Carbon Capture Science & Technology 7 (2023) 100112

Contents lists available at ScienceDirect

Carbon Capture Science & Technology

journal homepage: www.elsevier.com/locate/ccst

Review

Quantitative analysis of carbon dioxide emission reduction pathways: Towards carbon neutrality in China's power sector

Rida Maheen[a], Liya Cai[b], Ye Shui Zhang[c,*], Ming Zhao[a,*]

[a] *Tsinghua University, Beijing, China*
[b] *State Power Investment Corporation Research Institute, Beijing, China*
[c] *School of Engineering, University of Aberdeen, Aberdeen AB24 3UE, UK*

ARTICLE INFO

Keywords:
Power generation
Carbon neutrality
Carbon emission reduction
LEAP model

ABSTRACT

China has continually reduced the intensity of its carbon emissions, increased its efforts to fulfil its Nationally Determined Contributions, and boosted its efforts to mitigate climate change. Due to its vast power generation sector, China is at present the world's top carbon dioxide emitter (CO_2). Utilizing the Low-Emissions Analysis Platform (LEAP) – which is an integrated, scenario-based energy and environmental modelling tool created by the Stockholm Environment Agency – four scenarios other than the baseline scenario were devised and compared. The current study builds on two Nationally Determined Contributions (NDC) scenarios and two Carbon Neutral (CNT) scenarios in which emissions peak in the year 2025 or 2030, allowing for an examination of ambitious actions necessary beyond business as usual and existing policy trajectories to attain net-zero emissions. This study also looked at how the learning curve affected the expenses in the aforementioned scenarios. It was determined that scenarios that deployed Carbon Capture and Storage (CCS) and Bioenergy with Carbon Capture and Storage (BECCS) technologies were more favourable in realizing China's carbon neutrality goal before 2060 by reaching negative emissions, and scenarios that achieved emissions peak earlier proved higher cost benefits as well. The findings of the study further revealed that the Greenhouse Gas (GHG) savings in the NDC 2025, NDC 2030, CNT 2025, and CNT 2030 scenarios will be 104.23 Gt, 76.77 Gt, 142.74 Gt, and 130.92 Gt respectively, in the study period 2020–2060 and the cost-benefit associated with them per tonne of CO_2 will be 8.4, 8.5, 26.4, 30.4 CNY/t CO_2, respectively. Moreover, under the CNT 2025 scenario, annual installed capacity of wind power should be greater than 46.8 GW between 2025 and 2030, and greater than 55.2 GW between 2030 and 2060; while the annual installed capacity of solar PV should be greater than 59.2 GW between 2025 and 2030, and greater than 61.3 GW between 2030 and 2060. The Chinese power production industry must seek to convert to a larger-scale deployment of carbon capture technologies such as CCS and BECCS.

1. Introduction

The extraordinary speed of China's economic growth has propelled the demand for electricity, which has grown from 1387 terawatt hours (TWh) in 2000 to 7511 TWh in 2020, making China the world's largest electricity consumer with the world's largest power sector. China now has the largest installed generation capacity in the world (2202 GW by 2020), nearly 60% of which is generated from coal. According to the Global Coal Plant Tracker, there were 1110 coal-powered plants in 2020 with an installed capacity of 1064 GW (Tracker, 2019). Despite the COVID-19 pandemic, the growth rate of power consumption stayed positive. Electricity usage increased by 3.1% in 2020, compared to 4.5% in 2019 (Mastoi et al., 2022).

Steel, chemicals, and aluminium are amongst the energy-intensive industries driving China's fast expansion in power consumption. However, the continuous economic transformation and structural change toward service-based businesses may increase the importance of service industries, residential consumption, and perhaps transportation power usage in the future (Fu et al., 2020; Hong et al., 2022; Nayak et al., 2022; Anika et al., 2022). Energy demand has prompted the need for extensive expansion in the power sector on a large scale in China. This makes China the world's largest electricity producer to meet its increasing demand. China, as the world's top carbon emitter, produced 32% of global carbon emissions by the end of 2020 (Wu et al., 2022). Fossil fuels, especially coal, are the dominant resource in power generation in China. Coal power accounted for about 60% of the electricity generation mix in 2020. Because of China's reliance on coal, the power generation sector

---

* Corresponding authors.
E-mail addresses: rd19@mails.tsinghua.edu.cn (R. Maheen), loveparadise15@163.com (L. Cai), yeshui.zhang@abdn.ac.uk (Y.S. Zhang), ming.zhao@tsinghua.edu.cn (M. Zhao).

https://doi.org/10.1016/j.ccst.2023.100112
Received 4 March 2023; Received in revised form 19 April 2023; Accepted 19 April 2023

in China emitted around 5.4 Gt of CO_2, or around 47% of the country's total energy sector emissions in 2020 (IEA, 2021), which accounts for 15% of total CO_2 emissions worldwide (Li et al., 2017).

The future development pathways of China's power system had been widely studied before the goal of carbon neutrality was set forth. However, due to a lack of top-level design and national support, the planning duration, milestones, and mitigation objectives are not specified in these studies and are inferred by the authors. The years 2030 (Yu et al., 2019; Zhu et al., 2021) and 2050 (Guo et al., 2017; Zhang et al., 2012) are commonly chosen years as the end of the planning period. Furthermore, because there are no mitigation targets, the emission abatement level is mostly utilized for scenario analysis or policy effect comparison (Zhang et al., 2020). Even if a stricter and clearer CO_2 emission target has been put forward, there are still many debates about the clean transition of China's power generation sector, especially the way to trade off coal-fired power against renewable energy (Zhang et al., 2022).

LEAP is an integrated, scenario-based energy and environmental modelling tool created by the Stockholm Environment Agency which can be used to track an economy's energy use, output, and resource extraction across all sectors (Cai et al., 2022). Furthermore, LEAP may be used in energy planning for long-term forecasts of energy consumption and related environmental challenges. As a result, the LEAP model is widely adopted to investigate and model energy consumption, GHG emissions, and energy policy formulation in many locations and industries (Liang et al., 2014). Comprehensive modelling of decentralised energy networks is possible with LEAP because it supports both top-down/macroeconomic modelling and bottom-up/end-use accounting methods for the demand side. It supports accounting and simulation approaches on the supply side and has modelling tools for optimisation. Models of various energy systems at various scales, each with its own special data structures, can be built using LEAP. The IPPC Database, which has data on the costs, performance, and emission factors of more than 1000 energy technologies, is a component of the LEAP model. Given that just the base year requires in-depth statistical data, LEAP has the advantages of having a minimal skill and initial data demand. LEAP's adaptability and transparency make it possible to include information and findings from other independent models (Ugwoke et al., 2021). As a result, LEAP can function as a hybrid energy analysis tool. The LEAP time horizon is infinite and can be described as a sequence of years divided into different time slices. In developing nations, LEAP has a user-friendly interface and is free to use. Because of these traits, the LEAP model was chosen for this study.

The LEAP model has been used in several studies to investigate energy demand, GHG emissions, and energy planning policies in a variety of industries. Hernandez and Fajardo (Hernández and Fajardo, 2021), for example, used the LEAP Programme to project air pollutant emissions through 2050. The variation of emissions for alternative assumptions of industrial energy matrices in the three scenarios was also analysed, providing solutions for emissions reduction in the city. The model yielded considerable co-benefits for the development of alternative transportation modes and electrification. Although there are several studies that have used the LEAP model in their research, there is no study, to the best of the author's knowledge, that adopts specifically the LEAP model to project the future emissions of China's power generation sector up till the year 2060, keeping into account China's carbon neutrality goal.

Additionally, there are several studies analysing and predicting the peak of China's power sector for carbon emissions. There are also some studies that link the peaking of carbon emissions with a tentative carbon neutrality timeline by either the year 2050 or comparing scenarios where global temperature rise is kept at 1.5 °C and 2 °C. But there are hardly any studies that consider both peaking the power sector's emissions and achieving China's carbon neutrality goal by 2060. Most studies that study carbon emissions of China's power sector mostly adopt the TIMES model as their main methodology instead of other proven methodologies like the LEAP model. Moreover, to the best of the author's knowledge, those limited studies that have predicted the emissions, or negative emissions, of the Chinese power sector by 2060 have not calculated the costs and benefits associated with their low-carbon scenarios or the costs of avoided GHGs (CNY/t CO_2e) in their stipulated scenarios or the learning model. By bridging these gaps, this study aims to quantitatively unravel low-carbon pathways that can be used to design and incorporate low-emission and negative-emission technologies into future five-year plans of China's power industry, and associated costs and practicality in realizing their consolidation. This study closes in on these goals by:

1. Firstly, total future installed capacities of each technology, power generation mix and GHG emissions associated with each technology are quantified. This shows policy makers in China how the quantities can be used as a strategy to reduce GHG emissions.
2. Secondly, this study also considers the learning rates of each technology and how it affects the capital costs of the technologies taken into consideration. By establishing the link between the costs and experience gained over the years for certain technologies showed that when we take the learning rate into account, future capital costs will be lower compared to the base year. This will prove that the earlier a technology is commercialized, the experience gained over time will eventually lead to lower investment costs hence attracting more investment possibilities in said low-carbon technologies.
3. Thirdly, we quantify the negative emissions from the power sector towards the last patch of our study period. To the author's knowledge, the Chinese power system does not consider negative emissions as of now and there is no action plan set in place that details on how to incentivize negative emissions from the Chinese Emissions Trading System (ETS). Therefore, this study also suggests approximate noncompliance penalty costs that can be considered by the Chinese ETS in further strengthening their carbon credit mechanism.
4. Lastly, in addition to the technicalities associated with power generation and low-carbon technologies, this study also aims to briefly look at and discuss loopholes in the national ETS of China and offer suggestions to better facilitate the adoption and dissemination of CCS and BECCS at a larger scale and their monitoring, especially through financial media, within the ETS.

2. Methodology framework

The methodology chosen for this research is based on the LEAP model, which is a bottom-up model using the LEAP software developed by the Stockholm Environment Institute. The technical roadmap of the study is sketched in Fig. 1.

The basic model in this study consists of majorly two key parts: (1) Demand module, (2) Transformation module. For better visualization and for the sake of simplicity, the model was divided into sections as shown in the **Fig. S1.** The technological factors being shown in the **Fig. S1** were input for the transformation module. And the power generation technologies that were taken into account were: Coal power, Natural gas power, Nuclear power, Hydropower, Wind power, Solar PV power, Biomass power, Coal CCS, Natural gas CCS, BECCS.

For the demand module, forecasts of future electricity generation were taken from other studies, so the values were exogenously input into the software. For the transformation module, **Fig. S2** shows the costs and environmental inputs. The demand and transformation modules were the main modules that were used in the LEAP software for this study. The **Fig. S3** shows the general "direction" of calculations conducted within LEAP, going from top to bottom – i.e., from demand to transformation/supply. As can be seen from the figure, the overall electricity demand has to be input into the demand module. Whereas the transformation module considers transmission and distribution of electricity, or in other words transmission losses, electricity generation, and electricity generation processes, which are basically our power generation technologies. When we further expand any power generation

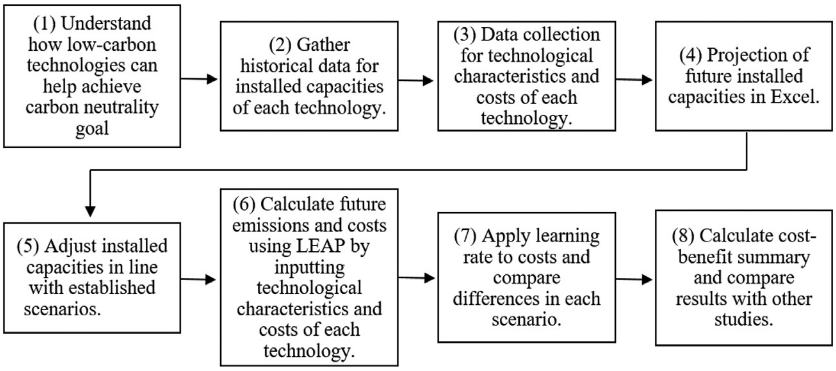


Fig. 1. Technical roadmap of the study.

technology, for instance coal power, we get the option to select the fuel input, which in the case of coal power is bituminous coal, for gas is natural gas, for nuclear power is nuclear and so on. Henceforth, we also attach the detailed pollutants emitted by the burning of each fuel into the software. The details of each pollutant that were imported from the LEAP IPCC Tier 1 database were used can be found in **Table S3.** The LEAP model is used to build up on several low-carbon scenarios in this research for the future emissions and the scenario manager of the software is used to quantify the emissions, costs and power generation mix of each scenario.

2.1. *Description and scope of main data sources and assumptions*

The base year chosen for this year is 2020 due to ease of availability of data on national platforms.

2.1.1. *Description of the demand module*

Since the transformation module builds up on the demand module in the software, future electricity demands for the years 2030, 2050 and 2060 were taken from different sources. According to the report "China Zero-Carbon Energy Growth in the 2020s: A Vital Step Toward Carbon Neutrality", China's electricity demand will reach 10–12 trillion kilowatt-hours (10,000–12,000 TWh) by 2030 as electrification continues to increase (Cao et al., 2021). Moreover, according to this study that mentions that the data for electricity demand was taken from China's Power Statistical Yearbook and the China Energy Transformation Outlook report (Zhang and Chen, 2022b), the electricity demand will be 11,300 TWh in 2030, 13,300 in 2050 and 17,300 TWh in 2060. Therefore, these key values are taken as input for the electricity demand module in LEAP, and the total electricity demand for all scenarios is assumed to be the same to allow better comparison of the emissions in all scenarios.

2.1.2. *Description of the transformation module*

All parameters that were enabled in the transformation model are shown in the **Fig. S4**, and data was input accordingly. Definitions of the input parameters according to LEAP are given in the **Supplementary Table S1**.

The Transformation and Distribution category in the Transformation Module includes national power grid line loss rate. According to the historical line loss rate in **Table S1**, taken from China Electricity Council (CEC) annual development reports, the distribution loss rate was assumed to not have changed significantly and was fixed at 4% for the year 2060 for all scenarios. For the years between 2020 and 2060, the loss rate was calculated within LEAP using the Interp time-series function.

The Interp function in LEAP calculates a value in any given year by linear interpolation of a time-series of year/value pairs and each intermediate year's value is calculated as follows:

$$Value_{iy} + Value_{fy} + \left[Value_{ey} - Value_{fy}\right].\left[\frac{Year_{iy} - Year_{fy}}{Year_{ey} - Year_{fy}}\right] \quad (1)$$

Where:

iy = the intermediate period, the value of which is to be interpolated.
ey = the end period used as the basis for the interpolation.
fy = the first period used as the basis for the interpolation.

Parameters for the model are based on national electric power planning reports, the 14th Five Year Plan (FYP), latest statistics taken from CEC, National Energy Administration (NEA), National Bureau of Statistics of China, and data from industry experts (Council, 2021; Stern and Xie, 2022). The historical data for installed capacities, power generation by technology and line loss rates were taken from CEC's Annual Power Development Reports (China Electricity Council, 2021, 2020, 2019, 2018, 2017, 2016) (Zhang and Chen, 2022a). Historical data for installed capacities and power generation by technology can be found in the **Supplementary Table S3.**

Values including the fuel cost, capital cost, process efficiency, capacity credit etc. in the model are referenced from IEA reports (Zhongming et al., 2020), different published studies (Fan et al., 2018; Liang et al., 2013) and industry experts from State Power Investment Corporation Research Institute. Key technological characteristics such as the lifetime, process efficiency, maximum availability, and capacity credit of relevant technologies that were input in the model are shown in Table 1. Capital costs, variable and fixed operation and maintenance costs and fuel costs of each technology that were input in the model are shown in Table 2.

Moreover, studies by Global Interconnection Development and Cooperation Organization and SNEC were referred to as a guiding source for the share of each technology in the total installed capacity in this study's scenario setting (SNEC, 2021; Wei et al., 2022). The proportions from each source were compiled and demonstrated in the **Fig. S5** for better visualization and the exact proportions from each report are given in the **Supplementary Table S4.**

2.2. *Carbon emissions from electricity production*

2.2.1. *Role of CCUS and BECCS in decarbonizing China's power generation sector*

The low-carbon power transition in China has been a hot-debated topic. Many scholars have studied the role of technological advance in reducing emissions and driving carbon neutrality (Lin and Ma, 2022; Yang and Li, 2017), with a focus on renewable resources (Wang et al., 2021). Technological advancement and carbon emissions reduction are closely associated (Wu et al., 2022). This section discusses low-carbon technology pathways through Carbon Capture and Storage (CCS), Carbon Capture, Utilization and Storage (CCUS), and Bioenergy with Carbon Capture and Storage (BECCS) technologies.

Table 1
Technological characteristics input into LEAP.

Technology	Lifetime (years)	Process Efficiency (%)	Maximum availability (%)	Capacity credit (%)	Merit Order
Coal	30	45	90	75	1
Natural gas	25	58	80	75	2
Nuclear	35	33	90	85	1
Hydropower	60	65	50	50	2
Wind	20	50	50	25	1
Solar	20	25	25	25	1
Biomass	20	40	80	52	1
Coal CCUS	30	31	90	75	1
Natural gas CCUS	25	58	80	75	2
BECCS	20	40	80	52	1

Table 2
Costs of each technology input in LEAP.

Technology	Capital Cost (Thousand Yuan/MW)	Fixed O&M Cost (Thousand Yuan/MW)	Variable O&M Cost (Yuan/MWh)	Fuel Cost(Yuan/kWh)
Coal	5180	208	39	13.31
Natural gas	3626	117	39	25.43
Nuclear	16,187.5	455	58.5	4.75
Hydropower	5850	260	390	0
Wind	7601.65	331.5	85.67	0
Solar	4726.15	325	52.13	0
Biomass	6000	292.5	39	0.44
Coal CCUS	9336.84	332.8	62.4	10.63
Natural gas CCUS	9186.88	234	78	10.88
BECCS	10,156.84	468	62.4	0.44

According to IPCC mitigation scenarios for RCP 2.6, CCS from fossil fuels and bioenergy-fired power stations (BECCS) might contribute to a 25% decrease in CO_2 emissions by the year 2100. As a result, CCS is regarded as a mitigation tool and has received major attention from governments, the fossil sector, and key other parties such as the IEA (Bruhn et al., 2016; Edenhofer, 2015). The IEA has released several reports stressing on the importance CCS technologies will play in achieving global energy and climate goals, and in the transition to carbon neutrality (IEA, 2020). BECCS, also known as negative-emissions technology, also provides a considerable benefit over other mitigation options, which just reduce the number of emissions to the atmosphere. Policymakers are increasingly paying more attention to the benefits inherent in this technology (IEA, 2021).

CCS refers to the process of mitigating CO_2 emissions by capturing/separating CO_2 from the flue gas at the point of combustion, and subsequently compressing and transporting it through pipelines to a geological formation (Smit et al., 2014). CCUS, on the other hand does not merely store CO_2. As evident from the word “utilization” in its name, it not only captures/separates CO_2 from emissions sources, but also distributes the CO_2 for different intermediate utilization and/or final storage choices (Tapia et al., 2018). So, it can be said that CCS is useful in a linear economy, however carbon dioxide usage is important to a circular economy as CCUS takes into account both economic and environmental benefits (Nocito and Dibenedetto, 2020). Several studies (Cavanagh and Ringrose, 2014; Yao et al., 2018; Yu et al., 2019) evaluated the benefits of CCUS in emission-intensive industries and how they can prove to be more advantageous over renewables.

BECCS technology, which is different from CCS and CCUS, combines carbon capture and storage with bioenergy and removes carbon dioxide from the atmosphere, playing an important role in climate change mitigation and carbon neutrality (Emenike et al., 2020). BECCS technology comes in several forms, including as biomass power generation with CCS, liquid biofuels with CCS, bio-Synthetic Natural Gas (bio-SNG) with CCS, and biohydrogen with CCS. Given China’s current energy supply and demand, biomass power production with CCS may become a crucial technology in China (Hao-Nan et al., 2022). Different studies have researched the role of BECCS in significantly reducing carbon emission and in achieving carbon neutrality. BECCS has the potential to lower the costs of achieving carbon neutrality, which is a vital technology for the IPCC’s 2°C and 1.5°C objectives (Huang et al., 2020; Weng et al., 2021).

2.2.2. *Calculation of carbon emissions from electricity production*

An emissions factor is a representative value that attempts to link the amount of a pollutant emitted into the atmosphere to an activity connected with that pollutant’s release. These parameters are typically stated as the weight of the pollutant divided by a unit weight, volume, distance, or time of the polluting action (e.g., kilogrammes of particulate emitted per mega gram of coal burnt). Such parameters make it easier to estimate emissions from diverse sources of air pollution. Most of the time these characteristics are simple averages of all available data of acceptable quality that are believed to be reflective of long-term averages for all facilities in the source category (i.e., a population average) (EPA, 2022).

Carbon emissions from electricity production were calculated using emission factors of each technology. The emission factors in the software were imported from the LEAP emissions database which uses the default IPCC Tier 1 and Tier 2 emission factors in the calculations. Because coals are not categorised in official data as anthracite, bituminous coal, lignite, and so on, they are not appropriate for a precise calculation of CO_2 emissions using the calorific values in national greenhouse gas inventories (Cui-Mei and Quan-Sheng, 2014). Therefore, by making-do of the LEAP database at hand, we assume the coal being used to generate electricity as bituminous coal on a national level.

$$TE = \sum_t \sum_f EF_{f,t} \times \frac{1}{E_t} \times OP_t \tag{2}$$

Where:

TE = GHG emissions.
t = type of power generation technology.
f = primary fuel type.
$EF_{f,t=}$GHG emission factor from one unit of primary fuel type f used to generate electricity using technology t.
E_t = efficiency of technology t.
OP_t = the output power from technology t.

Table 3
Details of the IPCC Tier 1 emission factors of different pollutants imported from the LEAP database, 2020 values.

Technology	CO_2 (Metric Tonne/TJ)	CO (kg/TJ)	CH_4 (kg/TJ)	NMVOC (kg/TJ)	NOx (kg/TJ)	N_2O (kg/TJ)	SO_2 (kg/TJ)
Coal	92.64	20	1	5	300	1.4	0.028
Natural Gas	55.78	20	1	5	150	0.1	0
Coal CCS	9.26	20	1	5	300	1.4	0.028
NGCCS	5.58	20	1	5	150	0.1	0
BECCS	−453.24 g_{CO2}/kWh	0	0	0	0	0	0

Note: TJ=Terajoule; Carbon dioxide=CO_2; Carbon monoxide=CO; Methane=CH4; Non-Methane Volatile Organic compounds=NMVOC; Nitrogen Oxides=NOx; Nitrous Oxide=N_2O; Sulfur Dioxide=SO_2.

Table 3 shows the 2020 values of Carbon dioxide (CO_2), Carbon monoxide (CO), Methane (CH_4), Non-Methane Volatile Organic compounds (NMVOC), Nitrogen Oxides (NOx), Nitrous Oxide (N_2O), Sulfur Dioxide (SO_2) that were imported from the LEAP emissions database. Environmental loadings for Hydropower, Nuclear, Wind, Solar, and Biomass were kept at 0 because the emissions associated with the power generated using these technologies were assumed to be none. The capture rate of CCS was kept at 90% as according to previous studies and IEA (IEA, 2021) and the emission intensity of biomass power generation without CO_2 absorption is kept at 503.6 g_{CO2}/kWh, according to a study by Tsinghua University (Guo, 2011). Biomass power generation using CCS is considered a carbon-negative technology, with a CO_2 capture rate of 90%, so, as a result, the CO_2 collected by biomass power generation using CCS is determined to be and kept at 453.24 (503.6*90%) g_{CO2}/kWh.

According to the author's knowledge, there are no studies that provide data on the load shapes of China at a national level and almost all studies on China only elicit either city-level or provincial-level load shapes of the power system.Therefore, the load shape and hourly load data for China were referred to from this study by Kahrl et al. (2021), which reflects current characteristic load shapes in Guangxi Province, based on an average day winter and summer load shapes. The author in the study used normalized load shapes in the study, which was the hourly load divided by the total daily load. Complete hourly load data for China can be found in the **Supplementary Table S5**.

The yearly shapes setting in LEAP allows to browse and update a library of any number of distinct shapes that may be used to indicate how values change throughout the year based on season and time of day. Each year shape in LEAP is defined by entering data that correspond to various time slices throughout a year. Hence, the time slices within the software, comprising of a total 8760 h, were divided into 48 time slices for this research – 24 h for each season.

Other parameters that were considered and their respective values that were input in the software on an industry expert's recommendation are shown in **Table S6**.

Reserve margin, set at 25% in the model, is the available capacity when system is at peak load, and can be calculated using the following formula:

$$\frac{\sum (Capacity \times CapacityCredit) - PeakLoad}{PeakLoad} \times 100 \tag{3}$$

Discount rate is the interest rate imposed on the loan to cover the capital cost, which is set at 7% in our model. And externality costs are the social costs of pollution that are quantified per unit of pollutant, or in other words, the carbon price for 1 tonne of CO_2 into the atmosphere. By providing/inputting an externality cost for an impact, LEAP multiplies it by the total emissions of that effect in each year of each scenario to calculate the overall externality cost of each pollutant. This expense will be accounted for in LEAP's cumulative cost-benefit analysis.

2.3. Calculation of total costs for power generation

Total costs for power generation in the LEAP software took into account the following equation that considered variables such as the total years, discount rate, installed capacity, and different costs including the initial capital cost, fixed operation and maintenance costs, variable operation and maintenance costs, and finally the fuel costs of each technology.

$$TC = \sum_{y}^{T_y} \sum_{t} \frac{1}{(1+d)^y} \left(C_i \times Cp_y + Fom_y \times Cp_y + Vom_y \times OP_y + Fc_y \right) \tag{4}$$

Where:

TC = Total cost, in CNY
T_y = total years from 2020 to 2060
y = year
t = power generation technology
d = discount rate, in%
C_i = initial capital cost, in CNY
Cp_y = capacity in year y, in MW
Fom_y = fixed operation and maintenance costs in year y, in CNY
Vom_y = variable operation and maintenance costs in year y, in CNY
OP_y = output power in year y, in MWh
Fc_y = fuel cost, in CNY

Total costs and emissions calculations were referenced from two previous studies by Handayani et al. (2019).

2.4. Calculation and integration of the learning model for the capital cost of each technology

Monetary savings via technological learning are especially appealing to emerging nations, which are still experiencing fast increases in power use while simultaneously committing to their NDCs. Understanding how power generation costs change over time is critical for analysts and decision-makers associated with technology development, the evolution of national and global energy systems, and the implications of proposed policy measures to address global climate change or other energy-related issues. The idea of a learning curve (or experience curve) has been used in the literature over several decades to tie historically observed declines in the cost of a technology to major elements determining its deployment and dissemination. These include cumulative installed capacity or units of output generated. Researchers and policy analysts have been using technology "learning rates" produced from such models to forecast future trends in the energy and environmental sectors (Rubin et al., 2015). The "one-factor learning curve" (or "experience curve") is by far the most prevalent model used in the energy literature to predict changes in technology costs. This commonly used methodology is based on actual data across a wide range of power generation technologies, which typically show a log-linear connection between the technology's unit cost and its cumulative output (production) or installed capacity (McDonald and Schrattenholzer, 2001).

Cost reductions with growing cumulative experience may be categorised into three groups. First, lower costs are attributed to improvements or modifications in the manufacturing process, such as technological advances, increases in worker productivity as they get more familiar with process equipment, improvements in overall management, and economies of scale. Second, cost reductions are related to changes in the product itself (including innovations, re-design, and technological standardisation). While the third links cost reductions to changes in material

Table 4
Learning rate of each power generation technology.

Technology	Learning rate
Coal	1.00%
Natural Gas	0.83%
Nuclear	5.80%
Hydropower	1.40%
Wind	8.00%
Solar	10.00%
Biomass	15.00%
Coal CCS	7.00%
NGCCS	7.00%
BECCS	7.00%

and labour input prices. These three groups are not mutually exclusive and frequently coexist. Furthermore, some or all of these elements may be influenced by other factors such as market demand changes or legislative actions (including public R&D spending, technology standards, and technology incentives) (Yeh and Rubin, 2012).

In this study, we incorporate technological learning into the Long-term Energy Alternative Planning System (LEAP) model to investigate the effect on the costs in our scenarios. Since LEAP does not have a built-in option for considering technological learning, this study incorporates the one-factor learning model into LEAP in this work that represents the learning curve of electric power technologies. Regarding different performance and experience measures, (McDonald and Schrattenholzer, 2001) determined that learning rates calculated using investment/capital costs and cumulative installed capacity are lower than those calculated using production costs and cumulative production. Therefore, the factors considered in this study's learning curve model were the capital costs of each technology and the installed capacity. The equation below primarily analyses the trends of cost decline produced by cumulative experience, and it may be used to characterize the link between production costs and continuous cumulative outputs (Liya and Jianfeng, 2018).

$$ec_i(n) = ec_i(1) \times E(n)^{-\varphi} \tag{5}$$

Where:

$ec_i(n)$ = per unit electric investment cost, which is a function of the cumulative electricity installed capacity E(n)
$ec_i(1)$ = initial per unit capital investment cost
$-\varphi$ = elasticity of cumulative electricity installed capacity to unit capital investment cost; the declining rate of investment cost or technological progress rate is decided by ϕ

The "learning rate" (LR) is the fractional cost decrease associated with doubling experience and is given by the following equation:

$$LR = 1 - PR \tag{6}$$

$$LR = 1 - 2^{-\varphi} \tag{7}$$

The "progress ratio" (PR) is a measure widely published in the literature that indicates the fractional cost decrease with a doubling of cumulative capacity (or production).

Eq. (2.7) is then transformed to a log-linear equation as follows:

$$\varphi = log2(1 - LR) \tag{8}$$

Learning rates of each power generation technology were taken from two sources (Cai et al., 2022; Liya and Jianfeng, 2018) and are listed in the Table 4:

2.5. Scenario development and description of each scenario

Five scenarios, including the business-as-usual scenario, are developed in this section based on existing policies and trends to analyse the

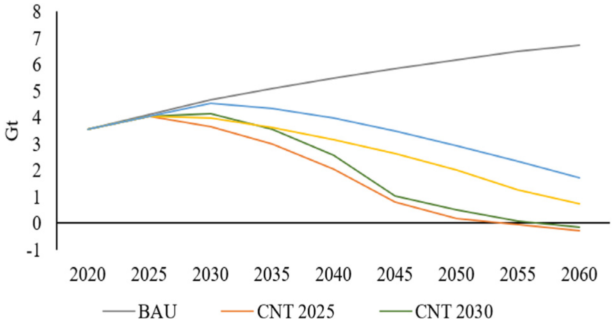


Fig. 2. Carbon emission trajectories of the power generation sector under all scenarios, in Gt.

mitigation potential for carbon emissions reductions by different technologies and different carbon peak timelines. The three major scenarios that were included were: BAU scenario, NDC scenario, and CNT scenario.

A complete description of each scenario can be seen in the Table 5.

The scenarios were designed on China's historical trends in installed capacities of each technology taken from CEC annual development reports, future policies and commitments and other reports, China Energy Transformation Program, 2021; Global Energy Interconnection Development and Cooperation Organization, 2021 (Huang, 2020; Liu, 2022).

Both the CNT scenarios in the model were built on the NDC scenarios, and both the NDC scenarios were built on the BAU scenario.

3. Quantitative analyses of different low-carbon scenarios

3.1. Scenario results

The installed capacities for the baseline scenario were extrapolated and calculated based on the historical installed capacities and extrapolated in Excel using the forecast tool. The total installed capacities calculated were kept the same for all scenarios for better comparison in all scenarios, as shown in **Table S7**.

Total installed capacities of all power generation technologies considered in this study reach a cumulative capacity of 7218.9 GW by 2060, assuming unlimited renewable resources. The installed capacities calculated in this study were almost homogeneous with installed capacities in other reports (Huang, 2020) and IEA's World Energy Outlook 2021 Extended Dataset (IEA, 2021), which verifies the integrity of the calculations.

The calculations conducted within LEAP allowed to project China's power generation sector's future emissions under different scenarios as shown in the Fig. 2 and Table 6. Figures in Mt were converted and expressed in Gt for better presentation and comparison of data.

According to the results, emissions in the BAU scenario keep increasing throughout the study period. Under the NDC 2025 and CNT 2025 scenarios, emissions peak in the year 2025 and then fall. Under the NDC 2030 and CNT 2030 scenarios, emissions fall after peaking in the year 2030. It is rather crucial to note both CNT scenarios; in the CNT 2025 scenario, emissions reach a peak of 4.05 Gt by 2025 year and then fall to zero before 2055 and are marginally negative in 2060. In the CNT 2030 scenario, emissions reach a peak of 4.13 Gt by 2030 year and then fall to zero before 2060 and are marginally negative in 2060. These negative emissions can help to offset residual hard-to-abate emissions, particularly in the heavy industry and long-distance transport sub-sectors and the waste management sector.

As for the total associated social costs of the module for all scenarios, they are shown in Fig. 3. Social costs in LEAP describe the entire societal costs of a scenario, as opposed to the specific costs of production seen by producers or consumers.

Table 5
Scenario description.

Scenario	Description
BAU Scenario	Under the baseline scenario, continuance of the base-year technology portfolio was assumed, and existing and future climate mitigation policies and the carbon peak and neutrality goals were ignored. Fossil-fuel-based power plants remained dominant throughout this scenario
NDC Scenario	In line with China's NDCs and policy targets. This scenario includes the following characteristics: - The capacity expansion aims to achieve China's renewable energy targets. Thus, the renewable energy targets function as constraints for the models. - The types of technologies considered include power generation from coal, natural gas, hydro, wind, biomass, solar PV, and nuclear. - CCS and BECCS were not included in these scenarios. The NDC scenario was further branched into 2 scenarios: NDC 2025 and NDC 2030.
NDC 2025	Power sector peaks carbon emissions in the year 2025
NDC 2030	Power sector peak carbon emission in the year 2030
CNT Scenario	This scenario is built up on the NDC scenarios. In this scenario, the Chinese power generation sector goes beyond the current NDC commitments, aiming at carbon neutral emissions by 2060. The main characteristics of this scenario include: - Achieve carbon neutrality by 2060. - Types of technologies to be considered for future capacity expansion include hydro, wind, biomass, solar PV, nuclear, coal with CCS, NGCCS, and BECCS. The CNT scenario was further branched into 2 scenarios: CNT 2025 and CNT 2030.
CNT 2025	Carbon neutrality achievement in the case the power sector peaks carbon emissions in the year 2025
CNT 2030	Carbon neutrality achievement in the case the power sector peaks carbon emissions in the year 2030

Table 6
Carbon emissions under all scenarios (Gt).

Scenario	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
BAU	3.55	4.12	4.68	5.08	5.48	5.84	6.17	6.50	6.73	48.15
CNT 2025	3.55	4.05	3.65	2.99	2.04	0.78	0.17	−0.07	−0.30	16.87
CNT 2030	3.55	4.03	4.13	3.55	2.55	1.01	0.50	0.07	−0.15	19.24
NDC 2025	3.55	4.05	3.98	3.63	3.16	2.64	2.02	1.24	0.73	24.99
NDC 2030	3.55	4.03	4.53	4.32	3.98	3.49	2.92	2.34	1.71	30.85

Table 7
Total costs of all Scenarios, without considering the learning rate of each technology for operation costs, in billion CNY.

Scenario	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
BAU	1898	2748	3656	4535	5463	6244	7083	7958	8884	48,469
CNT 2025	1898	2734	3896	4979	6159	7244	7913	8493	8699	52,016
CNT 2030	1898	2713	3783	4912	6146	7358	8437	8878	9057	53,182
NDC 2025	1898	2734	3762	4730	5726	6538	7133	7706	8024	48,250
NDC 2030	1898	2713	3682	4667	5659	6507	7302	7920	8296	48,643

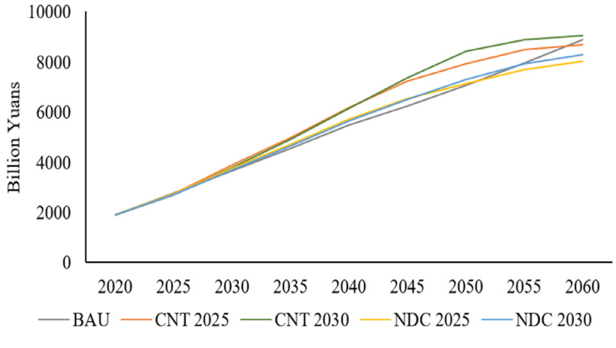


Fig. 3. Total costs of all scenarios, without considering the learning rate of each technology for operation costs, in Billion Yuans.

In Fig. 3 and Table 7 total costs in all scenarios are increasing. Towards the end of the study period, CNT 2030 has the highest total costs, amounting to 9057 billion Yuans in 2060, out of all scenarios, followed by CNT 2025 at 8699 billion Yuans, BAU at 8884 billion Yuans, NDC 2030 at 8296 billion Yuans and NDC 2025 at 8024 billion Yuans.

The difference in these costs is due to the difference in the shared capacities of power generation technologies and their associated capital costs, variable and fixed Operating and Maintenance (O&M) costs and fuel costs. For instance, the reason total costs are higher in BAU than both NDC scenarios is because BAU is still predominantly coal, whereas the NDC scenarios have phased out most of it, hence cutting down costs.

As we know that as experience for a technology accumulates and progresses over time, unit prices for a particular technology fall with time That is, the influence of technical learning on cost projections varies non-linearly with the change in learning rate. The findings of this study reveal that as compared to the costs that did not consider the learning rate of relative power generation technologies were higher as compared to the ones that did. It was determined that costs that adopted the learning rates of technologies under the baseline, CNT 2025, CNT 2030, NDC 2025, and NDC 2030 scenarios were 10.26%, 20.36%, 19.92%, 16.20%, 14.95%, respectively, lower under the same scenarios that did not take into account the learning rates. Trends of total costs that consider the learning rates are shown in Fig. 4 and details are given in Table 8.

Because learning is a self-executing process, more collected experiences in technology lead to lower costs, and increased technological competitiveness leads to even more acquired experience. As a result, it is not always the case that a new technology is employed because it is cheap; rather, a technology becomes inexpensive due to greater usage and understanding. Aside from cost savings, learning may lead to increased competency in technology operation as well as the institutional transformation required to enable for the widespread deployment of new technologies (Handayani et al., 2019).

Table 8
Total costs of all scenarios, taking into account the learning rate of each technology for operation costs, in Billion Yuans.

Scenario	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
BAU	1898	2687	3426	4093	4809	5427	6190	7029	7938	43,496
CNT 2025	1898	2674	3546	4245	4939	5496	5898	6251	6476	41,424
CNT 2030	1898	2654	3491	4247	5001	5629	6345	6588	6730	42,584
NDC 2025	1898	2674	3460	4114	4751	5249	5704	6127	6455	40,432
NDC 2030	1898	2654	3439	4134	4813	5354	5930	6433	6715	41,369

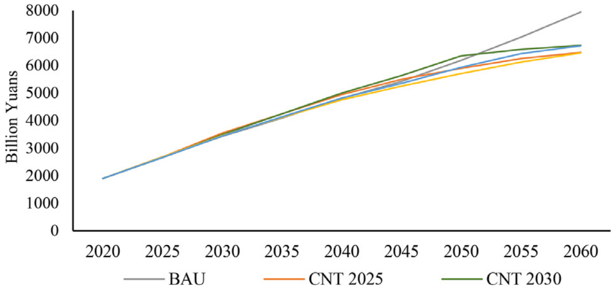


Fig. 4. Total costs of all Scenarios, considering the learning rate of each technology for operation costs, in billion Yuans.

3.2. *Application of CCS and BECCS technologies*

The future capacity of coal-fired and gas-fired units in China is heavily reliant on CCS and its integration with bio-energy, i.e., BECCS technologies. Coal-fired power stations with CCS will capture 90% of carbon emissions, making it a comparatively low-carbon power generating technology. BECCS is a negative-emission technology that can compensate for leftover emissions from the power generation industry. CCS penetration is dependant on future cost reductions, whereas both cost reduction and biomass resource availability are critical criteria for BECCS scale-up. According to some projections in other studies, 400–700 GW of coal-fired power should be set aside by 2050 for basic load, peak load management, and heating, while existing units should be modified for greater flexibility and Combined Heat and Power output (CHP) (Tsinghua, 2022). The results in this study are somewhat almost consistent with these studies.

CCS and BECCS technologies will be critical in the CNT 2025 and CNT 2030 scenarios. Under the CNT 2030 scenario, CCS is expected to scale up in coal-fired power plants by 2030 and reach an installed capacity of 416 GW by 2060. Whereas for natural gas power plants, CCS is expected to scale up in them by 2035 and reach an installed capacity of 454 GW by 2060. On the other hand, BECCS will be deployed by 2030 and reach a capacity of 216 GW by 2060. Under the CNT 2025 scenario, because action will be taken sooner, it will not be as hectic to retrofit a lot of coal-fired plants with CCS all at once. Hence, the maximum capacity that reaches in coal-fired power plants is 565 GW by 2045, which then decreases to 74 GW by 2060. BECCS deployment will be beginning in 2030 just as in the CNT 2030 scenario and will be reaching a maximum installed capacity of 216 GW by 2060.

3.3. *Carbon emissions under different low-carbon scenarios*

Under the NDC 2025, carbon emissions from the power generation sector continue to rise slowly until it peaks in 2025 at 4.1 Gt CO_2 and then downward to 0.7 Gt in 2060. Under the NDC 2030 scenario, the emissions prior to 2030 stay on the same trajectory with the NDC 2025 scenario, reach a peak at 4.5 Gt by 2030, gradually fall after 2030 and to 1.7 Gt in 2060. In this study, the target of "non-fossil energy representing 50% of primary energy consumption by 2050″ is incorporated into the NDC scenarios, which is also characterized by a scale-up of renewables before 2030 and the rise of non-fossil energy to 25% of primary energy consumption by 2030.

The carbon trajectories of both scenarios point to a failure in attaining the carbon neutrality goal, i.e., China's current mid- to long-term energy and power policies and targets fall short of the carbon neutrality target it wants to achieve. In this study, strengthened efforts in emission reduction are seen in the CNT 2030 and the CNT 2025 scenarios compared to the NDC 2030 and NDC 2025 scenarios prior to 2030. Efforts are sped up after 2030 in the CNT 2030 and the CNT 2025 targets.

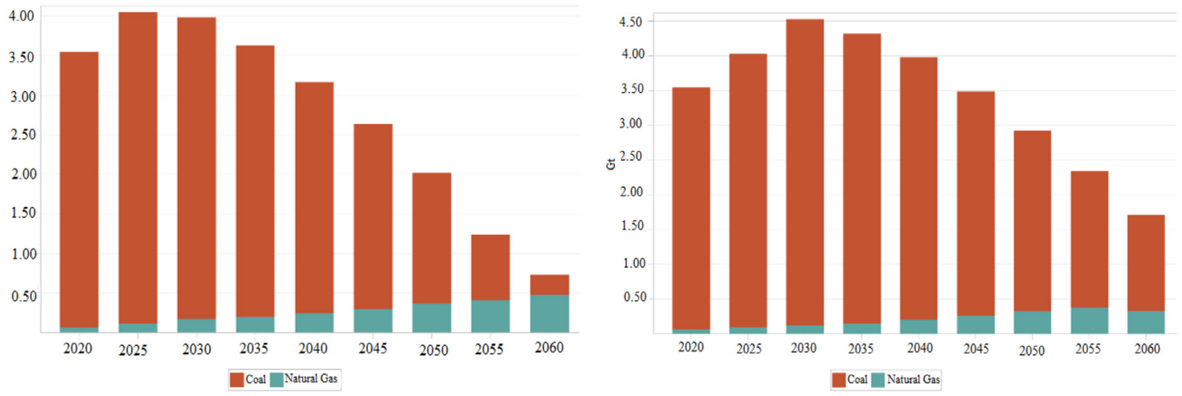
Under the CNT 2030 scenario, carbon emissions from the power generation sector reach the peak in 2030 at 4.1 Gt and take a nosedive after 2030, falling to merely 0.1 Gt by 2050 before falling to 0 Gt around 2053 and becoming marginally negative after 2054, and reaching negative emissions of 0.1 Gt by 2060 with the aid of BECCS. Under the CNT 2025 scenario, the power generation sector sees its emissions peak at 4.1 Gt in 2025, followed by a drop after 2030, before falling to 0 Gt around 2056 and becoming marginally negative after that, reaching a negative emission of 0.3 Gt by 2060 with the aid of BECCS, which is 0.2 Gt worth of negative emissions more than the CNT 2030 scenario. As is illustrated in the Fig. 5, the carbon emissions profile features a sharp fall after 2030 under the CNT 2030 scenario, which presents daunting challenges in the short term to the industry, technology, market, and policy, and puts enormous pressure on emission reduction in the later phase with the massive retirement of coal-fired power units after 2030.

3.4. *Share of each technology in the total installed capacity under different scenarios*

This section details on the total installed capacities by each technology that were calculated in Excel **(Supplementary Tables S8–S12).** Amongst the available studies, a maximum of 630 GW, 540 GW and 510 GW are forecasted for hydropower, nuclear power, and intermittent renewable energy (wind and solar) respectively by 2050 (Tsinghua, 2022).

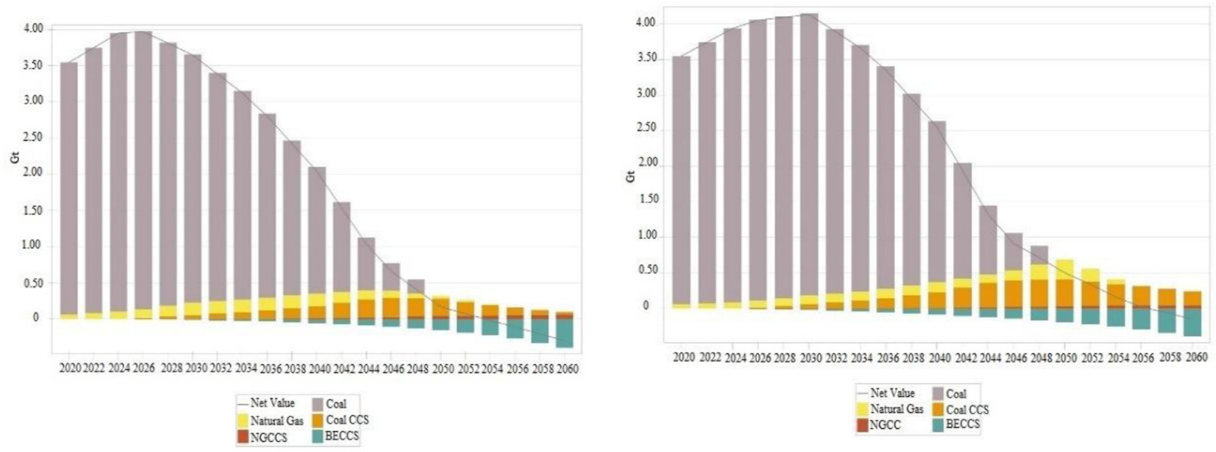
Under the baseline scenario – which assumes the continuation of the base-year technology portfolio and ignores current climate-mitigation policies and the carbon neutrality goal – fossil fuel-based power plants remain dominant throughout the study period, 2020–2060. The share of installed capacities by each technology in the baseline scenario is shown in Fig. 6. The share of fossils, especially coal, is predominant throughout the baseline scenario, however, based on historical trends, China's share in coal power has been decreasing with an average annual rate of about 2%.. Whereas the share of renewables has been significantly increasing over the past decade. Thermal power, namely coal and gas in this model, accounted for 54.55% of total capacity and non-fossils accounted for 45.45% in 2020. Whereas, towards the end of the study period, in 2060, the share of renewables and thermal power was 62.52% and 37.48% respectively, where coal accounted for a whopping 32.5% and gas 5% of the total capacity. Breakdown of renewables in 2060 was as such: solar, 27.1%; wind, 19.7%; hydro, 10.2%; nuclear, 3.2%; biomass, 2.3%.

For both NDC scenarios, 30,000 MW of coal was phased out by 2025 from the 2025 baseline value. For NDC 2030, 50,000 MW of coal was phased out by 2030 followed by a gradual phase-out after. Whereas for NDC 2025, a relatively vigorous phase-out started after 2025, and about 60,785 MW of coal was phased out by 2030. Both scenarios' nuclear power share and hydropower share was 72,502 MW and 418,279



(a) NDC 2025

(b) NDC 2030



(c) CNT 2025

(d) CNT 2030

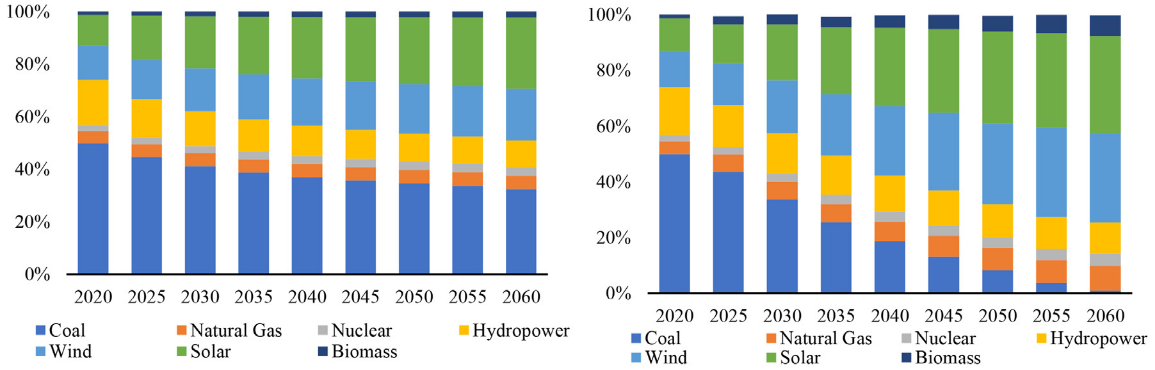
Fig. 5. Carbon emissions under different low-carbon scenarios, in Gt.

MW respectively by 2025, whereas for NDC 2025, share of wind and solar combined was 1,339,268 MW in 2030 and for NDC 2030 it was 1,201,907 MW combined for both solar and wind power. It is important to note that these installed capacities align with China's target capacities for these technologies. These scenarios only consider non-fossil power generation technologies and do not adopt any CCS or negative-emissions technologies, like BECCS.

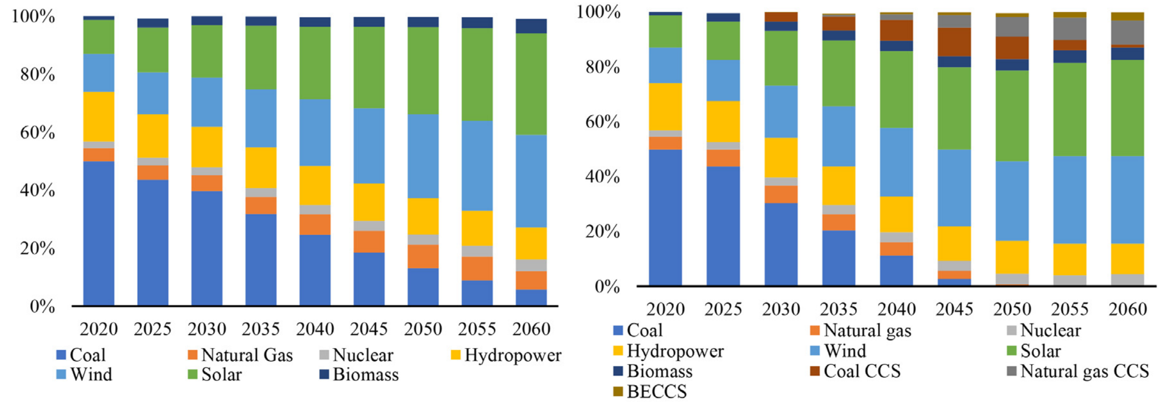
In the NDC 2025 scenario, the share of fossils, especially coal, is phased down through the study period. the total thermal power share drops to 9.8% in 2060, and coal power is 1.03% out of the total in 2060. Non-fossils on the other hand accounted for 90% of the total share in 2060. Breakdown of renewables in 2060 was as such: solar, 35%; wind, 32%; hydro, 11%; nuclear, 4.5%; biomass, 7.5%. As for the NDC 2030 scenario, the share of thermal power in this scenario is also being phased down, however as compared to the NDC 2025 scenario, the final share of fossils, including coal and gas, is relatively higher, making up 12.1% of the total installed capacity. Non-fossils, on the other hand, make up the remaining 87.9%. Share of coal power was 5.76% in 2060 which was 4.73% higher than the share of coal power in the NDC 2030 scenario.

As opposed to the NDC scenarios, both CNT adopt CCS and BECCS technologies. For both CNT scenarios, 30,000 MW of coal was phased out by 2025 from the 2025 baseline value.Coal CCS and BECCS were deployed from 2030, and gas CCS was deployed from 2035 in both scenarios. For better comparison of the NDC and CNT scenarios' emissions, the shares of hydropower, nuclear, wind and solar were in both CNT scenarios was kept the same as in the NDC scenarios. To determine the shares of thermal power technologies and CCS technologies, the installed capacities of respective capacities in the NDC scenarios were taken as the base values.

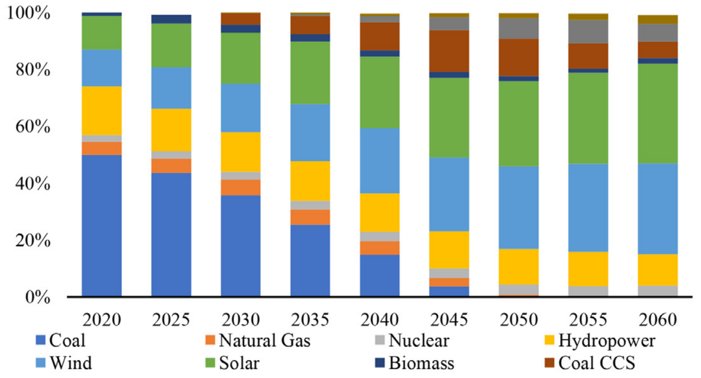
In the CNT 2025 scenario, for coal, gas, biomass, coal CCS, gas CCS, and BECCS share in the total installed capacity. Their shares were calculated based on the NDC 2025 shares of each mentioned technology. For instance, for coal, the installed capacity of coal in NDC 2025 was taken as reference value, out which 90% of it was assigned to coal power in 2030, and 10% to coal CCS. So, in this way, the share of coal was phased down, and was completely phased out by 2050, and the remaining was retrofitted with CCS. The same method was applied for gas power, which was completely phased out by 2055. Therefore, by 2060, the share of coal from total capacity 1.03% was retrofitted with coal CCS, gas was 8.8% of the total capacity, which was retrofitted with gas CCS, biomass on the other hand was 4.5% and BECCS 3% of the total installed capacity. The share of each technology in the CNT 2030 scenario was calculated just like the shares calculated in the CNT 2025. The shares of coal, gas, biomass, coal CCS, gas CCS, and BECCS in the total installed capacity were calculated based on the NDC 2030 shares of each mentioned technology. The share of coal was phased down and was also completely phased out by 2050. The remaining was retrofitted with CCS, whereas gas was completely phased out by 2055. Since the shares of nuclear, hydropower, wind and solar were kept the same the NDC 2030 scenario, the shares of other technologies were adjusted accordingly. By



(a) BAU scenario (b) NDC 2025 scenario



(c) NDC 2030 scenario (d) CNT 2025 scenario



(e) CNT 2030 scenario

Fig. 6. Share of each technology in the total installed capacity under different scenarios.

2060, shares of coal and gas in the total installed capacity was 0% each, whereas the share of biomass was 4.5%, which is 2.5% higher than the share of biomass in the CNT 2025 scenario.

3.5. Power generation mix under different scenarios

Power generation mix in all scenarios by 2060 is shown in Fig. 7. Towards the end of the study period, in 2060, thermal power still accounted for more than half of the power generation, 52.5%.Whereas non-fossils accounted for 47.5% of the generation mix in the baseline scenario. Changes in power generation mix suggest that newly emerged demand is mainly met by power from non-fossil sources, which, in the long-term, will further replace coal-fired power units to meet low-carbon emission and carbon neutrality goals. Total power demand is the same in all scenarios for better comparison. Speedy growth and ambitious scale-up will be needed as the power generated from non-fossil resources in the baseline scenario, NDC 2025 scenario, NDC 2030 scenario, CNT 2025 scenario and CNT 2030 will comprise 47.5%, 89.5%, 82.5%, 84.2%, and 77.6%, respectively by 2060. Increase in the share of intermittent renewable energy (wind and solar power) will also be seen in 2060 under the baseline scenario, NDC 2025 scenario, NDC 2030 scenario CNT 2025 scenario and CNT 2030 scenario reaching 29.9%, 54.9, 54.1%, 54.9% and 54.1% respectively of the total power generation by 2060. It is rather crucial to observe that both the 2025 scenarios and

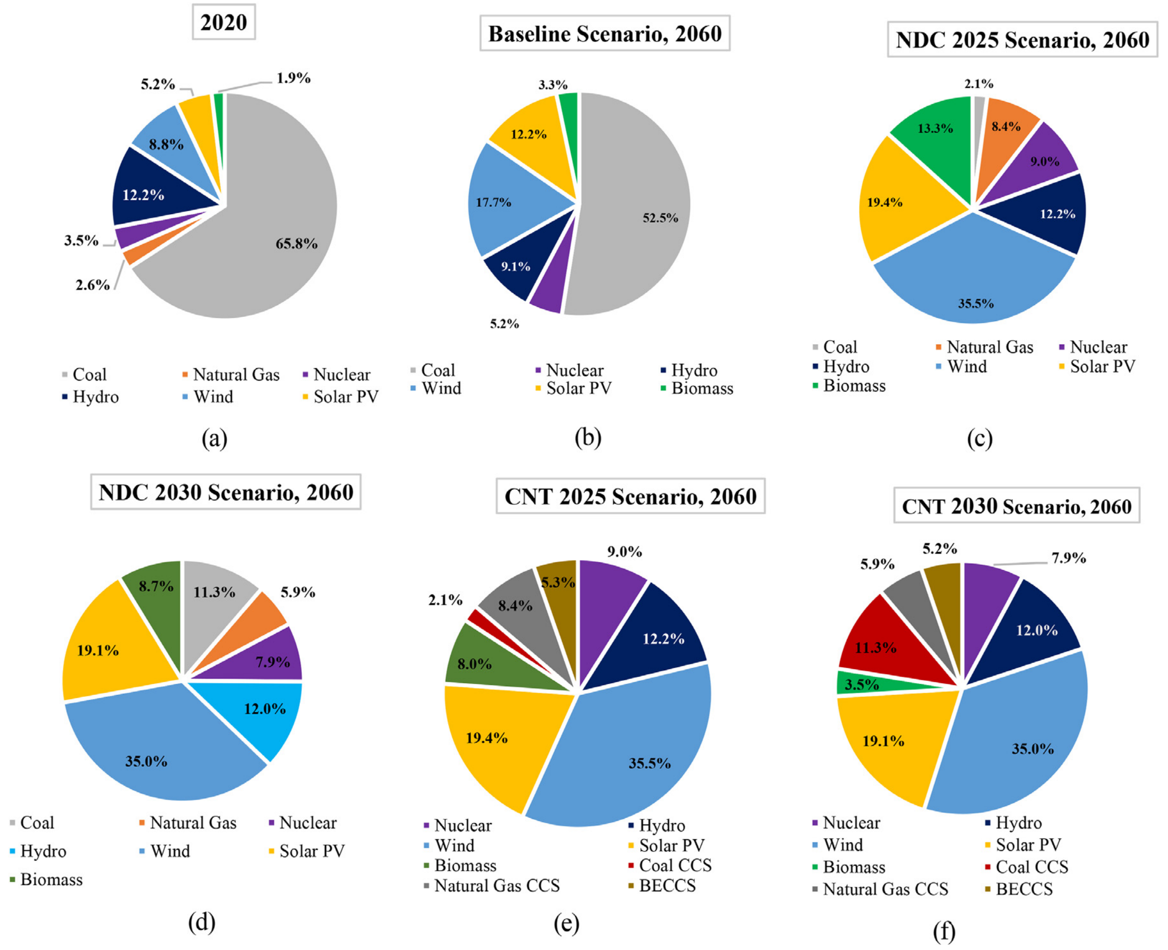


Fig. 7. Power generation mix under different scenarios in 2060.

2030 present the same shares of intermittent renewable energy in the power mix because in the installed capacity calculations we kept the shares the same for them to allow a better comparison for the CCS and BECCS technologies.

Under the NDC 2025, NDC 2030, CNT 2025 scenario and CNT 2030 scenarios, the share of intermittent renewable energy is predicted to surge to above 50% by 2060, presenting a greater challenge for system balance and grid flexibility. Compared to the CNT 2030 scenario, power generation from coal-fired and natural gas CCS and BECCS will soar under the CNT 2025 scenario. The power generation of coal-fired power and natural gas will continue to shrink in the low-carbon scenarios, with a drop of nearly 57.9% and 51.2% the NDC 2025 and NDC 2030 scenarios, respectively, in 2060 as compared to 2020. Whereas for the CNT 2025 and CNT 2030 scenarios, these thermal power plants will be retrofitted with CCS. Under the NDC 2025 and NDC 2030 scenarios, the installed capacity of natural gas power will reach 635 GW and 454 GW, respectively, by 2060, but its share in total power production is insignificant due to its primary role in peak regulation.

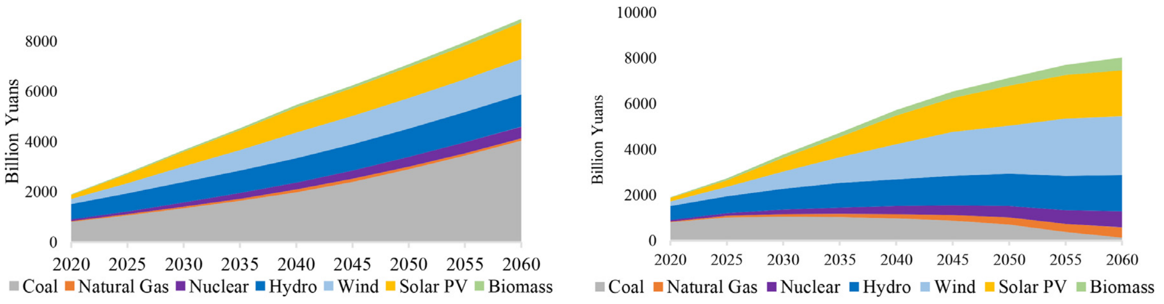
Under CNT 2025 and CNT 2030 scenarios where net zero-emissions are to be achieved by 2060 in the power generation sector with the aid of CCS and BECCS, coal-fired power and natural gas power will see a steep reduction and will eventually be completely retrofitted with CCS. The same goes for biomass power plants, which will be replaced with BECCS. Under the CNT 2025 scenario, power generation from coal CCS 2.1%, natural gas CCS will be 2.1% and 5.3% from BECCS. Whereas under the CNT 2030 scenario, power generated from BECCS will be 5.2%, 11.3% from coal CCS, and 5.9% from natural gas CCS.

3.6. Total costs under different scenarios

The total costs are discussed under this section for all scenarios considered in this study. Under the baseline scenario, as shown in the Fig. 8 below, costs were totalling at 8884.4 billion Yuans in 2060, out of which 46.4% was thermal power and non-fossil costs were 53.6%. Social costs under the NDC 2025 scenario, solar, wind and hydropower account for most of the costs towards 2060.

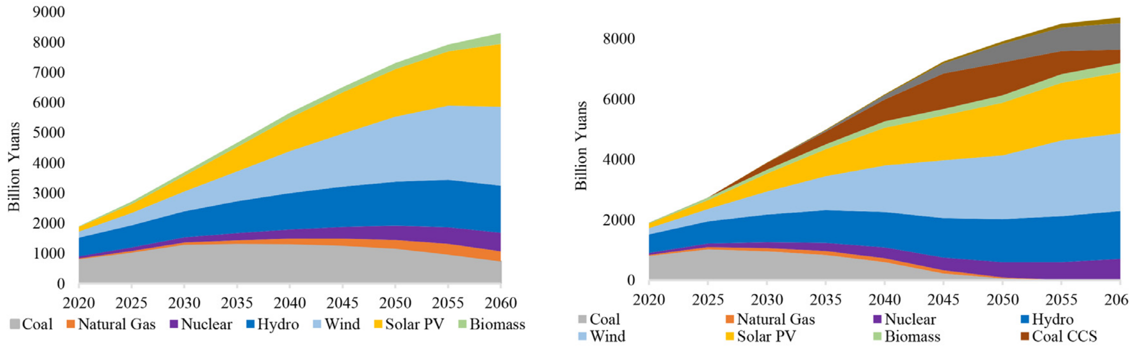
Total costs in 2060 were 8023.5 billion Yuans, out of which thermal power social costs accounted for 7.2% and non-fossils accounted for the remaining 92.8% of the total costs. Total social costs for the NDC 2030 scenario amounted to 8296.1 billion Yuans in 2060, which were 3.2% higher than the total costs in the NDC 2025 scenario. Total associated costs with the CNT 2025 scenario were 8698.8 billion Yuans in 2060, and total costs from 2020 to 2060 were 52,015.7 billion Yuans. Total costs associated with the CNT 2030 scenario, from 2020 to 2060, were 53,182 billion Yuans, and 9057 billion Yuans in the year 2060 only.

Total costs associated with coal power were 19,576 billion Yuans, 6973 billion Yuans, 9801 billion Yuans, 4498 billion Yuans, and 5073 billion Yuan under the baseline, NDC 2025, NDC 2030, CNT 2025 and CNT 2030 scenarios, respectively. Costs spent on coal-fired plants are substantially lower in the low-carbon scenarios due to a phasing out of coal-fired power plants in them; they are particularly lower under the CNT 2025 and CNT 2030 scenarios due to an early and heavy phase-out of coal-fired power plants and their retrofitting with CCS technologies. Total costs associated with coal CCS, natural gas CCS and BECCS under the CNT 2025 scenario were 4846 billion Yuans, 2769 billion Yuans, and 556 billion Yuans, respectively, for the entire study period.Whereas



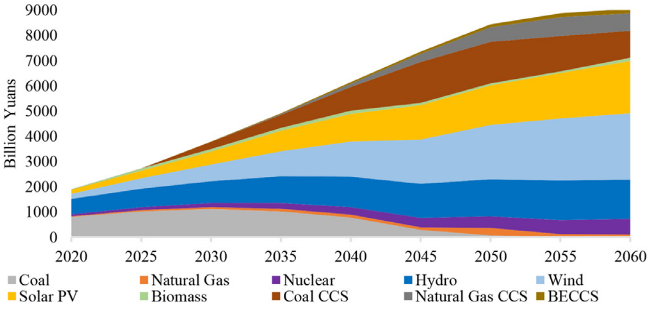
(a) BAU scenario

(b) NDC 2025 scenario



(c) NDC 2030 scenario

(d) CNT 2025 scenario



(e) CNT 2030 scenario

Fig. 8. Total costs under different scenarios, in billion Yuans.

under the CNT 2030 scenario, costs for coal CCS, natural gas CCS and BECCS were 7491 billion Yuans, 2504 billion Yuans, 661 billion Yuans, respectively. This difference in costs is due to the different installed capacities of the CCS and BECCS technologies under each scenario. In the case of the CNT 2025 scenario, because thermal power plants were phased out and retrofitted earlier, hence the associated costs were comparatively lower than the costs under the CNT 2030 scenario. Detailed costs by technology and year-wise can be found in **Tables S13–S22**.

4. Avoided emissions in different scenarios

4.1. Comparison and analysis of avoided emissions in different scenarios

This section briefs on and analyses the emissions that could be avoided by comparing one scenario to another. Fig. 9 shows the avoided emissions of the NDC 2025 scenario as compared to the BAU scenario. With the progression of the NDC 2025 scenario, a total of approximately 23.2 Gt of GHG emissions can be avoided from 2020 to 2060 as compared to the baseline scenario. In the first five years of the study period, avoided emissions were merely 64.7 Mt by 2025, but as emissions continue to ramp up in the baseline scenario while coal-fired power plants were phased out in the NDC 2025 scenario, more emissions were avoided after 2030. After 2035, avoided emissions were approximately 800–900 Mt on average every 5 years. The reason for the large difference in emissions is because thermal power plants, including coal and gas, were phased out and the electricity demand was fulfilled by other non-fossil energy resources. With the gradual phasing out of coal in the NDC 2025 scenario, after a peak in 2025 at 3939 Mt of emissions from coal power, the emissions emitted over the rest of the study period up until 2060 kept decreasing until reaching 249.1 Mt in 2060. The total emissions from coal and gas were collectively 48,150 Mt in the NDC 2025 scenario, which were 23,152 Mt less than the total emissions in the BAU scenario. A complete overview of the avoided emissions can be seen in Table 9.

When it comes to the NDC 2030 scenario, the avoided emissions in the first 10 years of the study were not as significant as compared to the baseline scenario's emissions. A visualization of the avoided emissions in the NDC 2030 versus the BAU scenario can be seen in Fig. 10**.**

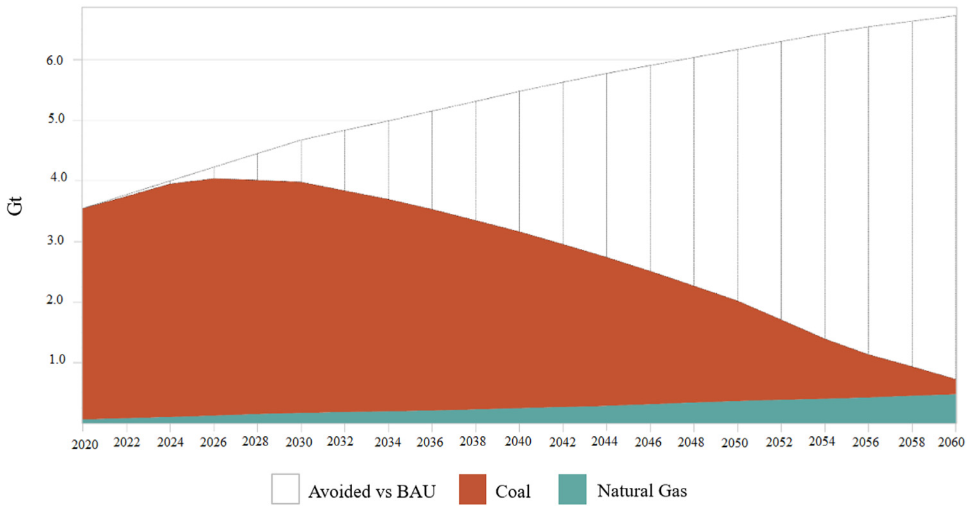


Fig. 9. Avoided emissions of NDC 2025 scenario vs BAU scenario, in Gt.

Table 9
Avoided emissions of NDC 2025 scenario vs BAU scenario (Mt).

Branch	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
Avoided Emissions vs. BAU	–	64.7	692.6	1447	2314	3207	4154	5264	6006	23,152
Coal	3483	3939	3811	3426	2918	2339	1652	826.9	249.1	22,647
Natural Gas	64.1	113.1	172.5	201.4	246.6	296.6	366.9	411.1	478.3	2350
Total	3547	4117	4676	5075	5479	5843	6174	6502	6734	48,150

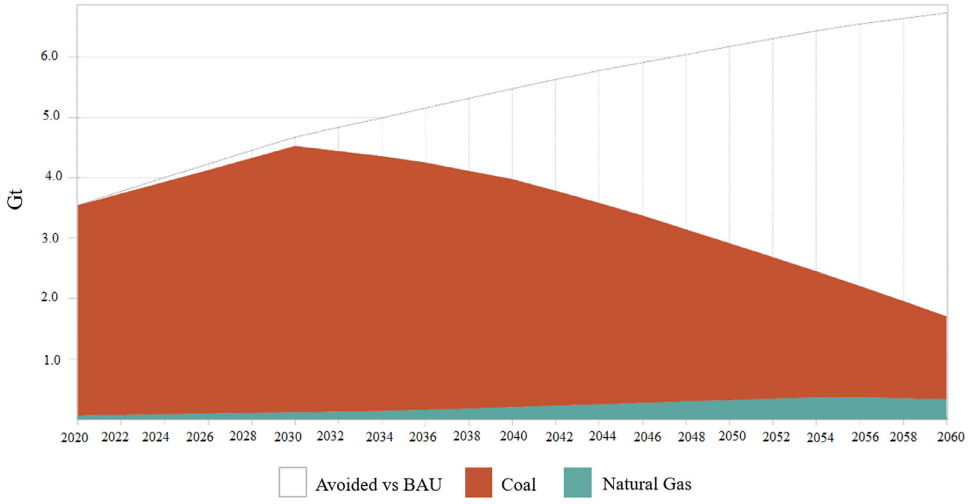


Fig. 10. Avoided emissions of NDC 2030 scenario vs BAU scenario, in Gt.

Before 2035, avoided emissions were merely around 100 Mt on average every 5 years.However, after 2030, when coal was phased out from the NDC 2030 scenario and more renewables power generation capacities were expanded, we witness an average increase of 700–800 Mt of avoided CO_2, on average, every 5 years. In this case, the total emissions avoided over the whole study period were 17,291 Mt (approximately 17.3 Gt), which were 25.4% lower than the avoided emission in the NDC 2025 vs BAU emissions, and 5028 Mt in 2060 alone as compared to the BAU scenario. A detailed overview is given in Table 10.

On the other hand, the CNT scenarios' emissions, as opposed to the NDC scenarios' emissions, consider emissions of coal CCS and natural gas CCS and negative emissions of BECCS along with coal and gas alone, so expected avoided emissions when compared to the baseline scenario will be higher than the previous two low-carbon scenarios. Fig. 11 depicts the emissions that can be avoided versus the BAU scenario if the CNT 2025 pathway is adopted.And how, with the aid of BECCS, a total of 975.6 Mt negative emissions can be achieved in the power generation sector, which assist in increasing the avoided emissions even more, up to 31,278 Mt (approximately 31.3 Gt) in the entire study period (25% more than the NDC 2025 vs BAU scenario). We saw when the power generation sector peaked its emissions in the 2025 under the NDC 2025 scenario, avoided emissions compared to the baseline scenario were 64.7 Mt in 2025, which posed the same value as in the CNT 2025 versus the BAU scenario (Table 11). This was because the proportion of installed capacities were kept the same to allow better comparison after the 2025 mark, which we can clearly witness. After 2025, avoided emissions were 1029 Mt for the CNT 2025 vs BAU scenario in 2030, whereas only 692.6 Mt in the NDC 2025 vs BAU scenario. This significant difference in the avoided emissions was achieved not only with the expansion of non-fossil power generation technologies, but also CCS and BECCS.

Conversely, the CNT 2030 scenario vs BAU scenario has relatively lower avoided emissions than the CNT 2025 scenario vs BAU scenario. It can be observed from the data that avoided emissions in 2025 were

Table 10
Avoided emissions of NDC 2030 scenario vs BAU scenario (Mt).

Branch	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
Avoided Emissions vs. BAU	–	84.8	149.3	754.0	1498	2355	3254	4166	5028	17,291
Coal	3483	3939	4408	4175	3775	3228	2598	1959	1373	28,940
Natural Gas	64.1	93.0	119.2	145.7	204.8	260.2	321.6	376.1	333.0	1917
Total	3547	4117	4676	5075	5479	5843	6174	6502	6734	48,150

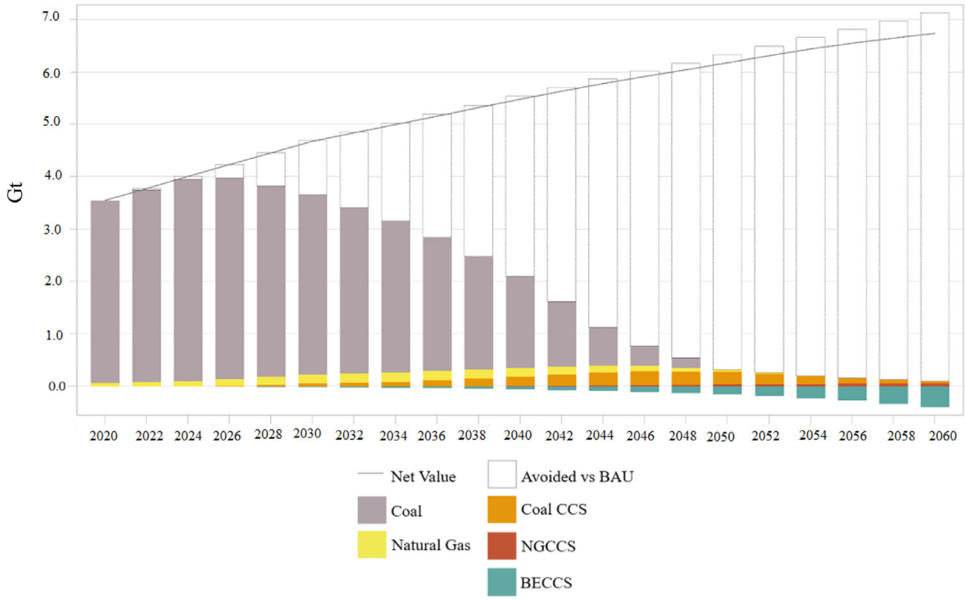


Fig. 11. Avoided Emissions of CNT 2025 scenario vs BAU scenario, in Gt.

Table 11
Avoided emissions of CNT 2025 scenario vs BAU scenario (Mt).

Branch	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
Avoided Emissions	–	64.7	1029	2080	3434	5059	6007	6567	7034	31,278
Coal	3483	3939	3430	2741	1750	468	–	–	–	15,812
Natural Gas	64.1	113.1	172.5	181.2	172.6	118.7	36.7	–	–	858.8
Coal CCS	–	–	55.3	99.5	169.4	271.7	239.9	120.0	36.2	992.1
Natural Gas CCS	–	–	–	2.5	9.1	22.0	40.7	50.7	59.0	184.1
BECCS	–	–	−10.8	−29.2	−57.3	−96.7	−150.3	−236.1	−395.2	−975.6
Total	3547	4117	4676	5075	5479	5843	6174	6502	6734	48,150

Table 12
Avoided emissions of CNT 2030 scenario vs BAU scenario (Mt).

Branch	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
Avoided Emissions	–	84.8	544.8	1526	2926	4829	5671	6436	6882	28,901
Coal	3483	3939	3967	3340	2265	645	–	–	–	17,641
Natural Gas	64.1	93.0	119.2	131.1	143.4	104.1	281.9	–	–	936.8
Coal CCS	–	–	64	121.2	219.2	374.9	377.1	284.5	199.3	1640
Natural Gas CCS	–	–	–	1.8	7.6	19.3	31.3	46.4	41.1	147.5
BECCS	–	–	−18.7	−45.8	−82.4	−129.4	−187.7	−265.1	−388.5	−1117
Total	3547	4117	4676	5075	5479	5843	6174	6502	6734	48,150

the same (84.8 Mt) for both the CNT 2030 vs BAU and NDC 2030 vs BAU scenarios because efforts were ramped up after this mark. Where avoided emissions in the CNT 2030 vs BAU scenario were 544.8 while avoided emissions for NDC 2030 vs BAU scenario were 149.3 Mt in 2030.

Total avoided emissions in this case were 28,901 Mt (28.9 Gt) from 2020 to 2060, which was 7.66% less than the CNT 2025 vs BAU avoided emissions. Fig. 12 shows a visualization of what the avoided emissions look like, and Table 12 shows detailed avoided emissions in CNT 2030 vs BAU. Lastly, we compare the avoided emission in both NDC and CNT scenarios with each other respectively (Fig. 13).

Total emissions avoided in the NDC 2025 vs NDC 2030 were 5860 Mt (approximately 5.9 Gt) for the entire study period. This was due to the ramping up in the expansion of renewables and the timely phase-out of the thermal power generation technologies. Highest avoided emissions were seen in the 2055 at 1097.6 Mt. Breakdown of the avoided emissions can be seen in Table 13 and Fig. 13.

Total emissions avoided in the CNT 2025 and CNT 2030 were 2376 Mt (2.3 Gt) for the entire study period. The difference is significant, but not as much as the avoided emissions in the NDC scenarios because the deployment of CCS and BECCS technologies in both scenarios was carried out gradually along with the same capacities of renewables in both

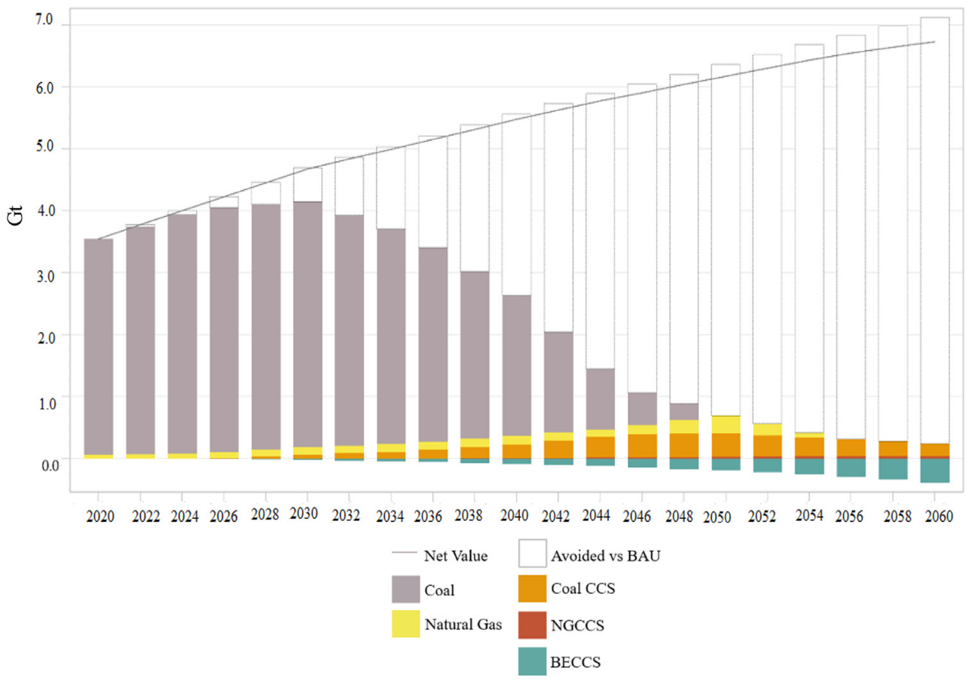


Fig. 12. Avoided Emissions of CNT 2030 scenario vs BAU scenario, in Gt.

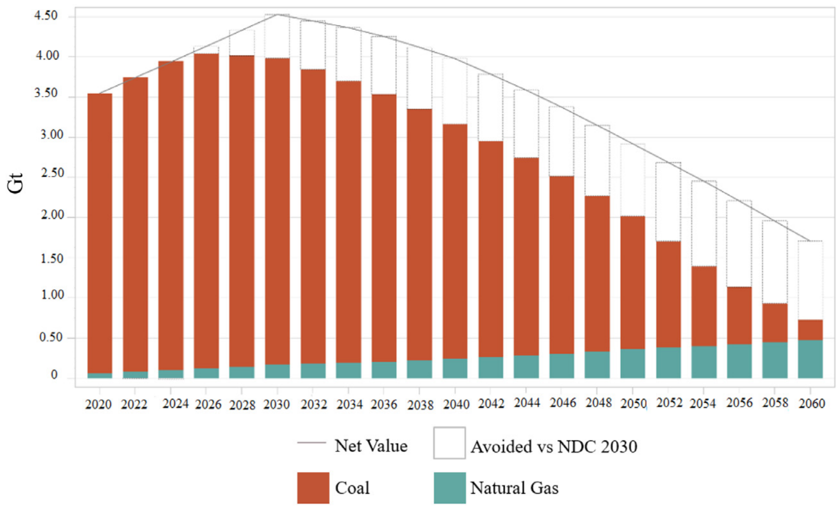


Fig. 13. Avoided Emissions of NDC 2025 scenario vs NDC 2030 scenario, in Gt.

Table 13
Avoided emissions of NDC 2025 scenario vs NDC 2030 scenario (Mt).

Branch	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
Avoided Emissions	–	−20.1	543.3	693.8	815.9	851.8	899.8	1097.6	978.7	5860
Coal	3483	3939	3811	3426	2918	2339	1652	826.9	249.1	22,647
Natural Gas	64.1	113.1	172.5	201.4	246.6	296.6	366.9	411.1	478.3	2350
Total	3547	4032	4527	4321	3980	3488	2919	2335	1706	30,858

scenarios as well. Table 14 and Fig. 14 below show a proper comparison of the avoided emissions between the two scenarios.

Despite current research, there are various views on the capacity of coal-fired electricity that can be preserved in the future. Some studies conclude that China can achieve its carbon neutrality goal at a lower economic cost by completely eliminating coal-fired power between 2050 and 2055.However, others argue that 400–700 GW of coal power will be required in 2050 for basic load, peak load regulation, and heating, assuming that existing units are retrofitted for flexibility and CHP (Tsinghua, 2022). The authorised coal power capacity for China will be heavily reliant on the potential and success of CCS and BECCS, where research is critically lacking. So, to sum it up, judging from the emissions can be avoided in each scenario as compared to either the baseline scenario or another low-carbon scenario, it is evidently beneficial for the power generation sector to peak earlier to avoid more emissions if it were to peak later.

4.2. Cost-Benefit summary of GHG savings and cost of avoided emissions in low-carbon scenarios vs baseline scenario

A cost-benefit analysis is an analytical tool/technique used to determine which solutions give the best potential approach in terms of

Table 14
Avoided emissions of CNT 2025 scenario vs CNT 2030 scenario (Mt).

Branch	2020	2025	2030	2035	2040	2045	2050	2055	2060	Total
Avoided Emissions	–	−20.1	484.4	554.0	508.5	230.8	335.6	131.1	152.0	2376
Coal	3483	3939	3430	2741	1750	468.0	–	–	–	15,812
Natural Gas	64.1	113.1	172.5	181.2	172.6	118.7	36.7	–	–	858.8
Coal CCS	–	–	55.3	99.5	169.4	271.7	239.9	120.0	36.2	992.1
Natural Gas CCS	–	–	–	2.5	9.1	22.0	40.7	50.7	59.0	184.1
BECCS	–	–	−10.8	−29.2	−57.3	−96.7	−150.3	−236.1	−395.2	−975.6
Total	3547	4032	4131	3548	2553	1014	502.7	65.8	−148.0	19,248

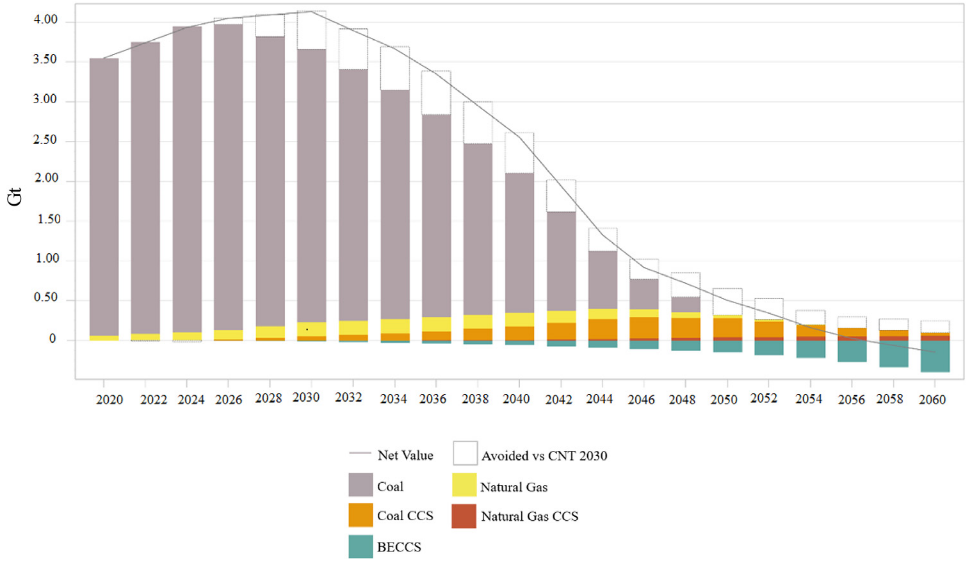


Fig. 14. Avoided Emissions of CNT 2025 scenario vs CNT 2030 scenario, in Gt.

labour, time, and cost savings. It is a systematic process of calculating and comparing the benefits and costs of a project, decision, or government policy.It also involves the goal of determining whether an investment decision is feasible and establishing a basis for project comparison, which includes comparing the total expected cost of each option against the total expected benefits.

LEAP performs cost-benefit calculations from a societal perspective by counting all of the costs in the system and then comparing the costs of different scenarios, in this study, the costs of scenarios were compared to the baseline scenario. The calculations include all costs associated with the model: process capital costs, fixed and variable operating and maintenance costs, fuel costs and externality costs. The cost-benefit summary shows cumulative costs and benefits for the Demand and Transformation modules. Additionally, the cost-benefit estimates may be expanded to analyse environmental externalities by attributing prices to pollutant emissions and any other direct social and environmental repercussions of the energy system. LEAP calculates the societal cost-benefit ratio by calculating the expenses in the energy system and then comparing the costs of any two scenarios. In other words, it also shows total costs for the system as a whole and the overall benefit/cost ratio of each scenario and the cost summary also compares the environmental externality costs of each scenario.

Costs relative to the baseline scenario are shown as positive values, while benefits are shown as negative values. By default, LEAP uses the 100-year integration global warming potential factors suggested by the IPCC. The cost summary also displays the overall cost of saving CO_2 emissions in each scenario (with and without the co-benefits of avoided emissions of non-greenhouse gas pollutants). And lastly, the Net Present Value is the sum of all discounted costs and benefits in one scenario minus another (summing across all years of the study). Fig. 15 **and Table S23** show the cost-benefit analysis of the entire model and scenarios compared to the BAU scenario at a discount rate of 7% in 2020.

When we look at the results in the Table below, we have the costs of electricity generation in the first column of all the scenarios compared to the BAU scenario. The reason they are all higher than BAU is clearly because the share of renewables in these low-carbon scenarios is higher than that in the BAU scenarios, and because the costs associated with non-fossil power generation is higher than thermal power, the costs are comparatively higher. The NDC scenarios have lower costs as compared to the CNT scenarios because they do not consider the CCS or negative-emissions technologies, like BECCS.Hence the costs associated with CNT scenarios are higher than the NDC scenarios. The costs of NDC 2025 are higher than NDC 2030 due to the fact coal power was phased out 5 years earlier in NDC 2025, hence the additional costs associated to it. Same reasoning applies for the CNT 2025 and CNT 2030 scenarios.

Moving on to the environmental externalities, these are defined as the benefits in the model because of the negative values. So, the costs of power generation in each scenario are more than the benefits, relative to the BAU scenario. Because an externality cost (carbon price of 50 Yuan/t CO_2) was assigned to CO_2 in the model, the benefits are due to that, which makes using renewables and CCS technologies less costly due to not having to pay the carbon price from thermal power generation emissions.

The Total Net Present Value (NPV) is the difference between the values of electricity generation and the benefits (environmental externalities). In other words, the NPV means how much more the low-carbon scenarios cost compared to the BAU scenario. So, in the case of the results of this model, the CNT 2030 scenario is the costliest scenario out of all the other scenarios compared to the BAU scenario.

Lastly, the cost of avoided GHG emissions – in other words, the cost of saving carbon emissions in each scenario – is given by dividing the NPV by the tonnes of CO_2 emissions avoided. So, it can be said that the cost of avoided GHG emissions is the cost of CO_2/t to achieve the mentioned GHG savings in each scenario. Leading to the conclusion that

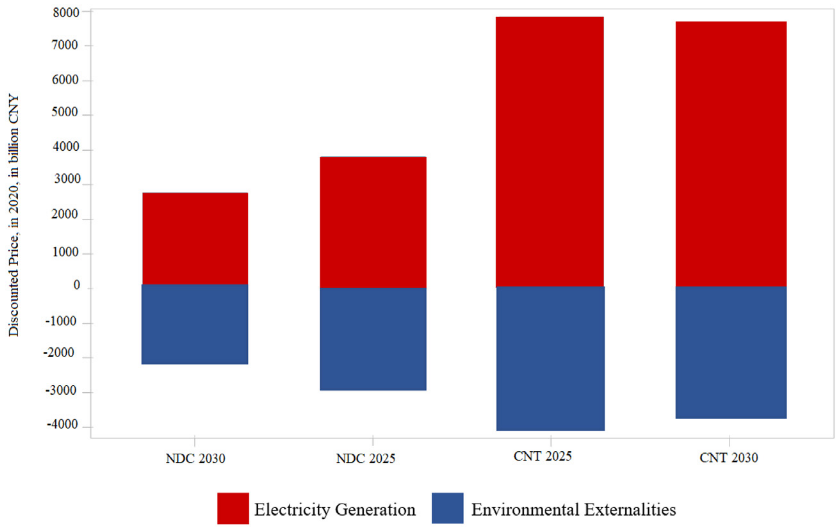


Fig. 15. Costs and Benefits of Low-Carbon Scenarios vs BAU Scenario.

NDC 2025 scenario is more cost-effective out of the two NDC scenarios, and CNT 2025 is more effective than the two CNT scenarios. In other words, the earlier the power sector peaks its emissions, the better in terms of cost-effectiveness and GHG emission savings/mitigation.

5. Outlook

As a developing country, China tends to lack in some technical research and innovation, providing hurdles to upgrading sectors and, by extension, economic structure modification. A lack of openness and transparency on relative generating technology prices is a significant impediment to the shift away from coal-fired power. Government agencies have established incentive-based feed-in tariffs across several generating technologies over the last decade and a half, but these prices have only weakly mirrored real generation costs. China's further transformation to wholesale energy markets may assist to better expose supply costs and internalise coal price concerns. Limiting new investment in coal-fired generating capacity throughout this transition, and maybe even longer term, would almost certainly need significant legislative commitment.

Breakthroughs in global carbon neutrality technologies, particularly negative-emission technologies, are critical for international collaboration. In order to take major steps into realizing the carbon neutrality goal for the power sector, China must first isolate its CO_2 emissions from its economic development. So, given the increase of residential consumption of electricity and infrastructure expenditures, lowering emissions on demand side (or consumption side) remains critical to attaining both carbon neutrality and economic growth. Coal remains China's primary energy source and power generation source – before making any significant advances in the application of renewable energy technology on an even larger scale, as well as the technology of using coal in a clean way, China must strike a balance between coal phase-out, prices, and energy security. Finally, present attempts to cut emissions are primarily in reaction to top-down measures implemented by the central government, which is the State Electricity Regulatory Commission (SERC) and National Development and Reform Commission (NDRC).

Some key goals mentioned in the 14th Modern Energy System Planning are to phase out 30,000 MW of coal-fired power plants by 2025, reach a total installed capacity of wind power and solar power combined to 1200 GW by 2030, 70,000 MW of nuclear power by 2025 and 380,000 MW of hydropower by 2025.

The national ETS of China would play an extensive role in China's decarbonization and carbon neutrality goals, however, one of the most condemned aspects of the national ETS policies is the low penalty (30,000 Yuan/4605 USD) for noncompliance or falsification of information. Instead of a fixed penalty, inspiration should be taken from the penalty system of the EU ETS and noncompliance should be penalized with around 600–650 CNY/t of CO_2. Additionally, as carbon leakage has also proven to be a barricade in the development of the EU ETS, and because the Chinese legislation does not yet protect against physical carbon leakage in CCS, China can learn from the setbacks of the EU ETS and set mechanisms and methods in place to assure low carbon leakage to further improve the credibility of its national ETS. This, in return, would ensure the inclusion of CCS technologies and BECCS to be quite favourable in the national ETS. Lastly, carbon credit mechanisms, such as those provided for negative carbon emissions, should be explored by the ETS in the future, evoking more bottom-up programs on improving carbon capture.

6. Conclusion

According to the findings of this study, the emission reduction path based on present policies falls short of the carbon neutrality targets for the power generation sector. To accomplish the emission reduction objectives, power generating operations should be increased to enable an earlier peak with faster and more aggressive decreases. Significant initiatives include expanding non-fossil and renewable energy sources, hastening the phase-out of coal-fired power facilities, and substantially implementing CCS technology. Adequate solutions for safe grid operation, retirement of coal-fired power fleet, investment, and research and deployment of CCS and BECCS technologies must be examined during the power generation sector change.

According to the study done by Zhang et al. (2022b) using the TIMES model, China's power sector's peak emissions between 2025 and 2030 will be around 4.5 Gt CO_2, and negative emissions in 2050 will be below 0.8 $GtCO_2$. Comparing this research's results to Zhang's study, the power generation sector emissions will peak its carbon emissions at 4.1 $GtCO_2$ in the NDC 2025, CNT 2025 scenarios, and 4.5 $GtCO_2$ in the NDC 2030 scenario. Negative emissions in the CNT 2025 and CNT 2030 scenarios will be at −0.3 $GtCO_2$ and −0.1 $GtCO_2$ in 2060, respectively. Moreover, the cost benefits associated with peaking earlier are also favourable. If the power generation sector is to peak its emissions in 2025, the cost of avoided GHG emissions will be 8.4 CNY/t CO_2 if no CCS technologies are adopted.And 26.4 CNY/t CO_2 if CCS and BECCS technologies are deployed. On the other hand, if it is to peak in 2030, the cost of avoided GHG emissions will be 8.5 CNY/t CO_2 without CCS technologies, and 30.4 CNY/t CO_2 with CCS and BECCS technologies. So, to sum up the findings of this research, it can be concluded that if China's power sector can peak its emissions by the end of the 14th Five-Year Plan period, it will be in a stronger position to meet the carbon neutrality objective by 2060, because it will likely strive to achieve net-zero emissions from a lower peak and over a longer duration, allowing it to pragmatically achieve the carbon neutrality goal without having to rush given a tighter timeline. Early peaking might be achieved by hastening many of the measures and investments that China will undertake in order to transition to sustainable development. This acceleration during the 14th Five-Year Plan period would allow China to reap the economic advantages of these measures and investments sooner.

This study, therefore, not only suggests that the next Five-Year Plan should limit the construction and approval of coal-fired power plants, but also implores the recognition of CCS and BECCS as vital technologies to achieve deep decarbonization in the Chinese power generation sector. Additionally, because the scenarios all lead to an expansion of renewable power generation, it is imperative to create roadmaps for technological R&D, demonstration, and implementation to ensure the wide used of intermittent renewable energy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research did not receive any specific grant(s) from funding agencies in the public commercial or not-for-profit sectors.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ccst.2023.100112.

References

Anika, O., Nnabuife, S., Bello, A., Okoroafor, E., Kuang, B., Villa, R., 2022. Prospects of low and zero-carbon renewable fuels in 1.5-degree net zero emission actualisation by 2050: A critical review. Carbon Capture Sci. Technol. 5, 100044.

Bruhn, T., Naims, H., Olfe-Kräutlein, B., 2016. Separating the debate on CO2 utilisation from carbon capture and storage. Environ. Sci. Policy 60, 38–43.

Cai, L., Duan, J., Lu, X., Luo, J., Yi, B., Wang, Y., Jin, D., Lu, Y., Qiu, L., Chen, S., 2022. Pathways for electric power industry to achieve carbon emissions peak and carbon neutrality based on LEAP model: a case study of state-owned power generation enterprise in China. Comput. Ind. Eng. 170, 108334.

Cao, Y., Chen, J., Liu, B., Turner, A., Zhu, C., 2021. China Zero-Carbon Electricity Growth in the 2020s: A Vital Step Towards Carbon Neutrality. Energy Transitions Commission and Rocky Mountain Institute Retrieved from:.

Cavanagh, A., Ringrose, P., 2014. Improving oil recovery and enabling CCS: a comparison of offshore gas-recycling in Europe to CCUS in North America. Energy Procedia 63, 7677–7684.

China Electricity Council, 2021. China Electric Power Industry Statistics. China Electricity Council.

Cui-Mei, M., Quan-Sheng, G., 2014. Method for calculating CO2 emissions from the power sector at the provincial level in China. Adv. Clim. Chang. Res. 5 (2), 92–99.

Edenhofer, O., 2015. Climate Change 2014: Mitigation of Climate Change. Cambridge University Press.

Emenike, O., Michailos, S., Finney, K.N., Hughes, K.J., Ingham, D., Pourkashanian, M., 2020. Initial techno-economic screening of BECCS technologies in power generation for a range of biomass feedstock. Sustain. Energy Technol. Assess. 40, 100743.

EPA, U., 2022. Basic information of air emissions factors and quantification. (Accessed 5th May 2022).

Fan, H., Zhang, Z., Dong, J., Xu, W., 2018. China's R&D of advanced ultra-supercritical coal-fired power generation for addressing climate change. Therm. Sci. Eng. Prog. 5, 364–371.

Fu, S., Du, X., Clarke, L., Yu, S., 2020. China's New Growth Pathway: From the 14th Five Year Plan to Carbon Neutrality. Energy Foundation China, Beijing.

Guo, X., 2011. The Life Cycle Accounting of CO2 Emissions For wind, PV and Biomass Power Generation in China. Tsinghua University, Beijing.

Guo, Z., Cheng, R., Xu, Z., Liu, P., Wang, Z., Li, Z., Jones, I., Sun, Y., 2017. A multi-region load dispatch model for the long-term optimum planning of China's electricity sector. Appl. Energy 185, 556–572.

Handayani, K., Krozer, Y., Filatova, T., 2019. From fossil fuels to renewables: an analysis of long-term scenarios considering technological learning. Energy Policy 127, 134–146.

Hao-Nan, Z., Rong-Rong, S., Xing-Ping, Z., Jun-Jie, K., Jia-Hai, Y., 2022. Implications and pathways of China's carbon neutrality: a review. Adv. Clim. Chang. Res. 18 (2), 240.

Hernández, K.D., Fajardo, O.A., 2021. Estimation of industrial emissions in a Latin American megacity under power matrix scenarios projected to the year 2050 implementing the LEAP model. J. Clean. Prod. 303, 126921.

Hong, W., 2022. A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO2 emissions future. Carbon Capture Sci. Technol. 3, 100044.

Huang, Q., 2020. Insights for global energy interconnection from China renewable energy development. Glob. Energy Interconnect. 3 (1), 1–11.

Huang, X., Chang, S., Zheng, D., Zhang, X., 2020. The role of BECCS in deep decarbonization of China's economy: a computable general equilibrium analysis. Energy Econ. 92, 104968.

IEA, 2020. A new era for CCUS – CCUS in Clean Energy Transitions. www.iea.org (Accessed 5th May 2022).

IEA, 2021. An Energy Sector Roadmap to Carbon Neutrality in China. IEA, Paris.

Kahrl, F., Lin, J., Liu, X., Hu, J., 2021. Sunsetting coal power in China. iScience 24 (9), 102939.

Li, X., Chalvatzis, K.J., Pappas, D., 2017. China's electricity emission intensity in 2020–an analysis at provincial level. Energy Procedia 142, 2779–2785.

Liang, M., Wang, Y., Wang, G., 2014. China's low-carbon-city development with ETS: forecast on the energy consumption and carbon emission of Chongqing. Energy Procedia 61, 2596–2599.

Liang, X., Wang, Z., Zhou, Z., Huang, Z., Zhou, J., Cen, K., 2013. Up-to-date life cycle assessment and comparison study of clean coal power generation technologies in China. J. Clean. Prod. 39, 24–31.

Lin, B., Ma, R., 2022. Towards carbon neutrality: the role of different paths of technological progress in mitigating China's CO2 emissions. Sci. Total Environ. 813, 152588.

Liu, Q., 2022. Prospects For China's Economic Development During the 14th Five-Year Plan Period, Annual Report On China's Petroleum, Gas and New Energy Industry. Springer, pp. 3–24 (2021).

Liya, C., Jianfeng, G., 2018. Scenario analysis of CO2 emission abatement effect based on LEAP. Energy Procedia 152, 965–970.

Mastoi, M.S., Munir, H.M., Zhuang, S., Hassan, M., Usman, M., Alahmadi, A., Alamri, B., 2022. A comprehensive analysis of the power demand–supply situation, electricity usage patterns, and the recent development of renewable energy in China. Sustainability 14 (6), 3391.

McDonald, A., Schrattenholzer, L., 2001. Learning rates for energy technologies. Energy Policy 29 (4), 255–261.

Nayak, N., Mehrotra, R., Mehrotra, S., 2022. Carbon biosequestration strategies: a review. Carbon Capture Sci. Technol. 4, 100065

Nocito, F., Dibenedetto, A., 2020. Atmospheric CO2 mitigation technologies: carbon capture utilization and storage. Curr. Opin. Green Sustain. Chem. 21, 34–43.

Rubin, E.S., Azevedo, I.M., Jaramillo, P., Yeh, S., 2015. A review of learning rates for electricity supply technologies. Energy Policy 86, 198–218.

Smit, B., Reimer, J.A., Oldenburg, C.M., Bourg, I.C., 2014. Introduction to Carbon Capture and Sequestration. World Scientific.

SNEC, 2021. To be carbon neutral in 2060, the proportion of coal power installed capacity and power generation should both be reduced to 1%. http://www.energynews.com.cn/show-55-24749-1.html (Accessed 5th May 2022).

Stern, N., Xie, C., 2022. China's new growth story: linking the 14th Five-Year Plan with the 2060 carbon neutrality pledge. J. Chin. Econ. Bus. Stud. 21, 1–21.

Tapia, J.F.D., Lee, J.Y., Ooi, R.E., Foo, D.C., Tan, R.R., 2018. A review of optimization and decision-making models for the planning of CO_2 capture, utilization and storage (CCUS) systems. Sustain. Prod. Consum. 13, 1–15.

Tracker, G.C.P., 2019. Global energy monitor. Endcoal. org https://endcoal.org/global-coal-plant-tracker.

Tsinghua, 2022. China's Long-Term Low-Carbon Development Strategies and pathways: Comprehensive Report. Springer Verlag, Singapore.

Ugwoke, B., Corgnati, S.P., Leone, P., Borchiellini, R., Pearce, J.M., 2021. Low emissions analysis platform model for renewable energy: community-scale case studies in Nigeria. Sustain. Cities Soc. 67, 102750.

Wang, F., Harindintwali, J.D., Yuan, Z., Wang, M., Wang, F., Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., 2021. Technologies and perspectives for achieving carbon neutrality. Innovation 2 (4), 100180.

Wei, W., Ge, Z., Geng, Y., Jiang, M., Chen, Z., Wu, W., 2022. Toward carbon neutrality: uncovering constraints on critical minerals in the Chinese power system. Fundam Res. 2, 367–374.

Weng, Y., Cai, W., Wang, C., 2021. Evaluating the use of BECCS and afforestation under China's carbon-neutral target for 2060. Appl. Energy 299, 117263.

Wu, X., Tian, Z., Guo, J., 2022. A review of the theoretical research and practical progress of carbon neutrality. Sustain. Oper. Comput. 3, 54–66.

Yang, L., Li, Z., 2017. Technology advance and the carbon dioxide emission in China–Empirical research based on the rebound effect. Energy Policy 101, 150–161.

Yao, X., Zhong, P., Zhang, X., Zhu, L., 2018. Business model design for the carbon capture utilization and storage (CCUS) project in China. Energy Policy 121, 519–533.

Yeh, S., Rubin, E.S., 2012. A review of uncertainties in technology experience curves. Energy Econ. 34 (3), 762–771.

Yu, S., Horing, J., Liu, Q., Dahowski, R., Davidson, C., Edmonds, J., Liu, B., Mcjeon, H., McLeod, J., Patel, P., 2019a. CCUS in China's mitigation strategy: insights from integrated assessment modeling. Int. J. Greenh. Gas Control 84, 204–218.

Yu, S., Zhou, S., Zheng, S., Li, Z., Liu, L., 2019b. Developing an optimal renewable electricity generation mix for China using a fuzzy multi-objective approach. Renew. Energy 139, 1086–1098.

Zhang, D., Liu, P., Ma, L., Li, Z., Ni, W., 2012. A multi-period modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation. Comput. Chem. Eng. 37, 227–247.

Zhang, H., Zhang, X., Yuan, J., 2020. Transition of China's power sector consistent with Paris Agreement into 2050: pathways and challenges. Renew. Sustain. Energy Rev. 132, 110102.

Zhang, S., Chen, W., 2022a. Assessing the energy transition in China towards carbon neutrality with a probabilistic framework. Nat. Commun. 13 (1), 1–15.

Zhang, S., Chen, W., 2022b. China's energy transition pathway in a carbon neutral vision. Engineering 14, 64–76.

Zhang, Y., Zhang, X., Lan, L., 2022. Robust optimization-based dynamic power generation mix evolution under the carbon-neutral target. Resour. Conserv. Recycl. 178, 106103.

Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z., Wei, L., 2020. Projected costs of generating electricity.

Zhu, F., Wang, Y., Xu, Z., Li, J., Dong, Y., Li, H., Li, X., Hu, Y., Sun, X., Ding, L., 2021. Research on the development path of carbon peak and carbon neutrality in China's Power Industry. Electr. Power Environ. Prot. 37, 9–16.