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Research article

Potential of China's national policies on reducing carbon emissions from coal-fired power plants in the period of the 14th Five-Year Plan

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ABSTRACT

Coal-fired power is one of the largest contributors to China's carbon emissions. To promote its national low-carbon transition ambitions, the Chinese government has issued a series of policies to reduce emissions from coal-fired power plants (CFPP) during its 14th Five-Year Plan (2021-2025). This study mainly focuses on the mitigation potential of related national policies, using global optimization methods with double constraints on different policy implementation extents and power supply security under different scheduled views of national new energy developments. Thereby, 81 scenarios are set, and policy simulations till 2025 are conducted, achieving emission reductions ranging from 0.39 Gt to 1.04 Gt across scenarios. Specifically, if all policies are implemented as planned, they can bring significant changes, 0.64 Gt CO2 cumulative reduction and 25 Mt/GWh emitting efficiency improvement. But the simulated emission-changing trend shows that they may not be sufficient for the nation's target of peaking emissions before 2030, while results in higher-extent scenarios indicate that stronger implementation is required for this target. More relevant recommendations are also provided for subsequent sustainability policies on CFPPs in China.

1. Introduction

Carbon emissions lead to increasing global climate change problems and human health. To balance the relationship between environmental conservation and industrial developments, the Paris Agreement [1] has proposed long-term temperature control requirements and has secured commitments on carbon reductions from many countries [2]. Among them, China, the world's largest carbon emitter and second-largest economy, plays an integral role. Fortunately, China's leadership attaches great importance to reducing carbon emissions and developing clean energies. In 2020, at the United Nations General Assembly, China pledged to adopt stronger policies to peak the country's carbon emissions by 2030 and achieve carbon neutrality by 2060. These commitments show that this country is determined to reduce its national emissions, although facing heavy tasks [3–5]. One of the most essential parts of China's carbon emissions is the power sector, while the coal-fired power plants (CFPPs) are the largest contributor to China's power sector. In 2021, China's power sector contributed about 35% of national total carbon emissions [6], most are from coal-fired power [7]. By the end of 2021, China still has a stock of 1.12 billion kilowatts of installed CFPP generation [8], locking in huge potential

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emissions, about 83.6 to 187 giga-ton carbon dioxide (Gt CO2) [9,10]. Therefore, CFPPs' carbon emission reduction is vital, and the speed of the reduction will have a significant impact on the process of China's carbon peaking and neutralization.

Realizing such pollution and high-emission problems of CFPPs, the Chinese government has formulated a series of measures related to the mitigation of CFPPs during the past four Five-Year Plans (FYP) from 2001 to 2020 and has achieved specific results [11]. For example, in 2007, to accelerate the elimination of outmoded coal-fired technologies, the National Development and Reform Commission (NDRC) put forward the policy entitled "Opinions on Accelerating the Shutdown of Small Thermal Power Units" [12]. It required closing small and outdated units and giving priority to the development of high-efficiency and large-scale CFPP units. This policy was regarded to have particular success in reducing emissions of all types of air pollutants, especially CO2, and contributed significantly to lowering the CFPP emissions in China [13]. Besides, to reduce the use of bulk coal, the coal-to-gas project advocated by the government plays an essential role in reducing the stocked carbon emissions of CFPP, and the implementation of this policy is expected to reduce emissions by 280 to 300 million tons (Mt) by 2030 [14]. Some other series of plans and documents targeting upgrading the energy efficiency of CFPPs were also developed by the government on the issue of emission reduction [15]. In 2014, there was "Opinions on Promoting the Clean Development and Efficient Use of Coals" [16], and in 2015, a similar plan entitled "Implementation Work Plan of Retrofits for Ultra-Low Emissions and Energy Savings of CFPPs" was formulated [17]. Moreover, during the 13th FYP (2016-2020), the implementation of the five-year-long plan of electricity development [18] has resulted in significant progress. In 2020, China's installed CFPP capacity fell below, for the first time, 50% of the nation's total power capacity, and carbon emission factors have fallen by 3%-6% in most provinces [19]. Recently, the Chinese government has formulated its latest national 14th FYP. Carbon emission reduction is still an important issue. Following the overall development plan, specific policies on CFPPs were also developed subsequently [20,21]. They have given specific cleaning requests on CFPPs from the national level and will guide the development, renovation, and retirement of all CFPP units till 2025.

Reducing the carbon emissions of CFPP is a critical issue, yet the 14th FYP has also emphasized the necessity of ensuring the security and stable operation of electric power supplies. With the development of the national economy, the social demand for electricity is increasing. Restrictions on coal-fired power plants may pose specific problems for electricity supplies [22]. In China, clean or not, CFPPs are responsible for more than half of the electricity supply (about 60% in 2021 [23]). Premature and rapid cuts on CFPP capacities will have negative impacts on society [24]. For example, at the end of 2021, there was a shortage of electricity supply in some places due to the impact of the "double control" policy on energy consumption. Although the Chinese government is actively promoting the development of new energies, it still faces many problems and difficulties in replacing coal power in a short period [25,26]. Therefore, the Chinese government is now emphasizing that while implementing the latest policies related to CFPP transformations, the balance of carbon emission reductions and ensuring necessary power supplies must be considered [27,28].

In summary, the 14th-FYP policies are important guides for China's future CFPP industry and are also critical for the nation's target of reaching the carbon emission peak by 2030. Some related research has already discussed the potential influence of these policies [24,28–31]. However, there is a lack of quantitative research on how the implementation of the 14th-FYP policies will impact the carbon reduction of CFPPs while ensuring national power supply security. Besides, current studies have come up with some helpful policy assessment methods. For example, a production-operation model is proposed in [32] to evaluate carbon emission at the unit level qualitatively, and reference [33] mainly focuses on evaluating the effectiveness of policy implementation, which evaluate future emission potential by analyzing the strength of emission reduction capabilities via effectiveness modeling. Also, some papers use scenario-based assumptions to calculate the potential for policy emission reduction [34], yet not considering policy implementation degrees. So to provide more realistic full-cycle CFPP emission simulations and policy mitigation potential assessments, this paper has added some key constraints and conducted cross-scenario simulations and studies.

Specifically, our paper presents quantitative analyses of the impact of related 14th-FYP policies and proposes a clean method of carbon reduction policy. Based on national documents and Chinese new energy generation plans, 81 different simulation scenarios are constructed by assuming different policy implementation performances and new energy growth rates till 2025. Then, we use a Global Optimization Method under Double Constraints to calculate the annual total carbon emissions of CPFFs in different simulation scenarios. This article takes into account both meeting the quantitative assumption of policy performances and the requirement of CFPP power supplies in order to reflect practical policy implementation. Those emission results are compared with baseline conditions without considering 14th-FYP policies. Via comparing impacts in different scenarios, whether these policies can support the government's long-term plan and some critical influences on carbon reduction results are discussed. Accordingly, this paper can provide more concrete support and guidance to the Chinese government and relevant organizations in their efforts to reduce CFPP emissions during the 14th-FYP period and after.

2. Methods and materials

2.1. Annual CFPP carbon emissions and power generation

One of our study objectives is to calculate Chinese total CFPP emissions during the 14th-FYP period. Considering the different operating conditions of CPFFs in different administrative regions (provinces, autonomous regions, and municipalities), we adopt a region-based model with a typical top-down approach to calculate the nation's total emissions. Besides, to provide more practical references, compared with some existing studies [32,35], we not only calculated the direct emissions from coal-fired power production and operation but also considered the implicit carbon emissions brought about by coal during the mining process, inter-provincial transportation and other related processes before coal firing. Because of the full life cycle of coal-fired power generation, not only the carbon emissions from operational production but also the carbon dioxide generated by other links, the implicit carbon emissions

Table 1
The data sources of CFPP parameters in simulations.

Key parameter	Denoted as	References
Installed capacity	Cap_p^a	[19]
Heat rate	R_p^a	[38,39]
Emission factor	F_p^a	[19]
Implicit emission factor	α_i^a	[40,41]

Table 2
The referenced average annual utilization hours from the National Bureau of Statistics. Note that in 2021 no plants are operated in Xizang and Beijing.

Province	H_i^{2021} (hours)	Province	H_i^{2021}
Xinjiang	4738	Guizhou	3926
Anhui	4777	Hunan	3964
Shandong	4825	Guangxi	4381
Jiangsu	4417	Heilongjiang	4046
Guangdong	3899	Jiangxi	4966
Inner Mongolia	5224	Gansu	3732
Henan	3591	Jilin	3899
Shanxi	4382	Tianjin	4282
Zhejiang	4015	Sichuan	3201
Hebei	5487	Chongqing	3570
Shaanxi	4245	Yunnan	2051
Liaoning	4276	Hainan	4512
Fujian	4434	Qinghai	2715
Hubei	4646	Shanghai	3164
Ningxia	4401		

will make us underestimate the emissions from coal-fired power generation. We use implicit carbon emission factors to correct our calculations through previous studies, as summarized later.

$$E^a = \sum_{i=1}^{31} E_i^a \tag{1}$$

$$E_i^a = \sum_{p \in \mathcal{P}_i^a} Cap_p^a R_p^a F_p^a H_i^a (1 + \alpha_i^a) \tag{2}$$

E_i^a, denotes the total carbon emission in the ith region in year a, and there are total of 31 administrative regions in the Chinese Mainland. So, as in (1), E^a, the summation of emissions of 31 different regions is the total annual CFPP carbon emission in year a. The term $Cap_p^a R_p^a F_p^a H_i^a (1 + \alpha_i^a)$ calculates the emission from regions i in year a.

Specifically, $\mathcal{P}_i^a$ represents the set of all CFPP units in region i in year a, and the national CFPP set $\mathcal{P}^a = \cup_{i=1}^{31} \mathcal{P}_i^a$. For a unit p, Cap_p^a represents its installed capacity, which reflects the rated capacity of the generator. R_p^a represents its heat rate, and the coal plant's heat rate is a measurement of how well a plant performs the task of converting one form of energy (coal) to another form of energy (electricity). F_p^a represents its emission factor in year a. It measures the carbon dioxide emission coefficient per unit of production or consumption activity. Besides, H_i^a denotes the average annual utilization hours, which are derived from the national and provincial statistical yearbooks. The α_i^a denotes the implicit carbon emission factor of CFPPs in the region i in year a, which means the proportion of coal supply emissions from electricity consumption in various provinces to total emissions. The higher the carbon sequestration is, the more severe the underestimation of emissions in the power industry will be. These two region-based parameters, H_i^a and α_i^a, can reflect the operating efficiencies of units in different administrative regions.

Table 1 concludes the data sources used in this study. Key data, including the capacity, emission factor, location, and some other key parameters of existing and planned coal-fired units, are mainly from the Endcoal database (updated January 2022) [36]. They are also corrected based on China Electric Power Statistical Yearbooks [37]. The data inventory includes additional coal power that has been previously approved and may be put into production during the 14th FYP. As for additional CFPPs after 2022, the construction cycle of the coal power project was changed to 2-3 years. Therefore, only a small number of the coal power projects approved after 2022 and successfully completed can be put into service during the 14th Five-Year Period. Heat rates are calculated from the type of combustion technology, coal type, and unit capacity using methods suggested in [38]. We also refer to [39] to correct heat rate results according to the age of each unit. Utilization hours are derived from the national and provincial statistical yearbooks, as summarized in Table 2, and α_i^a are from studies in [40,41]. Based on all these references, a detailed inventory of existing and planned CFPP units in 2021, $\mathcal{P}^{2021}$, is created.

Emission calculations using similar models as (1) and (2) are standard in existing publications [32,34,35], so the detailed description of how (1) is derived is presented in S1. The main difference between our model and existing ones is that we have considered the implicit carbon emission factor, α_i. This factor can estimate the carbon emissions of coal mining, dispatching, transportation, and other processes before coal firing. By adding them to the direct emissions at the unit level, a full-cycle calculation of CFPP carbon emissions is done. It can measure all emissions originating in CFPP power generations more comprehensively compared to existing studies.

Furthermore, G_i^a, the CFPP power generation in region i in year a, can be calculated as in (3), and the summation of all regional results is the annual total generation in the Chinese Mainland, denoted as G^a in (4).

$$G_i^a = \sum_{p \in \mathcal{P}_i^a} Cap_p^a H_i^a \tag{3}$$

$$G^a = \sum_{i=1}^{31} G_i^a \tag{4}$$

2.2. Modeling CFPP mitigation policies

In China, the NDRC and the National Energy Administration (NEA) have recently launched their 14th-FYP CFPP mitigation government documents [21]. The main purpose of our study is to measure the potential of policies in these national top-level documents. Three major policies (namely, controlling the entrance of new units, phasing out old units, and the cleaning transformation of existing units) are advised by NDRC and NEA, so by modeling their annual influences onto E^a and G^a ($a \in [2022, 2025]$). To reflect policy requirements, we use a Global Optimization Method under Double Constraints to calculate the annual total carbon emissions of CPFFs in different simulation scenarios. The first constraint is on G_{min}^a, stating that the annual CFPP power generation should always meet a certain power security requirement. The other constraint is on C^a to indicate that the annual capacity of early retired units. Accordingly, the changing regularities of carbon emissions and power generation are calculated. The optimal objective is to minimize carbon emissions after retirement under two constraints. Double Constraints is used to select specific units to retire. Because the objective function is minimizing carbon emissions from CFPPs, the constraints in turn require meeting power generation and exit requirements. Naturally, efficient clean units will be left behind and inefficient backward units will be eliminated. There are literature using optimal methods to evaluate the effect of different policies [42,43], and we have used similar ideas.

2.2.1. Policy I: strict control of new units

Under the 14th-FYP policies, those new CFPPs in plan and under construction are facing stricter clean requirements. Quantitative requirements in [21] are as follows: ultra-supercritical units with heat rates lower than 270 gce/kWh are recommended, and the construction of units with heat rates more than 285 or 300 gce/kWh are restricted. So new CFPP units in $\mathcal{P}_i^a$ ($a \in [2022, 2025]$) are updated in our model accordingly.

2.2.2. Policy II: early retirement of old units

Not only new plants but also operating ones are restricted. Those units with too outdated technologies are urged to be retired earlier than planned. NEA has proposed to retire units for at least 30 gigawatts (GW) in total by 2025 [21]. To study the full potential of this policy, in our work, a Global Optimization Model under Double Constraints is used to select specific units to retire. In this model, by year a, the set of early retirement CFPPs is denoted as $\mathcal{P}_R^a$, and $\mathcal{P}_R^a = \cup_{i=1}^{31} \mathcal{P}_{Ri}^a$. Units to retire are chosen to meet (5) subsequently from $a = 2022$ to $a = 2025$.

$$\begin{aligned} &\text{minimize } E^a - E_R^a \\ &\text{s.t. } G^a - G_R^a > G_{min}^a \quad \text{and} \quad \sum_{p \in \mathcal{P}_R^a} Cap_p^a \approx C^a \end{aligned} \tag{5}$$

E_R^a and G_R^a denote the emission and power generation of units in $\mathcal{P}_R^a$ if they are not retired, as shown in (6) and (7).

$$E_R^a = \sum_{i=1}^{31} \sum_{p \in \mathcal{P}_{Ri}^a} Cap_p^a R_p^a F_p^a H_i^a (1 + \alpha_i^a) \tag{6}$$

$$G_R^a = \sum_{i=1}^{31} \sum_{p \in \mathcal{P}_{Ri}^a} Cap_p^a H_i^a \tag{7}$$

The optimal objective is to minimize carbon emissions after retirement under two constraints. The first constraint indicates that the annual CFPP power generation should always meet a certain power security requirement, G_{min}^a. CFPP's retirement will severely affect its generation, and we have emphasized that ensuring power supply security is also a national necessity during the 14th-FYP period [26]. The determination of G_{min}^a is presented in later subsections.

Meanwhile, the other constraint is the annual capacity of early retired units, C^a. To simulate the results under different policy implementation conditions, we have set different C_{total}, the number of retired unit capacities during the 14th-FYP period, in different simulation scenarios. The retirement is assumed to proceed evenly, so $C^a = \frac{1}{4}(C_{total} - C_{2021})$ ($a \in [2022, 2025]$), where C_{2021} is the actual retired amount in 2021. Considering the non-continuous growth of unit capacity summations, the second constraint is relaxed to approximately equaling by tolerances of 1%.

Table 3
Growth Rate Summary and Projection of New Energy Power Generations in China.

	13th-FYP annual rate	2021 rate	Projected 14th-FYP annual rate	Data source referenced
Hydro	3.7%	-1.1%	3.3%	[20,48,50,51]
Wind	17.4%	40.5%	14.9%	[44]
Nuclear	16.4%	11.7%	16.4%	[20,44,45]
Photovoltaic	46.1%	25.1%	14.9%	[44,53]
Biomass	20.3%	22.0%	18.1%	[46,47,49]

2.2.3. Policy III: transformation to cleaner technologies

Early retirement isn't the only way to reduce carbon emissions from existing units. The other approach is to transform old CFPP units using cleaner technologies to get lower heat rates, thus, fewer emissions. A target of reducing the national average CFPP heat rate to 300 gram-coal-equivalent per kilowatt-hour (gce/kWh) has been put forward in [20]. So another Constrained Global Optimization Model is used to select which units will be transformed by reducing heat rates to 300 gce/kWh (the specific transformation threshold raised in [21]). We denote the set of transformed units as $\mathcal{P}_T^{2025}$ ($\mathcal{P}_T^{2025} = \cup_{i=1}^{31} \mathcal{P}_{Ti}^{2025}$). It is chosen to meet (8).

$$\begin{aligned} &\text{minimize } E^{2025} - E_R^{2025} - \Delta E_R^{2025} \\ &\text{s.t. } ave(\mathcal{P}^{2025}, \mathcal{P}_R^{2025}, \mathcal{P}_T^{2025}) = \bar{R}_{aim} \end{aligned} \tag{8}$$

ΔE_R^a denotes the emission reduction by transforming, as in (9),

$$\Delta E_R^{2025} = \sum_{i=1}^{31} \sum_{p \in \mathcal{P}_{Ti}^{2025}} Cap_p^{2025} (R_p^{2025} - R_0) F_p^{2025} H_i^{2025} (1 + \alpha_i^{2025}) \tag{9}$$

where $R_0 = 300$ gce/kWh.

The function $ave(\cdot)$ calculates the average heat rates of all units after the retirement of $\cup_{k=2022}^{2025} \mathcal{P}_R^k$ and transformations of $\mathcal{P}_T^{2025}$, as in (10).

$$ave(\mathcal{P}^{2025}, \mathcal{P}_R^{2025}, \mathcal{P}_T^{2025}) = \frac{\sum\limits_{p \in \mathcal{P}^{2025} - \mathcal{P}_R^{2025} - \mathcal{P}_T^{2025}} Cap_p^{2025} R_p^{2025} + \sum\limits_{p \in \mathcal{P}_T^{2025}} Cap_p^{2025} R_0}{\sum\limits_{p \in \mathcal{P}^{2025} - \mathcal{P}_R^{2025}} Cap_p^{2025}} \tag{10}$$

Furthermore, similar to Policy II, in simulations, we conduct different policy implementation conditions by setting different average heat rate expectations, $\bar{R}_{aim}$. When $\mathcal{P}_T^{2025}$ is determined by solving (8), transformations are then assumed to take place evenly between 2022 and 2025. Also, note that in this model, retirement and transformation will not happen at the same unit, so $\mathcal{P}_T^{2025} \cap (\cup_{k=2022}^{2025} \mathcal{P}_R^k) = \emptyset$.

2.3. Prediction of national power supply-demand

The development of CFPP is under strict limits in China. So to meet the increasing power demand, the country is vigorously developing various new energy power generation technologies, including hydro, wind, nuclear, photovoltaic, and biomass [44,20, 45–51]. We have summarized the current power generation of different new energies and the forecast for their development speed during the 14th-FYP period in Table 3, while detailed explanations are provided in the supplementary file. Besides, referring to [52], we set the annual growth of national power demand as 4.8%. So, based on the prediction of power demands and new energy supplies during the 14th-FYP period, the supply requirement of CFPPs can be calculated as in (11), where D^a is the national power demand and G_{rest}^a is the total supplies of rest of energy types in year a.

$$G_{min}^a = D^a - G_{hyd}^a - G_{win}^a - G_{nuc}^a - G_{pho}^a - G_{bio}^a - G_{rest}^a \tag{11}$$

2.4. Scenario setting and simulation

As we have reviewed, the Chinese government has clear and quantified plans in the three significant policies, and strategies for new energy growth are given. However, policy forecasting is inevitably prevented from being implemented for a variety of practical reasons, such as carbon price, electricity price, uncertainties of the power demands, etc. Scenario analysis can help us see the upper and lower limits of policy effectiveness, thus providing reference value to the policy formulation.

In addition, many studies also use scenario-setting methods for policy simulations and building scenarios through simulation for future comprehensive analyses [54–56]. So different scenarios have been set in our work by assuming higher or lower policy implementation results compared with plans. Different new energy growth rates are also considered, and projected growth rates from

Table 4
Parameter Setting in Different Scenarios.

Views on new energy growth rates		Implementation	Policy I	Policy II	Policy III
Positive	+10% than Table S1	OP	Cancel units with HR > 285 gce/kWh Reduce HR of others to 270 gce/kWh	$C_{total} = 50$ GW	$\bar{R}_{aim} = 298$ gce/kWh
Regular	As predicted in Table S1	AP	Cancel units with HR > 300 gce/kWh Reduce HR of others to 285 gce/kWh	$C_{total} = 30$ GW	$\bar{R}_{aim} = 300$ gce/kWh
Negative	-10% than Table S1	BP	All units constructed as old plans	$C_{total} = 15$ GW	$\bar{R}_{aim} = 302$ gce/kWh

Abbreviations: over planned (OP), as planned (AP), below planned (BP), heat rate (HR).
The "Implementation" column indicates different expected extents of the implementation of each policy.
Via combinations of different parameter setting, there are $3 \times 3 \times 3 \times 3 = 81$ scenarios in total.

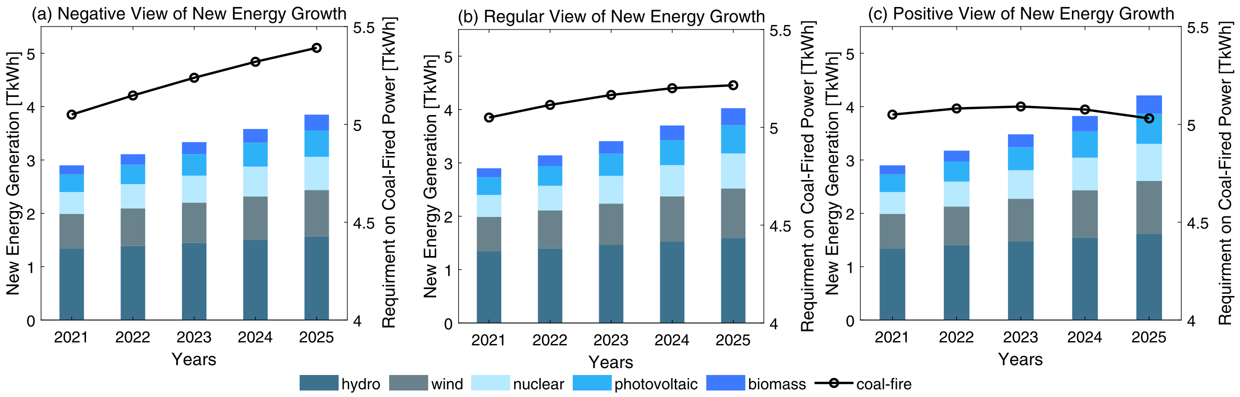


Fig. 1. Under the three views, (a) Negative, (b) Regular, and (c) Positive, different increments of new energy power generation result in three different representative changing trends of the requirements on CFPP power generation, i.e. G^a_{min}.

the governments, listed in Table S1 in detail, are used as the basis. These scenarios are set as in Table 4. Three kinds of assumptions are made for each policy and the new energy growth. Hence, by combinations, there are 81 scenarios.

In different scenarios, simulations are conducted by considering the influences of the three policies using mathematical models introduced previously. We adopt the hard constraints to simplify the model and cross-contrast related procedures with multiple scenarios to provide a more comprehensive result. The optimization problem in (5) and (8) are convex, so they can be programmatically solved using open-source tools [57]. Then, the changing regularities of CFPP emissions in each scenario are calculated.

3. Simulation results

3.1. The state of CFPPs in 2021

From our data set, a general view of CFPPs in the Mainland in 2021 is conducted, and some key statistics are calculated. They are the basis of simulations in our work. By the end of 2021, the estimated national capacity of CFPPs is 1119 GW, and the annual generation is about 5.05 trillion kWh. These statistics meet the numbers from official documents [37], verifying that our data set is trustworthy. Besides, the annual CFPP emission we calculated is 4.74 Gt, which is larger than the numbers in some existing works (from 4.10 Gt to 4.70 Gt in [58] and 3.87 Gt in [34]). This is mainly because we have considered the full-cycle process of coal-fired powering instead of merely at the unit level to provide more comprehensive assessments of the practical CFPP emission problem.

3.2. Power security requirements on CFPPs

As we have discussed, during the 14th-FYP period, there will be certain requirements on CFPP generations to ensure the security of the national power supply. We use G^a_{min} to denote this requirement, and it will change related to different new energy development. Under the three views of new energy growth, the increments of new energy generation amounts and the change of G^a_{min} in our simulations are demonstrated in Fig. 1 (Fig. 1(a) for negative views, Fig. 1(b) for regular views, and Fig. 1(c) for positive views). Under the regular view, when new energies are developed as planned, the increasing speed of G^a_{min} declines year by year and gradually becomes stable by 2025. These results show that following the Chinese government's plan for new energy development, the increase of CFPP generation may reach its peak around 2025 and begin to decline afterward without affecting the national power security demand. This can be a landmark event for energy transitions in China as the amount of Chinese CFPP generation has increased for over 30 years.

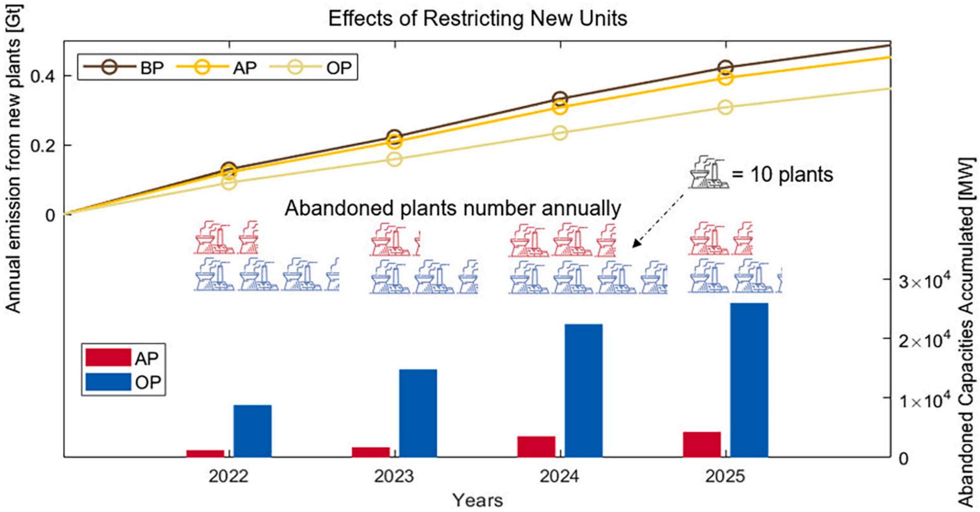


Fig. 2. Comparing the results under the three conditions, we can see the influences of Policy I. If this policy can be implemented ideally, e.g., realizing the recommendation of units with heat rate lower than 270 gce/kWh nationwide during the 14th-FYP period, the consequent carbon reduction is significant. Abbreviations: BP, below planned; AP, as planned; OP, over planned.

Besides, G^a_{min} also increases under the negative view, yet the trend is different. There are no evident drops in increasing speed. Under the positive view, the decrement of G^a_{min} appears in the later stages of the 14th FYP. So the requirements for coal power show three different kinds of trends under the three views. That means these views set in our study can be representative of different types of new energy development influences on G^a_{min}.

3.3. *Impact analyses of CFPP mitigation policies*

Having calculated G^a_{min} under different views, then we discuss the effect of different mitigation policies on CFPP emissions under power supply security requirements.

3.3.1. *Baseline condition*

We set the baseline condition by assuming no mitigation policy is conducted during the 14th-FYP period. That is, all approved and in-construction units are completed as planned and all operating units work without transformations or early retirements. In the baseline condition, the installed capacity of CFPPs in the Mainland increases from 1087 GW (at the start of 2021) to 1225 GW (at the end of 2025), bringing about 5.16 Gt full-cycle carbon emissions in 2025. More detailed baseline results are shown in Fig. S1, and by comparing with them, the impact of implementing the aforementioned three policies is analyzed from different aspects in the following contents.

3.3.2. *Effectively controlling new units*

The effects of Policy I in different assumed implementation conditions are shown in Fig. 2. In the AP simulation scenario, 4.31 GW planned capacities are being canceled and the construction of 67 units ceased during the 14th-FYP period. Consequently, 0.03 Gt total cumulative emissions are reduced. Additionally, when the heat rate threshold for new units is tightened to 270 gce/kWh, as in the OP scenario, the construction of new CFPP units decelerates significantly. 118 planned units with 25.9 GW total capacities are forced to be canceled. These numbers may be hard to achieve for policy implementations, but they can reduce 0.13 Gt CO2 cumulatively during the 14th-FYP period. This can be a very positive impact on national carbon reduction.

3.3.3. *Capacity reduction under power security requirements*

As just mentioned, the effect of Policy I may reduce the increment of new CFPP capacities. Moreover, currently installed capacities will also decrease due to the early retirement of outdated operating units resulting from implementing Policy II. However, these capacity reductions may only partially meet the predefined objective, e.g., 30 GW in the AP scenario, because the requirement of the adequate power supply must go first.

The simulated capacity reduction results under power security requirements are shown in Fig. 3 (Fig. 3(a) for negative new energy views, Fig. 3(b) for regular views, and Fig. 3(c) for positive views), together with consequent carbon reductions. The influences of different new energy growth are distinct. First, under the regular view, when the two policies are both assumed to be implemented over planned (O/O), the total capacity lost by the end of the 14th-FYP is 70.47 GW, including 25.9 GW planned units being canceled. So, the retirement amount of operating units is smaller than expected (50 GW). This indicates the contradiction of power security and capacity reduction, showing that the concern in our work is of practical significance. Also, when new energy growth is decreased by 10%, changes are dramatic. Yet only rather small changes appear under the positive view with 10% growth speeds. This problem will be further discussed in Section 4.2.

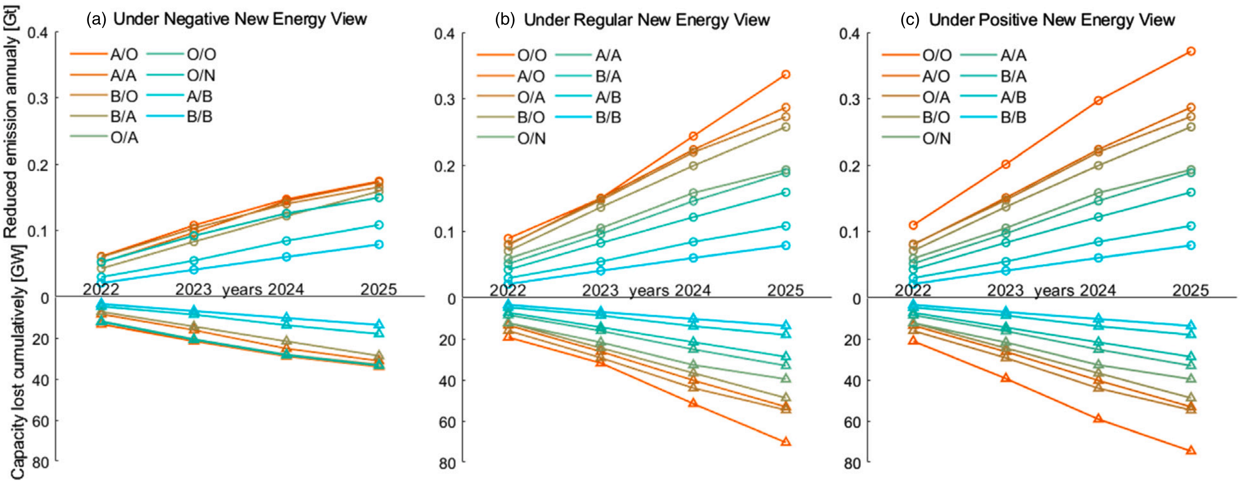


Fig. 3. CFPP capacities can be reduced differently due to the different power security requirements under the three new energy views, (a) Negative, (b) Regular, and (c) Positive, and the annual carbon reductions directly related to cutting off CFPP units are shown. Note that abbreviations are used to represent different policy implementation conditions, e.g., O/A represents the scenario where Policy I is assumed to be implemented over planned (OP) and Policy II is assumed to be implemented as planned (AP).

Additionally, under the regular view, compared to the baseline condition, capacity decreases by 13.69 GW in total in the B/B scenario, directly reducing 0.078 Gt emissions in 2025. These numbers correspond to a ratio of 5.76 t/kW. However, in the A/A and O/O scenarios, these ratios are 5.70 t/kw and 4.78 t/kw respectively. So when policies are implemented more aggressively, their efficiency will be declined. Meanwhile, capacity reductions under the A/O scenarios are smaller than reductions in the O/A scenario. This indicates that losing the same unit capacity and retiring old units is more effective than canceling planned units.

3.3.4. Overall policy effect on CFPP emission reduction

Based on the different implementation settings in the Table 4, 81 different serials of simulation results are derived. The final 2025 CFPP emission results in these scenarios are shown in Fig. 4 (Fig. 4(a) for negative new energy views, Fig. 4(b) for regular views, and Fig. 4(c) for positive views), while the annual result changes during the 14th-FYP period are in Figs. S2-S4.

In Fig. 4, we can see that CFPP full-cycle emissions in different scenarios are controlled to certain extents by 2025. Further, under the regular new energy view, the annual emission changes in the three most typical scenarios are picked out, resulting in 5.028 Gt, 4.925 Gt, and 4.784 Gt in 2025, respectively. Compared with the results in [59], which predicts 2025 annual emission as 4.5 Gt, our result when all policies are as planned is slightly larger. Yet it is similar to results given in a national technical report [60] (5.08 Gt). Still, when the demand for energy security rises, policies may be partially restricted, resulting in higher carbon emissions.

Besides, we calculate the average emission differences between all below-planned conditions and all over-planned conditions of one policy to test its efficiency. The results are 0.094, 0.127, and 0.034 Gt, respectively for Policy I, II, and III. Thus, the impact of implementing Policy I and II on emission reduction effectiveness is relatively greater in our models.

3.3.5. Uncertainty analyses

The uncertainty analysis is calculated under the 95% confidence interval around the arithmetic mean. We estimate the uncertainties in the effect of CFPP emission reduction under the 14th-FYP period using the Monte Carlo approach, as recommended in [61,62].

First, uncertainties can arise from unplanned coal power, unplanned CFPP exit, and flexibility modification. These may affect the implementation of related policies. Then to assess the related policy potential especially, we directly conducted an uncertainty analysis on policy implementation and assumed a 10% coefficient of variation (CoV) for this. With Monte Carlo simulations, the uncertainty ranges of the carbon emissions are calculated accordingly. Some typical results are shown in Fig. 5(a), while full uncertainty results are provided in Tables S2-S7. They indicate that our estimates are quite strong with the 95% confidence interval (+2 standard variation length) of the emission results within ±1.16% range, averaging at ±0.55% across all scenarios.

Moreover, uncertainties can also arise from other parameters, including those related to CFPP operation and new energy development. Also, unpredictable changes such as carbon price, electricity price, investment of renewable technologies, and uncertainties of the demands may also bring further uncertainties to parameters relating to carbon emission. So we also assume an additional 10% CoV for parameters together with policy implementations as previously. Monte Carlo simulations are conducted via setting random variations, and some typical 95% confidence intervals calculated around the emission result are shown in Fig. 5(b), while full results across all scenarios are in Table. These results range from ±0.56% to ±1.69%, indicating our estimates of the effect of CFPP emissions during the 14th-FYP period are rather robust.

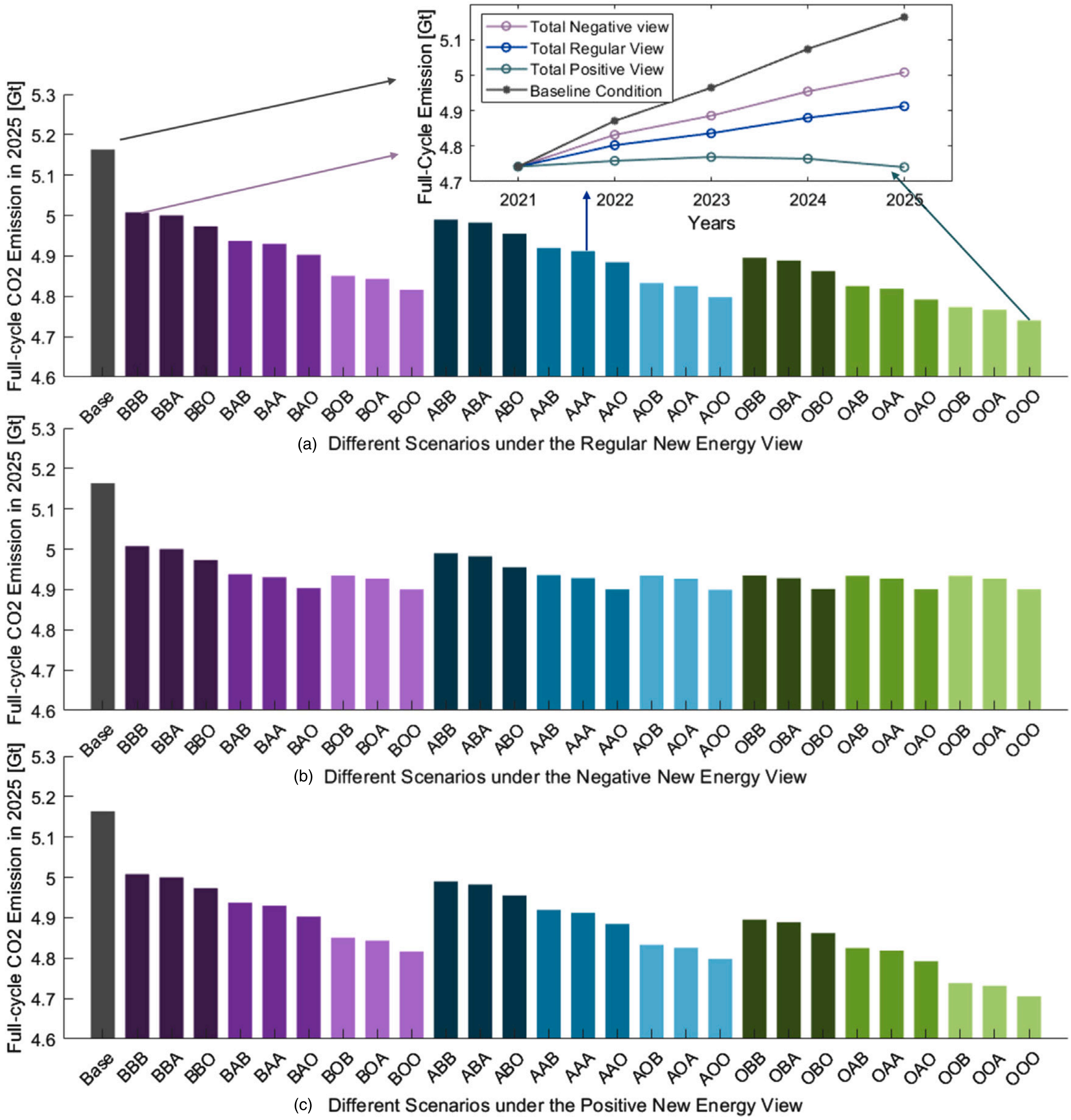


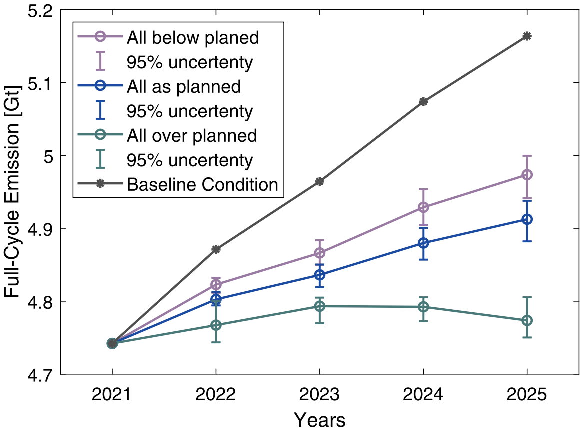
Fig. 4. This figure shows annual full-cycle emissions in 2025 in different scenarios, (a) Negative, (b) Regular, and (c) Positive, together with the annual emission changing regularities in the three most typical scenarios, i.e., all policies are assumed to be implemented below planned, as planned, or over-planned, under the regular view of new energy growth. Abbreviations are used to represent different policy implementation conditions, e.g., BAO represents the scenario where Policy I is assumed to be implemented below planned (OP), Policy II is assumed to be implemented as planned (AP), and Policy II is assumed to be implemented over planned (OP).

4. Discussion and policy recommendations

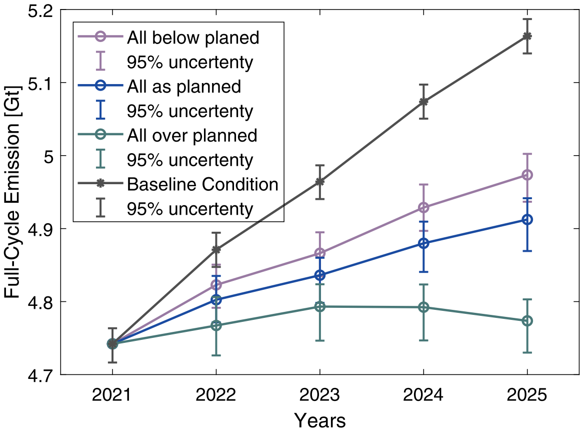
4.1. Stronger policy implementation is required

From Fig. 4, it is clearly verified that these emission mitigation policies for CFPPs in the 14th-FYP can be rather effective, by bringing 0.39 Gt to 1.04 Gt cumulative carbon reductions and 0.16 Gt to 0.41 Gt annual reductions in 2025 across all simulation scenarios under the regular new energy view.

Specifically, in the scenario that all policies are implemented as planned, 0.25 Gt annual emission reduction in 2025 is achieved, larger than the 2021 annual emission in Henan Province, China's third most populous province. So it is not a small number, yet the influence may not be enough. The growth trend of carbon emissions is still rising steadily during the 14th-FYP period, although slower by 60% compared with the baseline condition. There is still 32 Mt emission increment in 2025. So following this growth, the 2030 emission peaking target will require stricter policies in the next FYP. The exact policies in [20,21] may have little capacity to



(a)



(b)

Fig. 5. This figure gives typical 95% confidence intervals for CFPP emissions annually when (a) policy implementations are with 10% CoVs; (b) other parameters related are also with 10% CoVs. Not that only when CFPP unit parameters are with uncertainty (in (b)), the baseline condition has uncertainty ranges.

entirely limit CFPPs to the final level, i.e., the level that can ultimately support the government's long-term carbon control ambitions [28].

In our simulation, only when some policies are implemented over planned, the changes in annual carbon emissions can show the trend of reaching a plateau before or after 2025, as shown in Figs. S2-S4, indicating steady emission drops afterward. But it makes higher demands for policy implementation and follow-up.

Therefore, current policies may be implemented with greater intensity to promote the national emission peaking target. Further and stricter limitations upon CFPPs should also be considered in the near future.

4.2. The necessity to keep projected new energy growth

Simulation results under different views on new energies indicate the essential significance of their developments. Comparing the final 2025 results of scenarios under regular and negative new energy views, the average emission reduction decreases by 19.9% due to the 10% growth rate drop. Yet, the 10% growth rate rise in the positive new energy view can only bring 1.4% more reduction. These comparison results can be visibly seen in Fig. 3 and Fig. 4, where the policy performance degradation due to the 10% rate drop under negative views is obvious, especially when the policy implementation reaches planned levels. Emission reduction results under negative new energy views are inferior to results under regular or positive views by a significant margin. This is because enough power generation is fundamental to national energy security. So the decrement in new energy generation growth has put more pressure on CFPPs, preventing them from being canceled or retired as policies required [31].

More specific comparison results are presented in Fig. 6(a). It shows that as long as 14th-FYP policies are implemented around planned levels, the necessity of maintaining the existing new energy development plans is critical. Besides, if the government hopes to achieve carbon reductions appreciably above current plans, increased investments in new energies should be considered [24]. Yet, integrating more proportions of new energies into current power grids will further bring challenges to the abilities to spin reserve and peak-load regulations among CFPP units [63]. These problems are not that clearly guided in current government documents.

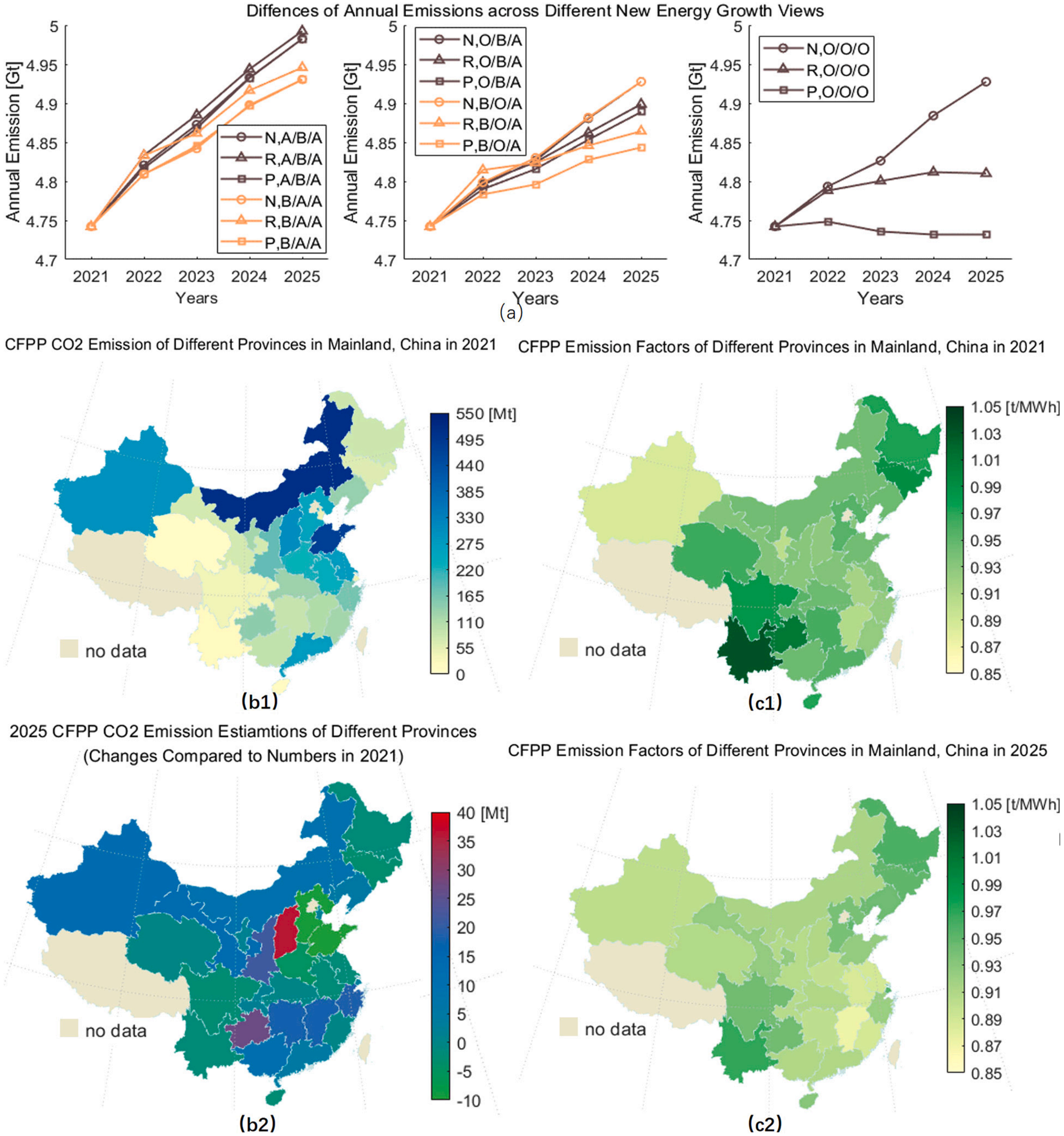


Fig. 6. This figure shows some detailed derived results from the simulations, including (a) the emission differences between scenarios with the same policy implementation setting but under different new energy views, three groups of typical results are exampled, and abbreviations are the same as Fig. 4; (b) the emission changes in different regions in the Chinese Mainland from 2021 to 2025, in the simulation that new energies and policies implementations are all as planned; (c) the emission factor changes in different regions, similarly. Note that maps in this figure only include the Mainland, not all of the complete Chinese territory, and there are already no CFPP units in Tibet and Beijing currently.

4.3. Adopting favorable policies for specific regions

In Fig. 6(b1) and Fig. 6(b2), we demonstrate the distinctions of CFPP carbon emissions in different regions with the simulation that new energies and policies implementations are all as planned. Emissions in two-thirds of all regions still increase, while in Shanxi, Guizhou, and Shaanxi Provinces, carbon emissions rise by 36.8, 27.1, and 21.8 Mt, respectively. The name of different regions in the Chinese Mainland is mapped in Fig. S6.

Notably, as in Fig. 6(b1), Shandong and Inner Mongolia are clearly the top two high-emission regions in 2021, leading other regions by a notable margin. Yet, in our simulation, emissions in Shandong will decline by 2025 while emissions in Inner Mongolia continue to rise, indicating that the two regions are affected differently by specific policies. The reason is that our model searches for the global optimized results, which are to reduce the national emission to the greatest extent possible. There are many CFPP units in Shandong with low efficiency, small capacity, and long service time [64]. They should be chosen to retire early. Therefore, the coal-fired power units in Inner Mongolia are primarily large-scale and advanced ones, and during the 14th-FYP period, there are still more efficient new units being approved by Policy I.

On the other hand, as in Fig. 6(c1) and Fig. 6(c2), the overall cleaning efficiency of CFPPs across the country is significantly improved. Specifically, the northeast and southwest China regions are making the most progress. These are due to the relatively backward technical level of coal-fired powering and lower powering efficiency in these regions [65]. Meanwhile, another interesting thing is that in areas like Shaanxi and Guizhou, the efficiencies of CFPP units have improved, but regional emissions still increase significantly. In these regions, due to the technical level, a certain number of old units are modified or chosen to phase out, yet more advanced and efficient new units are planned and finally approved.

All the above results, under the global optimization model of maximizing national CFPP emission reduction, indicate that more favorable regional policies should be adopted to promote the implementation of national policies in those regions whose units are more backward. When implementing the national target of mitigating and upgrading CFPPs, these regions may need to take larger quotas for the sake of national carbon reduction efficiency [66]. Also, special financial compensations and incentive measures should be given to support the actual progress of meeting these quotas during the 14th-FYP period.

4.4. Limitations and suggestions for future research

First, this study focuses on the relative effectiveness of relevant 14th-FYP policies to measure their potential to reduce CFPP emissions nationally rather than developing novel carbon emission computation methods. Considering the policy implementation across all regions cannot be consistent with the optimized prerequisite [29]. There needs to be a further in-depth discussion of the implementation path and implementation costs. The actual reductions by 2025 may be weaker. In future research, we will pay attention to all kinds of relevant regional policies on CFPPs and paths of influencing factors to establish a more sophisticated inventory to enhance our optimization models.

Second, although data used in this study have been filtered carefully, the update was stopped at the beginning of 2022. So unplanned changes after, like those caused by epidemics or energy shortages [67,68], are not fully considered. They may lead to an underestimation of total coal-fired powering emissions. In subsequent studies, further tracking of additional changes in CFPP units is also necessary for the supplementary of our inventory. Moreover, the setting of new energy growth rates depends on projections from national perspectives. The rate is affected by many factors, such as investment in new energy. Thus the results may be overly broad. The development of new energies also varies by region. Thereby, more detailed inventories and projections about new energies in different regions should be considered in the following studies.

5. Conclusion

The study investigates the carbon reduction potential of recent Chinese national policies on mitigating and updating CFPP units during the 14th-FYP period. By modeling related policy effects on current units with global optimization methods, the changes in national total full-cycle emissions are measured. For power supply security considerations [27,28], the requirements on CFPP power generation under different new energy growth views are included to constrain the mitigation process of CFPPs in our models, and via setting various implementation performances, 81 simulation scenarios are conducted to comprehensively assess the potential of related policies.

Results in the scenario where all policies are set to be implemented fully as the government planned to show that they could reduce 0.64 Gt carbon emissions cumulatively during the 14th-FYP period and improve the average cleaning efficiencies of CFPP units in the Chinese Mainland by 25 t/GWh. Meanwhile, annual carbon emissions in one-third of regions begin to decrease. These will be significant improvements for the national largest emitting sector, yet, may not sufficient for the nation's 2030 emission peaking target. Based on simulation results, only when related policies are executed beyond planned levels do the changes in annual national emissions show the trend of reaching a plateau. Therefore, the government should take steps to enforce policy measures more vigorously or formulate stricter policies in the next five-year plan.

Besides, this study also verifies the necessity of ensuring the national expected development speed of different new energies. Otherwise, the high remaining power supply requirements on coal-fired powering will delay its mitigation [26]. We measure that if the projected new energy growth rate drops by 10%, the reduction effect of policies on CFPP will decrease by 19.9%. Moreover, the recommendation of allocating more policy quotas and supports to regions with more backward units is proposed based on regional result comparisons.

Thereby, this study may increase public confidence in related 14th-FYP policies that can support the long-term carbon control ambitions of the Chinese government to a reasonable extent, also offering practical guides for actual policy implementations and adjustment in the near future.

CRediT authorship contribution statement

Rui Yang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Wenshen Wang: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e19868.

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