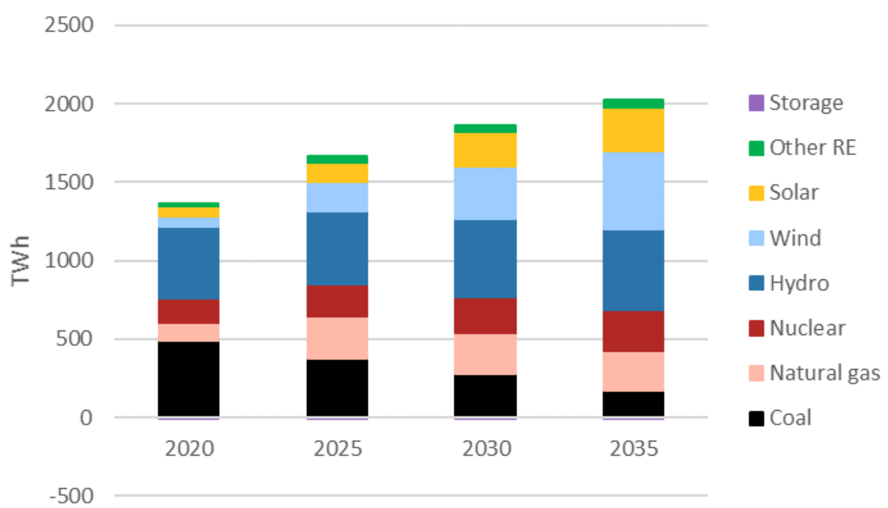
6.1. Business as Usual scenario

With the CREO 2019 Stated Policies scenario forming the starting point of the analysis, one must recognize that the BAU scenario essentially tells a story of energy transition in the system. CREO 2019 finds that the firm implementation of Stated Policies combined with the cost reduction in renewable energy sources realized over the past decades as well as projected over the coming decades, sets China's energy system on a pathway of Energy Revolution. The dominance of coal in the power system is gradually broken by the rapid introduction of wind, solar, natural gas and nuclear power.

Annual electricity generation in CSG transitions towards clean energy

The generation mix in CSG system, is as a starting point less coal intensive than the average for the country. Guanxi, Guizhou and Yunnan in particular, feature large proportions of hydro power in their generation capacity mix. Guangdong, Guangxi and Hainan together account for 39% of the country's nuclear generation capacity, while CSG accounts for approximating 17% of the power consumption. Gas-fired generation is also higher than the average accounting at about 21%.

Figure 6-1: Annual electricity generation development in CSG in the BAU scenario[12].

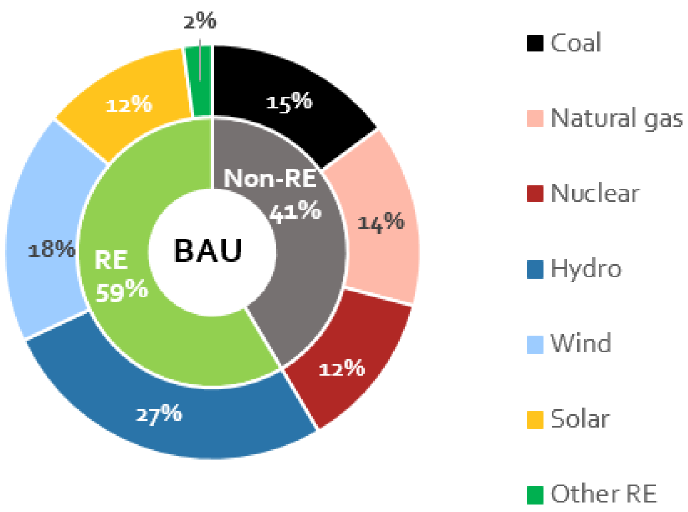


[12] Storage shows negative annual generation due to losses

The increased power demand in CSG is primarily supplied from variable renewable sources. Natural gas and nuclear generation replace coal as thermal generation.

The evolution in the BAU scenario demonstrates that, as for the rest of the country, wind and solar power expansion dominates in CSG, and essentially covers the incremental demand from 2020 to 2035. Meanwhile, nuclear capacity increases, whose expansions are exogenous and therefore not cost-optimised (sensitivity analyses on nuclear capacity is presented in section 6.3). Combined with the substantial increase of natural gas, this leads to 44% of coal-fired generation being displaced by 2030.

Figure 6-2: Electricity generation mix in 2030 for CSG in the BAU scenario.



By 2030, the CSG electricity generation mix is almost 60% from renewable sources. By the applied categorisation of fuel sources (see Figure 6-2), hydro accounts for the largest source at 27%, but wind and solar together (at 18% and 12% respectively) account for 30% of the power generation mix. Natural gas and coal are roughly identical with 14% and 15% respectively, while nuclear has grown to account for 12%.

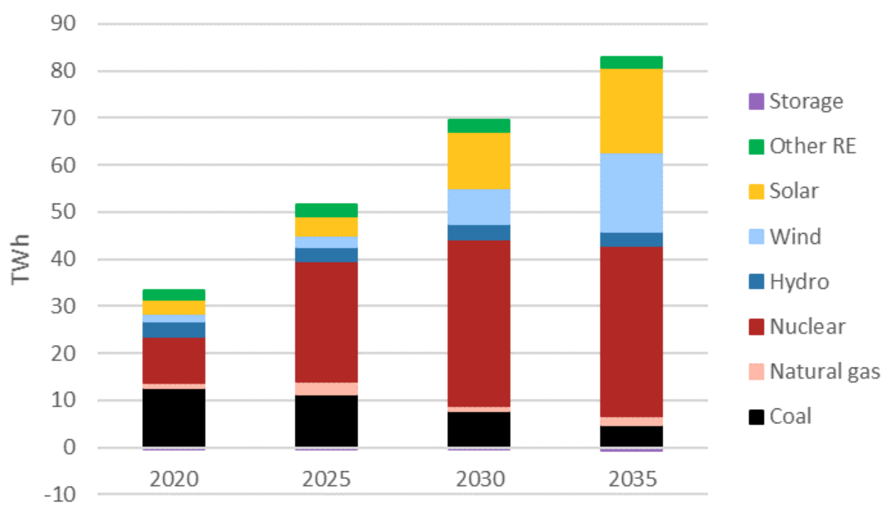
Electricity generation on Hainan converges towards 50/50 RE and nuclear

The energy transition on Hainan in the BAU scenario is equally significant. The ongoing development of nuclear power capacity especially, leads to an increase in nuclear generation by a factor of 3.7, by 2035. Wind generation increases from 1.7 TWh in 2020 to 7.6 TWh in 2030 and 16.8 TWh in 2035. Meanwhile solar increases from 3.0 TWh in 2020 to 12.1 TWh in 2030 and 17.9 TWh in 2035. Thereby, wind and solar account for 11% and 17% of the electricity generation mix respectively in 2030, in the BAU scenario.

Nuclear becomes the primary generation in Hainan in the near-term. Towards 2035, combined wind and solar power reaches the same share as nuclear.

It is also noted, that the RE share and non-hydro RE share of generation in Hainan are 29% and 20% respectively in 2020. The NEA's renewable portfolio standard target policy[13] sets the minimum renewable electricity consumption percentage for Hainan to 13.5% and the minimum non-hydro RE consumption percentage requirement to 6.5%, while the motivational consumption percentages are 14.9% and 7.2% for RE and non-hydro RE respectively.

Figure 6-3: Annual electricity generation development in Hainan in the BAU scenario.



By 2030, the BAU scenario features 8 TWh of coal-fired generation.

This sets the measure of the reduction needed for the cleaning of Hainan's power sector.

Transmission flow to Hainan reverses flow direction

In Hainan's present situation, the four subsea cables to the mainland are used primarily for imports. Hainan's power generation is generally more costly, than generation in Guangdong. The assumed completion of several nuclear projects (see section 8.8) before 2025, are largely responsible for a reversal of this trade pattern, and a simulated 2020 net-import of 10 TWh

[13] NEA (2020), Renewable energy power consumption responsibility weight, 各省（自治区、直辖市）2020 年可再生能源电力消纳责任权重, http://www.nea.gov.cn/139105253_15910013573071n.pdf, Accessed 10-06-2020

changes to a net-export of 1.4 TWh by 2025. This is despite, having increased the load forecast on Hainan specifically, relative to CREO 2019.

6-1: Transmission flow between Hainan and Guangdong in the BAU scenario, TWh.

	2020	2025	2030	2035
Import	10.0	1.5	0.8	1.9
Export	0.0	2.9	5.1	5.2
Net Export	**-10.0**	**1.4**	**4.3**	**3.2**

Towards 2030, additional expansion of nuclear together with significant scale-up of wind and solar installations, further expands the net-export to 4.3 TWh. Hereafter, the net-export recedes slightly until 2035, despite accelerated variable RE deployment, as the pace of nuclear additions declines. Note that while the net-flows recede between 2030-2035, the gross flows (counting flows in both directions) increase towards 2035. This may be equally significant, that with the introduction of more market-based use of the transmission lines, what is essentially unidirectional trade flow in 2020, becomes bidirectional, also to support the efficient integration of variable RE sources and the expanded nuclear share of capacity.

Power related CO_2 emissions in Hainan and China Southern Power Grid decline considerably

Finally, pertaining to the BAU scenario, the CO_2 emissions from the power sector are shown on Table 6-2. In the BAU scenario, the 14th and 15th FYP periods yield 8% and 31% reductions in Hainan's carbon emissions, compounding to 36% over the ten years towards the CEI plan.

6-2: CO_2 emissions in CSG and Hainan and 5-year reduction percentage in the BAU scenario.

From	To	2020	2025	2030	2035
CSG	**Mill. tons**	432	396	314	229
	%	-	8%	21%	27%
Hainan	**Mill. tons**	11	10	7	5
	%	-	8%	31%	27%

While the BAU scenario reduces Hainan's power sector carbon emissions by 36%, the CEI scenario converge on 100%, relative to 2020.

Essentially, this leaves a gap of around 7 million tons of annual CO_2 emissions reductions in 2030, for which additional measures should be defined in the CEI scenarios.

6.2. Clean Energy Target in Hainan

The scene has been set for what should be achieved in the CEI scenarios by 2030:

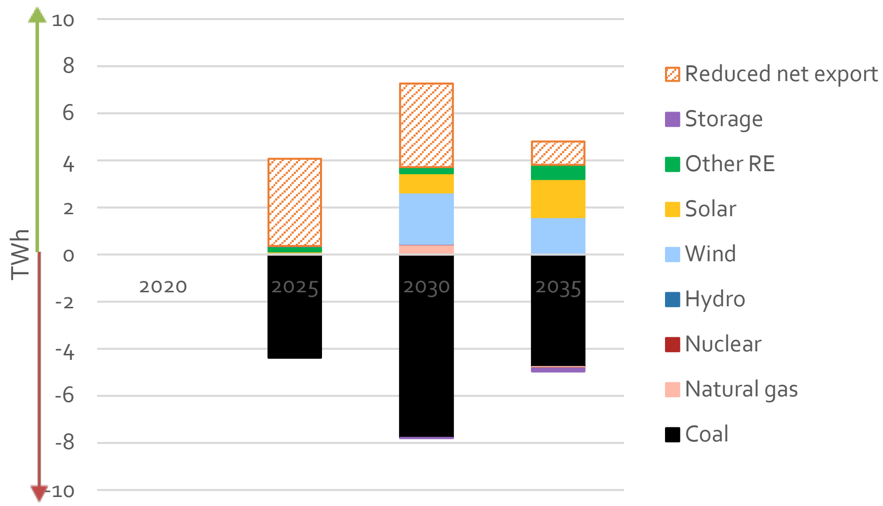
- Reduce 8 TWh of coal-fired power generation,
- Reduce 66 PJ (2.3 mtce) of coal consumption,
- Reduce 5.7 million tons of CO_2 emissions.

Impact on annual generation and transmission in Hainan

In the CEI scenario, the coal-fired generation is reduced by 8 TWh in 2030, beyond which there is no coal-fired generation on Hainan. This is compensated for in part by increased generation and in part by reduced net-exports. The reduction in exports for 2030 is around 3.6 TWh out of the 4.3 TWh net exports in the BAU scenario. Local generation additions amount to around 2.2 TWh of wind and 0.8 TWh of solar and 0.4 TWh natural gas-fired generation.

The difference in generation mix between the 2035 BAU and CEI scenarios is less than in 2030. This reflects the fact that the BAU scenario itself is indicative of the acceleration of energy transition in China. Thus by 2035, there is simply less dirty fuel use to displace, specifically in support of the CEI policy requirement.

Figure 6-4: Impact of the CEI Target on the annual generation and import in Hainan, comparison of the CEI to the BAU scenario, TWh.



Note: Positive numbers indicate higher generation/net imports in the CEI scenario relative to the BAU scenario. The positive numbers for import here represent a decrease in annual exports from Hainan to Guangdong.

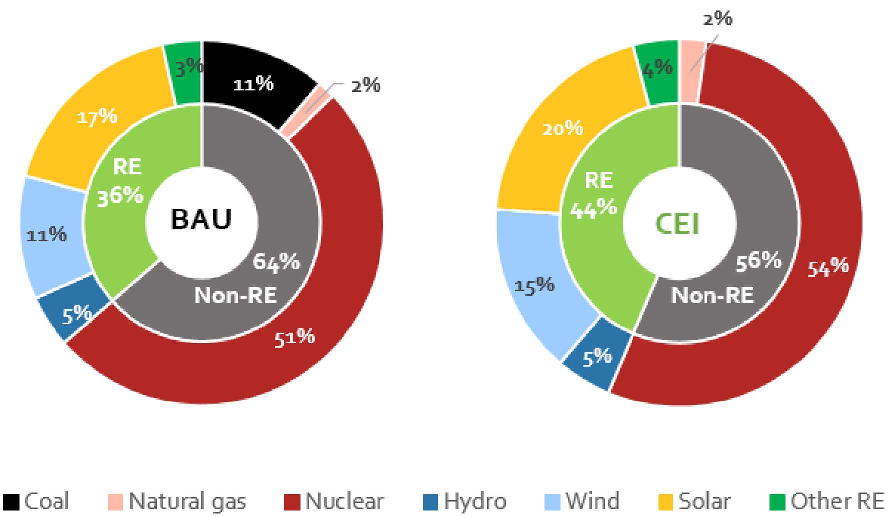
Hainan's Clean Energy Island 8 TWh coal reduction is achieved by scaling up wind, solar, natural gas generation as well as importing renewable energy from the mainland.

The steppingstone of 2025 shows that in the short-term, the additional clean energy would be supplied primarily by reducing net-exports. The scenario invokes a critical reminder that as Hainan's electricity generation mix is cleaned, a regional view must be taken to the policy measures directing this. Coal use on Hainan is reduced in the CEI scenario, but especially in the short-term is offset by generation on the mainland. For Hainan's CEI pathway to be a net positive, there must be policy links between the limitations set on the island province, and the trading systems for electricity and renewable electricity consumption in the region. This reflects the priorities of the Hainan Comprehensive Energy Reform Plan, and has emphasis on the development of a unified, open and orderly competitive market.

The cleaning of Hainan's electricity generation results in reduced net-exports which highlights the importance of a regional policy view, less net-exports be offset by dirty generation on the CSG excluding Hainan.

However, since Hainan's increase in wind and solar in by 2025 is modest in the BAU scenario as well only to scale-up later, it may in practice be more reasonable to increase variable RE in the short-term.

6-5: Electricity generation mix in 2030 for Hainan.



Hainan's CEI target increases the 2030 RE percentage from 36% in the BAU to 44%.

Looking again to 2030, Hainan's power generation mix naturally becomes cleaner in the CEI scenario. Wind adds 4 %-points in the mix relative to BAU. Solar adds 3 %-points while biomass adds 1 %-point. Nuclear generation adds 3 %-points, but this is a function of the total generation on Hainan being reduced, given that net-exports decrease, relative to the BAU scenario. The hydro share and generation are the same in both scenarios since the development of additional hydro has not been considered as part of this analysis.

Changes to power system balancing from increasing clean energy on Hainan

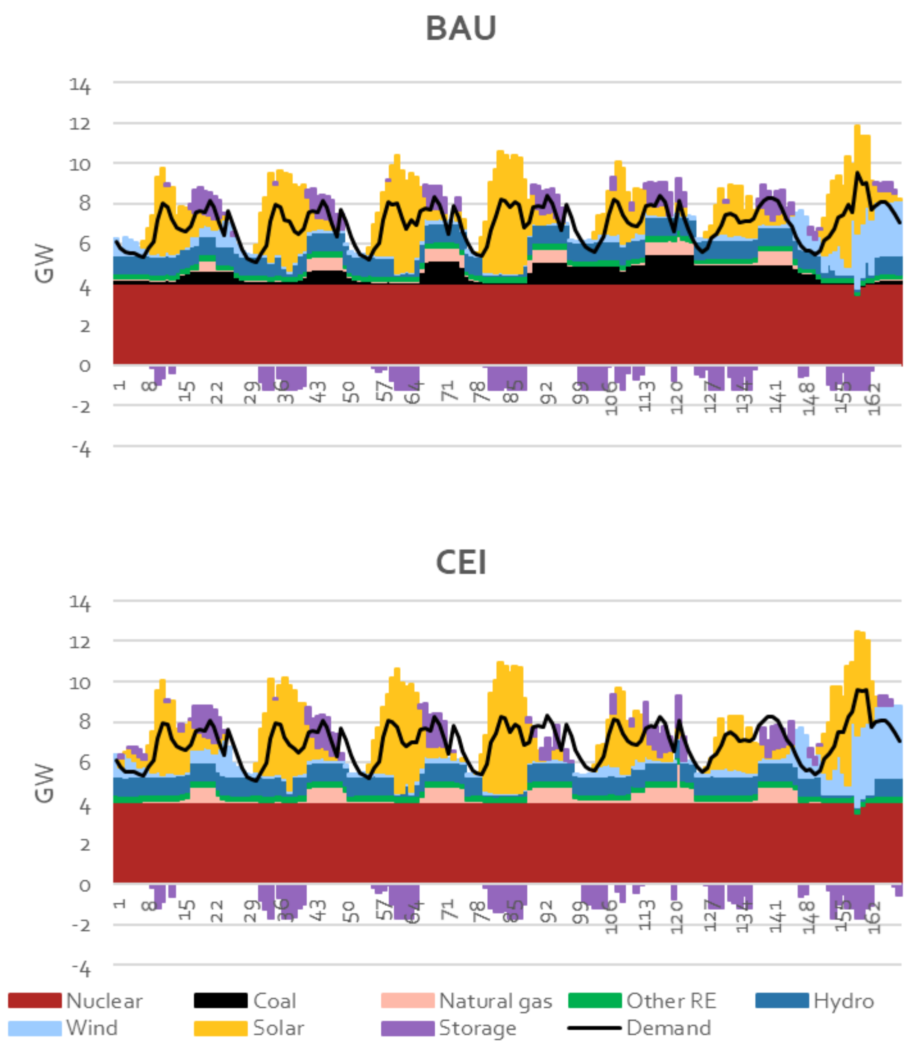
A challenge to highlight in this transition, particularly for an island system like Hainan, is that the increased generation from variable renewables as well as high fixed cost nuclear generation sets increased requirements for the power system flexibility.

In Figure 6-6, an example for a single summer week of the hourly generation dispatch demonstrates the importance of this. It is notable that even in the BAU scenario, one of the nuclear plants ramps down slightly, to avoid curtailment of wind or solar. The thermal assets in the system ramp considerably: down during the solar peak and up during the evening demand peaks. Many units, and almost all gas and coal units, are de-committed during the Sunday of the particular week, which features high winds and solar, together with lower demand. Note that to operate like this, the coal plants have undergone retrofits to increase flexibility. Underlying assumptions of costs and technical parameters of these retrofits are based on a study of the potential for flexibilization of China's coal fleet conducted in 2018[14].

Hainan's power system in 2030 employs all forms of flexibility to compensate for the fixity of generation from variable renewable and nuclear sources.

[14] DEA, EPPEI, CNREC, Energinet.dk and Ea, Thermal Power Plant Flexibility, a publication under the Clean Energy Ministerial campaign (2018), https://ea-energianalyse.dk/wp-content/uploads/2020/02/thermal_power_plant_flexibility_2018_19052018.pdf, Accessed 10-06-2020

6-6: Hourly generation in Hainan for a summer week in 2030 in the BAU and CEI scenarios, GW.

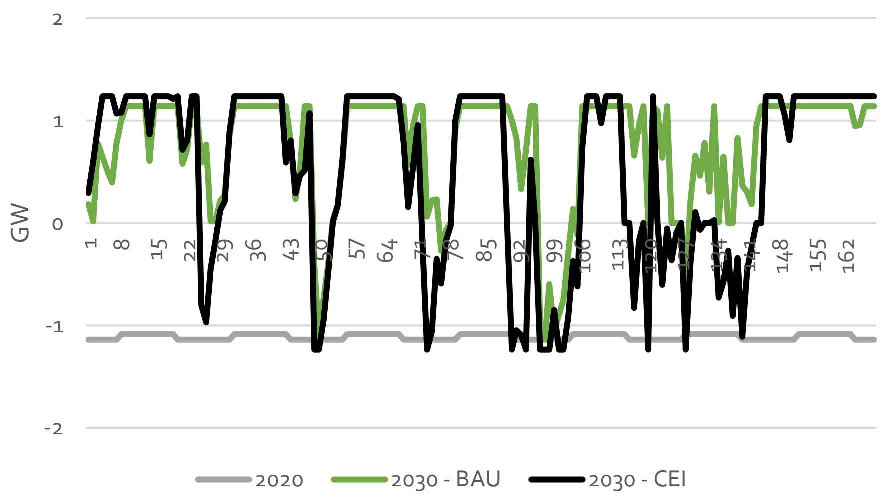


Note: The negative generation values for storages indicate storage loading, consuming electricity from the grid.

Hainan's hydro plants are also contributing to the balancing, at several times ramping down generation during the solar peak.

In the charts (Figure 6-6), *storages* include pumped storages as well as battery storages. The province's pumped storage capacity is actively used in balancing the system, predominantly charging the storages at the solar peak or night-time valley load and discharging to compensate for the drop-off in evening solar and cover evening demand peak. Both scenarios, the pumped storages are supplemented by stationary battery storages, but in the specific week they are one activated in the CEI scenarios. These operate similarly to the pumped storages, but with fewer operating hours, as the operating cost assumptions consider the limited number of cycles available, before the battery cells need to be replaced.

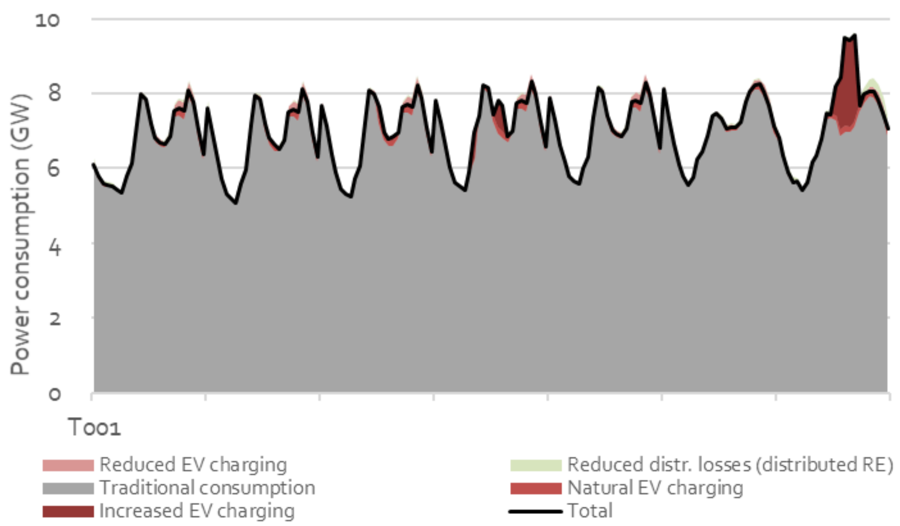
6-7: Hourly export from Hainan for a summer week in 2030 in the BAU CEI scenarios, GW.



In addition to the generation-side balancing, there is also a more active use of the transmission system to level out hourly differences through the connection with the mainland. Compared to 2020, where the flow is unidirectional towards Hainan, the 2030 scenarios feature active balancing. There is also a slight increase in the transmission capacity between Hainan and Guangdong in the CEI scenario. The capacity is around 100 MW. The model's approach for calculating investments allows for investments in variable sizes of transmission capacity with a range of constant marginal costs (up to a threshold) and therefore, modelling results can include minor investments in transmission (or generation) capacity, which are not at minimum efficient scale. The results thus provide an indication, that additional transmission capacity is valuable for the system, given the cost assumptions, however, this result is sensitive to these cost assumptions. Whether a realistic scale expansion project is economical requires further analysis. For this reason, a sensitivity analysis is performed evaluating the impact of increased transmission capacity between Hainan and Guangdong (see Section 5.5).

Figure 6-8, shows the composition of the hourly demand in the CEI scenario for a summer week. The resulting profile consists of traditional demand, generation facilities' own consumption, distribution losses and the flexibly charged electric vehicles and the charging and discharging of storage (pumped hydro and batteries).

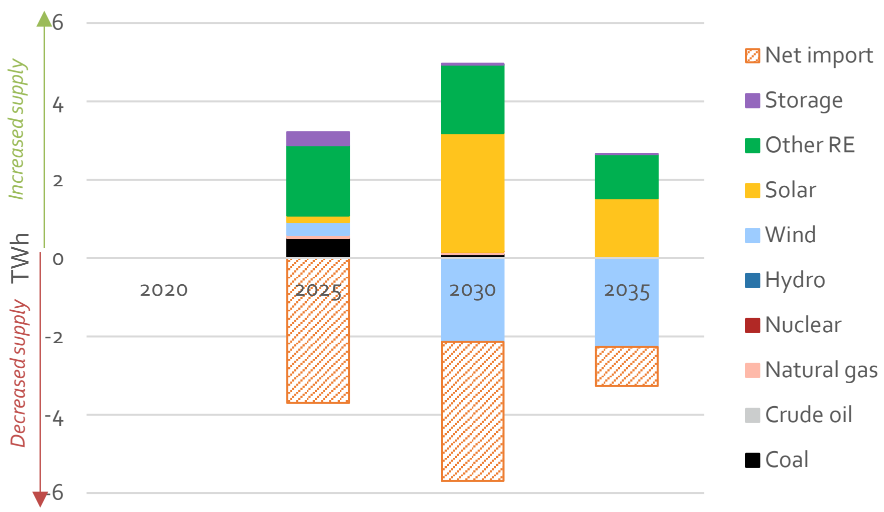
Figure 6-8: Hourly demand for Hainan from Hainan for a summer week in 2030 in the CEI scenario, GW.



Impact on annual generation and transmission in China Southern Power Grid

Given the size of the CSG system, the impact of Hainan's CEI strategy is relatively small. The reduction of net-exports from Hainan to Guangdong, creates a shortfall of electricity supply on the mainland, which is made up for with local resources. In 2025, a combination of biomass, wind, coal and solar makes up the increase.

Figure 6-9: Impact of the CEI target on the annual generation and import in CSG excluding Hainan, comparison of the CEI to the BAU scenario, TWh.



Note: Positive numbers indicate higher generation/net imports in the CEI scenario relative to BAU. The negative numbers for net import here represent a decrease in annual imports from Hainan to Guangdong.

The relative reduction in wind power generation in CSG (excl. Hainan) relates to binding thresholds in the industrial scaling of the wind industry. This implies that between 2025-2035, the additional wind turbines put up in Hainan, are compensated by reduced deployments in mainland CSG. The additional generation of wind on CSG excl. Hainan in 2025, precedes Hainan's relative wind expansion in the simulations, and is the part of the compensation for export reduction from Hainan.

CO_2 emissions 5.7 million tons less per year by 2030 in Hainan

Hainan's clean and low-carbon energy system by 2030, has reduced the 7.0 million tons of annual CO_2 emissions from the power sector in the BAU scenario to 1.3 million tons in the CEI scenario corresponding to 83 % fewer CO_2 emissions. The residual CO_2 emissions comes from natural gas and the plastics component of municipal solid waste, which is incinerated on the island in waste-to-energy plants. Increasing recycling or otherwise implementing alternative treatment of the waste could be considered, to strengthen the requirement for a clean transition. Analysing measures for reducing plastic waste generation and utilization is beyond the scope of the present study, however.

6-3: Power sector CO_2 emissions in CSG and Hainan in the BAU and CEI scenarios, Mill. tons - as well as the % decrease due to the CEI target in Hainan.

From	To	2020	2025	2030	2035
CSG	**BAU**	432	396	314	229
	CEI	432	393	309	226
	%	0%	1%	2%	2%
Hainan	**BAU**	11	10	7	5
	CEI	11	7	1	1
	%	0%	35%	83%	73%

91% CO2 reductions in the power sector is achievable from 2020-2030.

The scenarios' power sector CO_2 emissions outside of Hainan are virtually unchanged in the two scenarios by design. Hainan's power related CO_2 emissions are reduced by 91% from 2020-2030, compared with 36% in the BAU scenario.

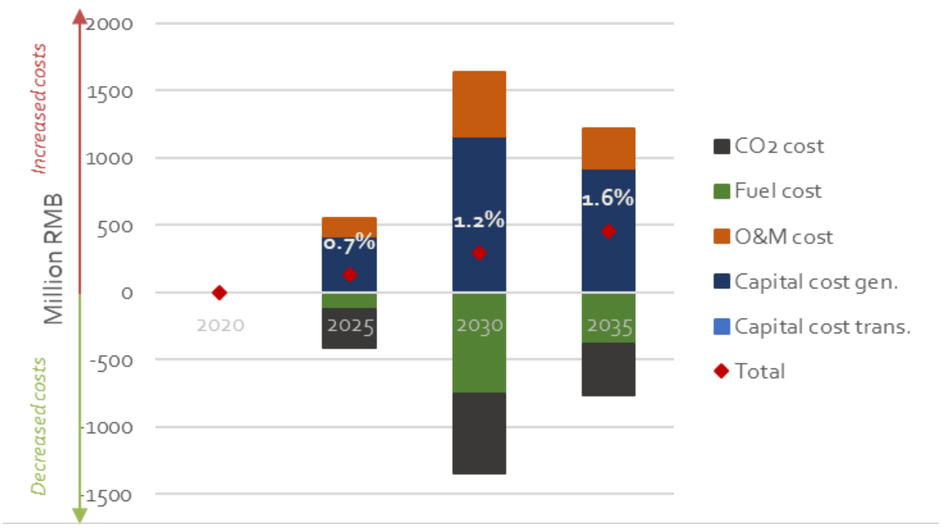
Annual costs increase slightly due to the Clean Energy Island target

The cost to the power sector of achieving Hainan's clean energy target as set forth in these calculations, amounts to around 400 million RMB annual in 2030-2035. If attributed per ton of CO_2 abatement, this additional cost amounts to around 50-60 RMB/ ton in 2030.

The attributable CO_2 abatement cost of establishing a clean power sector in Hainan is in the 50-60 RMB/ton range in 2030, which is low.

It could be said that including the exogenous 100 RMB/ton CO_2 price of both scenarios, yields a combined marginal abatement cost of 150-160 RMB/ton.

Figure 6-10: Impact of the CEI target on the annual system costs in CSG, comparison of the CEI to the BAU scenario.



The additional costs are attributed to additional investments in solar capacity, battery storage and transmission. These costs, which accrue to an annual value of 1600 million RMB in 2030 are at least partly offset by decreased fuel costs and CO_2 costs, based on the scenarios' Emissions Trading System (ETS) price at 100 RMB/ton in 2030. The fuel costs displaced are mainly coal, while there also an increase the utilisation of biomass.

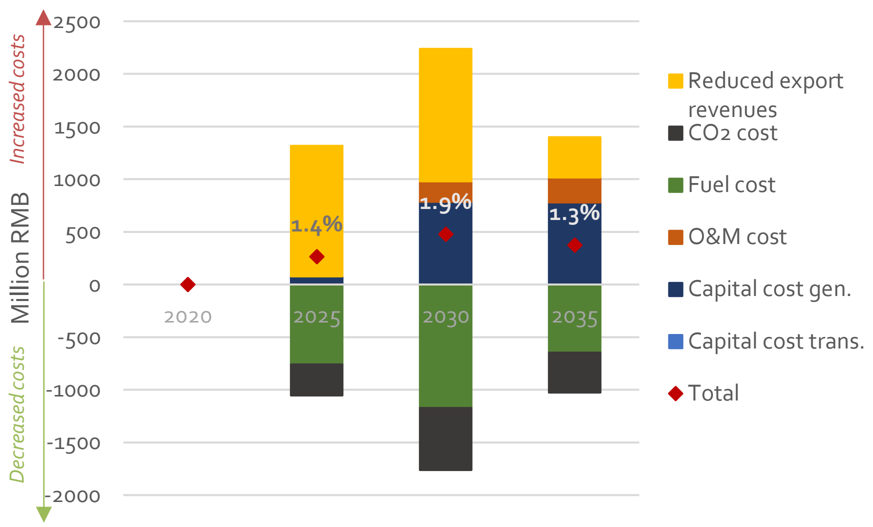
Table 6-4: Impact of the CEI target on the generation and transmission capacities and capital costs in CSG, comparison of the CEI to the BAU scenario.

	Fuel	2020	2025	2030	2035
Capacity (MW)	**Coal**	0	500	-580	-710
	Natural gas	0	70	90	90
	Wind	0	0	0	-240
	Solar	0	0	3370	2600
	Other RE	0	320	330	320
	Storage	0	0	490	490
	Transmission	0	45	440	30
	Coal	0	112	22	-18
	Natural gas	0	10	18	18

Capital cost (mill. RMB)	**Wind**	0	90	47	-30
	Solar	0	0	778	671
	Other RE	0	210	226	210
	Storage	0	0	52	52
	Transmission	0	4	42	8

From Table 6-4 it is evident that the CEI scenario does move forward some coal generation capacity investments on the mainland. This was also seen from the generation results, that more power was generated by coal in CSG excluding Hainan, to offset the reduction in gas and imports in 2025. The total coal consumption has not increased (as it is restricted) due to compensatory declines in coal use in the heating sector.

6-11: Impact of the CEI target on the annual system costs in Hainan, comparison of the CEI to the BAU scenario.



Note: The positive numbers for reduced export revenue are cost increases due decreasing income from export from Hainan to Guangdong, under the assumption that power is traded under market conditions.

6.3. Sensitivity analysis

In the CEI scenario, the CEI target ensures a gradual reduction of coal consumption in Hainan towards 2030. Power generation fuelled by coal is replaced by a combination of increased variable RE generation and decreased export out of the region. This balance of additional wind and solar generation combined with reduced exports represents the most economic path for Hainan to become a CEI.

In this section, a comparative analysis is made, showing to which degree alternative pathways for coal displacement are less cost-efficient and whether they show other benefits such as reduced emissions.

In the three sensitivities, 650 MW additional capacity (compared to the CEI scenario) is installed in Hainan's power system by 2030:

1. 650 MW gas capacity,
2. 650 MW nuclear capacity,
3. 650 MW interconnector capacity to Guangdong.

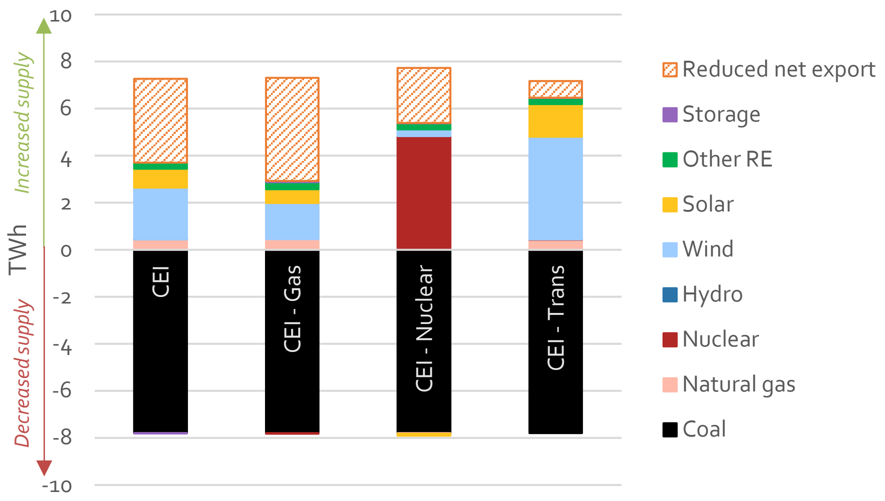
Impact on annual generation and transmission in Hainan by 2030

In the CEI-Gas scenario, the additional gas unit has not impacted the annual fuel use for power generation in Hainan compared to the CEI scenario. Gas prices are high and minimal consumption is kept. The consumption profile has changed however, where natural gas fulfils the role of peak-load generation, using maximum capacity in few hours and fewer baseload, low generation hours. Hainan decreases the wind and solar generation slightly and exports less.

The additional nuclear capacity in the CEI-Nuclear scenario has a larger impact on the power mix in Hainan. The additional nuclear generation is able to make up for 62% of the reduction of generation of coal. Compared to the CEI scenario, generation of wind and solar has decreased significantly.

In the CEI-Trans scenario, where an additional 650 MW interconnector is installed to Guangdong, the additional capacity allows for a greater installation of wind and solar capacity on Hainan. This increases exports, as more variable RE can be balanced in conjunction with the wider CSG system. The CEI – Nuclear scenario has a similar result, as the additional capacity increases net-exports, but without the additional transmission.

Figure 6-12: Impact of the CEI target on the annual generation and import in Hainan, comparison of the CEI and sensitivities to the BAU scenario, TWh.



Note: Positive numbers indicate higher generation/net imports in the CEI scenario relative to BAU. The positive numbers for reduced net export here represent a decrease in annual exports from Hainan to Guangdong.

Sensitivities reveal alternative pathways to the same CO_2 emissions reductions

The sensitivity scenarios all change the composition of power generation and export/import balance in Hainan. The CEI-gas and CEI-Trans sensitivity vary the amount of RE that is exported from Hainan to Guangdong and the amount of RE that is produced in CSG outside of Hainan. The CEI-Nuclear sensitivity exchanges RE generation in Hainan with nuclear generation. None of these displacements impact the CO_2 emissions, nor in the CSG region nor in Hainan.

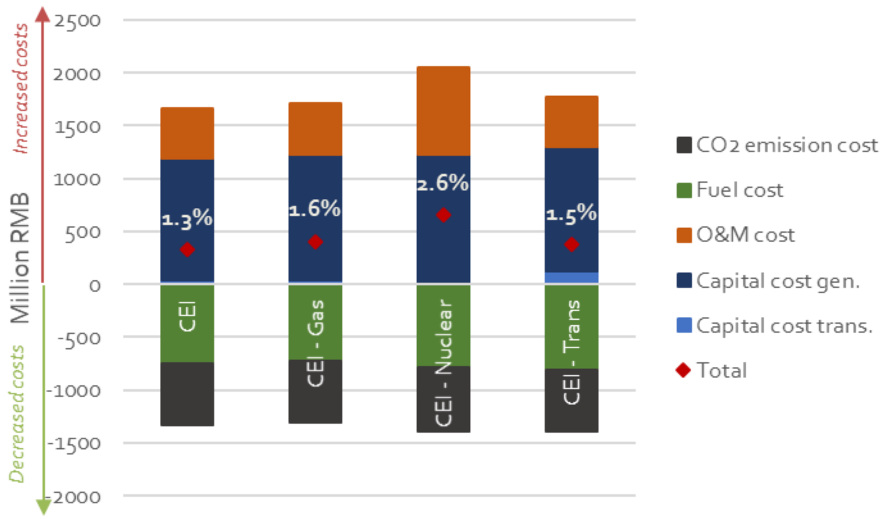
Annual costs in the sensitivities are all higher than in the main CEI scenario

Each of the four sensitivity analyses show a higher cost in 2030 relative to the original CEI scenario, indicating that these approaches are inferior economically to the original scenario. The highest additional cost is rendered from the additional nuclear generating unit. This generation is not only more expensive on a per MWh basis than the alternatives from wind and solar but are also challenging to integrate in the island system.

The optimised approach to achieving the CEI objective, which focuses primarily on building variable RE sources, is less costly than the alternatives.

The additional transmission connection is only marginally more expensive, with the transmission investment partly offset by the efficiency gains in trading between provinces, and the increase penetration of low-cost variable RE sources that it supports.

Figure 6-13: Impact of the CEI target on the annual system costs in CSG in 2030, comparison of the CEI and the sensitivities to the BAU scenario.



The sensitivity analyses demonstrate that there are several pathways which can be taken to achieve Hainan's CEI objectives. In the medium term, the optimised pathway involves emphasis on the expansion of local variable RE.

Each approach has merits and demerits, and supply route taken clarifies additional steps needed.

7. Conclusions

Hainan's power sector can remove coal from its electricity generation mix at less than 2% higher annual costs than the Business-As-Usual (BAU) reference. By 2030, the BAU scenario features 8 TWh of coal-fired generation (down from 13 TWh in 2020), which is displaced entirely in the Clean Energy Island (CEI) scenario. From now until 2030 the CEI scenario leads to a 91% reduction in CO_2 emissions compared to 36% by continuing the planned reforms/current policies. The attributable CO_2 abatement cost of establishing a clean power sector in Hainan is in the 50-60 RMB/ton range in 2030, which is low.

This is achieved primarily by reducing exports to the mainland and investing in renewable sources. The BAU scenario features energy transition driven by economics and national policies but is not as ambitious as the CEI scenario. Nuclear becomes the primary generation in Hainan in the near-term, based on existing plans. Towards 2035, combined wind and solar power reach a similar share as nuclear in the BAU. With the CEI target, the RE percentage in electricity supply could reach 44% by 2030, up from 36% in BAU. Hainan has opportunities to develop both utility-scale and distributed wind and solar projects. Hainan also has considerable potential for offshore wind. The cheapest option for energy supply is wind and solar deployed both in Hainan and the rest of the CSG area, which must then be supplemented by investments in system flexibility, additional storage and optimized use of interconnections.

Although different paths can be taken, electricity from wind and solar provides the lowest cost route for Hainan. When displacing coal from the generation mix in Hainan Province, alternative dispatchable capacity is needed. This can be natural gas, which is expensive, must be imported and is not free of carbon. It can be nuclear with the promise of clean and carbon free energy, but which, as demonstrated here, comes with a price tag as well as other security concerns and different environmental considerations. Transmission with the mainland will be important but can also be overbuilt. The results highlight the importance of consistently analysing how much interconnection shall possibly be built and to which function, i.e. clean imports, export of surplus generation and/or provision of balancing services.

The implementation of the policy mechanisms supporting the CEI target must be coordinated with electricity market reforms. High proportion variable resources are best integrated through short-term (spot) markets, which incentivises generators, grid companies, storage assets and consumers alike to provide flexibility for continuous system balancing. Expanding Guangdong's spot market pilot to Hainan is an option. Alternatively, a Hainan provincial spot market is needed. In such case, it would be critical to have efficient market coupling mechanism to coordinate flows on the interconnectors. For electricity trade with Guangdong to facilitate the CEI target, there must be also be mechanism to ensure that the lines' flows are clean electricity.

The broader regional context of local analyses is critical. This analysis provides an example of how important the power system's interaction with the region is. The results for achieving clean electricity generation in Hainan indicate reduced net-exports relative to the BAU scenario. This highlights the importance of a regional policy view to achieve real impact of the policies piloted, preventing net exports being offset by dirty generation on the CSG excluding Hainan. In the analysis, this rebound effect was explicitly prevented such that as exports from Hainan are reduced, clean sources on the mainland must make up the difference. A regional approach to policy making would be needed to replicate this effect. Moreover, in this analysis, a link is maintained between the national policies and strategies, as the national level scenarios from CREO 2019 anchor the present regional analysis.

Comprehensive and systematic analyses are needed to ensure efficient balancing resources and cost-efficient energy transition. Hainan's power system in 2030 employs all forms of flexibility to compensate for the fixity of generation from variable renewable and nuclear sources. This combination is challenging but can be addressed by:

- combining flexible use of residual thermal assets;
- using existing and new storage options;
- activating demand response potential – particularly linking the power system and market development with the transport electrification polices;
- and actively using the existing grid link to Guangdong.

Full energy systems analysis is urgently needed as Hainan's primary energy consumption should be 50% delivered by clean energy by 2025. This analysis supports that direct and perhaps indirect electrification would likely be the linchpin, beyond what is assumed as relating to the transport sector. The power sector can be made clean and low carbon at low cost, and the power system can be run safely and with low dependence on imports. Yet fossil-fuel consumption, especially in buildings, industry and transport, also needs to transition.

8. Appendix 1: Modelling assumptions and approach

This appendix briefly provides and introduction to the modelling and scenario framework and documents key data assumptions used for the analysis. Firstly, the broad outline of the starting point for the scenarios from CREO 2019 are introduced. Second, the power system model applied, EDO, is introduced. Finally, key data assumptions are presented.

8.1. Starting point from CREO 2019

CREO 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 the long-term development as basis for short-term decisions. These scenarios are used as the national frame for the regional analysis covering the CSG footprint.

In CREO 2019, 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 guide the development trends in the desired direction and to ensure fulfilment of the goals for the 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 China Renewable Energy Outlook applies two main scenarios.

Stated Policies Scenario expresses firm implementation of announced policies

The scenario assumes full and firm implementation of energy sector and related policies expressed in the *13th FYP* and in the *19th Party Congress announcements*. Central priorities are the efforts 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 Emissions Trading scheme*.

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

Below 2 °C Scenario shows the building of an ecological civilisation energy system

The Below 2 °C Scenario shows a pathway for China to achieve the ambitious vision for an ecological civilisation and the role China could take in the fulfilment of the Paris agreement. The main driver is a hard target for energy related CO_2 emissions through a strategy with renewable electricity, electrification and sectoral transformation at the core. The target is set at 200 billion tons of energy related CO_2 emissions in total between 2018-2050.

The scenarios were designed to provide a clear long-term vision and combine this with a clear view of the current situation, trends, market and policy direction, and project this into the future.

8.2. Applying the CREO scenarios to Hainan and CSG

The CREO scenarios are applied here as a framework and boundary conditions for analysing Hainan in conjunction with the CSG footprint towards 2035. In the next 15 years from now to 2035, China will be in the middle and later stages of industrialization and urbanization. It will have the world's largest manufacturing, service industries, urban agglomerations, and middle- and high-income groups. The mode of economic growth is undergoing major changes.

For this study, CREO's Stated Policies Scenario is the starting point.

Thereby framing Hainan's journey towards a clean energy island in context of other established national policy priorities.

8.3. Key aspects from the CREO scenarios

The scenarios adopt the strategy that the crux of the energy system transformation is the development of non-fossil and renewable energy, which primarily is implemented through the power sector.

Statistics regarding installation, operating hours, as well as hourly power load profiles are used to calibrate the base year (2018) for simulations. The model elaborates wind solar resource potentials, power demand growth rate, fuel cost estimation, cost development of technologies of different provinces so that it represents the characteristics of Chinese power sector development. New load types such as electric vehicles and heat pumps are introduced as well. More than 30 types of technologies are used for capturing the availability, operating characteristics as well as cost development of technologies. 13th FYP, Energy Production and Consumption Revolution Strategy and other energy and environment policies are implemented as constraints and targets to represents the most updated development environment for Chinese power sector. To adapt to the current operating scheme in China, generation rights and full load hours are implemented as constraints and are relaxed while electricity market develops.

Table 8-1: Key figures in the energy sector development in the Stated Policies scenario.

		2018	2020	2025	2030	2035
Energy basis						
Total Primary Energy Supply (TPES)	Mtce	4 346	4 476	4 730	4 718	4 412
Total Final energy consumption (TFE(	Mtce	3 165	3 251	3 427	3 510	3 463
CO_2 emission	Mton	9 526	9 337	9 077	8 223	6 640
Non-fossil fuel share of TPES (NFF)	%	10%	14%	19%	24%	32%
RE share of TPES	%	8%	11%	15%	20%	27%
Coal share of TPES	%	61%	56%	47%	40%	30%
Coal share of TFEC	%	33%	29%	21%	15%	11%
Gas share of TPES	%	8%	10%	14%	16%	20%
Oil share of TPES	%	20%	20%	20%	19%	17%
Electrification rate	%	26%	29%	34%	39%	43%
Coal substitution method						
Total Primary Energy Supply (TPES)	Mtce	4 685	4 892	5 318	5 599	5 610
Non-fossil fuel share of TPES (NFF)	%	17%	21%	28%	36%	47%
RE share of TPES	%	15%	18%	24%	32%	42%

Table 8-2: Key figures in the energy sector development in the Below 2 °C scenario.

		2018	2020	2025	2030	2035
Energy basis						
Total Primary Energy Supply (TPES)	Mtce	4 346	4 476	4 610	4 432	4 025
Total Final energy consumption (TFEC)	Mtce	3 165	3 252	3 396	3 438	3 349
CO_2 emission	Mton	9 525	9 337	8 804	7 184	5 079
Non-fossil fuel share of TPES (NFF)	%	10%	14%	19%	29%	42%
RE share of TPES	%	8%	11%	16%	25%	37%
Coal share of TPES	%	61%	56%	47%	36%	23%
Coal share of TFEC	%	33%	29%	20%	14%	10%
Gas share of TPES	%	8%	10%	13%	15%	18%
Oil share of TPES	%	20%	20%	21%	19%	16%
Electrification rate	%	26%	29%	35%	41%	48%
Coal substitution method						
Total Primary Energy Supply (TPES)	Mtce	4 684	4 891	5 253	5 549	5 603
Non-fossil fuel share of TPES (NFF)	%	17%	21%	29%	44%	59%
RE share of TPES	%	15%	18%	26%	40%	55%

The scenarios feature significant scale-up of RES, energy efficiency and electrification.

Table 8-3: Scale of installed capacities and key indicators.

Scenario	2020	Stated Policies			Below 2℃		
Year		2025	2035	2050	2025	2035	2050
Total Capacity (GW)	**2053**	**2539**	**4027**	**5395**	**2717**	**5124**	**6730**
Coal	1023	950	691	420	1037	730	445
Oil	2	1	0	0	1	0	0
Natural gas	104	165	263	214	132	197	152
Nuclear	53	70	95	110	66	87	100
Total RE Capacity (GW)	**870**	**1352**	**2979**	**4651**	**1482**	**4110**	**6033**
Hydro	347	386	455	533	347	386	455
Wind	242	425	1121	1922	507	1763	2636
Solar	246	485	1346	2135	536	1836	2803
Bio	35	56	55	57	51	54	55
Geothermal	0.06	0.10	0.45	2.00	0.12	0.60	5.00
Ocean	0.05	0.28	0.88	2.00	0.28	0.87	2.00
Fossil fuels (%)	55%	44%	24%	12%	43%	18%	9%
Non-fossil fuels (%)	45%	56%	76%	88%	57%	82%	91%
Renewable (%)	42%	53%	74%	86%	55%	80%	90%

The power sector is the crux of the energy system with wind and solar as the core.

8.4. Power and district heating sectors are modelled in EDO

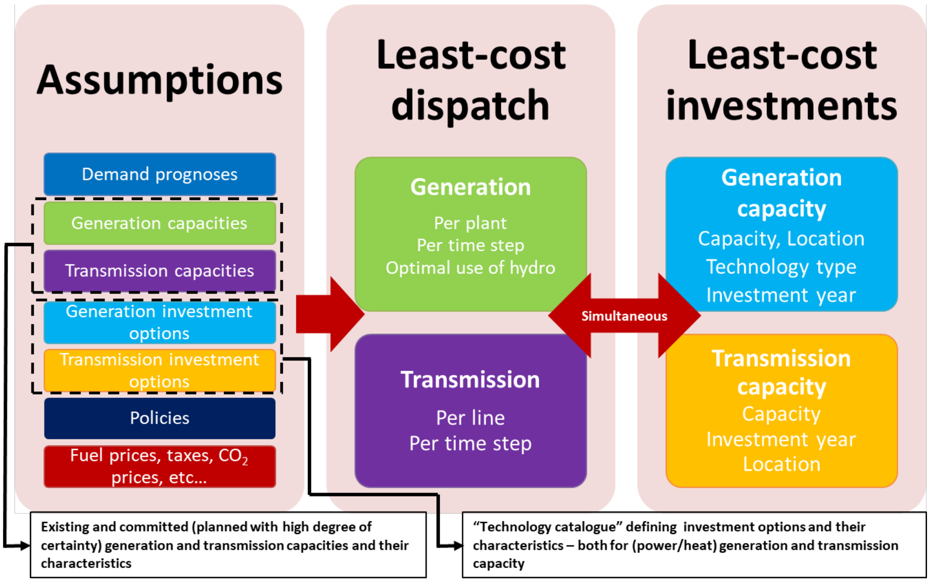
The analysis has been carried out using the electricity and district heating optimisation model (EDO) of CNREC. EDO is an important part of the China Renewable Energy Analysis Model (CREAM) and determines how electricity and district heating demands (from the CREAM END-USE model) are met and balanced.

EDO is based on the Balmorel model (www.balmorel.com), which is an open source economic/technical partial equilibrium model that simulates a power system and market. The model runs by solving mixed integer/linear programming problems, optimising the combined power and district heating systems. It is a combination of a capacity expansion model and a unit commitment and economic dispatch model.

Simultaneously optimized investment, unit commitment, and dispatch.

The model optimises the generation at existing and planned generation units. The model can also allow for new investments in generation capacity and transmission capacity to be made, as well as refurbishment of existing generation technologies. If enabled, the investments are chosen by the model on a cost minimising basis.

Figure 8-1: Simultaneous optimization of operations and investment. :



Essentially, the model finds the cost-optimal solution for the power and district heating sectors by minimizing total costs including capital, operation and maintenance, and fuel costs, subject to constraints imposed on the solution such as specific targets or polices that must be achieved.

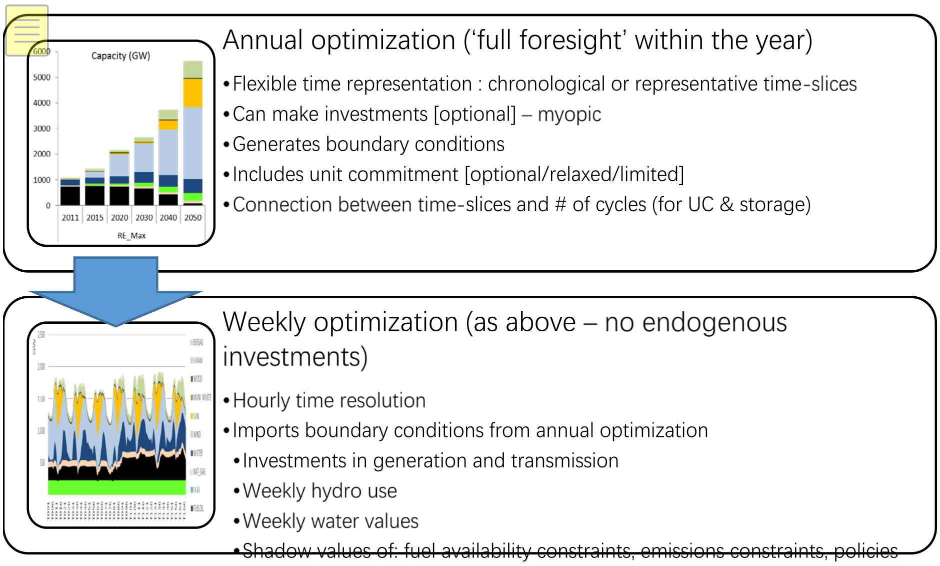
The power system is represented at provincial level, considering the interprovincial grid constraints and expansion options. The model includes all relevant production units, i.e. thermal (including CHP), wind, solar (including CSP), hydro, power storage, heat boilers, heat storages, heat pumps, etc. on the supply side. Moreover, it also considers options for demand-side flexibility, e.g. from industries, smart charging of electric vehicles, as well as the option of a full integrated coupling with the district heating sector.

Represents generation, storage, grid and consumption technologies.

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 power market, provincial, regional or national, based on the least-cost marginal price optimization. Key characteristics relate to the detailed representation of 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.

A model run consists of one or more linear programs solved either in parallel or sequentially. In general, each year is solved sequentially without foresight to the years beyond the current. There are two basic modes which can interact. The first mode looks at a full year at once. In this mode, the user configures the time resolution, which, for computational reasons, is normally less than full hourly resolution. The second mode looks at a full week at once at hourly resolution. The model therefore runs 52 times for each week of the year simulated. This second mode can use results from the first to set boundary conditions, e.g. capacity installations, seasonal allocations (e.g. hydro), and can attribute apply shadow prices as cost modifiers to capture the effect of annual constraints. Each of these modes can be run for successive years creating a pathway for development of the power and district heating systems. In the first (annual) model, when running with investments, the capacity installed by the model in one year is available in subsequent years until the end of technical lifetime.

Figure 8-2: Flow diagram of EDO operation.



Investments resulting from one scenario can be tested in detailed runs.

An EDO calculation yields results in terms of setting values for quantities and prices (shadow costs) for millions of variables. To make sense out of this in an analytical content, data must be pivoted, filtered and/or aggregated to provide meaningful insights in the problem being analysed. At the core the data output can be characterized as follows:

- **Generation of electricity** and heat associated with units in geographical locations and each simulation time step.
- **Consumption for electricity, heat and primary energy (fuels)** distinguished by geography, units (fuel) and simulation time step.

- **Transmission of** electricity between connected regions.
- **Prices of electricity** can be extracted distinguished by the region and time steps in the simulation. Similarly, a fair market value of other limited resources can be extracted from (e.g. fuels or CO_2-emission permits) or generated heat.
- **Investments** in electricity and heat generation capacity, transmission and storage capacity can be extracted 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 similarly be evaluated on background of shadow prices.
- **Emissions** from generation of electricity and district heat distinguished by geography, units and time steps.

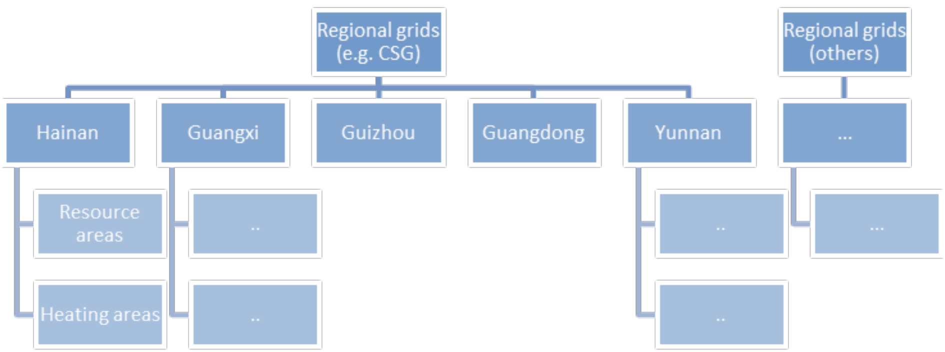
8.5. Geographical topology in EDO

CREAM-EDO is configured to cover 31 provinces and autonomous regions in mainland China including the 4 provincial level municipalities. Inner Mongolia is divided into the 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. Associated 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 time as it is consumed and therefore in each time step, the balance between supply and demand must be maintained at every point in the system. The time resolution is customized but can go down to the hourly level.

Provincial level power grid representation.

Above provincial level, regional grids are represented in EDO as well. According to the current grid area, these areas are Northeast, North, East, Central, South and Northwest China.

Figure 8-3: Illustration of the entities in the EDO model.



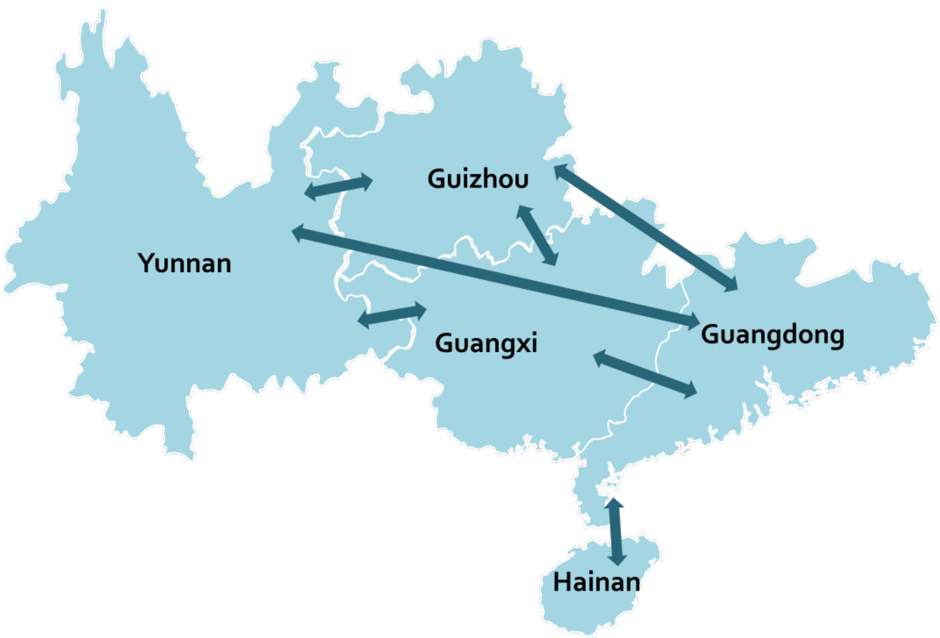
Electricity balances are given on a provincial basis. In each province an electricity balance must be fulfilled in the model either by generation, the transmission of electricity into or out of the region or a combination of generation and transmission. When using transmission for exchange of electricity between regions transmission constraints, losses and costs are included. This allows the model to determine the value of placing infrastructure investments in different provinces of a power system as well as the different costs associated with generation and consuming electricity in different provinces within the regional grid.

8.6. Power grid data and assumptions

The regional grid does not have any generation or consumption apart from that which follows as the sum of the provinces in the regional grid. However, a number of characteristics may be identical for all entities in a regional grid (e.g. generation units, demands, prices and taxes). A regional grid is constituted of more than one province when required to represent constraints in the electricity transmission system within the country that limit the ability of generation capacity in one region to supply another region with electricity. Between areas within the same provincial grids, there are no transmission constraints represented.

The representation of the CSG and its provincial subsidiaries are represented on Figure 8-4.

Figure 8-4: Illustration of China Southern Power Grid footprint. The arrows between the regions indicates an interregional transmission systems in the model.



Multiple areas are embedded in each provincial. Areas can contain one or more generation/storage capacities and generation profiles e.g. wind speeds and solar radiation. This enables a representation of varying weather conditions between different areas. The also represent a subdivision in the heating and cooling demands between industrial heating, urban heating, county level heating and finally, town townships and below. For this study, it is predominately the industrial heating category that influences the results.

Constraints on investments in new generation and storage capacities e.g. in renewable energy technologies can be defined on each level. Investment constraints are defined by a maximum capacity of e.g. wind turbines or an available fuel potential within that level. This allows for a specification of area specific potentials for investments in e.g. wind turbines and solar photovoltaics (PV).

This setup of the model offers for an optimization of investments and placement of generation technologies and investments in interprovincial transmission capacity.

Interprovincial transmission constraints

To simulate the economic dispatch of generation capacity in a power system, the model considers the most important transmission constraints in the power system. This has been configured to the transmission limitations between the 5 provinces under the CSG footprint. Transmission constraints represent the maximum amount of electricity that can flow between regions and is defined by a capacity in MW.

The transmission constraints between provinces in the model by 2020 are listed in GW in Table 8-3.

Table 8-4: Transmission constraints in GW included in the model (capacity from "row name" to "column name") 2020.

	To Region				
From Region	**Guangdong**	**Guangxi**	**Guizhou**	**Hainan**	**Yunnan**
Guangdong	-	14.4	7.4	1.2	25.3
Guangxi	14.4	-	8.0	-	3.8
Guizhou	7.4	8.0	-	-	-
Hainan	1.2	-	-	-	-
Yunnan	25.3	3.8	-	-	-

A significant proportion of interprovincial transmission capacity in the CSG area, comes from national key projects, including DC connections from Yunnan to Guangdong. These include the Yunnan-Guangzhou line completed in 2009, the Nuozadu-Guangdong line completed in 2013 and the Yunnan-Northwest

Guangdong (Shenzhen) line completed in 2017 – all ±800 kV UHVDC.

Figure 8-5: Ultra-High Voltage infrastructure of China Southern Power Grid[15].

From Guangdong to Hainan, there are now 4 parallel 500 kV sea cables, making landfall west of Haikou. These provide a total transfer capacity of approximately 1200 MW.

Transmission capacity investment cost

The investment costs for increasing interregional transmission capacities are listed in Table 8-4. These investment costs are cursory and based on a simple cost per MW per km metric supplemented by a cost per substation per MW in each end of the transmission reinforcement.

Table 8-5: Table of investment cost of increasing transmission capacity between provinces in mRMB18/MW.

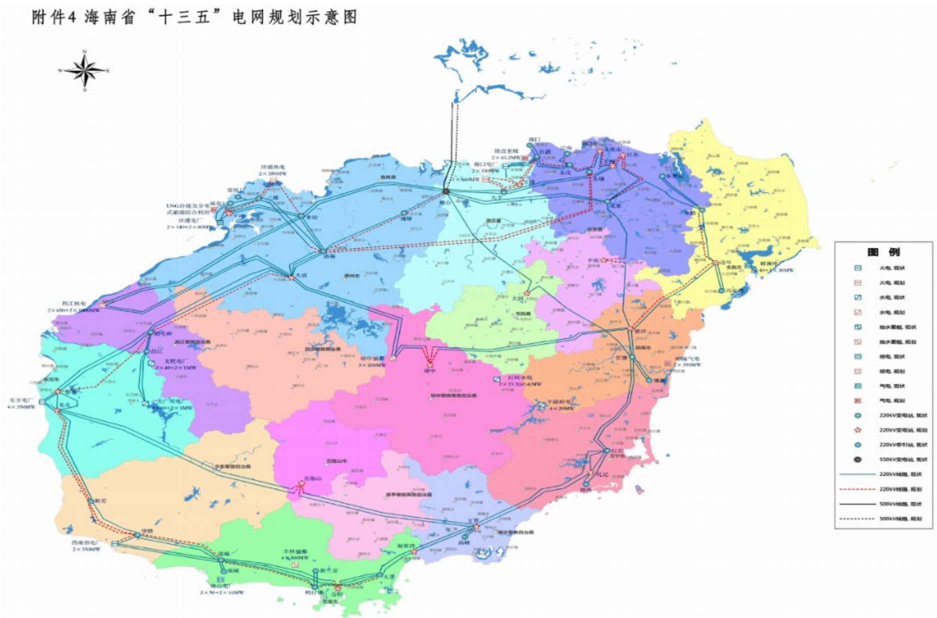
Cost of substation per MW of transmission capacity (thousands RMB/MW)	700
Cost of transmission capacity per MW distance (RMB/MW/km)	2500
Cost of transmission per MW distance (RMB/MWh/km)	0.02

[15] Peter Fairley (2016), Why Southern China Broke Up Its Power Grid, https://spectrum.ieee.org/energy/the-smarter-grid/why-southern-china-broke-up-its-power-grid, Accessed 08-06-2020

Hainan's internal grid

Hainan's internal transmission grid consists of double circuit 220 kV grid encircling the island, connecting the main industrial, commercial and tourist load centres such as Haikou, Wenchang, Qionghai, Wanning, Sanya, Dongfang and Danzhou, as well as most of the provinces thermal power generation. The grid also traverses the island's interior connecting thereby connecting cities including Wuzhishan and establishing grid connection to the hydro plants.

Figure 8-6: Grid map of Hainan power grid as per 13th FYP.



In the present analysis, internal grid constraints within Hainan province are not applied.

8.7. Electricity demand projection

The electricity demand projection for all of mainland China is based on the demand side modelling carried out as part of the CREO 2019 – Stated Policies Scenario. Herein, the Mainland electricity demand reaches 7700 TWh by 2020, 11900 TWh in 2035, and 13200 TWh in 2050, when the electrification level will be 54%. This includes grid losses and own consumption from power generation.

The whole society's electricity demand is composed of the exogenously provided end-use electricity demand (based on the LEAP model), plus the grid losses, own consumption in power generation (including storage losses) and endogenous consumption from power to heat. Electricity demand from end-use is shown on Table 8-5.

Hainan power demand is updated based on input from EPPEI (Electric Power Planning Engineering Institute).

Table 8-6: Electricity demand projection (excluding grid losses and own consumption from power generation) in TWh.

	National	China Southern Power Grid				
		Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	6010	29	147	150	130	555
2020	6796	41	169	170	154	617
2025	8469	47	214	222	195	743
2030	9822	61	251	2714	231	833
2035	10762	75	277	306	256	890

Electricity demand from electric vehicles is included in the above but treated separately with respect to load profiles and demand response potential. The total demand from EV's in CREO's Stated Policies Scenario is 20 TWh by 2020, 377 TWh by 2035 and 946 TWh by 2050. The electric vehicle (EV) electricity consumption is also split by province, with the demand from the 5 provinces in the CSG provided in Table 8-6 below.

Table 8-7: Electricity demand from electric vehicles in TWh.

	National	China Southern Power Grid				
		Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	7	0.03	0.09	0.17	0.06	1.16
2020	20	0.10	0.30	0.49	0.21	3.13
2025	95	0.54	2.11	2.76	1.48	14.65
2030	220	1.41	6.43	7.38	4.54	33.22
2035	377	2.70	13.62	14.32	9.69	55.66

Load profiles and smart charging

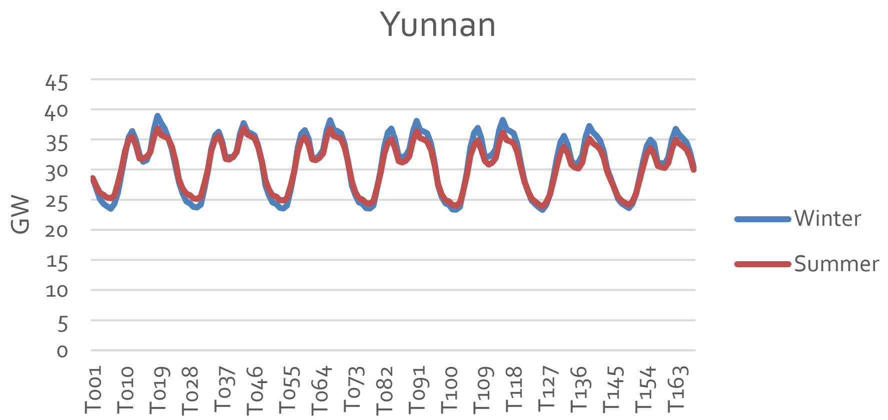
The provincial electricity demand is based on time segments aggregated from hourly profiles. Each province is attributed an hourly load profile for traditional electricity demand, based on typical load profiles published by the NDRC in 2019[16]. This is supplemented by a stylised profile for electric vehicle charging, based on assumed driving and parking behaviour. Examples of hourly load profiles for 2030 are shown in Figure 8-7.

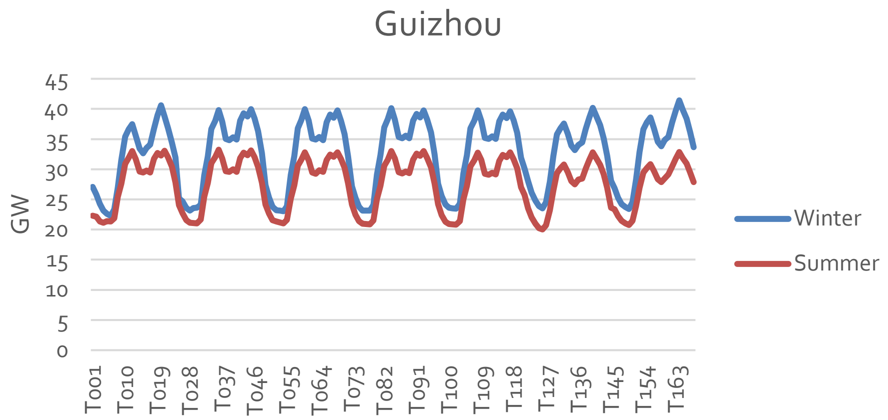
[16] NDRC (2019): Notice on tasks regarding signing of mid-to-long term power contracts in 2020国家发展改革委关于做好2020年电力中长期合同签订工作的通知, https://www.ndrc.gov.cn/xxgk/zcfb/tz/201912/t20191230_1216857.html, Accessed 2-1-2020

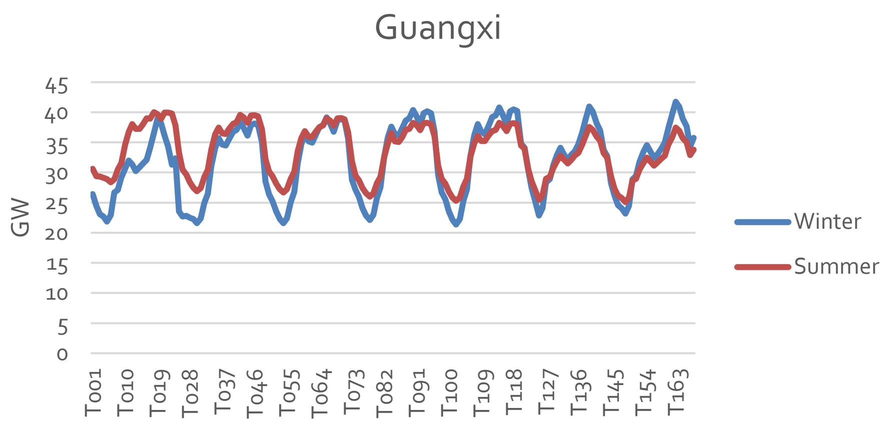
By 2030 100% of electric vehicles can have their charging smartly adjusted. Vehicle-to-Grid (V2G) is introduced from 2030 and by 2050 50% of electric vehicles provide V2G services and deliver power the grid when needed.

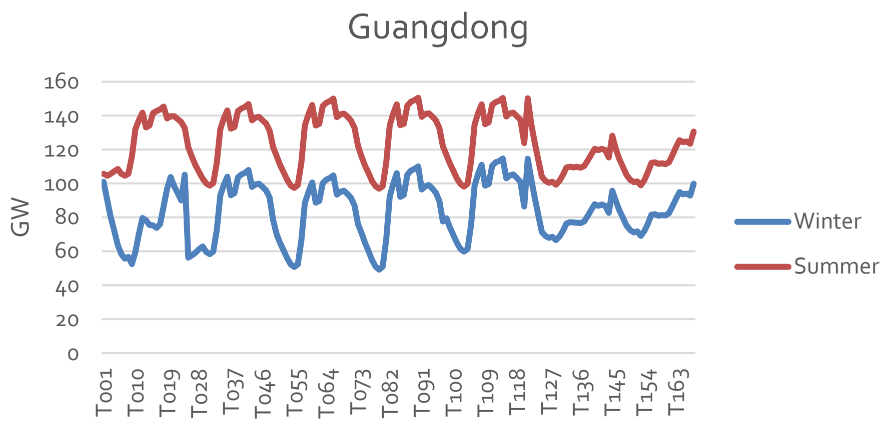
It is assumed that, by 2030, demand response technology will be widely used based on the electricity market. By 2030, industrial demand response provides up to 8 GW of flexibility. By 2050, this is increased to 14 GW. By 2030, industrial demand response provides up to 41 GW of flexibility. By 2050, this is increased to 69 GW. Additionally, aluminium smelters provide 5 GW of demand response flexible capacity in 2025, which drops to 4 and 3 GW by 2035 and 2050, respectively.

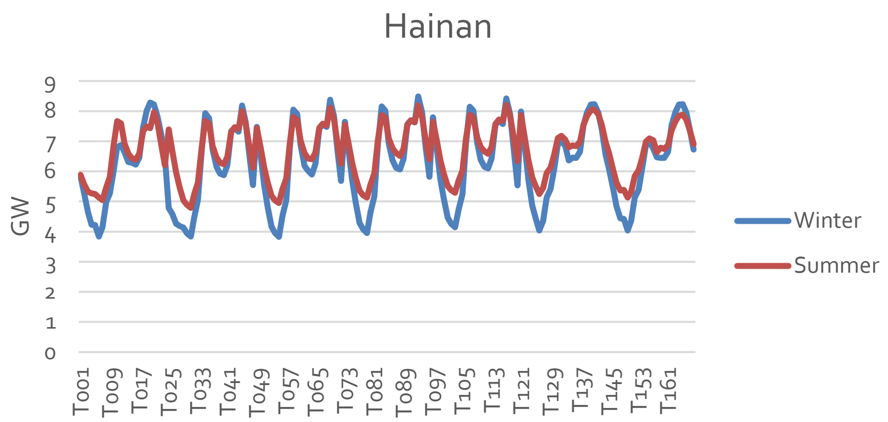
Figure 8-7: Hourly demand profiles for two exemplary weeks in the winter and summer 2030, for the five regions constituting China Southern Power Grid, GW.











8.8. Generation

In the EDO model, types of power stations (aggregated groups) are represented by different technical and economic parameters, e.g.:

- Technology type
- Type of fuel
- Capacity

- Efficiency
- Desulphurisation
- NOx emission coefficient
- Variable production costs
- Fixed annual production costs
- Investment costs

Hydropower

Hydro power is well developed in China, and the remaining resource has been planned to be developed in the future, mostly concentrated in Sichuan, Yunnan, Tibet and Qinghai. In total, 530 GW hydro power will be gradually developed by 2050.

In the CSG region, Yunnan accounts for the largest proportion of hydropower.

Table 8-8: Hydro power capacity assumed in the simulations, GW.

	Mainland China	China Southern Power Grid				
		Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	322	1	67	17	22	8
2020	347	1	67	19	22	8
2025	386	1	70	19	22	8
2030	438	1	76	19	22	8
2035	455	1	82	19	22	8

For each province there is set an annual number of full load hours which is applied on average to the generation capacity.

Table 8-9: Hydro power full load ours assumed in the simulations.

Province	Full load hours
Hainan	3412
Yunnan	4187
Guangxi	3936
Guizhou	3708
Guangdong	2183

Table 8-10: Hydro power annual possible generation in the simulations, TWh.

	Mainland China	China Southern Power Grid				
		Hainan	Yunnan	Guangxi	Guizhou	Guangdong

2018	1191	3	279	66	82	18
2020	1266	3	279	74	82	18
2025	1399	3	292	74	82	18
2030	1577	3	317	74	82	18
2035	1626	3	342	74	82	18

Hainan's hydro power is concentrated on the Changhua river, Nandu river and the Wanquan Basin. The reservoirs on these rivers have a combined storage capacity in excess of 5.7 billion m3.

Pumped storage capacity and potential is restricted according to Table 8-10.

8-11: Hydro pumped storage minimum development and maximum capacity potential, GW.

	Mainland China	Hainan	Guangdong
2018	30.0	0.6	7.3
2020	32.4	0.6	7.3
2025	43.1	0.6	7.3
2030	88.7	1.2	8.5
Max	713	10	68

Hainan Qiongzhong Pumped-storage Power Station, the first on Hainan, went into full operation in 2018, with a generation capacity of 600 MW. It is expected that an additional 600 MW of Pumped storage capacity will be brought online by 2030.

Nuclear

Nuclear power is not developed endogenously in the modelling through cost optimal capacity expansion. Historically, nuclear development has primarily been driven to satisfy policy objectives, with governments providing the support needed. However, nuclear development is rapid in China, while at the same time safety issues, and concerns have stalled some of the more optimistic timelines for nuclear scale-up. In this, following the assumptions of the CREO 2019 report, a gradual development of nuclear power is employed exogenously, however, only the sites for nuclear power along the coast is considered. This leads to a deployment of 110 GW capacity by 2050.

In the CSG region, nuclear power is power is installed in Guangdong, Guangxi and on Hainan – the three coastal provinces in CSG.

Table 8-12: Nuclear power capacity assumed in the simulations, GW.

	Mainland China	Hainan	Guangxi	Guangdong
2018	44.6	1.3	2.1	13.3
2020	53.3	1.3	3.3	16.1
2025	66.2	3.2	4.5	17.0
2030	78.8	4.4	5.6	18.6
2035	86.8	4.4	6.8	20.2

On Hainan, the Changjiang nuclear plant presently has two units of approximately 650 MW capacity each. The second phase of Changjiang nuclear reactors will be two units of Hualong one reactors, each with a gross capacity of 1150 MW. The plan is to start pouring concrete for Changjiang unit 3 in August 2020 and for unit 4 around June 2021.

Two demonstration multi-purpose modular ACP100 units, small modular pressurized water reactors, each with 125 MW of gross power capacity, are also being constructed[17]. Preparatory construction work started in 2019.

Thermal power

China's power system remains dominated by thermal power capacity today and despite the significant increases in renewable capacity installations, thermal power is expected to continue to play a dominant role for years to come.

Table 8-13: Thermal power capacity in the simulations, GW.

		China Southern Power Grid

[17] World Nuclear Association (2020), Nuclear Power In China, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx, Accessed 08-06-2020

	Mainland China	Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	1142	5	15	23	33	80
2020	1163	5	14	17	32	76
2025	1171	5	10	14	32	63
2030	1139	5	7	14	25	65
2035	1009	4	3	12	17	59

The capacity illustrated on Table 8-12 shows the installed capacity in the scenarios, including both exogenous (existing) and endogenous capacity established as result of the model simulations. The table includes coal, natural gas and biomass fuelled generation capacity.

While coal-fired capacity is nearing its peak according to the simulations, gas-fired capacity is set to expand, particularly in more affluence coastal provinces, as a measure to deal with local air quality.

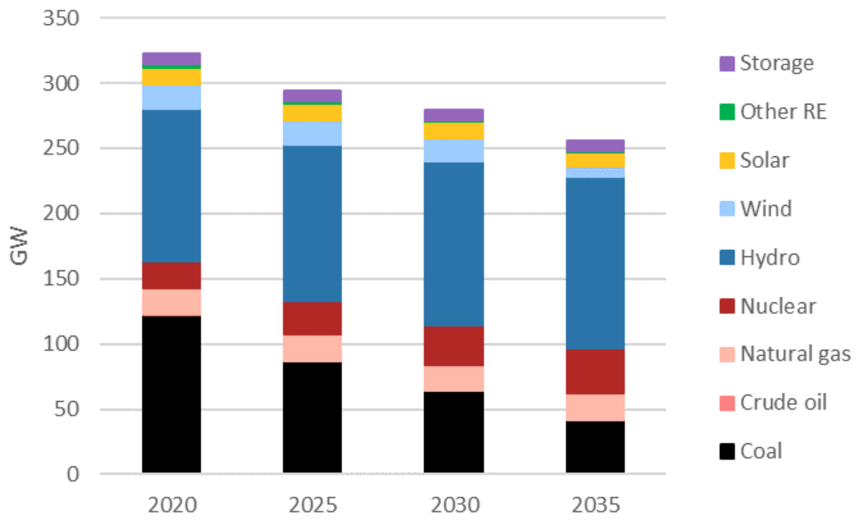
Table 8-14: Natural gas fired power capacity in the simulations, GW.

		China Southern Power Grid				
	Mainland China	Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	83.7	0.7	0.0	0.4	0.0	19.3
2020	103.9	0.7	0.0	0.4	7.3	20.4
2025	165.1	3.2	0.2	1.4	7.3	24.4
2030	198.1	3.2	0.2	1.4	7.3	32.7
2035	262.7	3.2	0.2	1.4	7.3	32.7

Natural retirements

Thermal power units, wind and solar installations installed today are all expected to have a finite lifetime. Thus, the exogenously provided capacity from the base year, decreases over time (and must be supplemented by new capacity). A simple procedure is determined by the asset classes, e.g. smaller thermal units (typically older) are forced to retire earlier than larger thermal plants which are typically newer. The exogenous capacity development in the CSG region is presented on figure.

Figure 8-8: Gradual reduction in exogenous capacity in the China Southern Power Grid provinces, GW.



Resource potential for wind and solar power

Technical and economical feasible resource potentials of wind power and solar PV are set in the model for different provinces. The overall potential for onshore wind is 4900 GW, of which less than 2000 GW can be developed in the form of distributed wind. The potential of offshore wind is 217 GW (mostly considering nearshore). The resource potential of solar PV is 2537 GW for utility-scale PV plants, and 1633 GW for different types of distributed PV including Building Integrated PV and roof-top PV.

Table 8-15: Resource potentials in the CSG provinces, GW.

	China Southern Power Grid				
	Hainan	Yunnan	Guangxi	Guizhou	Guangdong
Nat. Gas	-	-	-	-	25.0
Coal	-	-	-	54.0	75.2
Wave	12.9	-	0.4	-	14.0
Wind onshore	56.6	141.7	129.3	62.5	92.5
Wind offshore	8.0	-	1.1	-	38.6
Solar	79.9	153.4	85.8	84.8	102.0

8.9. Fuel cost

Coal prices

Fuel costs from CREO 2019 are used for the analysis, most importantly coal and natural gas prices. The coal prices from the Stated Policies scenario are projected from 2018 average market prices according to the trend from the IEA's World Energy Outlook (2018).

Table 8-16: Coal prices used in the simulations, RMB/GJ.

		China Southern Power Grid				
	National average	Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	23.2	25.6	21.6	31.8	21.8	27.5
2020	21.3	23.4	19.9	28.7	20.1	25.0
2025	19.9	21.5	18.8	25.7	18.9	22.8
2030	20.4	21.7	19.5	25.1	19.6	22.8
2035	20.9	21.9	20.2	24.6	20.2	22.7

Guangdong, Guangxi and Hainan generally have coal prices higher than the national average, whereas Guizhou and Yunnan's coal trades at a lower power.

Natural gas prices

Hainan receives natural gas at the Hainan CNOOC LNG Terminal in the Yangpu Economic Development zone. The approximate handing capacity is about 3 million tons per year. The terminal has a storage capacity of 480 thousand m^3.

Table 8-17: Natural gas prices used in the simulations, RMB/GJ.

	National average	China Southern Power Grid				
		Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	43.8	39.9	41.7	49.0	41.7	53.5
2020	48.1	43.8	45.8	53.9	45.8	58.8
2025	59.0	53.6	56.1	66.0	56.1	72.0
2030	60.2	54.8	57.3	67.4	57.3	73.5
2035	60.9	55.4	57.9	68.1	57.9	74.3

The price of natural gas is comparatively high in China relative to alternatives, but the expanded use of gas is part of the national strategy. In the CREO Stated Policies Scenario, the consumption of gas required to increase to cover 10% of the gross energy consumption by 2020 as stipulated in the 13th FYP and to reach 15% of gross energy consumption in 2030 as stipulated in the Energy Production and Consumption Revolution Strategy. Expanding on this, the targets for natural gas consumption is a peak in 2040 is in the range 630-650 BCM.

Table 8-18: Minimum natural gas consumption in the power sector, PJ.

	Mainland China	(Coastal South)	Hainan	CSG-Hainan
2018	3077	820		
2020	6446	1362	6	654
2025	7325	1905	16	1538
2030	9669	1742	7	1520
2035	3077	820	11	1467

Straw prices

Straw prices (agricultural residues) represent the cost of biomass for heat and electricity generation.

Table 8-19: Straw prices used in the simulations, RMB/GJ.

	National average	China Southern Power Grid				
		Hainan	Yunnan	Guangxi	Guizhou	Guangdong
2018	24.72	24.23	21.67	22.73	21.13	27.24
2020	26.17	25.65	22.94	24.06	22.36	28.83
2025	29.00	28.43	25.43	26.67	24.79	31.96
2030	31.84	31.21	27.92	29.28	27.21	35.08
2035	33.61	32.94	29.47	32.94	28.72	37.03

Carbon price assumptions

Based again on the assumptions of the CREO 2019 Stated Policies scenario, cost of emissions under the Chinese ETS system is expected to develop and affect merit order dispatch as well as the choice of investment technologies in the power sector. The price of carbon dioxide in the power sector rises from 50 RMB per ton in 2020 to 100 RMB per ton in 2030, where after it is assumed to stay constant in real terms.

8.10. Technology catalogue

To ensure an adequate system generation capacity to meet the system load, new investments in generation capacity is necessary.

Table 8-20: Key technology data assumptions for major technologies.

Technology Type	Year	Efficiency %	Invest. cost mRMB/MW	Fixed O&M kRMB/MW	Variable O&M RMB/MW
Nuclear	2020-2050	35%	17	820	29
Coal USC	2020-2050	43%	3.2	100	4.6
NG CCGT	2020-2050	63%	2.6	104	0.1
MSW	2020-2029	26%	16.2	300	87
	2030-2049	27%	13.5	300	87
	2050	28%	11.3	300	87
Biomass	2020-2029	33%	8.7	118	8.3
	2030-2049	36%	8.7	118	8.3
	2050	40%	8.7	118	8.3
Pumped storage	2020-2029	75%	5.3	158	-
	2030-2039	75%	5.4	162	-
	2040-2049	75%	5.6	167	-
	2050	75%	5.7	172	-

Note: Pumped hydro storage has a storages size which can contain 8 hours of loading capacity.

The energy generation costs from solar and wind rapidly decline, making wind and solar more competitive. Fossil generation costs 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.

Table 8-21: Cost reduction of typical emerging technologies.

Year	**RMB/kW**	**Wind**			**PV**		**Chemical storage**
		Onshore	DG	Offshore	Utility scale	DG	
2020	Investment	6900	8250	15000	3600	3420	Investment cost is 1.5 RMB/Wh, and the cycle lifetime is 4000 rounds.
	O&M	145	154	290	68.4	85.5	
2025	Investment	6500	7700	12800	3300	3135	Investment cost is 1.2 RMB/Wh, and the cost of “DG+storage” is competitive for commercial users.
	O&M	142	150	285	67.2	84.5	
2035	Investment	6200	7250	8900	2870	2640	Investment cost is 1 RMB/Wh. The cycle lifetime is more than 10000 cycles.
	O&M	139	144	277	65.5	87.8	

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