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Toward a Carbon-Neutral State: A Carbon–Energy–Water Nexus Perspective of China's Coal Power Industry

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Abstract: Carbon neutrality is one of the most important goals for the Chinese government to mitigate climate change. Coal has long been China's dominant energy source and accounts for more than 70–80% of its carbon emissions. Reducing the share of coal power supply and increasing carbon capture, utilization, and storage (CCUS) in coal power plants are the two primary efforts to reduce carbon emissions in China. However, even as energy and water consumed in CCUS are offset by reduced energy consumption from green energy transitions, there may be tradeoffs from the carbon–energy–water (CEW) nexus perspective. This paper developed a metric and tool known as the "Assessment Tool for Portfolios of Coal power production under Carbon neutral goals" (ATPCC) to evaluate the tradeoffs in China's coal power industry from both the CEW nexus and financial profits perspectives. While most CEW nexus frameworks and practical tools focus on the CEW nexus perturbation from either an external factor or one sector from CEW, ATPCC considers the coupling effect from C(Carbon) and E(Energy) in the CEW nexus when integrating two main carbon mitigation policies. ATPCC also provides an essential systematic life cycle CEW nexus assessment tool for China's coal power industry under carbon-neutral constraints. By applying ATPCC across different Chinese coal industry development portfolios, we illustrated potential strategies to reach a zero-emission electricity industry fueled by coal. When considering the sustainability of China's coal industry in the future, we further demonstrate that reduced water and energy consumption results from the energy transition are not enough to offset the extra water and energy consumption in the rapid adoption of CCUS efforts. However, we acknowledge that the increased energy and water consumption is not a direct correlation to CCUS application growth nor a direct negative correlation to carbon emissions. The dual effort to implement CCUS and reduce electricity generation from coal needs a thorough understanding and concise strategy. We found that economic loss resulting from coal reduction can be compensated by the carbon market. Carbon trading has the potential to be the dominant profit-making source for China's coal power industry. Additionally, the financial profits in China's coal power industry are not negatively correlated to carbon emissions. Balance between the carbon market and the coal industry would lead to more economic revenues. The scenario with the most rapid reduction in coal power production combined with CCUS would be more sustainable from the CEW nexus perspective. However, when economic revenues are considered, the scenario with a moderately paced energy transition and CCUS effort would be more sustainable. Nevertheless, the ATPCC allows one to customize coal production scenarios according to the desired electricity production and emission reduction, thus making it appropriate not only for use in China but also in other coal-powered regions that face high-energy demands and carbon neutrality goals.

Keywords: carbon–energy–water nexus; CCUS; energy transition; life cycle coal power production

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1. Introduction

1.1. Background on Carbon Neutrality and China's Coal Industry

Greenhouse gases absorb infrared radiation and retain heat, warming Earth's surface and driving global warming. Anthropogenic emissions have contributed to most atmospheric CO_2 over the past 150 years [1]. As global warming imposes significant impacts on extreme weather, rising sea levels, environmental stress on terrestrial and aquatic ecosystems, and food insecurity, there is a need to constrain global warming to 1.5 °C through carbon neutrality by 2050 [1].

Carbon neutrality means that emitted CO_2 is equal to the eliminated/sequestered CO_2 in the atmosphere within the same period. To mitigate climate change and global warming triggered by carbon emissions, reaching carbon neutrality is one of the world's most urgent missions [2]. Present efforts largely include sustainable economic growth and energy consumption goals [3]. 29 countries or regions have already declared carbon-neutral climate goals [4].

Globally, electricity and heat-related energy production accounts for around 31% of carbon emissions and is the most significant contributor by sector. As the most populous country with the most rapidly developing economy globally, China has the largest energy consumption demand, which is still increasing. With 3000 million tons of oil equivalent (Mt) energy consumed each year, China accounts for about 28% (9.8 Gt/year) of all greenhouse gas (GHG) emissions. Additionally, the type of primary energy used to generate electricity is a significant contributor to China's GHG emissions. For electricity generation alone, traditional thermal sources account for around 70% of the total share, compared to a 30% share of green energy sources, such as wind, hydro, and nuclear. Coal contributes to about 92% of all thermal energy sources, making it the dominant energy source in China for electricity generation [5]. In 2019, coal accounted for greater than 60% of the total energy consumption in the country.

Coal has long been one of the biggest shares in the mix of energy sources due to its low cost and high accessibility in China [6,7]. However, the economic benefit comes hand in hand with negative impacts on the environment [8–10]. Coal combustion has long been recognized to account for an enormous carbon emission [11]. Approximately 80% of CO_2 emissions in China between 2000 and 2013 were from coal combustion alone [12]. Far beyond that, carbon emission from the process of coal mining is also significant. Mining activities release a large amount of methane (CH_4), the second most important greenhouse gas after CO_2, as well as CO_2 and other gases from coal and surrounding rock strata [13]. Additionally, emissions during the process of mining and washing, as well as transportation, significantly contribute to the total carbon emissions of generating coal power [14,15]. Therefore, it is essential to consider the entire coal power generation process in calculating total carbon emission and the environmental cost of utilizing coal power.

In the 2020 United Nations General Assembly, President Xi Jinping declared that China would aim to cut peak emissions before 2030 and pledged to achieve carbon neutrality before 2060 [16]. To accomplish carbon neutrality, the energy sector, especially coal power generation, should be the first emission source that needs urgent action. Generally, two pathways of action can reduce carbon emissions in power generation in countries where coal is the primary power source. The first is to reduce the share of coal power in the country's total power supply, and the second is to reduce carbon emissions from coal power generation by applying the technology for carbon capture, utilization, and storage (CCUS).

The best and only approach to, while ensuring sufficient power, reduce the emissions is energy transition, defined here as shifting the energy sector from fossil-based production and consumption systems to renewable energy sources [17,18]. Currently, China is enthusiastically promoting zero-emission green energy, such as wind, solar, and hydropower, to replace coal power to reduce emissions. Over the past 30 years, China has reduced the share of coal power by ~20% and vastly increased the percentage of green energy by distributing subsidies to the industry.

In addition to reducing the coal energy, investing in and applying the technology of CCUS is another effective component of the national strategy to reduce carbon emissions in China [19,20]. The CCUS is a processing chain that aims to capture and compress carbon emissions at the source plant and then transport the emissions for another utilization cycle or geological sequestration [21–23]. This technique is among the most cost-effective approaches to reducing carbon emissions and has the potential to reduce 20% of total emissions across the industry sector, which is projected to be above 28 Gt CO_2 by the year 2060. Currently, China is currently trying to develop and utilize CCUS in coal power plants. By the end of 2017, around 26 sites of CCUS had been put into service throughout the country [24,25].

When considering a sustainable coal power system, the water sector must also be considered as it provides a significant contribution to the life cycle of coal electricity production. Water is not only consumed in the mining, washing, and refining process, but also the combustion at power plants [26]. Most coal mines are in the arid region in western China, an area vulnerable to water stress. The energy transition process would significantly reduce water stress since most alternative power sources, except nuclear power, consume less water. However, extra water consumption is required for CCUS application in coal power plants. Studies show that the consumption of water in power plants increased by 50–90% after equipping CCUS [27–29]. Therefore, while water stress caused by coal-based power generation could be alleviated in future energy transitions, it will be exacerbated by integrating CCUS into coal-based electricity generation.

1.2. Literature Review on CEW Nexus Approach

As CCUS applications would significantly increase energy and water consumption at electricity generation facilities, it is crucial to understand the tradeoffs on water, energy, and carbon. This perspective is afforded by coupling two approaches to carbon reduction. The carbon–energy–water (CEW) nexus approach could offer a sustainability assessment perspective as it explores the effects of interactions between factors and the functionality of the entire system. Dynamics within the CEW nexus have been widely discussed, focusing on different driving forces. Some studies explored how external factors affected the CEW dynamics. For example, Yu et al. [30] assessed the effects of agricultural activities on the CEW nexus, and Li et al. [31] and Liang et al. [32] both considered socioeconomic cost as a significant external driving factor when investigating the CEW nexus. Internal driving forces are also widely discussed. Lim et al. [33] performed an energy-centric study that assessed how each factor in the nexus affects energy generation and the ultimate achievement of long-term energy plans in the United Arab Emirates. Water-centric [34–37], and carbon-centric [38,39] studies on the internal dynamics within the CEW nexus were also conducted. However, most of these studies primarily investigated only one individual sector's fluctuation in the nexus as an intrinsic driving factor for the nexus.

Focusing on one single centric driver of the CEW nexus can increase the understanding of the change in one sector and identify the relationship between the centric sector and other sectors in the system but may also lose the information on interactions between two or more sectors and their coupled effects on the dynamics of the nexus. The coupling effect needs to be considered, including both carbon and energy sectors as intrinsic driving factors to the CEW dynamics. In this research study, we explore the relationship between the two sectors and investigate how they are coupled to impact the CEW system.

CEW studies also set implementation goals in various industries or sectors, which implies the versatility and significance of CEW research. Wang et al. [40] made an effort to assist China's iron and steel industry achieve water and energy cost-effectiveness goals while reducing carbon emissions. Similar applications of the CEW were also explored in food and beverage products [41] and ceramic tile production [42]. Scott et al. [43], Gu et al. [44], and Trubetskaya et al. [37] attempted to put forward policy recommendations on water management and wastewater treatment. Emissions by sectors (e.g., agriculture, urban household, energy generation, and industry) were broadly estimated and discussed in the CEW framework [40,45–48]. Coal-based power generation sectors must be critically investigated as China's most crucial energy sector supplier and emitter. However, CEW studies on the coal sector are still lacking. To narrow this knowledge gap, the CEW nexus of China's coal power sector is first explored here in this study.

1.3. Literature Review on CEW Model Selection

Due to the complex interconnections between sectors in the CEW system, a comprehensive calculation of the perturbation in each component and the impact on the nexus is highly dependent on counting multiple sectors in multiple steps. Therefore, process-based models are widely adopted in CEW nexus studies. One of the most applied modeling techniques is the environmental input–output (EIO) model and life cycle assessment. The EIO model evolved from the economic input–output model that represented the interdependencies between different sectors of the economy [49]. EIO is suitable for CEW nexus analysis because it can adequately address direct and indirect contributions from each sector to the system's dynamics. It was widely applied in studies that calculated the direct and indirect effects of separate sectors to the CEW nexus [31,49,50] as well as the individual and combined contributions from different regions to the entire study area [51,52].

On the other hand, life cycle assessment is to evaluate processes within all stages of a product's life cycle and is commonly used to assess environmental impacts from the entire process [14]. Life cycle assessment is one of the most suitable approaches for those CEW nexus studies that need to comprehensively count procedural impacts on the CEW system from a sector [36,51,53] or industry [41,42]. However, previous studies mostly focused on a specific case study using EIO or life cycle assessment. In our opinion, it would be instrumental in generalizing these methods into a flexible tool to allow users in different research and geographic areas to fit in their cases and obtain their desired outcomes. Therefore, we applied life cycle assessment in the coal power generation process and proposed this method as a tool for customized uses. In addition to this generalization, we also improved the tool by adding an external factor, CCUS implementation, which integrates a more complex feedback loop to account for the interactions among CEW components. Adding CCUS as a factor in the CEW nexus is a significant improvement to the tool as it provides practical and valuable impacts on the coal electricity industry in China.

Since CEW nexus studies often aim at providing policy recommendations or environmental management solutions, scenario analysis is also widely adoptedto evaluate and compare the effectiveness of potential environmental acts [33,39,54–56]. The Assessment Tool for Portfolios of Coal power production under Carbon neutral goals (ATPCC) (Figure 1) is a scenario-based tool that can be used to inform future energy policy, especially for the policymakers that concerningthe coal electricity industry in China. The ATPCC offers scenarios to sustainably develop portfolios for the coal-based electricity industry to achieve the carbon neutrality mission in China.

1.4. Research Gaps and Goals

There are three major research gaps in the CEW literature. Theoretically, most approaches studied the external drivers or focused on one sector within the CEW system, rarely studying the coupled effects of two or more sectors. Second, there is a lack of a comprehensive and systematic life cycle assessment to address tradeoffs in the CEW nexus and financial benefits to the coal power industry. Third, the tradeoff analysis is rarely studied for the coupled effect of energy transition and CCUS application for China's coal electricity system at the national level.

In this study, we first developed a state-of-the-art life cycle assessment tool that includes the following features:

- A general framework to analyze the perturbation of the CEW nexus driven by coupled effects of carbon–energy sectors;

- A mechanism to account for the coupled effects of energy transition and CCUS applications in China with carbon mitigation synergy and sustainability tradeoffs for the CEW nexus and financial profits;
- A life cycle analysis of China's coal power industry; and
- Luxuriant and diverse empirical data for China's coal power industry from experts.

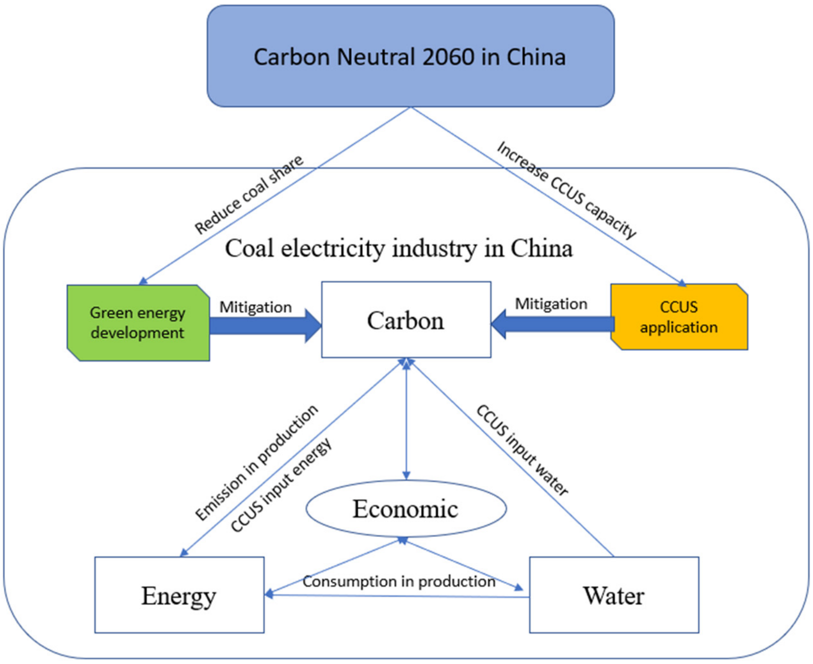

Figure 1. Conceptual framework of ATPCC design.

We then analyzed three coal power development portfolios that represent different pathways for the future of China's coal-based electricity generation based on an extensive literature review. We finally applied these three portfolios in the ATPCC assessment tool to address the following questions: (1) Is there a potential for China's coal power industry to achieve zero-emission under the present carbon neutrality goals; and (2) what are the tradeoffs when coupling CCUS and energy transitions in the CEW nexus and economic profit and do they vary by adoption scales?

2. Methodology

2.1. Conceptual Framework of ATPCC Design

The production portfolio for coal-based electricity under the carbon neutrality goal is crucial for policymakers in China, who seek to build a sustainable, profitable future. The feasibility of a given scenario relies on the relationship between the policies for energy transition and CCUS contribution to the CEW security and economy. This is not only an issue for the central government but also crucial to policymakers in China, especially for sectors where there is a risk of natural resources such as water or environmental costs or financial profits. There is a need to find a way toward a sustainable and profitable coal system under a carbon-neutral perspective.

The life cycle of coal electricity production is directly linked to energy, water, carbon emission, and financial profits. It includes coal mining and washing, coal transportation, and coal electricity production in power plants. Each process has a carbon–energy–water footprint and is associated with economic measurement. This is also true for the implementation of CCUS in coal industries with the extra energy, water footprint, and the financial profit regarding carbon trade. Therefore, the preparation of energy portfolio development and policies should integrate the assessment tradeoffs and synergies of energy, carbon, water, and economic profit (Figure 1).

By applying scenarios that represent different levels (intensities) of coal power share reduction and CCUS implementation, we produce quantitative water/energy consumption outputs, which is crucial for natural resources management. Considering the total amount of water/energy consumption, including reduced consumption in life cycle coal power production and the increased amount of water/energy used through CCUS application, is necessary from a resource management perspective. The total carbon emission from the coal power system is critical to achieving the expected carbon-neutrality goal. The economic profits from China's coal power system are also important for the economy.

Therefore, we provide a comprehensive assessment tool to help better understand the tradeoffs in China's coal power industry between environmental and economic outcomes.

Given these prerequisites, we constructed the ATPCC (Figure 1) and subsequently applied it to address the following specific tradeoffs:

- Energy consumption tradeoffs between the levels of energy transition and CCUS applications: Reducing more share of coal electricity would lead to less energy consumption. More carbon captured from CCUS would meanmore energy consumption.
- Water consumption tradeoffs between the levels of energy transition and CCUS adoptions: Reducing coal-generated electricity would lead to less water consumption. More carbon captured from CCUS would lead to more water consumption.
- Economic revenue tradeoffs between the levels of energy transition and CCUS applications: Reducing coal-based electricity would lead to less economic profits from electricity sales. More CCUS adoptions would increase economic profit from carbon trade.

2.2. The ATPCC

To study the tradeoffs and synergies of two main carbon-neutral policy impacts on the CEW nexus in the China's coal power system with complex interconnections, we propose a framework, "The Assessment Tool for Portfolios of Coal power production under goals or ATPCC". This tool is the first to integrate all components in China's coal production processes, including carbon, energy, water, and profit, with a CEW nexus approach. The scenario enabled ATPCC enables policymakers to create coal electricity portfolios based on carbon-neutral policies. Policymakers could assess portfolio scenarios by evaluating China's coal industry's CEW and economic sustainability.

The detailed structure of the proposed ATPCC, illustrated in Figure 2 provides specific factors in the life cycle of coal power production in four processes: coal mining and washing/refining, coal transportation to power plants, coal-based electricity production in power plants, and the CCUS adoption in coal power plants. The quantitative parameters, factors, and predicted future trends from 2020 to 2060 are sourced from the literature and in consultation with experts. The energy consumption includes nine energy sources: raw coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity. They are all estimated as standard coal transformation coefficients [57].

In the coal mining and washing/refining process, there are around 4700 coal mine pits in China, and approximately 7% of the coal was imported from other countries. Based on the national statistics on coal processing, we used the average parameter values for all the domestic and imported coal, where most of the imported coal is raw material and still goes through the washing/refining process. Parameters include energy consumption, carbon emission, water consumption, and financial cost. The energy consumption aggregates the whole energy inputs of all mechanical equipment used in the entire process, including shearers, road headers, washing equipment, transportation equipment in the well, and power boilers for workers. The carbon emission is the sum of energy-related emissions, emissions equivalent to underground mine gas emissions, and post-mining emissions. Water consumption is the sum of water usage in mining and cooling without considering the grey water footprint. The financial cost is the price of the sum of the energies used.

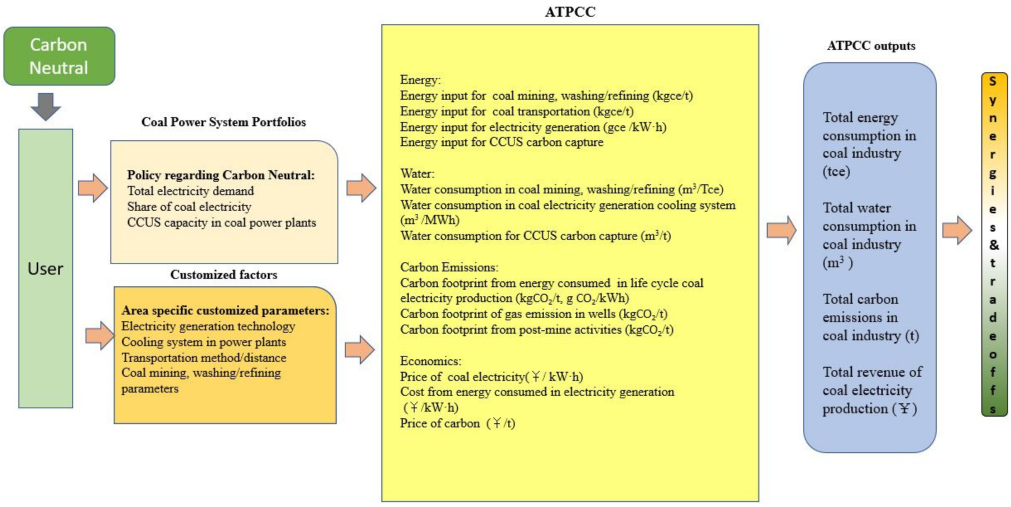

Figure 2. The Assessment Tool for Portfolios of Coal power production under Carbon neutral goals (ATPCC) structure.

The ATPCC provides the average distance of coal transportation to power plants on highways and railways in the transportation process. The energy consumption factors come from the sum of diesel and electricity usage. Carbon emission parameters are calculated based on energy consumption. The energy consumption also calculates financial costs. The ATPCC provides two options for input scenarios in coal-based electricity generation. By changing the parameters of selected types of electricity generation sets, the portfolio can provide a unique factor value for each scenario. The ATPCC provides factors and sets the parameters for average energy consumption, carbon emission related to energy, water consumption, and the cost of energy used in all processes.

CCUS is also considered in the ATPCC. Total extra energy and water consumption are the product of the carbon captured by CCUS facilities in coal power plants. The amount of economic costs for energy consumed from CCUS is also considered. With the given carbon price under global carbon-neutral missions, the financial profits gained from carbon sales can be calculated.

The ATPCC is a policy-driven, carbon–energy coupling effective tool, allowing users to apply it to any governance level or geographic area with the coal industry and under different carbon-neutral requirements. The user input portfolios comprise two major sub-scenarios: the total electricity generated from the coal industry and the total carbon captured by CCUS in the coal industry. There is also a customized option for users to provide specific parameters for electricity generation and cooling in the power plant, or users can directly replace parameters and their trends in ATPCC based on their status quo.

Given the scenario inputs and the user-defined parameter values, ATPCC is used to quantify the following outputs of the life cycle coal industry for electricity production in China: total water consumption, energy consumption, total carbon emissions, and total financial profits. Thus, a tradeoff analysis can be drawn based on ATPCC outputs and help policymakers find a sustainable pathway for coal power development. The customization feature of ATPCC can help users generate area-specific scenarios and the related tradeoff analysis.

3. ATPCC Model Parameters

3.1. Energy Consumption in Life Cycle Coal Electricity Production

The energy consumption in the life cycle of coal-based electricity production (Equation (1)) can be presented as a function that aggregates the energy input from three processes:

mining and washing/refining, transport, and coal combustion in power plants. Nine types of energy are accounted for, including raw coal and electricity.

$$E_{\text{Life Cycle}} = E_{\text{mine and wash/refine}} + E_{\text{transportation}} + E_{\text{electricity production}} \quad (1)$$

3.1.1. Energy Consumption in Coal Mining and Washing/Refinement

The energy used in the mining, washing, and refining can be expressed in Equations (2) and (3):

$$E_{\text{mine and wash/refine}} = M * e_{\text{mine and wash/refine}} \quad (2)$$

$$e_{\text{mine and wash/refine}} = \sum_{i}^{9} \alpha_i \times T_i \quad (3)$$

where M is the total raw coal consumed in a power plant. $e_{\text{mine and wash/refine}}$ is the energy consumption factor representing the average energy consumption of coal supply. α_i represents the conversion coefficient for each energy source to standard coal (Ce). i = 1–9 indicates for raw coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity, respectively. T_i is the mean energy input for unit coal production. Parameters α_i, T_i and average $e_{\text{mine and wash/refine}}$ are shown in Table 1 [58].

Table 1. The conversion coefficient of standard coal with different energy sources and unit energy consumption in coal mining, washing, and refining process and transportation.

Energy Category	Comprehensive	Coal	Coke	Oil	Gasoline	Kerosene	Diesel	Fuel Oil	Natural Gas	Power
Convert coefficient (kgce/kg) or (kgce/m^3) or (kgce/kW·h)		0.7143	0.9714	1.4286	1.4714	1.4714	1.4571	1.4286	1.330	0.1720
Energy consumption in coal mining and washing/refinement by sources		27.3	0.0	0.0	0.0	0.0	0.2	0.0	2.4	9.3
Energy consumption of coal mining and washing converted for standard coal (kgce/t)	24.6	19.5	0.0	0.0	0.0	0.0	0.3	0.0	3.2	1.6
Energy consumption in coal transportation (kgce/t)	4.2				0.5		2.5			1.2

The current value of $e_{\text{mine and wash/refine}}$ is 24.6 kgce/t, and there is a continuous improvement in mechanization for coal mining and washing in China that has reduced energy consumption [59]. The average energy consumption in coal mining and washing decreased rapidly from 30.6 kgce/t in 2010 to 24.6 kgce/t in 2020, with an average annual declining rate of 2.1% [60]. Energy consumption in China's coal-mining/washing/refining process could decline more rapidly in the future through continuous optimization of the coal production system under the carbon-neutral goal. However, the energy consumption level in most of China's coal mining and washing facilities is close to reaching an advanced level worldwide [61]. Therefore, we assumed that the comprehensive energy consumption of coal mining and washing would continue to decline, but with a shrinking magnitude. It would decrease at an average annual rate of 4.0% before 2030, 3% from 2030 to 2040, 2% from 2040 to 2050, and 1% from 2050 to 2060; the predicted factors are shown in Table 2.

Table 2. Prediction of the future trend in comprehensive energy consumption.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Comprehensive coal consumption of coal mining and washing (gce/t)	24.6	20.1	16.4	14.0	12.1	10.9	9.9	9.4	8.9
Comprehensive coal consumption in power generation and power supply (gce/kWh)	351.2	342.5	334.1	325.8	317.8	309.8	302.1	294.7	287.4
Coal consumption of coal power generation and power supply (gce/kWh)	305.5	297.9	290.6	283.4	276.4	269.5	262.8	256.3	250.0

3.1.2. Energy Consumption in Coal Power Transportation

Considering only domestic transportation, the average coal transport distance is 651km by railway and 162.7km on the highway. The railway coal transport is around 80% and 20% for highways [58]. The average energy consumed on the railway has 55% of diesel and 45% electricity. The mean fuel mix of highway transport is 68% diesel and 32% gasoline. The energy level (intensity) for coal transportation on railways and highways is 5.06 gce/t·km and 46.53 gce/t·km, respectively [62]. Therefore, the energy consumption of coal transportation is:

$$E_{transportation} = M \times e_{transportation} \tag{4}$$

$$e_{transportation} = \sum_{i}^{2} \theta_i \times D_i \times \ni_i \tag{5}$$

where θ_i represents the percentage of coal transported by transportation types, $\ni_i$ represents the average energy consumption by distance, D_i represents the average distance for transportation types, i = 1 or 2 representing railway or highway.

The calculated average $e_{transportation}$ value is 4.15 Kgce/t and is applied in this study (Table 1). Waterway coal transportation also exists in China, but most studies and the statistic yearbook suggest only considering railway and highway transportation of coal. This may lead to an underestimation of energy consumption and the related carbon emission by a magnitude of × 32–38 [63]. However, we still use this number due to the lack of historical data and references. We also assume the energy consumption factor in coal transportation would remain the same in the future.

3.1.3. Energy Consumption in Coal Power Generation

There are many kinds of coal electricity generator sets in the Chinese coal-fueled power industry, separated by the type (i.e., domestic, subcritical, supercritical, ultra-supercritical), capacity and the cooling method (air/water cooling). We specified nine typical sets and provided the unit consumption parameters for each energy source in Table 3. Thus, the total energy consumption in coal-based electricity can be calculated by:

$$E_{electricity\ production} = \sum\nolimits_{i,j} (Q \times \phi_{ij})\, e_{ij} \tag{6}$$

where Q is the total production of coal electricity, ϕ_{ij} is the share of different typical sets used, e_{ij} is the unit energy consumption for each typical set. The converted standard coal is based on the coefficient in Table 1, with results shown in Table 3 [64].

The current energy consumption factor in electricity generation $e_{electricity\ production}$ is 351.2 gce/kW·h (Table 4). According to the China Energy Big Data Report (2021) [5], the average coal consumption of Chinese coal-fueled power generation also had a declining trend in the last decade. Consumption reduced from 385.4 gce/kW·h in 2010 to 362.1gce/kW·h in 2015, with an average annual reduction of 1.2%. It slowly decreased to 351.2 gce/kW·h in 2020, with a slight yearly average decrease of 0.6%. A continuous declining trend is expected in the future. China's average energy consumption of coal-fueled units in 2060 could reach the currently most advanced state, the world's first 1350 MW ultra-supercritical secondary reheat coal-fueled generating unit with a comprehensive energy consumption level of 289 gce /kW·h [65]. Therefore, we assume the annual reduction rates in coal power energy consumption will remain at 0.5% till 2060. The specific predicted energy and coal consumption are shown in Table 2, assuming that the proportion of energy consumption in coal power production will not change.

Table 3. Energy consumption of power generation under different capacities of typical units.

Type	Capacity (MW)	Comprehensive (gce/kW·h)	Coal (gce/kW·h)	Coke (mgce/kW·h)	Oil (mgce/kW·h)	Gasoline (mgce/kW·h)	Kerosene (mgce/kW·h)	Diesel (mgce/kW·h)	Fuel Oil (mgce/kW·h)	Natural Gas (gce/kW·h)	Power (gce/kW·h)
Domestic	100	417.9	363.5	114.6	0.45	85.1	8.1	195.1	13.3	15.96	38.01
Domestic	125	342.7	298.1	94.0	0.37	69.8	6.7	160.0	94.0	13.1	31.2
Subcritical	300 Water-cooling	326.9	284.3	89.6	0.35	66.6	6.3	152.6	89.6	12.5	29.7
Supercritical	660 Water-cooling	314.2	273.3	86.2	0.34	64.0	6.1	146.7	86.2	12.0	28.6
Subcritical	600 Water-cooling	321.9	280.0	88.3	0.34	65.6	6.2	150.3	88.3	12.3	29.3
Ultra-supercritical	660 Water-cooling	294.2	255.9	80.7	0.31	59.9	5.7	137.4	80.7	11.2	26.8
Ultra-supercritical	600 Air-cooling	341.1	296.7	93.5	0.36	69.5	6.6	159.3	93.5	13.0	31.0
Subcritical	600 Air-cooling	337.7	293.7	92.6	0.36	68.8	6.6	157.7	92.6	12.9	30.7
Ultra-supercritical	1000 Water-cooling	303.4	263.9	83.2	0.32	61.8	5.9	141.7	83.2	11.6	27.6

Table 4. Unit energy consumption in coal power plants and the proportion of energy consumption.

Energy Category	Integrated	Coal	Coke	Oil	Gasoline	Kerosene	Diesel	Fuel Oil	Natural Gas	Power
Energy consumption in coal power generation (gce/kW·h)	351.2	305.5	0.1	0.0	0.1	0.0	0.2	0.0	13.4	32
Proportion of energy consumption (%)	100.00	86.98	0.03	0.00	0.02	0.00	0.05	0.00	3.82	9.10

3.2. Carbon Emission in Life Cycle Coal Electricity Production

The carbon emissions in the life cycle coal-based electricity production process can be divided into three categories: carbon emissions from energy consumption, gas emissions in mining (carbon emissions equivalent) and post-mine coal emissions [66]. Energy-related emissions are the emissions through the consumption of input energy. Gas emissions in mining mainly represent the CH_4 escaping from wells and open-pit mining before and during mining (converted to carbon emission). Carbon emissions from the post-mine activities are from open-pit mining, abandoned mines, and fugitive emissions during transportation, washing, refining, and storing raw coal. The function of total carbon emission is:

$$C_{\text{Life cycle}} = C_{\text{energy consumption}} + C_{\text{gas}} + C_{\text{postmine}} \tag{7}$$

The carbon emission related to energy consumption can be calculated by the total energy consumption times the carbon intensity coefficient widely used in the Chinese industry, δ = 2.66 kg CO_2/kgce [67].

Therefore, we can obtain the carbon emission from energy input in the following equation:

$$C_{\text{energy consumption}} = \delta \times E_{\text{life cycle}} \tag{8}$$

The future carbon emission intensity trends follows the energy intensity trend (Table 5).

The carbon equivalent coal mine gas is one of the most important sources of carbon emissions in coal production [68]. The carbon emission in coal mining and washing mainly lies in the direct emptying after gas extraction [69]. In recent years, with the improvement in the utilization rate of gas extraction, the carbon emission intensity of gas per ton of coal has shown a trend of gradually declining, from 123.7 kgCO_2/t in 2010 to 67.6 kgCO_2/t in

2020, with an average annual reduction rate of 5.8% [60]. With carbon neutrality efforts, coal mine gas extraction will be strengthened, the gas utilization rate will be improved, and the carbon emission of the coal mine will be reduced [70,71]. Therefore, we assume the carbon emission intensity of coal gas emissions per ton of gas will continue to decrease at an average annual rate of 5.8%, as shown in Table 5.

Table 5. Prediction of the future trend in carbon emission intensity life cycle coal electricity production.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Carbon emission intensity of coal mining and washing/refinement (kg CO_2/t)	65.4	53.5	43.6	37.2	32.2	29.0	26.3	25.0	23.7
Carbon emission intensity of coal transportation (kg CO_2/t)	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
Carbon emission intensity of coal-fired power supply (g CO_2/kWh)	934.3	911.0	888.7	866.7	845.3	824.2	803.7	783.8	764.5
Gas carbon emission intensity per ton of coal (kgCO_2/t)	67.6	50.1	37.2	27.6	20.5	15.2	11.3	8.4	6.2
Carbon emission intensity of post-mine activities (kgCO_2/t)	18.0	16.5	15.2	13.9	12.8	11.7	10.8	9.9	9.1

Carbon emissions equivalent from post-mine activities refer to the amount of gas discharged during storage, transportation, and stacking of coal after it leaves the mine. In recent years, with the widespread application of mine gas drainage prevention and control technologies, the carbon emission intensity of coal-mining activities has also shown a gradual decrease trend from 21.5 kgCO_2/t in 2010 to 18.0 kgCO_2/t in 2020, with an average annual reduction rate of 1.7% [60]. Under carbon neutrality, it is increasingly urgent to strengthen the supervision and control of gas emissions from post-mine activities and reduce the problem of unorganized gas emissions from coal mines. Therefore, we assume that it will continue to decrease at an average annual rate of 1.7%, as shown in Table 5.

3.3. Water Consumption in the Life Cycle of Coal Electricity Production

The function below (Equation (9)) can express the water consumption in the life cycle of coal electricity production for water consumption in coal mining and washing/refining and water consumption in the cooling system of coal electricity production. We ignored the water consumption in coal transport since it accounts for less than 1% of the total water consumption [72].

$$W_{\text{life cycle}} = W_{\text{mine and wash/refine}} + W_{\text{electricity production}} \quad (9)$$

3.3.1. Water Consumption in Coal Mining and Washing/Refinement

The water consumption in coal mining and washing/refining is the summation of mining, washing, processing, and dressing. Water consumption varies greatly in different regions of China, which is mainly determined by the water resources, economic conditions, and mineral conditions in different regions, ranging from 0.34 to 3.5 m^3/t [73]. The average coal mining and washing/refining consumption is estimated as 3.1 m^3/t in 2020 [74]. A continuously declining water consumption trend in coal mining, washing and refining is predicted. It is assumed that after 2030, the water consumption will reach the level of water areas in western China [75]. The predicted water consumption is shown in Table 6.

Table 6. Prediction of the future trend in water consumption factors.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Water consumption in coal mining and washing	3.1	2.55	2	1.35	0.85	0.68	0.47	0.33	0.14
Water consumption in coal power generation (m^3/MWh)	1.34	1.22	1.10	1.00	0.90	0.80	0.75	0.71	0.68

3.3.2. Water Consumption in Coal Electricity Production

Generally, the cooling method in Chinese coal electricity generation can be divided into three categories: closed-loop cooling, open-loop cooling, and air cooling. We picked 12 typical cooling sets for a customized cooling portfolio. Thus, the total water consumption in coal electricity production can be calculated by:

$$W_{\text{electricity production}} = Q \times \sum_{i,j}^{12} w_{ij} \times \gamma_{ij} \tag{10}$$

where Q is the total electricity generated, γ_{ij} represents the percentage of the total electricity generated by each set, w_{ij} represents the water consumption intensity for each set (Table 7) [76].

Table 7. Water consumption coefficient in coal power generation.

Cooling Method	Capacity (MW)	Leading (m^3/MWh)	Advanced (m^3/MWh)	Base (m^3/MWh)
Closed-loop cooling	<300	1.73	1.85	3.20
	300	1.60	1.70	2.70
	600	1.54	1.65	2.35
	1000	1.52	1.60	2.00
Open-loop cooling	<300	0.25	0.30	0.72
	300	0.22	0.28	0.49
	600	0.20	0.24	0.42
	1000	0.19	0.22	0.35
Air cooling	<300	0.30	0.32	0.80
	300	0.23	0.30	0.57
	600	0.22	0.27	0.49
	1000	0.21	0.24	0.42
Average		0.68	0.75	1.21

Due to technological development and changes in national water-saving requirements, the water consumption of coal-fueled power generation has a downward trend [77,78]. The literature [77,78] shows that, the average water consumption factor is 1.34 m^3/MWh. Therefore, we assumed that the average water consumption of coal power units would reach 1.21 (m^3/MWh) in 2025 and 1.10 (m^3/MWh) in 2030 at a rate of 0.024 (m^3/MWh) declining per year before 2030. The magnitude of such a declining trend would shrink, with a 0.02 (m^3/MWh) reduction per year from 2030 to 2045, and 0.01 (m^3/MWh) per year from 2045 to 2050. In 2050, the average water consumption of coal power units will reach the advanced value of 0.75 (m^3/MWh). In 2060, coal power units' average water consumption could have reached the advanced value of 0.68 (m^3/MWh). The prediction of China's average water consumption factors for coal power generation is shown in Table 6.

3.4. Profits in the Life Cycle of Coal Production

The economic profits of coal electricity production can be calculated through the difference in income and the cost of energy consumed in the life cycle of coal power production, including coal and other energy inputs.

$$\text{Profits}_{\text{life cycle}} = \text{price}_{\text{electricity}} \times Q - Q \times \text{Cost}_{\text{life cycle}} \tag{11}$$

$$\text{Cost}_{\text{life cycle}} = \text{Cost}_{\text{electricity production}} \tag{12}$$

Since the cost of coal mining, washing, and refining are included in the energy price, we only calculate the profits in coal power plants. The energy price for energy inputs and the calculated $\text{Cost}_{\text{electricity production}}$ is shown in Table 8. It is hard to predict the changing trend in raw material and currency inflation. Therefore, we assume the price of all the energy inputs remained unchanged through the years. However, the cost is declining due to the reduction in unit energy consumption. The predicted cost and profits are shown in Table 9.

Table 8. Different energy consumption costs per unit of power generation in coal power plants.

Energy Category	Comprehensive	Coal	Coke	Oil	Gasoline	Kerosene	Diesel	Fuel Oil	Natural Gas	Power
Energy prices (Yuanton) or (Yuan/m^3) or (Yuan/kW·h)		600	2600	4800	5700	3600	4800	3600	3.40	0.45
Energy consumption of coal power generation (gce/kW·h)	351.2	305.5	0.1	0.0	0.1	0.0	0.2	0.0	13.4	32.0
Cost of coal power generation (Yuan/kW·h)	0.397	0.26	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.08

Table 9. Prediction of energy consumption cost in the future.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Cost of coal power generation (Yuan/kW·h)	0.40	0.39	0.38	0.37	0.36	0.35	0.34	0.33	0.32

3.5. The CCUS Impacts

3.5.1. CCUS Impact on Energy and Water Consumption

The installation of CCUS equipment in coal-fired units will change the structure of the original power generation equipment, cause partial energy loss, increase energy consumption [79], significantly reduce carbon emissions and increase the water consumption of the power generation system. This will also cause water consumption across different types of units to increase by 31–91% [27]. The implementation of CCUS projects consumes water and energy during the process of capturing and storing carbon. The additional energy consumption is around 68.2–85.4 (kgce/t) [80] and the water consumption is around 20 to 40 (m3/t CO_2). There is no clear evidence for the development level of CCUS technologies to improve efficiency. We assume that the intensity of water and energy consumption by the CCUS process will decrease with an average annual rate of 5%, and the results are shown in Table 10.

Table 10. Prediction of the increased water and energy consumption with CCUS.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Increase in energy consumption by adding CCUS (kgce/ton)	76.8	59.4	46	35.6	27.5	21.3	16.5	12.8	9.9
Water consumption increase intensity (m^3/ton)	30	23.2	18	13.9	10.8	8.3	6.4	5	3.9

3.5.2. CCUS Impacts on Economic Profits

The national carbon market was officially established in December 2017. The first batch of about 1700 power generation enterprises was selected to be involved in the carbon emissions trade [65,81]. In 2020, China's average carbon trading price was 28.6 Yuan/ton. There are various predictions on the carbon price, but the price is expected to grow in the future, and the drivers include inflation and, most likely, carbon policy [82]. We excluded the inflation impact under the assumption of no change in energy and electricity prices. An official survey has shown that the carbon price in 2021–2022 is around 50 yuan/ton and is expected to reach 87 and 139 Yuan/ton in 2025 and 2030, respectively [82]. Based on the 25% yearly increase rate between 2020 and 2025 combined with the 10% annual increase rate between 2025 and 2030, we assumed that the increasing annual rate is 9% in 2030–2040, 8% in 2040–2050, and 7% in 2050–2060. The predictions are shown in Table 11. The carbon price would reach 710 Yuan/ton and 1397 yuan/ton in 2050 and 2060. This is lower than the prediction of the World Energy Outlook [83], where the carbon price would reach 250 $ton in advanced economies and 200 $/ton in China in 2050 under a zero-carbon emission world scenario. However, our estimation excludes the impact of inflation, and China's carbon-neutral goal is 2060 rather than 2050. Therefore, based on our prediction, the 2060 carbon price of 1397 yuan/ton or 216 $/ton fits into the 200–250 $/ton range and is believed to be more reasonable for China.

Table 11. Prediction on carbon price in 2020–2060.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Carbon Price (Yuan/ton)	28.6	87	139	214	329	483	710	996	1397

4. Scenarios

4.1. Baseline Scenario

4.1.1. Predicted Electricity Demand in China

The rapid modernization process and socio-economic development in China, combined with the changing consumption pattern, contribute to the fast-growing national electricity demand. The literature has forecasted future electricity demand in China using various methods and models based on key indicators [84]. We selected a reasonable prediction [85], which calculated the average of seven existing models and applied it to the baseline scenario input as shown in Table 12.

Table 12. Prediction of future electricity demand in China.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Electricity demand (trillion kWh)	7.4	8.8	10.2	11.3	12.2	13.1	13.6	14.1	14.4

4.1.2. Predicted Change in the Coal Electricity Share

The proportion of coal-fueled power generation in China dropped from 67.9% to 60.8% in 2015–2020. The coal power share in China would continue to drop, but the declining magnitude is hard to tell. For consistency, we further applied the companion prediction with electricity demand in Xie's study [85] as a baseline scenario input for coal electricity share (Table 13).

Table 13. The baseline scenario for coal electricity share in the future.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Coal electricity share (%)	60.8	49.9	40.9	33.5	27.5	22.5	18.5	15.2	12.4

4.1.3. Predicted Change in the CCUS Implementation in Coal Electricity Production

According to the statistics collected by the Ministry of Science and Technology for CCUS demonstration projects nationwide, since the first CCUS demonstration project in China was put into operation in Shanxi in 2004, there were 38 CCUS projects in operation before 2020, with a total capacity of 5 Mt/year [80]. Under the carbon-neutral target, the overall emission reduction demand of CCUS in China is ~20–408 Mt CO_2 in 2030, ~600–1450 Mt CO_2 in 2050, and ~1–1.82 Gt CO_2 in 2060 [86]. According to the CCUS special report of the International Energy Agency's power operation and maintenance platform, CCUS emission reduction capacity is expected to grow rapidly [87]. The capture scale of CCUS in China's thermal power plants is about 190 Mt CO_2/year by 2030; about 770 Mt

CO_2/year by 2050; and exceeds 1.2 Gt CO_2/year by 2070. Based on the prediction, we deliver a new forecast of carbon mitigation from CCUS in Table 14 and take it as the input for the baseline portfolio.

Table 14. Coal power and national CCUS-related emission reduction demand for baseline scenario, 2020~2060.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
From coal power (Mt/Year)	3	20	190	370	520	655	775	880	985
Total carbon mitigation (Mt/Year)	5	9–30	20–408	119–850	370–1300	500–1350	600–1450	800–1650	1000–1820

4.2. Alternative Portfolios and the Difference with the Baseline Scenario

4.2.1. Share of Coal Electricity

The baseline scenario on the contribution of shares changed from coal-based electricity production was based on Xie's study [85]. The prediction is based on an assumed scheme of 18% of change for every five years. The proportion of coal-fueled power generation in China dropped from 67.9% to 60.8% in 2015–2020 and the enhanced efforts of energy transition after 2020. Additionally, there was a 23% decrease in coal-powered electricity in the electricity mix every five years. However, there is a chance that the green energy transition will not go well. In the context of the global removal of coal power, the reduction rate should be faster than that in 2015–2020. Therefore, we assume the "slow" declining rate of coal electricity share in China to be 13% every five years. Three portfolios representing three levels of carbon mitigation were applied in the ATPCC and named "Baseline," "Slow," and "Radical" (Table 15).

Table 15. Scenarios for coal electricity share.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Coal electricity share (Baseline)	60.8	49.9	40.9	33.5	27.5	22.5	18.5	15.2	12.4
Coal electricity share (Slow)	60.8	52.9	46.0	40.0	34.8	30.3	26.4	22.9	20.0
Coal electricity share (Radical)	60.8	46.8	36.0	27.8	21.4	16.5	12.7	9.8	7.5

4.2.2. Carbon Emission Mitigation from CCUS

Based on the baseline scenario of CCUS capture capacity, we further developed the inputs for carbon capture through CCUS for "Slow" and "Radical" as 80% and 120%, respectively, of the baseline CCUS carbon emission capacity. When the two "Slow" scenarios are connected, they reflect a future that is less focused on carbon reduction. Alternatively, two "Radical" scenarios represent the other way around. Thus, the prediction reflects the different levels of carbon-neutral policy constraints. The CCUS capture capacity per scenario is shown in Table 16.

Table 16. Scenario inputs for CCUS carbon capture in 2020–2060.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
CCUS capture in coal power plants (Mt/Year) (Baseline)	3	20	190	370	520	655	775	880	985
CCUS capture in coal power plants (Mt/Year) (Slow)	3	16	152	296	416	524	620	704	788
CCUS capture in coal power plants (Mt/Year) (Radical)	3	24	228	444	624	786	930	1056	1182

5. Results

5.1. Scenario Outputs

5.1.1. Baseline Scenario Outputs

The baseline portfolios by 2060 are expected to decrease coal-powered electricity share to 12.4% and falls within the interval between n 20% (claimed by the conservative studies) and 10% (suggested by radical studies). In addition, around one billion tons of carbon could be captured by CCUS applications. Modeled outputs in Table 17 indicate that, in 2060, the two carbon mitigation efforts would reduce total carbon emissions to 0.4 billion tons, which is very close to the carbon-neutral goal. The total energy consumption has a trend of first increasing and then decreasing with a peak year in 2040–2045. Extra energy consumption from the CCUS application would overtake the energy consumption from the life cycle of coal production between 2025 and 2030. The total water consumption has an overall decreasing trend due to technological innovations and reduced coal production. Extra water consumption from CCUS overtakes the water consumption from the life cycle of coal production between 2035–2040. The total revenue in 2060 is the highest among all three scenarios and is 6.4 times the revenue in 2020 for China's coal industry, where 86% of the total revenue comes from the carbon trade through the CCUS implementation. The carbon trade becomes the dominant economic profit in 2040–2045.

Table 17. ATPCC Output of baseline portfolio for China's coal power industry.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total energy consumption (Gtce)	2.4	3.1	10.4	14.6	15.5	15.0	13.6	12.0	10.3
Energy consumption from CCUS (Gtce)	0.2	1.2	8.7	13.2	14.3	14.0	12.8	11.3	9.8
Total water consumption (billion m^3)	12.7	10.5	11.4	11.0	9.7	8.6	7.3	6.2	5.1
Water consumption from CCUS (billion m^3)	0.1	0.5	3.4	5.1	5.6	5.4	5.0	4.4	3.8
Total carbon emission (Gt)	4.8	4.2	3.7	3.0	2.4	1.8	1.3	0.8	0.4
Revenue from CCUS carbon trade (billion Yuan)	0.1	1.7	26.4	79.2	171.1	316.4	550.3	876.5	1376.0
Total revenue (billion Yuan)	251.2	277.7	328.1	388.4	475.6	610.4	823.1	1127.0	1599.4

5.1.2. Slow Scenario Outputs

In the "Slow" portfolio for coal power industry development, 20% of the coal electricity in the electricity mix will remain in 2060, and around 0.8 (Gt) of carbon will be captured annually through CCUS facilities in coal power plants. The total energy consumption will increase and then reduce, with the peak in 2040–2045 as in the baseline scenario (Table 18). The overall carbon emission will be around 1.5 billion tons in 2060, three times the emissions in the baseline portfolio. The total consumed energy would be 8.7 (Gtce), much less than the baseline portfolio. The extra water consumption of CCUS would overtake the water consumption in the life cycle of coal power production in 2040–2045, a different time from the baseline scenario. The total revenue in China's 2060 coal industry will increase by 481% from 2020. Economic benefits from carbon capture would overtake the electricity in 2045–2050, close to 2050 and fall behind the baseline scenario. The CCUS profits would reach 75% of the total revenue in 2060.

Table 18. ATPCC outputs of "Slow" portfolio for China's coal power industry.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total energy consumption (Gtce)	2.4	2.9	8.9	12.3	13.0	12.6	11.5	10.1	8.7
Energy consumption from CCUS (Gtce)	0.2	1.0	7.0	10.5	11.4	11.2	10.2	9.0	7.8
Total water consumption (billion m^3)	12.7	11.0	11.7	11.1	9.7	8.5	7.3	6.2	5.2
Water consumption from CCUS (billion m^3)	0.1	0.4	2.7	4.1	4.5	4.4	4.0	3.5	3.1
Total carbon emission (Gt)	4.8	4.5	4.2	3.8	3.3	2.8	2.3	1.9	1.5
Revenue from CCUS carbon trade (billion Yuan)	0.1	1.4	21.1	63.3	136.9	253.1	440.2	701.2	1100.8
Total revenue (billion Yuan)	251.2	293.9	360.5	432.5	522.3	649.0	829.6	1078.6	1461.1

5.1.3. Radical Scenario Outputs

The radical scenario has the least coal electricity share, only 7.5% in 2060, and with the greatest CCUS capacity, 1.2 (Gt) of carbon could be captured through the CCUS application. However, CCUS capacity cannot be fully utilized by 2060 because the zero-carbon emission in coal power plants could have been achieved between 2055 and 2060 (Table 19). We showed that, through the energy transition and the CCUS technology utilization, carbon-neutral goals could be achieved even in coal power plants. The total carbon emission would be very close to zero and thus would lead to the accomplishment of the carbon-neutral national goal. The output of this portfolio has a minor energy consumption but the same pattern through the years as other portfolios. It also accounts for the least overall water consumption. The percentage of water consumption from CCUS would take more than half of the total water consumption between 2030 and 2035. This portfolio will create the least revenue of the three portfolios, but this is the fastest for carbon trade to dominate the incomes of the coal industry, between 2040 and 2045 and close to 2040. The total revenue in 2060 is 5.2 times the revenue in 2020, and the carbon trade would account for 90% of the total economic profits of China's coal industry.

Table 19. ATPCC outputs of "Radical" portfolio for China's coal power industry.

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total energy consumption (Gtce)	2.4	3.2	12.0	17.0	18.1	17.5	15.9	14.0	8.6
Enrgy consumption from CCUS (Gtce)	0.2	1.4	10.5	15.8	17.2	16.7	15.4	13.5	8.2
Total water consumption (billion m^3)	12.7	10.0	11.1	11.0	10.0	8.8	7.6	6.4	4.0
Water consumption from CCUS (billion m^3)	0.1	0.6	4.1	6.2	6.7	6.5	6.0	5.3	3.2
Total carbon emission (Gt)	4.8	3.9	3.2	2.4	1.7	1.0	0.5	0.1	0.0
Revenue from CCUS carbon trade (billion Yuan)	0.1	2.1	31.7	95.0	205.3	379.6	660.3	1051.8	1159.5
Total revenue (billion Yuan)	251.2	260.9	297.3	351.6	442.3	595.2	847.6	1213.3	1294.6

5.2. Tradeoffs between Scenarios

Carbon emission mitigation is the most important goal in the carbon-neutral context. The coupled policy implementation of energy transition and CCUS applications has synergy to improve carbon mitigation. Unintended, complex consequences of these policy implementations also lead to tradeoffs between carbon emission reduction and water/energy consumption. The radical portfolio has the potential to achieve zero-carbon emissions in coal power plants, but with significantly higher energy and water consumption from CCUS application.

It is noted that the radical and baseline portfolios could achieve close to zero-carbon emissions in China's coal industry. Nevertheless, compared to the 2055 and 2060 states in a radical portfolio and the outputs from the baseline scenario, we also found the potential of reducing a large amount of extra water and energy consumption from CCUS with a tradeoff for slightly more carbon emissions. The highest revenues generated from the baseline scenario proved that the relationship between economic profits from China's coal industry and the magnitude of carbon emission reduction is not simply a negative correlation. A win–win situation can be found with high profits and high carbon emission mitigation. Therefore, the optimized equilibrium between two policies regarding the CCUS application and reduced share of coal-generated electricity is never simple and is crucial for the sustainability in the future of China's coal power industry concerning carbon emission mitigation, water/energy consumption, and financial profits.

The baseline and the slow scenario almost account for the same water consumption in 2060. However, the slow scenario has a higher coal share and lower CCUS applications. With the same water constraints, energy consumption in the baseline scenario is much larger than in the slow scenario, but more economic profits would be gained. Therefore, choosing between revenue and energy inputs is crucial for energy-stressed areas. Tough choices must also be made between radical and slow portfolios in water-stressed areas. With relatively similar energy consumption, the radical portfolio accounts for less water consumption and carbon emissions, but lower economic gains.

The radical portfolio has the most economic revenue and accounts for the lowest carbon emissions. Besides that, it illustrates a new way for China's coal power industry to increase revenues. The carbon trading profits only accounted for less than 0.1% of the total revenue in China's coal power industry in 2020. However, it would reach more than 50% before 2050 in each scenario. The carbon-trading profits would account for about

90% of the total revenue in the radical portfolio. This is an inspiring result of China's coal power industry development. One of the critical reasons is that although it is economically beneficial to produce coal electricity, many companies in China's coal industry are in a deficit situation. The reason is that we did not include coal power companies' salaries and administration costs. However, the carbon market and the CCUS implementation could provide a new pathway toward financial profits in this study. With the rapid growth in the amount of captured carbon and the increasing carbon price, the coal industry has the potential to transform the primary revenue source from electricity sales to captured carbon trade.

6. Discussion

6.1. Carbon Mitigation Policies and CEW Nexus in China

Findings in the tradeoff analysis between the portfolios' outputs have important implications for China's carbon neutrality goals. Our results proved the feasibility of carbon neutrality by 2060 in China if there is a zero-carbon-emission possibility in China's coal industry, which has long been considered the most significant contributor to China's carbon emissions [31]. Most of the mitigated carbon emissions come from the decreased contribution of coal-based electricity production to the electricity mix. The second is China's green energy transition policy that converts thermal-electricity-dominated energy systems to renewable-energy-dominated [88]. However, the transformation process may lead to new issues and thus weaken the carbon mitigation efforts. Hydropower accounts for China's largest share of renewable energy and has long been treated as green energy. However, recent studies contested its GHG emissions status and proved it can no longer be considered as a comparatively low-emissions energy source in the Mekong River Basin [89]. The same pattern also was observed in bioenergy efforts. Compared with thermal energy sources, biofuels may account for more carbon emissions [90]. The energy transition could be a solution toward a sustainable carbon-mitigated power system in China, but the featured development energy source must be considered cautiously.

The regulation on reducing coal shares in China's electricity mix is also of concern. The rapid growth of green energy could put the country's power system in a vulnerable situation. The current dominant renewable energy sources, including hydropower, wind parks, and photovoltaic and concentrated solar power plants (PV and CSP) are mostly naturally based. In particular, PV, CSP, and wind power rely on local weather conditions and possess intense space and time fluctuations. Hybrid power generation, including coupled renewable energy sources, is a proper solution but coal energy still needs to sustain the security of an energy system [85].

Coal transportation is a major carbon emission source in the coal power industry. It is due to the long distance between places of coal production and electricity production. Most coal mines are in western China and the power plants are mostly located in eastern China. The reduced coal electricity shares triggered by the green energy transition could relieve the emission stress from coal transportation. It helped water stress related to coal mining and washing where western China has limited water resources. The life cycle of coal electricity accounts for large amounts of water consumption and its water intensity is higher than most other energy resources, except for nuclear power. In this study, we demonstrated that the water consumption in the coal power industry could not compete with CCUS water consumption. This is mainly because we only considered the water consumed by evaporation. A large amount of water withdrawal and use in the coal industry is dissipated back to the environment as polluted water [72]. A "greywater footprint" study is needed for further assessment.

CCUS application in a coal-fueled power plant has been proven crucial and the tradeoffs on extra energy and water consumption should be considered significant even when they are coupled with the implementation of the energy transition. The CCUS had great potential to reduce the extra water consumption by replacing fracturing water with the captured CO_2 in the CCUS application [91]. The energy transition with reduced shares of coal-powered electricity leads to a decreased financial revenue from the coal industry, thus reducing the energy sector's profits nationally. Despite the high cost of electricity in renewable energy sources compared to coal, re-arranging and treating abandoned coal power facilities lead to more investments. However, the revenues from the captured carbon through the CCUS application can fill this gap and have the potential to make more profits. A win–win future can be achieved through the well-organized coupling of CCUS applications and coal power reduction through the economic and environmental energy transition.

6.2. Limitations of the Study

The ATPCC tool was developed with many assumptions, similar to other predictive models in the literature. Some assumptions are due to the lack of data and calculation barriers. We also excluded some parts within the life cycle of coal electricity production. For instance, we only calculated the domestic transportation of imported coal. As mentioned earlier, we only considered the water consumption but not the water withdrawal. We did not track the waste and polluted water treatment in this study. The indirect energy, water consumption, carbon emission, and economic cost were also not considered, including the construction of the power plant, mines, and the CCUS facilities. An enhanced and more comprehensive version of ATPCC could be conducted when more data become available.

Furthermore, the parameters in ATPCC are all in the form of a single value, rather than a range of possibilities. A fuzzy random number method to replace old parameters could be applied in ATPCC if users wish to include uncertainty in the tool. The fuzzy set is commonly used to generate a regular fuzzy number, and it does not refer to one single value but a connected set of possible values. Each potential value has its weight between 0 and 1 [92].

7. Conclusions

The main purpose of this research is to deliver a comprehensive assessment tool to analyze the sustainability of China's coal power industry from a CEW nexus perspective under carbon-neutral mission policy portfolios. The ATPCC developed in this study is a scenario-based life cycle assessment tool for coal-powered electricity production under the two major carbon mitigation policy implementations—energy transition and CCUS application. To the best of our knowledge, the ATPCC is the first study that applied the CEW system for coal-powered electricity production to evaluate the interrelationships of carbon and energy with financial profits. This is also the first study that integrates energy transition and CCUS impacts on the life cycle of coal-powered electricity production in China.

Furthermore, to find sustainable development pathways for China's coal electricity system before 2060 that meet carbon neutrality goals, three portfolios represented different efforts to reduce contributions of coal-generated electricity triggered by the energy transition and carbon captured by CCUS applications.

This study proved the possibility of zero emissions in China's coal electricity industry within the radical portfolio. We also showed that the extra consumption of water and energy from CCUS could create resource stress and would be the dominant consumption source for energy and water in the future. However, economic revenue lost from the reduced production in the coal industry could be compensated from profits in the carbon trade possible from CCUS applications. Revenues from the carbon trade would be the dominant source of profit for China's coal-based power industry in the future.

Comparing the ATPCC outputs across the three portfolios shows that the baseline scenario has the highest energy consumption and economic profits but moderate water consumption and carbon emission. The slow energy transition scenario has the highest water consumption and carbon emissions, but moderate revenues and energy consumption. The radical energy transition scenario has the lowest carbon emissions, water, energy consumption, and financial profit. Therefore, the radical portfolio is the most sustainable strategy from the CEW nexus perspective for China's coal power industry: reduce more coal share and apply as many CCUS facilities as possible. The most profitable scenario is the baseline scenario, balancingthe energy transition and CCUS application.

The major findings from our scenario analysis can be concluded in three aspects:

1. The carbon-neutral state in China's coal-powered electricity industry is achievable with significant efforts on energy transition and CCUS applications.
2. Different implementation levels for the coupling carbon mitigation policies with carbon-neutral synergy would lead to tradeoffs in the CEW nexus and economic profits in China's coal power industry.
3. The tradeoffs would impact the sustainability of China's coal power system development. The tradeoffs are not simply an inverse correlation between one and the other. Sustainability in coal electricity generation in China's future can be achieved by optimizing the energy transition and CCUS applications in different ways to balance carbon emissions, water consumption, energy consumption, and economic profits.

The ATPCC is a straightforward and flexible tool for policymakers to assess CEW tradeoffs. It provides a simple approach to analyzing complex issues with almost all parameters. Policymakers can evaluate the tradeoffs using the tool with only two numerical inputs from different portfolios. While the empirical parameters are based on China's coal industry, they can also be modified for other countries.

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