Combining mandatory coal power phaseout and emissions trading in China's power sector

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Abstract

China has launched its nationwide emissions trading system (ETS) in the power sector. Meanwhile, a mandatory phaseout policy for coal power is likely to be co-existing with China's nationwide ETS. These co-existing policies would interact with each other and, in certain cases, lead to unintended consequences, such as a policy overlap. This study aims to assess the impact of such combined policy in China by developing a multi-regional dynamic Computable General Equilibrium (CGE) model with specified modules of mandatory coal power phaseout and ETS. The results show that the impact of such policy combination depends on the type of ETS. Under China's current rate-based ETS, the co-existence of mandatory coal power phaseout would enhance the policy stringency and increase the coal power generation losses, carbon emission and intensity reductions. In contrast, the mass-based ETS with the combination of mandatory coal power phaseout would lead to a policy overlap and potential market failure in the ETS. The complementary provincial impacts and permit scarcity are two factors that could explain the combination mechanism of these policies. Furthermore, permit cancellation in a mass-based ETS would prevent the potential market failure but may lead to greater economic losses.

Keywords: ETS; Coal power decommissioning; Policy overlap; General equilibrium; Urban governance

1 Introduction

Mandatory regulations and market-based policies are two widely used instruments for reducing carbon emissions. These instruments have both pros and cons. For example, market-based policies are more economically efficient (Tietenberg, 1985), while they may lead to unintended consequences when there are market failures (Atkinson and Tietenberg, 1991). In this case, the combination of both policy instruments can make the situation more complicated.

One of the widely known market-based carbon abatement policies is the Emissions Trading System (ETS). An ETS allocates tradable permits to the emitters and mandates that each emitter must surrender the same number of permits when they release emissions. Ideally, these emission permits are redistributed through markets so that a minimised abatement cost can be achieved. But in the reality, these optimal assumptions can be distorted by the co-existing of mandatory policies. Assuming the existence of an ETS and a mandatory coal power phaseout standard, one coal power unit can be restricted by these policies at the same time, leading to potential policy overlaps. It is estimated that a sharp decrease in demand for permits would occur when implementing mandatory coal phaseout under EU-ETS, thus suppressing the permit price (Anke et al., 2020) and damaging the efficiency of the ETS. Furthermore, implementing mandatory coal power phaseout with the existence of ETS may restrict further carbon emission reduction if the overall emission cap does not change, because the emission reductions brought by mandatory phaseout will be substituted by emissions from other units or other industries. The Market Stability Reserve (MSR) with allowance cancellation in the Phase 4 of EU-ETS can temporarily "puncture the waterbed" (Perino, 2018) by actually reducing the overall emission cap under certain rules. However, whether the cancellation mechanism is sufficient to maintain a stable carbon price is still unclear (Rosendahl, 2019).

China is also facing the challenges induced by these co-existing carbon abatement policies. China has been implementing a mandatory coal power phaseout strategy since its 11th Five-year-plan (from 2006-2010) (National Development and Reform Commission, 2007). This strategy has played an important role in facilitating China's power system transition and climate mitigation. In 2016, a series of strengthened restrictions were released to promote mandatory coal power phaseout, including the guidelines for phasing out outdated coal power capacities (National Development and Reform Commission, 2016a) and a "traffic light" system that designates risks and viabilities of the provincial coal power development (National Energy Administration, 2016).

Meanwhile, China launched its nationwide ETS in 2017 and started the national online transaction on July 16th, 2021. Although only coal and gas power plants are covered currently, China's nationwide ETS has accounted for almost half of the total carbon emission covered by all the ETSs in the world (World Bank, 2021). China's nationwide ETS is considered the key policy instrument to achieve its pledge of reaching carbon peak before 2030 and carbon neutrality before 2060 (Zhang et al., 2021). A crucial feature of China's nationwide ETS is its rate-based design. According to this rate-based design, the overall emission cap for ETS is calculated by the annual production of each participating firm multiplying a benchmark rate. The benchmark rate is intensity-based, namely based on the carbon emission per unit of production, which is set up by the Chinese government. In this case, the overall emission cap can be dynamically adjusted according to the production level of the regulated participants. In contrast, conventional ETSs are mass-based where an absolute cap is given so that the overall emission cap is fixed. The feature of China's nationwide ETS would result in different consequences when combining mandatory coal power phaseout, because the overall cap can be automatically reduced with the phaseout of coal power plants. Given the high possibility of the co-existence of a rate-based ETS and a mandatory coal power phaseout policy in China, it is crucial to evaluate the impact of such combination so that adequate targets and standards for ETS and a mandatory phaseout plan can be put forward.

To date, there have been extensive studies on ETSs. The majority of previous ETS studies focused on the design or the impacts of a single ETS policy, such as its total cap and allocation rules of emission permits, and its regional and sectoral impacts on the economy and environment (Jin et al., 2020; Tang et al., 2020; Zhang and Wei, 2010). In addition, a number of studies focused on the combination and interactions of ETSs and other policies that promote power system decarbonisation, but most of these studies focused on the policies for renewable energy development, such as mandatory renewable energy targets (Dai et al., 2018), renewable energy quotas (Mu et al., 2018), tradable green certificates (Feng et al., 2018; Schusser and Jaraitė, 2018), subsidies and feed-in tariffs (Wu et al., 2020, 2017), as well as recycling ETS revenues into the renewable energy industry (Lin and Jia, 2020; Zhang et al., 2017). However, these previous studies seldom considered the combination and interactions of ETSs and mandatory coal power phaseout policies.

From the perspective of mandatory coal power phaseout, these previous studies mainly followed two main research directions. One research direction is to estimate committed emissions under existing infrastructure, such as comparing the committed emissions from existing coal power units to the remaining carbon budgets under the near term Nationally Determined Contributions (NDCs) and the long-term Paris Agreement goals (Cui et al., 2019; Osorio et al., 2020; Pfeiffer et al., 2018; Wang et al., 2020a). These studies agreed on that the current coal power infrastructure in the world would commit excessive emissions above the Paris Agreement goals. Another research direction is to design a phaseout plan for coal power under given climate goals. Various criteria and standards, such as the technical availability, profitability, economic and environmental performance, and affected population, have been evaluated and used to identify the prioritised coal power units to be phased out (Cui et al., 2021; Maamoun et al., 2020; Wang et al., 2020b). However, no matter which research direction is selected, only a limited number of studies considered the co-existence of a carbon price. In this regard, Anke et al. (2020) found that coal power phaseout would have a strong price-suppressing effect in EU-ETS, thus negatively affect the effectiveness of the carbon price. Mo et al. (2021) evaluated the operation lifetime and financial sustainability of China's coal power plants by using a stochastic Monte-Carlo model under certain carbon price levels. However, these studies only considered the one-way effect from either carbon price to coal phaseout or the contrary, without considering the fact that these two factors can be mutually connected.

To address these concerns, this study aims to develop a multi-regional dynamic

Computable General Equilibrium (CGE) model. Regional coal power phaseout trajectories are designed based on the unit level data and applied in this CGE model. Then, the impacts of those single policies (including a rate-based ETS, a mass-based ETS, and a mandatory coal power phaseout policy) and combined policies in China's power system are evaluated. Furthermore, the interaction mechanisms of the ETS and mandatory policy are elaborated. This study contributes to the current literature by (a) developing a CGE model that reflects regional mandatory coal power phaseout trajectories in the power system, (b) elaborating the interaction mechanisms of market-based and mandatory carbon abatement policies, and (c) providing new insights on the advantages and disadvantages of a rate-based ETS when there are co-existing mandatory policies. The potential findings can help those policymakers better understand the potential interactions within a policy mix.

The reminder of this paper is organised as follows. Section 2 introduces the developed CGE model in this study, as well as data sources. Section 3 analyses different impacts of those single and combined policies and illustrates the interacting mechanisms between them. Section 4 proposes policy recommendations and discusses broader implications in this study. Finally, section 5 draws research conclusions.

2 Methods and data

CGE models assume that the interaction of supply and demand will eventually result in an overall general equilibrium so that costs of producers are minimised and welfares of consumers are maximised. In this regard, CGE models use historical data to describe an economy and estimate how the economy may react to policy interventions. CGE models have been widely used for impact assessment of climate policies at global (Jacoby et al., 1997; Lu et al., 2020), national (Li et al., 2018; Lin and Jia, 2019), and regional levels (Cheng et al., 2015; Wu et al., 2016). Given its feature of reflecting price adjustment mechanisms behind supply and demand equilibrium, CGE models are particularly useful in emissions trading studies (Tang et al., 2020).

This study developed a CGE model based on our previous study (Yu et al. 2022). The original model is a China-based multi-regional recursive dynamic CGE model. The original model features a power generation module with disaggregated fossil fuel and renewable power technologies, and an ETS module with switchable rate/mass-based specifications. This study extends this previous model by designing a set of regional coal power phaseout trajectories based on unit level data so that this trajectory can be incorporated into the CGE model. Such a specification can reflect the mandatory phaseout policies that are likely to be imposed on the coal power units in China.

This section first presents a brief introduction of the original CGE model. A more detailed documentation of this model can be found in the appendix, as well as Yu et al. (2022).

2.1 Brief introduction about the original CGE model

This model covers 30 Chinese provinces and 13 sectors (Appendix, Table S2). Hongkong, Macao, Taiwan, and Tibet are not included due to the lack of relevant data. Production and consumption are province-specific. The commodities are allowed to be traded both interprovincially and internationally. Labour endowment and capital stock are also provincial-specific, but they are not allowed to transfer across provinces.

This model applies recursive dynamics. This means the model iteratively uses the output of the current year as the input of the next year. In addition, this model assumes two main drivers that drives the economic growth – factor endowment growth (including population growth and capital accumulation) and productivity growth. The growths of these drivers are exogenously given and calibrated using historical data from 2015 to 2019. Then, this model simulates economic growth from 2020 to 2030 at one-year intervals.

This model disaggregates the power generation sector into the power grid, which reflects the transmission and maintenance costs, and eight fossil fuel and renewable energy generation technologies. The disaggregated power generation technologies are listed in Table 1. Such disaggregation is region-specific. It is based on regional power generation data in 2015 derived from China Electric Power Yearbook (National Bureau of Statistics, 2016a).

Table 1 Abbreviations of the disaggregated subsectors from the power generation sector

Subsector code	Description
ELE_col	Coal power
ELE_gas	Gas power
ELE_ofu	Other fuel
ELE_bio	Biomass
ELE_hyd	Hydro
ELE_nuc	Nuclear
ELE_wnd	Wind
ELE_slr	Solar
ELE_grd	Power grid

This model is written in the General Algebraic Modelling System (GAMS) using its subsystem called MPSGE - Mathematical Programming System for General Equilibrium (Rutherford, 1999). This model is solved by the PATH (Ferris and Munson, 2000) solver. All the monetary values in this model are calculated based on the 2015 price. The CNY/USD exchange rate is 6.23.

2.2 Emissions trading module

The current stage of China's nationwide emissions trading only includes coal and gas power. The initial permits are freely allocated. In this model, the free allocation of permits is realised indirectly by recycling the revenue of permit auction (Wu et al., 2016). Specifically, we first assume that a full permit auction takes place and the revenue of the permit auction is collected by the government. Then the revenue is recycled back to the sectors based on the corresponding allocation rules.

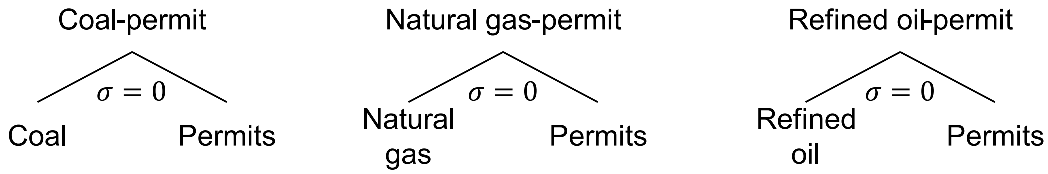

Figure 1 CES structure of carbon permits

As shown in Figure 1, if a certain power technology is covered in the emissions trading, its corresponding fossil fuel input (coal or coal power, natural gas for gas power, and refined oil for other fuel power) will be first nested with emission permits with an elasticity of zero. This specification simulates the reality that the producers are required to surrender the same number of emission permits when they release emissions. A dummy production block is activated to produce the fuel-permit bundle. The scarcity of carbon permits will rise the cost of producing the fuel-permit bundle, creating incentives to reduce the use of fossil fuels. The carbon permits can be freely traded among provinces and sectors.

The initial permits in a rate-based ETS are calculated based on benchmarks (Table 2) according to the latest National Carbon Emissions Trading Permit Setting and Distribution Implementation Plan 2019-2020 (Power Generation Industry) (Ministry of Ecology and Environment, 2020) – hereafter referred to as the Implementation Plan. In practice, some of the coal and gas power generation units are combined heat and power (CHP) units. However, the model is not able to distinguish CHP units and conventional units due to data unavailability, thus the model sees all coal (or gas) power units in a province as one aggregated CHP unit when allocating initial permits, and the output from this aggregated CHP unit as a fixed combination of heat and electricity. This means the production of heat and electricity of a specific technology in a specific region can only be scaled simultaneously. According to the Implementation Plan, the total initial permits for CHP units are the sum of the initial permits for power generation and heat generation. Hereafter, a parameter with a bar refers to an exogenous parameter.

$$permit_{r,elet,t} = ELET_{r,elet,t} \cdot \overline{BMK_{elet,t}^{ELET}} \cdot \overline{Fl_{r,elet}} \cdot \overline{Fr_{r,elet}} \cdot \overline{Ff_{r,elet}} + HEAT_{r,elet,t} \cdot \overline{BMK_{elet,t}^{HEAT}} \quad (1)$$

Where:

$ELET_{r,elet,t}$ and $HEAT_{r,elet,t}$ refer to the electricity and heat generation in region r from technology $elet$ in year t, measured in MWh and GJ, respectively.

$\overline{BMK_{elet,t}^{ELET}}$ and $\overline{BMK_{elet,t}^{HEAT}}$ refer to the benchmarks of electricity and heat generation from technology $elet$ in year t, measured in tCO_2/MWh and tCO_2/GJ, respectively.

$\overline{Fl_{r,elet}}$ and $\overline{Ff_{r,elet}}$ refer to the cooling correction factor and load correction factor, which both have a default value of 1.

$\overline{Fr_{r,elet}}$ refers to the heat supply correction factor which is calculated by the following equation 2 and 3.

$$\overline{Fr_{r,ELE_{col}}} = 1 - 0.22 \times \overline{Q_{r,ELE_{col}}^{HEAT}} \quad (2)$$

$$\overline{Fr_{r,ELE_{gas}}} = 1 - 0.60 \times \overline{Q_{r,ELE_{gas}}^{HEAT}} \quad (3)$$

Where:

$\overline{Q_{r,elet}^{H}}$ refers to the share of energy input that is used to produce heat, which is assumed to be constant during the dynamic process.

The benchmarks from the latest policy are listed in Table 2. These benchmarks were implemented in 2020 and are assumed to have a linear annual reduction rate of 2% during 2020-2030. In comparison, the average annual reduction rate of the carbon intensity of coal power in the previous five years was approximately 0.6% (National Development and Reform Commission, 2016b). We intentionally designed higher reduction rates in order to avoid the carbon constraint becoming insufficient during simulation. To the best of our knowledge, there is only one existing study focusing on the benchmark trajectory design in China’s rate-based power-sector-only ETS (IEA, 2021). Their reduction rate of the benchmark for coal power is 3% from 2020 to 2025, and 6% from 2025 to 2030, which can be roughly converted into a 0.6% and 1.2% annual reduction rate respectively.

Table 2 Benchmarks for coal and gas power generation in 2020

	Electricity generation (tCO_2/MWh)	Heat generation (tCO_2/GJ)
Coal power	0.877	0.126
Gas power	0.392	0.059

The mass-based cap is determined by carbon emissions from the results of rate-based scenarios. The initial permits of each province and power technology are calculated according to its share of carbon emissions in the previous year, which is also known as the grandfathering method (Wu et al., 2016).

$$permit_{r,elet,t} = \overline{CAP_t} \times \frac{CE_{r,elet,t-1}}{\sum_{r,elet} CE_{r,elet,t-1}} \tag{4}$$

Where:

$\overline{CAP_t}$ refers to the mass-based cap in year t, measured in Mt.

$CE_{r,elet,t}$ refers to the carbon emission of region r from technology $elet$ in year t, measured in Mt.

2.3 Coal power mandatory phaseout module

2.3.1 Mandatory coal power phaseout standard

We first calibrate the coal power generation from 2015 to 2019 according to China's latest Electric Power Yearbook. We assume that mandatory phaseout takes place in 2020. We also assume that no new installation has taken place since 2020 (Cui et al., 2021). The unit-level data are derived from the Global Energy Monitor (Global Energy Monitor, 2016). This database covers existing coal power plants before 2016, in which 84% of the total coal power capacity in 2016 was covered. Figure S10 in the Appendix shows the temporal and capacity distribution of the existing coal power plants from 1975 to 2016. Those power plants that are less than 300MW and were built before 2010 are designed to be phased out. The chosen capacities are assumed to be phased out through a linear trajectory from 2020 to 2030.

Those phaseout standards and assumptions are designed based on the following considerations. First, the Chinese central government announced to phase out those coal power units that are below 300MW and have been operated for 20-25 years if they do not comply with the national pollution standards (National Development and Reform Commission, 2016a). Second, the Chinese government also announced a different (less stringent) benchmark for coal power plants below 300MW in the ETS.

These policies indicate that units below 300MW are less efficient and outdated. Third, the average age of coal power plant is about 20 years in China (Mo et al., 2021). Therefore, coal power plants with over 20 years operation are chose to be phased out. It is possible to phase out the chosen units based on their exact operation years. Such setting is tested in the uncertainty analysis in the non-linear scenario (See Section 5 in Appendix). However, since the phaseout policy is assumed to take place in 2020, if the units were to be phased out based on their exact operation years, those plants that were built before 2000 would be phased out in the year 2020 at once. This would cause a sharp drop of coal power which would lead to unrealistic responses of the model. To avoid such consequence, a linear phaseout trajectory is assumed. Forth, the Chinese central government has stopped supporting new coal power projects below 600MW (National Development and Reform Commission, 2016c) since 2014. Therefore, although there were still new installations from 2016 to 2019 that are not covered by the GEM database, these units are unlikely to fall into the phaseout criterion in this study.

The phaseout of capacity is translated into the phaseout of generation by multiplying the national average annual operation hours (National Bureau of Statistics, 2016a). The mandatory phaseout policy is represented by setting an upper limit for the power generation in each province. As shown in Equation 5, the upper limit of coal power generation equals the generation in the last year before phaseout (2019) subtracts the generation that is chosen to be phased out. Normalised change rates of provincial coal power generation are calculated based on the year 2015 (Equation 6). These normalised change rates of the 30 provinces are provided in Table S8 in the Appendix. It is worth noting that Beijing phased out all the coal power plants in 2017 (Tang et al., 2019). In this model, the coal power generation limit of Beijing in 2017 is set to be 1% of its generation in 2015, namely the normalised change rate is 0.01 from 2017 to 2030 – a small enough but non-zero value can prevent this model from crashing.

$$\overline{Glim_{r,t}} = \overline{Glim_{r,2019}} - \overline{capacity_r} \times \overline{h_{avg}} \times \frac{t - 2019}{2030 - 2019} \tag{5}$$

$$\overline{\theta_{r,t}} = \frac{\overline{Glim_{r,t}}}{\overline{Gen_{r,2015}}} \tag{6}$$

Where:

$\overline{Glim_{r,t}}$ refers to the coal power generation limit of region r in year t, measured in MWh. Note that this parameter represents an upper limit rather than the actual generation.

$\overline{capacity_r}$ refers to the capacity to be phased out in region r, measured in MW.

$\overline{h_{avg}}$ refers to the national average annual operation hours of coal power, measured in hours.

$\overline{Gen_{r,2015}}$ refers to the coal power generation of region r in 2015, measured in MWh.

$\overline{\theta_{r,t}}$ refers to the normalised change rate of coal power generation limit of region r in year t. Here $\theta_{r,2015}$ is set to be one.

2.3.2 Energy efficiency improvement from mandatory coal power phaseout

The mandatory coal power phaseout policy tends to phase out the oldest and smallest units in the power system. These coal power units are likely to be the ones with lower energy efficiency, thus provincial average carbon intensities of coal power will be reduced when these units are phased out. This model adjusts the energy efficiency of coal power generation in addition to the baseline annual energy efficiency improvement (AEEI) when the mandatory coal power phaseout is implemented. The following assumptions are made.

As shown in Equation 7, assuming that coal power units in a specific province are activated in the order of their carbon intensities, the provincial average carbon intensity I will be a piecewise function of total coal power generation Y.

$$I = \begin{cases} I_0, & 0 \le Y < Y_0 \\ \dfrac{I_0 Y_0 + I_1(Y - Y_0)}{Y}, & Y_0 \le Y < Y_1 \\ \dfrac{I_0 Y_0 + I_1(Y_1 - Y_0) + I_2(Y - Y_1)}{Y}, & Y_1 \le Y < Y_2 \\ \quad\quad\quad \dots \end{cases} \tag{7}$$

Where:

I represents the carbon intensity of coal power.

I_0 represents the lower limitation of carbon intensity. This value is 0.742 tCO_2/MWh, which is the carbon intensity of recent ultra-super critical coal power units according to the investigation from IEA (2020). This value only constrains the carbon intensity reduction induced by mandatory phaseout policy. The actual carbon intensity in the model is allowed to be lower due to technological improvement induced by other factors, such as the ETS.

$I_1, I_2, \dots$ represents carbon intensities of different power units.

Y represents coal power generation.

$Y_0, Y_1, Y_2, \dots$ represents generation thresholds above which the next-level coal power unit must be activated.

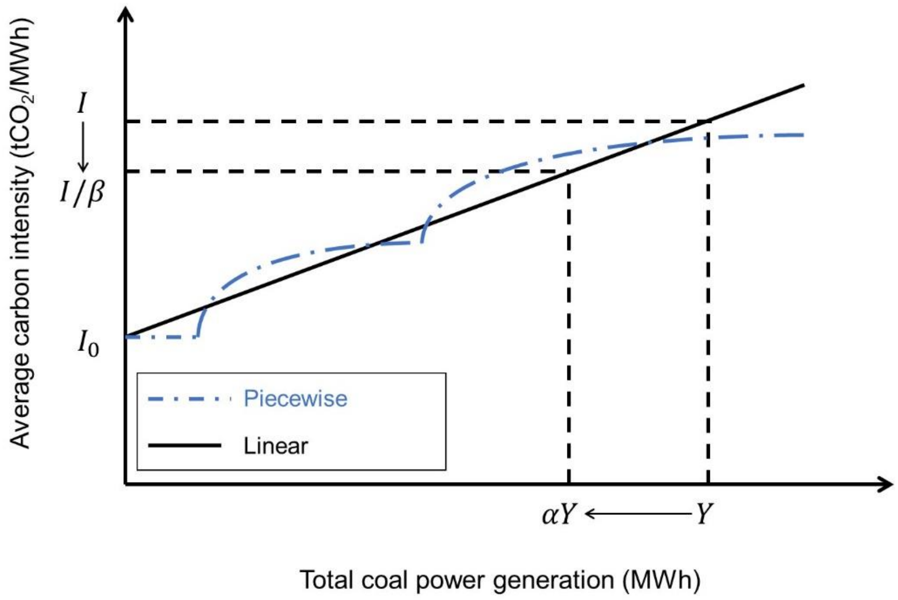

Figure 2 Illustrative graph of the relation between total coal power generation and average carbon intensity

Note: Y represents coal power generation; α represents the change rate of coal power generation after mandatory phaseout; I represents the carbon intensity of coal power; I_0 represents the technological limitation of carbon intensity; β represents the additional adjustment factor to energy efficiency.

The illustrative graph of the piecewise function in Equation 7 is shown in Figure 2. Due to the lack of data on unit-level carbon intensities and capacities, the relation between provincial total coal power generation and average carbon intensity is assumed to be linear. When the coal power generation is reduced from Y to αY due to the mandatory phaseout policy, the additional energy efficiency adjustment factor β can be calculated by Equation 8.

$$\beta = \frac{1}{\alpha + (1-\alpha) \cdot \frac{I_0}{I}} \tag{8}$$

Where:

α represents the change rate of coal power generation limit caused by mandatory phaseout.

β represents the additional adjustment factor for energy efficiency improvement.

Here the change rate α is derived from the generation limit $\overline{Glim_{r,t}}$, which means it only accounts for the generation losses that are induced by the mandatory phaseout policy, not including the generation losses that are induced by the ETS. This also means factors α and β are exogenous and remain constant across different scenarios. This mechanism applies to all scenarios where a mandatory coal power phaseout policy is implemented.

2.4 Data sources

The base year input-output data and energy consumptions are derived from the input-output table and energy inventory of China from CEADs in 2015 (Zheng et al., 2020). The provincial power generations are derived from China Electric Power Yearbooks (National Bureau of Statistics, 2016a). The transfer of payments among the households, the central government, and foreign accounts are derived from the national and provincial Statistical Yearbooks (National Bureau of Statistics, 2016b), Fiscal Yearbooks (National Bureau of Statistics, 2016c), Tax Yearbooks (National Bureau of Statistics, 2016d), and Social Statistical Yearbooks (National Bureau of Statistics, 2016e). Provincial and sectoral carbon emission inventories are derived from CEADs database (Shan et al., 2018). The unit-level coal power data are derived from the Global Energy Monitor (Global Energy Monitor, 2016).

2.5 Scenarios development

There is a Business-as-Usual (BaU) scenario and a series of policy scenarios in this study. The BaU scenario is called the baseline, which is a reference case where current policy maintains and no further policy is implemented.

The policy scenarios are categorised by **policy types** (*CP* for mandatory coal power phaseout, *RB* for rate-based ETS, and *MB* for mass-based ETS), **policy combination** (*S* for single policy and *C* for combined policy), **policy stringency** (*1*, *2*, and *3*). The combined policy refers to a combination of a mandatory coal power phaseout policy and an ETS. The policy stringency refers to different levels of emission reductions. The stringency level 1, 2, and 3 corresponds to marker scenario CP_S1, RB_S2, and RB_C3, respectively. The total carbon emission of coal and gas power generated by the marker scenarios are used as mass-based caps for other scenarios at the same levels. In this way, the policy scenarios at the same policy stringency level achieve the same emission reduction target. The carbon emission trajectories in the BaU and the marker scenarios are shown in Figure 3.

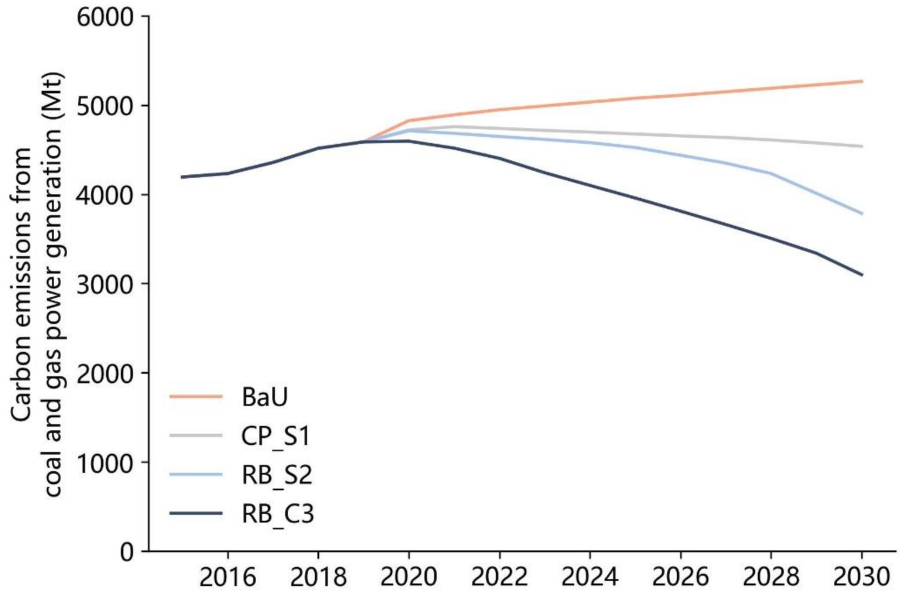

Figure 3 Carbon emission trajectories of the BaU and three marker scenarios

The rate-based (RB) ETS scenarios can only be used as marker scenarios because the emission trajectory cannot be exogenously fixed when a benchmark is given. In other words, it is only possible to develop emission-comparable scenarios applying a mass-based ETS. The scenarios development is summarised in Table 3.

Table 3 Summary of scenarios development

Scenario	**Mandatory phaseout**	**ETS**
BaU	No	No
CP_S1*	Yes	No
MB_S1	No	Mass-based
RB_S2*	No	Rate-based
MB_S2	No	Mass-based
MB_C2	Yes	Mass-based
RB_C3*	Yes	Rate-based
MB_C3	Yes	Mass-based

Note:

* Marker scenarios for each level of policy stringency. The total carbon emissions of coal and gas power in these marker scenarios are used as the emission cap in the mass-based ETS in the corresponding MB scenarios. The scenarios under the same level of policy stringency are therefore comparable because they achieve the same emission reductions.

3 Results

3.1 Impacts of the single and combined policies in the power system

3.1.1 National level

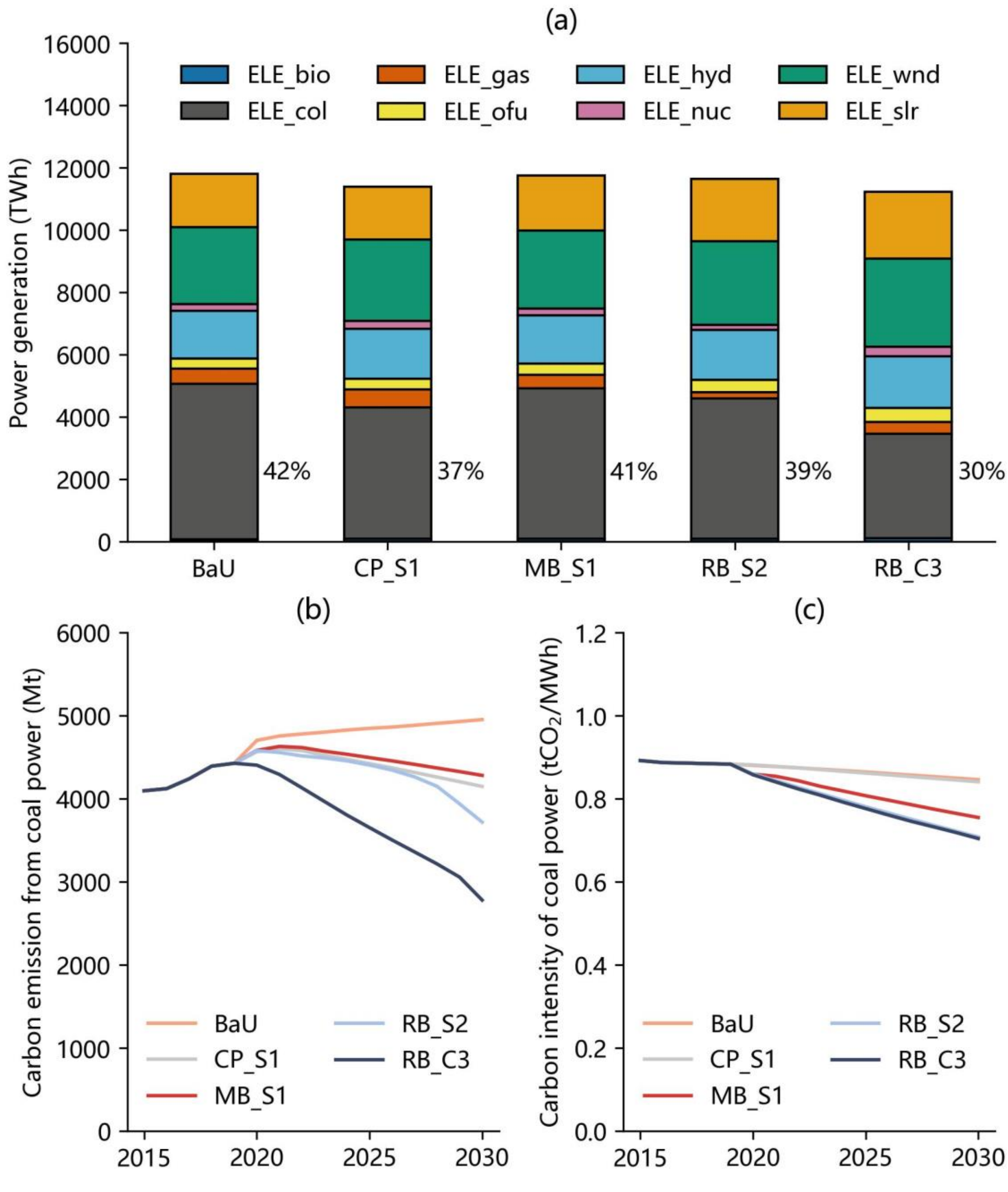

Figure 4 Impacts in China's national power system (a) Power generation of each technology; (b) Carbon emission from coal power; (c) Carbon intensity of coal power.

Note: Table 1 lists the descriptions of the power technology abbreviations.

This section first focuses on the three marker scenarios (CP_S1, RB_S2, RB_C3). The MB_S1 scenario is also included because it provides a comparable reference to the

CP_S1 scenario in terms of carbon emissions so that the difference between the single mandatory and market-based policies can be better identified.

Both mandatory and market-based policies lead to generation reductions, carbon emission reductions, and carbon intensity reductions in the coal power generation sector (Figure 4). The mandatory phaseout policy (CP_S1) is more effective than the mass-based ETS (MB_S1) in terms of coal power phaseout, leading to a more significant reduction in carbon emissions from coal power. Figure 4a shows that the share of coal power in 2030 will drop from 42% in the BaU scenario to 37% and 41% in the CP_S1 and MB_S1 scenarios, respectively. Figure 4b shows that the carbon emission from coal power will be 4146 Mt in the CP_S1 scenario in 2030, which is lower than that in the MB_S1 scenario (4280 Mt). However, the mass-based ETS is more effective in reducing the carbon intensity of coal power. As shown in Figure 4c, the carbon intensities of coal power will be 0.841 tCO_2/MWh and 0.755 tCO_2/MWh in the CP_S1 and MB_S1 scenarios in 2030.

Comparing the CP_S1 and RB_S2 scenarios, Figure 4b shows that the carbon emission from coal power in the RB_S2 scenario is lower than that in the CP_S1 scenario. However, the single mandatory phaseout policy in the CP_S1 scenario is still more effective in reducing the share of coal power in the power system. The share of coal power will be 39% in the RB_S2 scenario in 2030, which is still higher than that in the CP_S1 scenario (Figure 4a). In other words, the single rate-based ETS will result in higher coal power generation but lower carbon emissions. The reason behind these results is related to the carbon intensity changes. Figure 4c shows that the national average carbon intensity of coal power will be significantly lower in the RB_S2 scenario, reaching 0.708 tCO_2/MWh in 2030.

The combined policy scenario (RB_C3) further increases the policy stringency. The combination of a mandatory coal power phaseout policy and a rate-based ETS further will reduce the share of coal power to 30% in 2030. Consequently, the carbon emission reduction from coal power will reach 2173 Mt in 2030 (Figure 4b), which is larger than the sum of the emission reduction that is achieved by the single mandatory policy (805 Mt) and the single rate-based ETS (1234 Mt). The reason of such progressive emission reduction could be the power-sector-only coverage of the emission abatement policies. These power-sector-only policies, no matter mandatory or market-based, can reduce the carbon emissions from coal power, but also reduce the competitiveness of the power sector as a whole, thus reducing the demand for electricity. Figure 4a shows that the total power generation is lower in the policy scenarios compared with the BaU scenario, especially in the scenarios where the mandatory coal power phaseout policy is implemented.

The above results indicate that the effect of combining mandatory phaseout and a rate-based ETS is cumulative, which means the combined policy can promote carbon emission reductions compared with the single policy.

3.1.2 Provincial level

The provincial disparity of coal power generation changes under different policies is one important factor that explains how policies can be cumulative. In order to illustrate the combination mechanism of the mandatory coal power phaseout policy and the rate-based ETS, the provincial impacts on coal power generation in the CP_S1 and RB_S2 scenarios are compared in this section despite their different policy stringency levels.

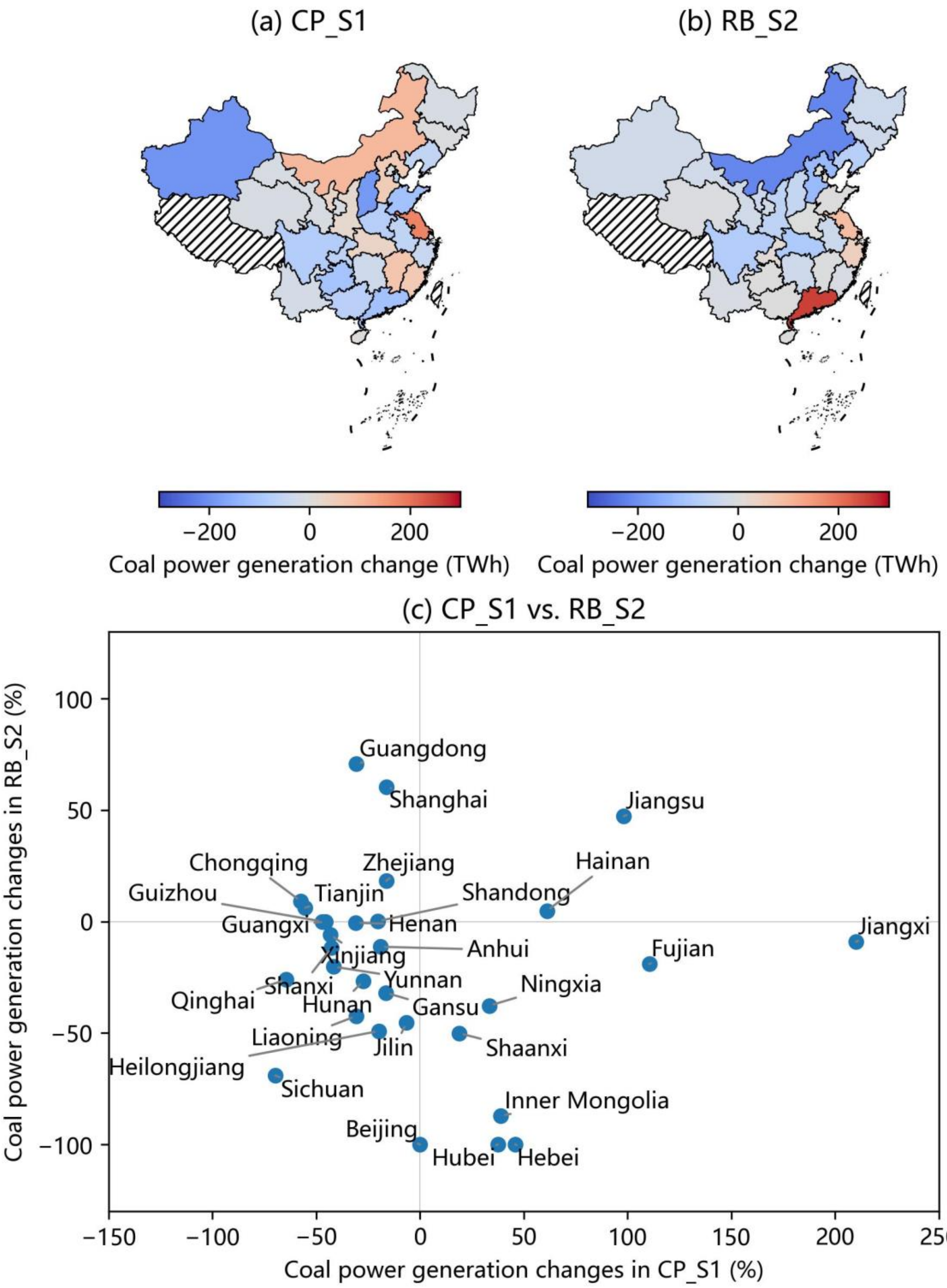

Figure 5 Changes of provincial coal power generation under mandatory phaseout (CP_S1) and rate-based ETS (RB_S2) in 2030. (a) and (b) show the absolute generation changes relative to BaU. (c) shows the relative generation changes relative to BaU.

Clear regional disparities exist in terms of the provincial responses to mandatory phaseout (CP_S1) and rate-based ETS (RB_S2). The responses under the two single policies are found complementary in some of the provinces. Figure 5 shows the absolute and relative changes in provincial coal power generation under the two single policies.

Most provinces are located at the bottom left in Figure 5c where mandatory phaseout and ETS have consistent impacts – they experience significant coal power generation losses under both single policies compared with the BaU scenario. Most of these provinces are located in central and southwest China, which are shown in Figure 5a and Figure 5b.

The provinces located at top left in Figure 5c are found to experience coal power generation increases in the rate-based ETS but coal power decreases under the mandatory phaseout policy compared with the BaU scenario, such as Guangdong, Shanghai, Zhejiang, Chongqing, Tianjin. These provinces are more economically developed and have relatively lower carbon intensities in coal power generation. A lower carbon intensity leads to advantages in a rate-based ETS, thus leads to greater coal power generation. The changes of coal power generation in these provinces range from 6% to 71% in the RB_S2 scenario compared with the BaU scenario. However, mandatory phaseout is found to be effective to constrain the increases of coal power in these provinces. The changes of coal power generation of these provinces range from -57% to -16% in the CP_S1 scenario compared with the BaU scenario.

The provinces located at bottom right in Figure 5c are found to experience coal power increases in mandatory phaseout but coal power decreases in a rate-based ETS compared with the BaU scenario. The most significant increases caused by mandatory phaseout occur in Jiangxi and Fujian. Especially in Jiangxi, the coal power generation in the CP_S1 scenario is more than three times than that in the BaU scenario. The coal power generation of Jiangxi is decreasing in the BaU scenario but increasing in the CP_S1 scenario, thus enlarging the difference between these two scenarios. Such contrary results could be explained by the reactivation of coal power units that are idle in the BaU scenario. These idle units are reactivated because first, the coal power generation in these provinces does not exceed the generation limit even after the coal power reactivation; second, power generation from other provinces are more severely affected by the mandatory policy, thus the coal power units in provinces such as Jiangxi are reactivated to fill the generation gap. The reactivation of coal power units hardly affects local renewable energy and electricity consumption. Thus, these coal power units are not substituting renewable energy but filling the generation gap created by the coal power phaseout in other provinces.

It is worth noting that the coal power generation in Jiangsu is greater than the BaU scenario under both the mandatory phaseout policy and the rate-based ETS. This could be explained by the relatively lower carbon intensity and higher installed capacity of coal power generation in Jiangsu, which enhances its advantage under both policy instruments.

The complementary provincial responses under the two single policies can partly explain why a mandatory phaseout and a rate-based ETS can be cumulative. The provinces that have advantages under one policy would lose the advantage when the other policy is implemented, and vice versa. Beyond that, another key driver that affects the policy combination is the permit scarcity, which will be further elaborated in the following section.

3.2 Impacts of the policy combination under different ETS types

3.2.1 Impacts on permit scarcity and market performance

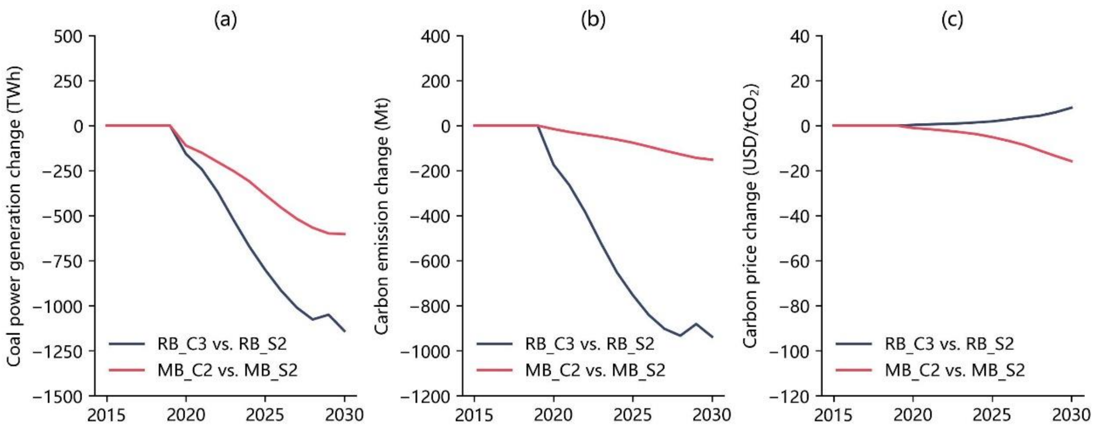

Figure 6 Additional effect of mandatory phaseout to rate-based (RB) and mass-based (MB) ETS (a) Coal power generation change; (b) Carbon emission change; (c) Carbon price change.

Figure 6 shows the additional impacts by comparing the combined policies with the single policies. It should be noted that the policy combination affects policy stringency. The analysis in this subsection specifically focuses on the additional impact of implementing mandatory coal power phaseout in the ETS and its combination mechanisms.

The results show that implementing mandatory phaseout in a rate-based ETS (RB_C3 vs. RB_S2) will lead to significantly larger impacts on coal power generation and its carbon emissions (Figure 6a and Figure 6b). The co-existing mandatory phaseout will lead to an additional reduction of 1141 TWh in coal power generation and 938 Mt in its carbon emission in 2030. In contrast, the implementation of mandatory phaseout in a mass-based ETS (MB_C2 vs. MB_S2) will only lead to an additional reduction of 603 TWh in coal power generation and 152 Mt in its carbon emission in 2030.

These results indicate that implementing mandatory phaseout in a rate-based ETS will lead to a policy enhancement. In this case, even a certain amount of coal power capacity is phased out, the total emission cap is still calculated based on the existing coal power generation. Therefore, the scarcity of the permits is hardly reduced. In addition, the coal power units that are chosen to be phased out under the mandatory policy are not necessarily the least efficient ones. Some of the coal power units below the benchmark may also be phased out, which further increases the permit scarcity. These factors result in a higher carbon price (Figure 6c).

On the other hand, implementing mandatory phaseout in a mass-based ETS leads to a policy overlap, which means even these two policies have the same aim, there is hardly any further emission reductions that can be achieved. This is because the coal power generation has been reduced by the mandatory phaseout policy, while the total emission cap has not been changed. Although there is still a notable reduction in coal power generation and corresponding carbon emissions, these generation losses are filled by gas power units which are also covered by the ETS. Consequently, there will be a surplus of emission permits, thus reducing the carbon price (Figure 6c).

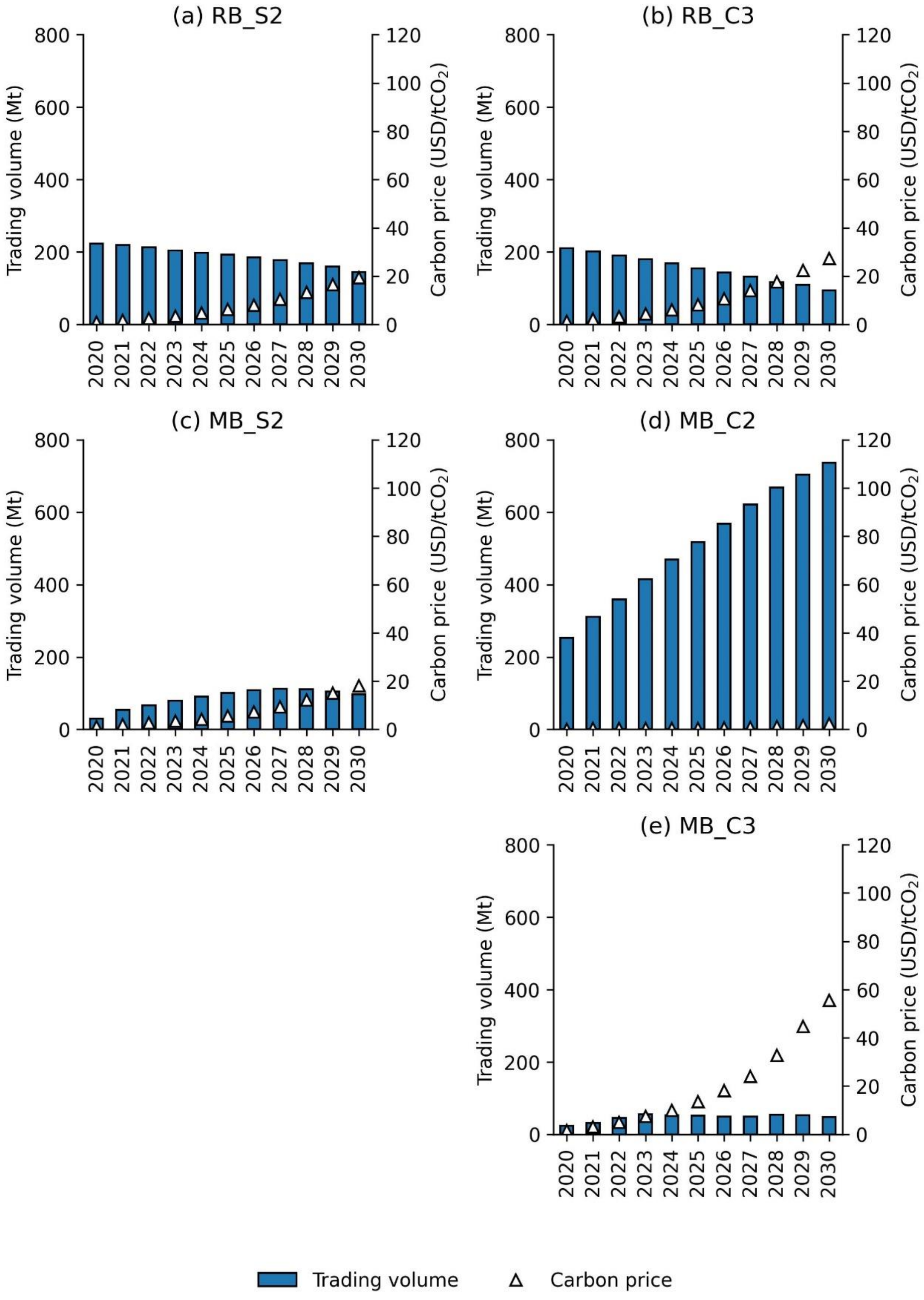

Figure 7 Trading volumes and carbon prices under the ETS scenarios from 2020 to 2030

The policy overlap in the mass-based ETS would lead to a decreased carbon price and further consequences. Figure 7 shows more details about the permit trading volumes and carbon prices in the ETSs. The results show that the permit trading volume is considerably larger in the MB_C2 scenario (Figure 7d) than those in the other scenarios. The trading volume in the MB_C2 scenario will increase rapidly from 2020 to 2030 and reach 736 Mt in 2030, while the trading volumes in the other three policy scenarios will be below 150 Mt. In contrast, the carbon price in the MB_C2 scenario (Figure 7d) will be very low – at 2.4 USD/tCO_2 in 2030. The model adopted in this study does not capture the possibility that participants would lose their interests on the ETS when the carbon price is low, thus these results of an active carbon market with a low carbon price are unlikely to come true. Instead, these results would indicate a potential market failure, in which the ETS is not able to motivate low carbon transitions.

However, the potential market failure could be avoided if the emission cap in a mass-based ETS is simultaneously reduced, which is also known as permit cancellation, along with the mandatory coal power phaseout policy. Figure 7e shows the permit trading volume and carbon price in the MB_C3 scenario where the emission cap is reduced overtime corresponding to the RB_C3 scenario. Such permit cancellation will result in the highest carbon price at 55.6 USD/tCO_2 among all the scenarios, while the annual permit trading volume will be lower but relative stable, reaching around 50 Mt in 2030.

3.3 Economic impacts

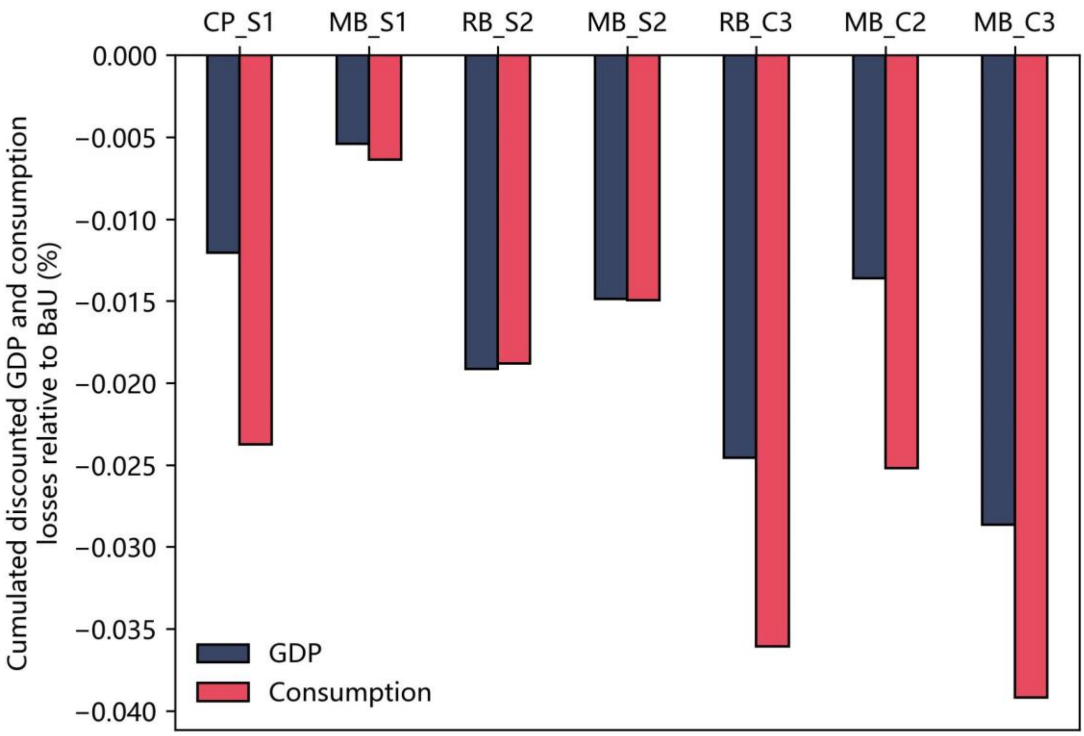

Figure 8 Cumulated discounted GDP and consumption losses relative to BaU from

2015 to 2030

Note: The consumptions from 2015 to 2030 are discounted and then aggregated. The annual discount rate is 5%.

The rate-based and mass-based ETSs also lead to different economic impacts. Figure 8 shows the cumulated discounted GDP and consumption losses relative to the BaU scenario from 2015 to 2030. The results show that the economic losses will increase when the policy becomes more stringent. The results in the level 1 scenarios show that the economic loss will be larger under the mandatory coal power phaseout policy (CP_S1) than that in the ETS (MB_S1) when they achieve the same emission reduction. Comparing the RB_S2 and MB_S2 scenarios under level 2 policy stringency, the results show that the economic losses in a rate-based ETS will be larger than that in a mass-based ETS. However, the combination of the mandatory coal power phaseout policy with the rate-based ETS will increase the GDP loss from 0.019% in the RB_S2 scenario to 0.025% in the RB_C3 scenario due to the policy enhancement effect. In contrast, the combination with the mass-based ETS will decrease the GDP loss slightly from 0.015% in the MB_S2 scenario to 0.014% in the MB_C2 scenario due to the policy overlap.

However, the consumption losses in the mandatory phaseout scenarios will be significantly larger than those scenarios without the mandatory phaseout. For example, the consumption losses in the MB_S2 and MB_C2 scenarios will be 0.015% and 0.025%, respectively; but the GDP losses in these scenarios will be similar (around 0.014%). This could be related to the competitiveness loss and power generation loss induced by the mandatory coal power phaseout policy. It can be found in Figure 4a that the single mandatory phaseout policy (CP_S1) will lead to a significant generation loss, and a similar effect will occur in other scenarios where mandatory coal power phaseout is implemented. This will lead to reductions in the household consumptions of electricity, and consequently lead to the reductions in the cumulated consumptions.

Furthermore, the permit cancellation will increase the economic losses in the policy combination in a mass-based ETS (MB_C3), which even surpass the economic losses in the policy combination in a rate-based ETS (RB_C3). This could be explained by the initial permit distortion induced by the mandatory coal power phaseout policy in the mass-based ETS. The initial permits in the mass-based ETS are allocated based on historical emissions in the previous year, while the mandatory policy may change provincial coal power generation thus increasing the deviation between the permits allocated and the permits needed, and consequently leading to larger economic losses.

4 Discussion

The key findings in this study indicate that the corresponding impact would vary significantly when combining a mandatory coal power phaseout policy and ETSs with different designs. When the ETS is rate-based, the co-existing mandatory phaseout policy would enhance the abatement target, leading to not only a quicker phaseout of coal power, but also a higher consumption loss. When the ETS is mass-based, the co-existing mandatory phaseout policy would lead to a sharp carbon price decrease, which is especially undesirable at the beginning stage of any ETS. Although a simultaneous permit cancellation could prevent the potential market failure in the combination of a mandatory coal power phaseout policy and a mass-based ETS, it would be difficult for the government to design appropriate cancellation rules in practice, and it would also lead to larger economic losses depending on the initial allocation of the permits. We therefore emphasise the previously overlooked advantage of maintaining a stable and sufficient carbon price under policy combinations in a rate-based ETS. In addition, the results of this study uncover the risk of enhancing the emission target by combining a rate-based ETS and mandatory coal power phaseout, which is often overlooked by assessments assuming a mass-based system. Therefore, those policy makers should be careful of putting excessive abatement pressure when designing the benchmarks.

To facilitate the nationwide ETS in China, the following recommendations are raised by considering the Chinese realities.

First, it is crucial to promote power system transition, such as scaling up the deployment of wind and solar power at low costs, and building a robust power system that can ensure a stable power supply. Recently, electricity shortage has been an emerging problem in China, mainly due to the growth in coal prices and the restrictions in electricity prices. The combination of the rate-based ETS and mandatory phaseout would lead to unintended target enhancement and further increase the cost of coal power. In the short-term, it would aggravate the risk of electricity shortage. A smart power grid with expanded transmission capacity could alleviate such risk (Zhang and Chen, 2020). Furthermore, the electricity market reform would help the power generation industry to transfer such abatement cost to those downstream users, thus avoiding the power generation industry from operating at a loss (Ju and Fujikawa, 2019).

Second, it is necessary to increase the flexibility in China's emissions trading market. Learning from the experience of the pilot ETS in several Chinese provinces, regular permit auctions should be conducted by the Chinese government at the market price, especially at the end of each compliance cycle, so as to prevent a lack of available permit due to the participants' underestimation on their permit demands. Furthermore, policy makers should consider expanding the coverage of ETS, such as sectors of cement, chemicals, oil refinery, and metal smelting. The current coverage of only coal and gas power has led to large homogeneity of the participants, resulting in fewer available permits and lower trading enthusiasm. In this regard, allowing financial institutions to enter the market and introducing various financial products can increase market liquidity.

Third, it is important to promote coordination among different governmental departments through capacity building efforts. China's policies on ETS and coal phaseout are designed and announced by two separate agencies, namely Ministry of Ecology and Environment (MEE), and National Development and Reform Commission (NDRC). The potential impacts and risks of the co-existing of ETS and coal phaseout policies indicate that it is necessary to coordinate among these departments so that they can share information and jointly prepare relevant policies. As such, local governments could mobilise financial and administrative resources to help those coal power companies to phase out their production, such as loans and permissions (Tan et al., 2021). On the other hand, a credible carbon emissions accounting and verification system should be developed. In order to respond to the policy enhancement effect of ETS and mandatory phaseout, firms may have a stronger motivation to manipulate their data to cope with the compliance requirement. Therefore, both Chinese central and local governments could work together to seek third-party verifiers to monitor the operation of these firms (Zhang et al., 2019).

Forth, local governments should implement region specific policies in response to the diverse impacts of the national policy. Provinces such as Jiangsu, Jiangxi, Fujian, Shanghai, Guangdong would have less incentives to reduce coal power generation under either the national level mandatory phaseout or the ETS. These provincial government should consider implementing more stringent restrictions on coal power development to prevent the reactivation of coal power units or the excessive subsidy in the ETS. In contrast, provinces such as Inner Mongolia, Hebei, Jilin, and Heilongjiang would experience significant coal power reductions in the future. As these provinces currently heavily rely on coal-burning thermal power, their provincial government should promote renewable energy development and prepare the phaseout plan of existing coal power units.

Several other studies also discussed the trade-offs in a rate-based system. The dominant concern is the lower economic efficiency due to multiple benchmarks and implicit subsidies (Goulder et al., 2022). Similarly, Zhu et al., (2019) found that a rate-based system can hardly encourage low carbon innovation in China's pilot ETS at the provincial level. In this regard, although the rate-based design would continue in the next five to ten years in China until the emission peak is achieved in the power sector (Zhang et al., 2021), it is anticipated that this rate-based system will be switched into a mass-based system in order to link with the international ETSs. If such a transition takes place, policy makers should be aware of the contrary impact of the co-existence of mandatory phaseout. Consequently, measures should be proposed to prevent the decrease of carbon price, such as a permit cancellation scheme or a floor price (Perino, 2018).

Internationally, this study provides valuable insights for other developing economies experiencing rapid economic growth and drastic decarbonisation. Bertram et al. (2015) found a similar result that coal power phaseout policies would be more effective in reducing the economic mitigation burden, and thus improving the political feasibility when combining with a carbon tax rather than a cap-and-trade (mass-based) system. They found that the stability of the carbon price under technology policies is the key to such advantage. In this regard, the findings in our study also indicate that such rate-based design could be an interim before switching to an absolute emission cap. In particular, the relatively stable carbon price would encourage more enterprises and financial institutions to participate in the carbon market and avoid the excessive permits.

Several research limitations exist in this study. First, data on unit-level carbon intensities of coal power (as well as other thermal power) are lacking, leading to simplified specification of energy efficiency improvement under the mandatory phaseout policy. This could be improved by further development of the current database and linkage with bottom-up energy models. Second, this study focuses specifically on the comparison between single and combined policies in order to emphasise the impacts of policy co-existence and different impacts of different ETS types, while future studies could focus on exploring the balance between mandatory and market-based policies under a given target by designing scenarios with different combinations of these policy instruments.

5 Conclusions

A mandatory coal power phaseout policy and a ETS are likely to co-exist in China's near-term development. This study adopts a multi-regional dynamic Computable General Equilibrium model to assess the impacts of these two policies when they are implemented individually and jointly. The main findings of this study are concluded as below.

(i) Combining mandatory phaseout with a rate-based ETS leads to further coal power generation reductions and carbon intensity reductions, namely enhancing the policy stringency.

(ii) Provinces respond differently to mandatory and market-based policies in terms of coal power generation, and some of the responses are complementary. Such impact disparity contributes to the policy enhancement under the combination of the mandatory coal power phaseout and the rate-based ETS.

(iii) The type of ETS affects the impacts of policy combination through permit scarcity. The combination in a rate-based ETS hardly affects the permit scarcity, while the combination in a mass-based ETS reduces the permits scarcity and leads to potential market failure.

(iv) The mandatory phaseout leads to significantly larger consumption losses when compared with ETS regardless of policy combination. Permit cancellation in a mass-based ETS with the co-existence of mandatory phaseout would prevent such market failure but increase the economic loss.

Author contributions

Conceptualization: Z.Y., Y.G. Methodology: Z.Y., A.C. Formal analysis, investigation, and visualization: Z.Y., Y.G., A.C., W.W., and R.B. Supervision: Y.G. and R.B. Funding acquisition: Y.G. Writing - original draft: Z.Y. Writing - review and editing: Y.G., A.C., W.W., and R.B.

Acknowledgement

This study is financially supported by Natural Science Foundation of China (Grant No. 71810107001; 72088101; 72192833), Special Fund for Creative Research Groups of Natural Science Foundation of China (72221001).

Conflicts of interest

We declare no conflict of interest.

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