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Promoting inter-regional cooperation to reduce CO_2 abatement cost in China

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A R T I C L E I N F O

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A B S T R A C T

CO_2 emissions reduction is a global challenge while the associated cost pressure presents a crucial issue. Within a country, each region, with different levels of abatement cost, may play different roles to achieve the national target of CO_2 emissions reduction. Such heterogeneity could play a role in the cost efficiency of national CO_2 emissions reduction, i.e. the minimum total abatement cost across the entire country. Previous models predominately focus on minimizing the total abatement cost, while the allocation of cooperative benefits is largely overlooked. We constructed a combined regional optimization and game model, i.e., the cooperative emission reduction model. The aim is to achieve the national carbon reduction target while reducing CO_2 emissions at a minimum cost through inter-regional cooperation. In order to achieve cooperation, it is imperative to ensure that every participating region can benefit from cooperation. This study developed a cooperative emission reduction model based on the Shapley value method of game theory to determine the mechanism to distribute cooperation benefits amongst participating regions in fairness. Compared to the total costs before applying this model, 17.04 % ~ 33.62 % and 19.59 % ~ 24.62 % total CO_2 abatement costs of China can be saved in 2025 and 2030, respectively. This method can be employed in other countries to assist policymakers to establish an appropriate goal for CO_2 emission reduction, and formulate a compensation mechanism to promote inter-regional cooperation with fairness and minimum cost.

1. Introduction

In recent years, with the rapid development of the economy, China's carbon emissions have increased steadily, and has become one of the largest carbon emitters in the world (World Bank, 2019; Lu et al., 2020). Due to the significant impact of CO_2 on global warming, China is facing significant pressure from the international community to reduce CO_2 emissions. In order to control the rise of global average temperature within 2 °C above the pre-industrial level and strive for the consensus goal of 1.5 °C (UNFCCC, 2010), the Chinese government has made a lot of efforts. As early as 2015, it announced the “National Determined Contribution” (NDC) goal of carbon emission reduction by 2030. This was further updated in 2020: CO_2 emissions will reach the peak by 2030, and strive to achieve carbon neutrality by 2060, and by 2030, the carbon emission per unit of GDP (carbon emission intensity) decreased by >65 % compared with 2005 (The Central People's Government of the People's Republic of China, 2022).

It is not easy to achieve these goals, as mitigating CO_2 inevitably incurs costs (possible economic losses) (Li et al., 2018; Fang et al., 2021). There is a growing level of interest in exploring mechanisms to improve the cost-effectiveness of CO_2 reductions (Cao et al., 2021; Dai et al., 2020; Zheng et al., 2022). By considering the differences in marginal abatement costs (MAC, i.e., the cost caused by an additional unit of CO_2 emissions reduction) amongst regions, the total abatement costs (total cost of reducing a certain amount of CO_2 emissions) of the entire country can be minimized (Terhaar et al., 2022). The inter-regional cooperation can reduce total abatement costs and plays a crucial role in solving environmental problems (Cui et al., 2014; Zhou et al., 2013). The cooperation in this study refers to the regions with high MACs could choose to transfer their abatement tasks to the regions with low MACs as long as the cost (financial compensation for transferring CO_2 reduction tasks) can be paid for the transfer of CO_2 emissions. Meanwhile, the capability (the difficulty of reducing CO_2 emissions) of CO_2 emissions reduction and the emission reduction target set by the central government are taken into account as constraints. However, these cooperation does not happen automatically. It is paramount to have fair distribution

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of cooperation benefits (cost savings from cooperation in reducing CO_2 emissions). Fyson et al. (2020) constructed a burden-sharing approach that considers cumulative per capita emissions (CPCE) and ability to pay (AP), to fairly allocate the burden of deploying CO_2 emissions reduction amongst countries and regions. Gazzotti et al. (2021) conducted a benefit-cost model to compare the self-interest and cooperative behavior of countries. Their results showed that without international cooperation, global temperatures would rise, and cooperation could stabilize global temperatures within the Paris target range. However, they only discussed how to fairly allocate emission reduction tasks, while the equality of allocating the savings from total abatement costs is overlooked. Xue et al. (2015) proposed a cross-provincial cooperation game model to reduce the cost of air pollution control in the Beijing-Tianjin-Hebei region in China. Their results show that cooperation can reduce the total abatement cost of air pollutants by as high as 11.29 %. Wang et al. (2019) examined the total cost of SO_2 abatement in the Yangtze River Delta region through a Generalized Nash Equilibrium Game (GNEG) model, noting that the optimal SO_2 removal scenario of the GNEG model saved 3.1 % of the total cost of pollutant removal. Zhao et al. (2021) developed a Cooperative Governance Model (CGM) and demonstrated that such model can reduce the total SO_2 reduction cost of the Beijing-Tianjin-Hebei region by 0.4 % compared to the independent autonomy model.

However, there are limitations associated with previous studies on inter-regional cooperation. The vast majority of previous studies focused on the effect of cooperative emission reduction efforts on SO_2 emission amongst provinces in China (Xie et al., 2016; Wang et al., 2019; Liu et al., 2022b; Xue et al., 2015). By contrast, there is a lack of studies on cooperative efforts on CO_2 reduction. Meanwhile, previous studies are mainly limited to the partial regions of China, such as Beijing-Tianjin-Hebei and Yangtze River Delta regions (Zhao et al., 2021; Liu et al., 2022a). In terms of the research period, most of the previous studies focused on the air pollution control that had occurred in the past. The single time scale and the cases that have occurred limit existing studies in guiding future scenarios (Yang, 2020; He et al., 2018b; Xue et al., 2019).

To address these gaps, in this study, we expand the scope to the whole of China under 1.5 °C and 2 °C scenarios in 2025 and 2030 (scenario design). We combine the optimization model (minimizing the total abatement costs) and game model (allocating the benefits of collaboration) to develop a Cooperative Emission Reduction (CER) model that can simulate 448 ways of cooperation. Through this model, we propose an inter-regional cooperation strategy to minimize the total CO_2 abatement cost and a corresponding mechanism to determine the compensation for regional transfer.

The method proposed in this study to establish a regional compensation mechanism is based on game theory, which can make full use of the optimization space provided by the regional differences in MACs to minimize the total cost of emission reduction and rationally allocate the cost savings. Firstly, this method provides a quantitative tool for promoting regional cooperation. Such method can help other countries and regions around the world to establish cooperative CO_2 abatement models for reducing the total cost of mitigating climate change. Secondly, quantitatively and reasonably allocating emission reduction cooperation benefits can enhance the enthusiasm of various regions and help consolidate the stability of cooperation.

The remainder of this study is presented below. Section 2 performs scenario setting and develops a regional Cooperation Emission Reduction (CER) model, which consists of two parts: (1) the total cost regional optimization cooperation model that accounts for CO_2 abatement costs; (2) the game model of the Shapley value that fairly allocates the benefits of cooperation. Section 3 conducts the empirical analysis of seven regions in China. Section 4 compares this study with other studies, discusses the limitations of this study, and provides policy implications and research implications. Section 5 concludes the study.

2. Method

It is assumed that all regions are rational decision-makers, that they will focus on achieving the national carbon reduction target, and pursue their own minimum total abatement costs by choosing the optimal CO_2 abatement rates. Each region should take into account the strategies of other regions in its decision-making. This is a classic cooperative game problem (Fukushima, 2011; Guo et al., 2015; Heusinger and Kanzow, 2009; Rosen, 1965; Wang et al., 2019).

Therefore, in this section, we construct a CER model with a scenario design that aims to achieve national CO_2 emission reduction targets at minimal cost through inter-regional cooperation. We divided 30 provinces of China into 7 regions for regional research, verifying the effectiveness of the CER model. The specific regional distribution is shown in Table 2. Finally, a benefit allocation mechanism was proposed to enhance the cooperation willingness of all participants.

2.1. The cooperation emission reduction (CER) model

This CER model consists of two parts: a total cost regional optimization model and a game model (a mathematical tool to analyze the multi-player decision-making process in which to achieve optimal outcomes (Gloria et al., 2011)), i.e., Shapley value, which is a concept in cooperative game theory used to determine the contribution value of each participant in a cooperative alliance (Shapley, 1953).

2.1.1. The total cost regional optimization model

This model includes two modules. The first one is the optimization calculation module, and the second one is the total abatement cost curve calculation module.

(1) The optimization calculation module.

This section establishes the optimization calculation module represented as Eqs. (1)–(3). By optimizing the abatement rates of each region to minimize the total abatement cost, following the formulas:

$$min \sum_{i=1}^{n} RC_i(P_i) \tag{1}$$

$$s.t. \sum_{i=1}^{n} (P_i \times E_{i0}) \geq R \tag{2}$$

$$\alpha_i \leq P_i \leq \beta_i, i = 1, 2, \ldots, n \tag{3}$$

Where $RC_i(P_i)$ is the total CO_2 abatement cost function for region i, which can be obtained from Eq. (9); P_i represents the CO_2 abatement rate of region i relative to the base year (P_i=$\Delta E_i/E_{i0}$); E_{i0} represents CO_2 emissions of region i in the base year; ΔE_i represents the CO_2 emission reduction in the target year of region i; R represents the national total emission reduction target under the 1.5 °C and 2 °C scenarios in the

Table 1
CO_2 reduction target under 1.5 °C and 2 °C scenarios by region (Mt).

	CO_2 reduction target in 2025		CO_2 reduction target in 2030	
Scenarios	1.5 °C	2 °C	1.5 °C	2 °C
North	808.09	668.17	1435.2	1256.26
Northeast	367.88	297.23	606.53	514.79
East China	997.43	905.86	1772.92	1569.84
South China	332.01	249.87	595.85	466.61
Central	356.75	377.03	685.87	608.40
Southwest	286.77	309.50	546.54	502.38
Northwest	423.40	289.99	709.32	570.95
Total	3572.33	3097.66	6352.75	5489.23

Note: The CO_2 reduction target data in this table are all annual emission reductions.

target yea, which can be obtained in Table 1 of the scenario design section. α_i and β_i represents the upper and lower bounds of the CO_2 abatement rate, respectively; i represents the number of regions, in this study, $n = 7$.

Eq. (1) is the objective function of the model, which indicates that the total CO_2 abatement cost of the whole region is minimized by choosing the optimal CO_2 abatement rate through cooperative emission reduction.

Eq. (2) represents the constraints for all regions, which means that the sum of regional CO_2 emission reduction should not be less than the national CO_2 emission reduction targets in the target year.

Eq. (3) represents the constraints for each region, which means that the emission reduction rate for each region should be within a reasonable range. The lower bound of CO_2 abatement rate (α_i) indicates the minimum level of regional abatement rate, which should take into account the national emission reduction target requirements for each region. The upper bound of CO_2 abatement rate (β_i) indicates the maximum limit value of regional CO_2 emission reduction, which should consider the independent emission reduction capacity of each region. The specific upper and lower bound parameters setting is shown in Supplementary Table S1 and Table S2.

(2) The marginal abatement cost curve for each region

The total abatement cost function ($RC_i(P_i)$) was obtained based on the marginal abatement cost (MAC) curves, where MAC curves refer to the cost caused by an additional unit of emissions reduction (Fabian and Neil, 2011; Wächter, 2013). The MAC curves depict the functional relationship between the MAC of CO_2 in each region and its emission reduction potential. Theoretically, the emission reduction potential reflects the difficulty level of the region's CO_2 emission reduction (Liu and Feng, 2018; Zhang et al., 2022). The level of MAC dominates the abatement behavior after inter-regional cooperation, which determines whether each region will help reduce emissions in other regions or transfer emission reduction tasks to other regions.

As for the calculation of MAC, many studies are based on the directional distance function model (DEA) to evaluate the MAC in various regions (Wang and Wang, 2022; Tang et al., 2016). However, this method depends on the selection of direction vectors. Different evaluation objects choose different direction vectors, which results in the limitation of inconsistent evaluation standards and greatly affects the robustness of the evaluation results. Although this method is widely used, the results obtained by different scholars differ greatly (He et al., 2018a). Therefore, this study based on the research method of Fang et al. (2021) and Zhang et al. (2022) does not rely on the selection of direction vectors, but instead uses carbon intensity and carbon productivity (i.e., the GDP output per unit of CO_2 emissions, which is the inverse of carbon intensity (Kaya and Yokobori, 1997)) to calculate total abatement cost, reflecting the potential economic losses caused by regional carbon production efficiency growth.

The relationship between abatement rate and MAC is not a simple linear relationship. As the abatement rate increases, emission reduction becomes more difficult and the increase in abatement cost is faster. In terms of fitting the MAC curve, different studies have used different function expressions, such as logarithmic function (Cui et al., 2014; Li et al., 2010), power function (Wu et al., 2019), and quadratic polynomial function (Fang et al., 2021; Zhou et al., 2013; Tang et al., 2016). We attempted to simulate the MAC curve using these functions and found that the quadratic polynomial function had the best degree of simulation (Supplementary Tables S3–S5). Therefore, the marginal abatement cost (MAC_i) and abatement rate (P_i) data of each region from 2010 to 2020 were regressed using a quadratic polynomial function to obtain the MAC curves in Eq. (4):

$$MAC_i(P_i) = a_iP_i^2 + b_iP_i + c_i \tag{4}$$

Where $MAC_i(P_i)$ represents the CO_2 marginal abatement cost function for region i. a_i, b_i and c_i are the parameters to be estimated.

It is necessary to obtain statistical data of MAC_i and P_i in order to perform least squares fitting on Eq. (4). Due to statistical data limitations, we lack data on the cost of CO_2 abatement in China over the years. Inspired by the research of Fang et al. (2021) and Zhang et al. (2022), the MAC_i can be represented by the potential economic loss, instead of the investment on the clean development mechanism (CDM), i.e., CO_2 emissions reduction mechanism. Therefore, the index of potential economic loss is expected to reveal both direct and indirect abatement costs (Nordhaus, 2017). By multiplying CO_2 emissions with the difference in emission productivity between corresponding years, the potential economic loss in the year t (PEL_i^t) could be calculated by Eqs. (5)–(6):

$$MAC_i^t = PEL_i^t = \left(CP_i^t - CP_i^{t_0}\right) \times E_i^{t_0} \tag{5}$$

$$CP_i^t = \frac{G_i^t}{E_i^t} \tag{6}$$

Where CP_i^t and $CP_i^{t_0}$ is the carbon productivity in year t and t_0 of region i, here t is 2020, t_0 is 2010; $E_i^{t_0}$ is CO_2 emissions in region i in the year t_0; E_i^t is CO_2 emissions in year t of region i; G_i^t is GDP in year t of region i.

As for the CO_2 abatement rate in the year t (P_i^t), there is also a lack of statistical data. Obtaining the corresponding year's CO_2 emissions reduction (ΔE_i^t) is the key to calculating the P_i^t. According to the statistical data, China's CO_2 emissions have increased in the vast majority of years, actually. Therefore, we lack annual statistics on CO_2 reduction. However, a large number of studies have shown that carbon intensity (CO_2 emissions per unit of GDP) can be used to estimate CO_2 emission reductions (Cai et al., 2020; Su et al., 2012; Wang et al., 2013; Wang et al., 2017; Wu et al., 2020). This method has been proven to be reasonable. Therefore, in this study, we also use similar methods. Based on the research of Fang et al. (2021) and Zhang et al. (2022), we used statistical data on carbon intensity and GDP (G_i^t) to calculate the CO_2 emission reduction (ΔE_i^t):

$$\Delta E_i^t = \left(CI_i^{t_0} - CI_i^t\right) \times G_i^{t_0} \tag{7}$$

$$CI_i^t = \frac{E_i^t}{G_i^t} \tag{8}$$

Where CI_i^t and $CI_i^{t_0}$ is carbon intensity in year t and t_0 of region i; $G_i^{t_0}$ is GDP of region i in the year t_0. The meaning of other variables is the same as Eq. (6).

Eventually, according to Eqs. (5)–(8), the data of marginal abatement cost (MAC_i) and abatement rate (P_i) data of each region from 2010 to 2020 can be obtained. Then we used these data to regress the marginal abatement cost function $MAC_i(P_i)$, i.e., the MAC curve of each region. Based on the derivative relationship between MAC and total cost, the total cost function (Eq. (9)) for each region is then acquired.

$$RC_i(P_i) = \int MAC_i\, d(P_i) = \frac{1}{3}a_iP_i^3 + \frac{1}{2}b_iP_i^2 + c_iP_i \tag{9}$$

Table 2
Seven economic regional divisions in China.

No.	Region	Provinces
1	North	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia
2	Northeast	Heilongjiang, Jilin, Liaoning
3	East China	Shanghai, Jiangsu, Zhejiang, Shandong, Anhui, Fujian, Jiangxi
4	South China	Guangdong, Guangxi, Hainan
5	Central	Henan, Hubei, Hunan
6	Southwest	Chongqing, Sichuan, Guizhou, Yunnan
7	Northwest	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

Note: Due to data unavailability, Tibet, Hong Kong, Macau, and Taiwan are excluded from this study.

Table 3
Comparison of CO_2 emission reduction effects before and after cooperation at 1.5 °C in 2030 (β_i=78 %).

Region	After optimized cooperation			Before optimized cooperation		
	P_i^*(%)	ΔE_i^*(Mt)	AC_i(billion USD)	P_i(%)	ΔE_i(Mt)	RC_i(billion USD)
East China	57.52	1734.85	174.96	58.78	1772.92	186.16
South China	39.33	329.64	51.04	71.09	595.85	292.88
Central	41.51	502.19	44.23	56.70	685.87	121.54
Northeast	65.56	630.21	71.68	63.09	606.53	65.06
North	78.00	1815.77	184.05	61.67	1435.2	96.99
Southwest	50.07	531.19	45.88	51.51	546.54	50.45
Northwest	76.86	808.90	87.97	67.40	709.32	62.23
Total	–	6352.75	659.80	–	6352.75	875.32

Note: P_i, ΔE_i and RC_i denotes the CO_2 abatement rate, the CO_2 emission reduction and the total CO_2 abatement cost before optimized cooperation in region *i*; P_i^*, ΔE_i^* and AC_i denotes the CO_2 optimal abatement rate, the CO_2 emission reduction and the total CO_2 abatement cost under the total cost regional optimization model (after optimized cooperation) for region *i*. The specific optimization calculation process can be found in the Method section.

Table 4
Comparison of CO_2 emission reduction effects before and after cooperation at 2 °C in 2030 (β_i=63 %).

Region	After optimized cooperation			Before optimized cooperation		
	P_i^*(%)	ΔE_i^*(Mt)	AC_i(billion USD)	P_i(%)	ΔE_i(Mt)	RC_i(billion USD)
East China	47.98	1513.82	104.48	49.75	1569.84	115.80
South China	39.33	326.66	51.04	56.18	466.61	145.28
Central	37.00	461.19	30.32	48.81	608.40	74.94
Northeast	52.22	514.81	40.54	52.22	514.77	40.55
North	63.00	1546.01	102.74	51.19	1256.26	58.87
Southwest	42.71	461.92	26.97	46.45	502.38	35.71
Northwest	61.93	664.90	49.90	53.18	570.95	33.68
Total	–	5489.23	405.98	–	5489.23	504.83

Note: P_i, ΔE_i and RC_i denotes the CO_2 abatement rate, the CO_2 emission reduction and the total CO_2 abatement cost before optimized cooperation in region *i*; P_i^*, ΔE_i^* and AC_i denotes the CO_2 optimal abatement rate, the CO_2 emission reduction and the total CO_2 abatement cost under the total cost regional optimization model (after optimized cooperation) for region *i*. The specific optimization calculation process can be found in the Method section.

Table 5
Cost savings and transferred compensation after optimized cooperation at 1.5 °C scenario in 2030 (β_i=78 %).

	Benefits (billion USD)							
	East China	South China	Central	Northeast	North	Southwest	Northwest	Total
A: Total CO_2 abatement cost before optimized cooperation (RC_i)	186.16	292.88	121.54	65.06	96.99	50.45	62.23	875.32
B: Actual total CO_2 abatement cost after optimized cooperation (AC_i) (before benefit allocation)	174.96	51.04	44.23	71.68	184.05	45.88	87.97	659.80
C: Total cost savings of CO_2 reduction after optimized cooperation: C = A-B	11.20	241.84	77.30	−6.62	−87.05	4.57	−25.74	215.51
D: Cooperation benefit allocation by Shapley value method (regional costs savings: BA_i)	9.37	134.75	21.58	6.50	29.79	4.98	8.55	215.51
E: Transferable compensation to other regions (TC_i): E = C-D	1.84	107.09	55.72	−13.12	−116.84	−0.40	−34.29	0.00

Note: "-"–represents economic compensation obtained from other regions. The results of 2025 are shown in Supplementary Tables S9–S10. The total cost of CO_2 abatement in each region before cooperation is A. Through cooperation, the total cost of CO_2 abatement in each region becomes B (obtained by the total cost optimization model), then the change of the total cost before and after cooperation is the difference between A and B, i.e., C. Based on the contribution of each region to cooperation (obtained by the Shapley value method), the regional cost savings D is obtained. Revise the cost after cooperation (C) to obtain the financial compensation E that each region should pay or receive from other regions.

Assuming that the total abatement cost function remains unchanged in 2025 and 2030. By substituting Eq. (9) into Eq. (1), the minimized total abatement cost can be obtained by Eqs. (1)–(3).

2.1.2. Game model: the Shapley value for allocation of the cooperation benefits

Although optimized cooperation can reduce the total cost of abatement, cooperation does not happen automatically, only the scientific and reasonable allocation of cooperation benefits can ensure the stable occurrence of cooperation. From the existing methods, the commonly used methods are the Shapley value (He et al., 2018b), core method (Dong et al., 2020), game quadratic programming (GQP) method (Lozano et al., 2013), minimum costs-remaining savings (MCRS) method (Driessen and Tijs, 1985). Compared with other methods, the Shapley value method takes into account the situation of cooperative pollution control alliance formed by some and all cooperative participants at the same time, that is, the contribution of all cooperative participants in the region in the state of comprehensive and non-comprehensive cooperation (Xue et al., 2019). Secondly, the Shapley value method can also allocate the cooperation benefits according to the contribution of the cooperative participants, thus reducing the governance costs of all participants (Xie et al., 2016; Yang, 2020). The benefits allocation scheme determined by this method is fair compared to other methods, which is conducive to achieving comprehensive cooperative governance of the whole region, so it is widely used in the field of air pollution control (Xue, 2014; Liu et al., 2022b).

Table 6
Cost savings and transferred compensation after optimized cooperation at 2 °C scenario in 2030 (β_i=63 %).

	Benefits (billion USD)							
	East China	South China	Central	Northeast	North	Southwest	Northwest	Total
A: Total CO_2 abatement cost before optimized cooperation (RC_i)	115.80	145.28	74.94	40.55	58.87	35.71	33.68	504.83
B: Actual total CO_2 abatement cost after optimized cooperation (AC_i) (before benefit allocation)	104.48	51.04	30.32	40.55	102.74	26.97	49.90	405.98
C: Cost savings of CO_2 reduction after optimized cooperation: C = A-B	11.32	94.24	44.63	0.00	−43.86	8.74	−16.22	98.85
D: Cooperation benefit allocation by Shapley value method (regional costs savings: BA_i)	4.65	54.99	13.35	2.88	15.31	2.83	4.85	98.85
E: Transferable compensation to other regions (TC_i): E = C-D	6.67	39.25	31.28	−2.88	−59.17	5.91	−21.07	0.00

Note: "-" –represents economic compensation obtained from other regions. The results of 2025 are shown in Supplementary Tables S9–S10. The total cost of CO_2 abatement in each region before cooperation is A. Through cooperation, the total cost of CO_2 abatement in each region becomes B (obtained by the total cost optimization model), then the change of the total cost before and after cooperation is the difference between A and B, i.e., C. Based on the contribution of each region to cooperation (obtained by the Shapley value method), the regional costs savings D is obtained. Revise the cost after cooperation (C) to obtain the financial compensation E that each region should pay or receive from other regions.

Set $C = \{1, 2, \ldots, n\}$ is a set containing n regions. Any subset cooperation alliance s (denoting any combination in the set C containing n regions, in this study, $n = 8$.), corresponds to a real-valued function $v(s)$ satisfying $v(\Phi)$=0, $v(s_i \bigcup s_j) \geq v(s_i) + v(s_j)$,where $[C, v]$ is said to be the cooperation strategy of n regions, v is called the characteristic function of the cooperation strategy, and $v(s)$ (billion USD) is benefit of the cooperation of the inter-regional cooperative alliance s. The Shapley value is determined by the characteristic function v, denoted as $Y = \{y_1, y_2, \ldots, y_n\}$, represents the allocation strategy for a cooperative game benefit amongst regions, where $y_i(v)$ (billion USD) denotes the cooperative gain obtained when participating in inter-regional cooperation for any region i, $y_i(v)$ can be calculated by the following formula (He et al., 2018b):

$$y_i(v) = \sum_{s_i \in i} w(|s|) \left[v(s) - v\left(\frac{s}{i}\right) \right] \tag{10}$$

Where $w(|s|)$ is a weighting factor denoting the probability that region i participates and forms inter-regional cooperative alliance s in a random form, $|s|$ representing the number of regions in the inter-regional cooperative alliance s, $v(s/i)$ denotes the benefits of cooperation when region i does not participate in the cooperation, and $v(s) - v(s/i)$ represents, for inter-regional cooperative alliance s, the impact on the alliance when region i does not participate in it, reflecting the contribution of region i to the cooperation benefits of inter-regional cooperative alliance s. The weighting factor $w(|s|)$ can be calculated as (He et al., 2018b):

$$w(|s|) = \frac{(n - |s|)!(|s| - 1)!}{n!} \tag{11}$$

Based on the total abatement cost before and after the cooperation and the cooperation benefits calculated by the Shapley value method, the transfer compensation (TC_i) of each region can be obtained (Yang et al., 2021). The calculation formula is Eq. (12):

$$TC_i = RC_i - AC_i - BA_i \tag{12}$$

Where RC_i is total CO_2 abatement cost of region i in the target year; AC_i is total abatement cost in region i after cooperation; BA_i is allocation of cooperation benefits for region i, i.e., contribution benefits. If $TC_i > 0$, it means that region i needs to pay financial compensation to other regions; if $TC_i < 0$, it means that region i should receive financial compensation from other regions.

2.2. Scenario design

In this study, scenario design is conducted based on the Dynamic Projection model for Emissions in China (DPEC) of Liu et al. (2022c) to consider multiple changes in future socioeconomic development and climate ambitions. By combining a shared socioeconomic pathway (SSP) with the representative concentration pathway (RCP), different levels of climate ambition are constructed, and two CO_2 reduction control scenarios are established for 1.5 °C and 2 °C. We explore the impact of cooperative emission reduction on CO_2 total cost savings in 2025 and 2030 under 1.5 °C and 2 °C scenarios.

1.5 °C baseline scenario: corresponds to the SSP1-RCP1.9 pathway, aiming to pursue a global temperature rise limit of 1.5°C, and requires CO_2 reductions of 3572.33 and 6352.75 Mt in 2025 and 2030 in China, respectively.

2 °C baseline scenario: follows the SSP1-RCP2.6 pathway, consistent with the Paris Agreement's goal of controlling the temperature rise to no >2 °C. Under this scenario, CO_2 reductions of 3097.66 and 5489.23 Mt. are required in 2025 and 2030 in China, respectively.

It is assumed that under 1.5 °C and 2 °C scenarios, each region conducts CO_2 emission reduction through independent means. The CO_2 reduction target in the target year (2025 and 2030) for each region under 1.5 °C and 2 °C scenarios are shown in Table 1. This is the baseline scenario before optimized cooperation. On this basis, we apply the CER model to optimize and establish compensation mechanisms, and compare the total abatement cost before and after optimized cooperation.

2.3. Data sources

Statistical data: The regional GDP data for each region from 2011 to 2020 are extracted from the China Statistical Yearbook (NBS, 2020), and all of which have been converted to the 2010 prices for comparability (NBS, 2020). Carbon emission data (2010−2020) are extracted from the provincial emission inventories in the China Emissions Account and Datasets (CEADs, 2021) and the China City CO_2 Emissions Dataset (2020).

Forecast data: The GDP growth rate targets for each province in 2025 are taken from the "14th Five-Year Plan (2021–2025)" of 30 provinces in China (The Central People's Government of the People's Republic of China, 2021a). Since the 15th Five-Year Plan has not yet been released, the GDP growth rate in 2030 is assumed to be consistent with that of the 14th Five-Year Plan. The carbon emission in 2025 and 2030 under 1.5 °C and 2 °C scenarios are from the DPEC model (Dynamic Projection model for Emissions, 2021), which is established by Liu et al. (2022c). The carbon intensity reduction target of the 14th Five Year Plan serves as the lower bound of the CO_2 abatement rate in 2025, and the lower bound of the CO_2 abatement rate in 2030 also continues the carbon intensity reduction target of 2025.

3. Result

3.1. The impact of optimized cooperation on the total CO_2 abatement cost savings

3.1.1. The total cost saving effects of optimized cooperation

The total CO_2 abatement cost after optimized cooperation will be significantly reduced with the total CO_2 emission reduction unchanged (see Table 3 and Table 4). For example, under 1.5 °C and 2 °C scenarios in 2030, the total CO_2 abatement cost decreases from US\$875.32 billion and US\$504.83 billion to US\$659.80 billion and US\$405.98 billion, respectively. This presents a saving of 24.62 % and 19.58 % of the total cost compared with that before optimized cooperation.

3.1.2. Analysis of the reasons for the total cost savings effects

This is due to the optimization result after taking into account the MAC of CO_2 in each region. The MAC curves of each region are shown in Fig. 1. Meanwhile, our results show that the relative ranking of MACs for CO_2 in the seven major regions of China is higher in the east, south and central, and lower in the west and north (Fig. 1). This is similar to other research results (Dai et al., 2020; Tang et al., 2016).

Globally, the average MAC of CO_2 in developed countries is around US\$700–800 ton^{-1} (Liu and Feng, 2018), such as Japan (US\$822 ton^{-1}), Italy (US\$761 ton^{-1}), UK and Spain (US\$742 ton^{-1}) and French (US \$760 ton^{-1}). The average MAC in the east, south and central regions (US \$800 ton^{-1}) of China is close to the average MAC of these developed countries. Therefore, the further reduction potential is limited in the east, south and central regions of China. If these developed regions continue to reduce emissions, they will need to suffer from more economic losses. On the contrary, the average MAC in the west and north region (US\$200 ton^{-1}) of China is only 1/4 of the average MAC in developed countries. Therefore, these regions have a large emission reduction potential and can help the east, south and central regions undertake more emission reduction tasks. This is different from Pollution Heaven Hypothesis as the developed regions transfer the carbon reduction demand to developing countries. In other words, in this circumstance, developing countries will carry more carbon reduction activities rather than high-polluted activities.

As a result, the CO_2 abatement rates in East China, South China and Central have significantly decreased after optimized cooperation. In 2025, the optimal abatement rates of the three regions decreased by an average of 1.01 % ~ 15.18 % under 1.5 °C and 2 °C scenarios (Supplementary Tables S6–S7). In 2030, the optimal abatement rates of the three regions decreased by an average of 1.52 % ~ 24.31 % under 1.5 °C and 2 °C scenarios (see Table 3 and Table 4). These regions may shift the task of reducing CO_2 emissions to the regions with low MACs, thereby reducing their own total abatement costs and the national abatement costs. The regions with low MACs such as North and Northwest, the abatement rate after optimized cooperation has increased significantly (see Table 3 and Table 4 and Supplementary Tables S6–S7). They may share more CO_2 emission reduction task to realize the minimization of national abatement costs. However, the total abatement costs of these regions will increase after optimized cooperation. From a cost perspective, these so-called loss-making regions are likely to be unwilling to participate in cooperation. Therefore, the cooperative benefits of CO_2 emission reduction need to be scientifically and reasonably allocated to each participating region to ensure the formation of a cooperative emission reduction relationship, thereby reducing the total abatement costs of the entire China.

3.2. The allocation of optimized cooperation benefits

In order to ensure that all regions can benefit from the cooperation and encourage them to actively participate in inter-regional cooperation in CO_2 emission reduction, the benefits of cooperation should be allocated fairly and effectively amongst the participating regions. In this study, the Shapley method is employed to allocate the benefits of cooperation in 2025 and 2030 (Eqs. (10)–(12) in the Method section).

3.2.1. Analysis of the total and different alliances' cooperation benefits

According to the calculation result of Shapley value in row D of Table 5 and Table 6, the total cooperation benefits (i.e., the total cost

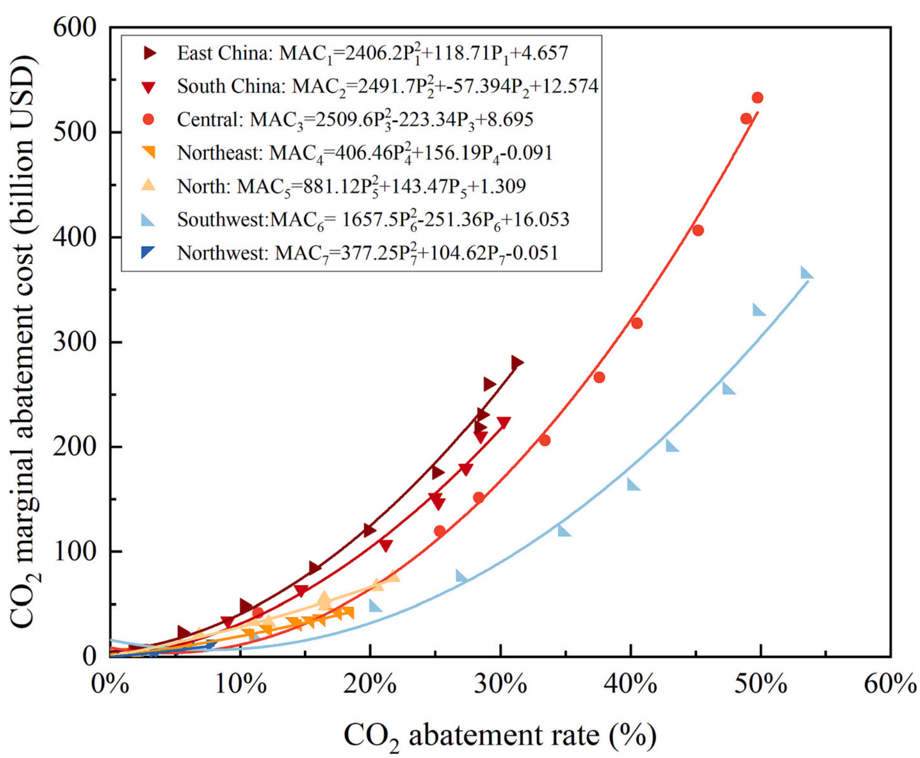

Fig. 1. The estimated CO_2 marginal abatement cost curves for seven regions.

saving) obtained by each region after optimized cooperation is US \$215.51 billion and US\$98.85 billion under 1.5 °C and 2 °C scenarios in 2030, respectively. That is, after optimized cooperation, the sum of cooperation benefits (D) allocated to each region is equal to the total cost savings of CO_2 emission reduction (C). Each participating region can obtain a certain amount of cooperation benefits. Fig. 2 shows the cooperation benefits under different cooperation alliances, taking North China under 1.5 °C scenario in 2030 as an example. Cooperation alliances range from two to seven. There are 64 possible alliances of cooperation. The sum of the benefits of all cooperative scenarios is the total benefits of cooperation in North Chian (row D in Table 5). We also discover that the benefits of cooperation show a U-shape. Although the alliance with the highest cooperation benefits is when there are the most participants, it is not necessarily the case that the more participants there are, the greater the cooperation benefits will be.

3.2.2. *Fair allocation scheme and compensation mechanism of cooperation benefits*

After considering the total cost savings of CO_2 emission reduction (row C in Table 5 and Table 6) and cooperation benefits (row D in Table 5 and Table 6) of each region, we calculated the compensation transfer between regions according to Eq. (12) in the Method section (see row E in Table 5 and Table 6).

The regions that pay compensation are mainly located in the economically developed regions in the east, south and central regions of China, such as East China, South China and Central. Because of their high economic level and high MAC, these regions can significantly reduce the total abatement costs after optimized cooperation (East China, South China and Central saved 7.89 %, 73.72 % and 61.58 % total CO_2 abatement costs respectively under 1.5 °C and 2 °C scenarios in 2030), and are the beneficiaries of cooperation. They should provide some additional financial compensation to other regions, which can help them to achieve their own emission reduction targets. Taking the 2 °C scenario in 2030 (Table 6) as an example, the total abatement cost in South China is US\$145.28 billion (row A in Table 6) before cooperation and decreased to US\$51.04 billion (row B in Table 6) after cooperation, so that South China saves US\$94.24 billion by optimized cooperation (row C in Table 6, i.e. A–B). However, according to the Shapley value calculation, its cooperation contribution is only US\$54.99 billion (row D in Table 6). Therefore, this region should take out the additional US \$39.25 billion (row E in Table 6, i.e. C–D) of cooperation benefit it received as compensation to other regions.

Most of the other regions that need to receive compensation are located in the economically underdeveloped regions in the west and north regions of China, such as North, Northeast and Northwest. These regions have large emission reduction potential due to their low MACs. They share the task of emission reduction for other regions after optimized cooperation, which increases their own total abatement costs (the total abatement costs of North, Northeast and Northwest increased by an average of 82.13 %, 10.17 % and 44.03 % respectively under 1.5 °C and 2 °C scenarios in 2030). If compensation is not given to these regions, they may not have the motivation to cooperate in reducing emissions. Therefore, calculating the contribution of these regions in cooperation and providing corresponding compensation is an important aspect of promoting cooperation in emission reduction. For example, under 2 °C scenario in 2030 (Table 6), the total abatement cost in North China is US \$58.87 billion (row A in Table 6) before cooperation and increased to US \$102.74 billion (row B in Table 6) after cooperation, so that North China needs to pay an additional CO_2 abatement cost of US\$43.86 billion (row C in Table 6, i.e. A–B) to help other regions to reduce emissions after optimized cooperation. However, after considering its cooperation benefit of US\$15.31 billion (row D in Table 6), North China can obtain a financial compensation of US\$59.17 billion (row E in Table 6, i.e. C–D) from other regions. Under such economic incentives, North China has the motivation to cooperate with other regions and achieve overall optimal results.

Through cooperation, the CO_2 abatement cost of each region can be reduced, thus minimizing the total abatement cost for the whole country. Compared with that before cooperation, the CER model fully takes into account in CO_2 emission reduction capabilities and economic

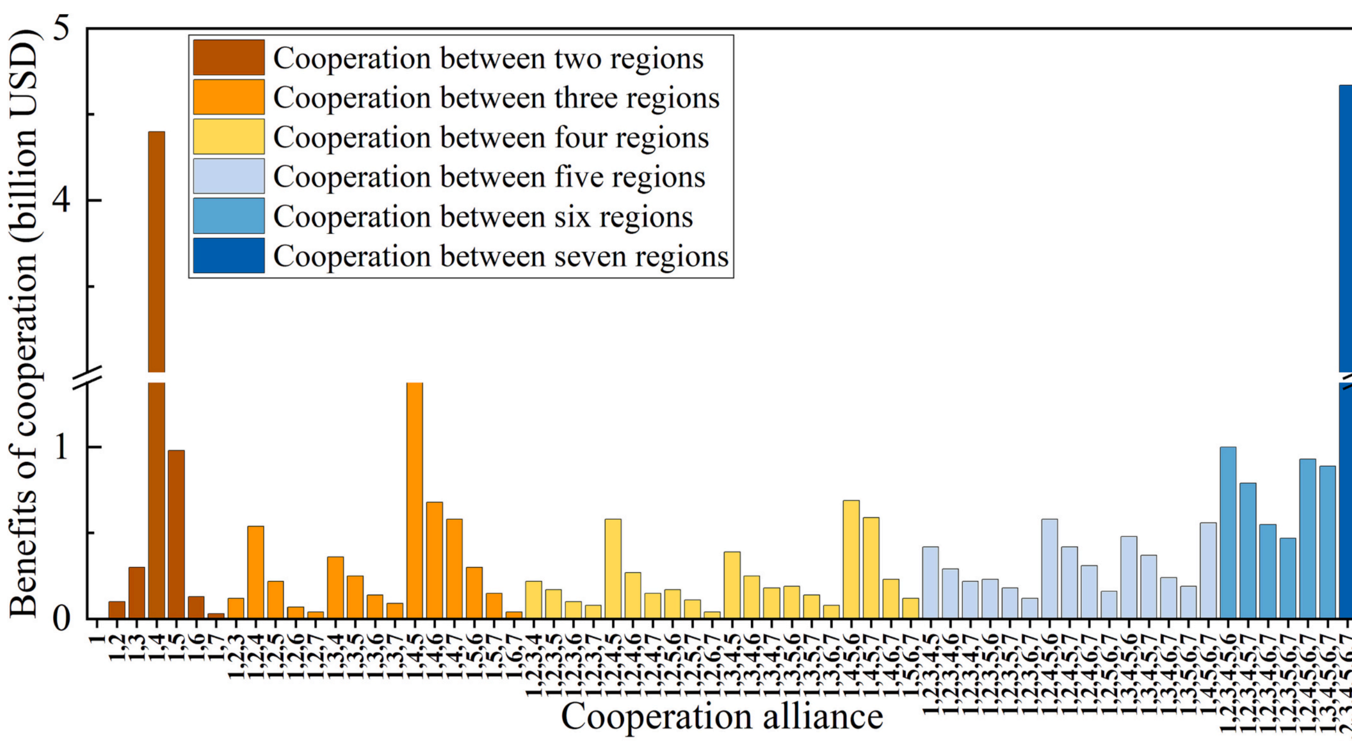

Fig. 2. The cooperation benefits under different cooperation alliances, taking North China under 1.5 °C scenario in 2030 as an example. 1, 2, 3, 4, 5, 6 and 7 represent North, Northeast, East China, South China, Central, Southwest and Northwest, respectively.

development level of different regions. This brings a win-win situation for each region and the whole country.

4. Discussion

4.1. Comparison with other similar studies

This study explored the positive effects of inter-regional cooperation and incentive mechanism on the total cost savings of CO_2 emission reduction. Previous studies placed more focused on the technological invitations to achieve carbon emission reduction while the associated cost is largely overlooked (Ang et al., 2023; Langie et al., 2022; Reis et al., 2023; Shi et al., 2022; Yang et al., 2021). In a complex system like a country, each region could play different roles considering their MAC. As a result, inter-regional cooperation may help to improve the cost efficiency of carbon abatement at the national level. The fair allocation of cost savings plays a crucial role in motivating local governments to participate into the cooperation. From the perspective of methodological innovation, this study proposed a CER model combining inter-regional optimization and a game model to ensure fair allocation of cooperation benefits amongst participating regions. Moreover, previous studies on inter-regional cooperation policies for CO_2 reduction lacked quantitative predictions (He et al., 2018b; Linsenmeier et al., 2023; Peng et al., 2022; Victor, 2012). To fill this gap, we explored the specific plans for allocating the benefit of cooperation for each participating region under different CO_2 emission reduction scenarios in 2025 and 2030, as well as the minimum total CO_2 abatement cost that can be ultimately achieved under this pathway.

4.2. Research limitations

Admittedly, there are still some limitations of this study, future research should consider the following improvements: (1) The game model in this study focuses on the CO_2 reduction strategies between regions at the same level, and then adopts a benefit allocation method based on game theory, such as the Shapley value method, to allocate the benefits of cooperation amongst the participants. In the future, we can establish a dynamic game model to study the participation of the central government and local governments as stakeholders in cooperation. (2) In this study, only the effect of cooperation on the reduction of total CO_2 abatement cost is considered. In the future, the model may be applied to the other pollutants to reduce total environmental governance costs.

4.3. Policy implications

It is worth noting that the regional cooperation compensation mechanism established in this study can be realized between regional governments through economic means.

For example, as a means of carbon market trading, companies or regions with high MACs purchase carbon emission rights from companies or regions with low MACs, and the price of carbon emission rights can reflect the compensation amount. On the other hand, the fiscal effect of carbon taxes in different regions can be leveraged (Landis and Bernauer, 2012). However, the situation faced by carbon tax policy will become more complex. Assuming that carbon taxes only have a fiscal effect in regions with high MACs, that is, these regions are unwilling to reduce emissions and are more willing to pay taxes. These taxes can be invested in areas with low MACs to reduce their emissions. At the same time, the carbon tax is more likely to have an environmental effect in areas with low MACs, which means that these areas are more willing to reduce emissions due to their low MACs and are unwilling to pay taxes. In the above situation, the carbon taxes also achieve the cost optimization results in the CER model. But there may also be another situation where carbon taxes also have a significant environmental effect in regions with high MACs. Then the average social abatement cost will increase, which cannot achieve the results of CER model. Therefore, carbon emission trading is a simple economic means to ensure inter-regional compensation mechanisms. The government should establish a systematic and reasonable policy system to achieve a cross-regional carbon emission trading system.

In 2021, China established a nationwide unified carbon emission trading market (The Central People's Government of the People's Republic of China, 2021a, 2021b), which provides a practical means to achieve inter-regional cooperation and reduce carbon abatement costs. In the future, more empirical research can be conducted on the Chinese carbon market to reveal and simulate the contribution of carbon emission trading systems in promoting inter-regional cooperation and reducing total abatement costs. This study proposes a game model based on emission reduction responsibility sharing and regional compensation mechanisms. The participants in the model are 7 regions in China, but in practice, the participants in cooperation emission reduction are not limited to the regional level. It can be provinces or provincial-scale cities, or different countries. Each participant considers the strategies of the other participants to achieve the overall CO_2 emission reduction target and to minimize the cost of reduction for each participant.

Therefore, although the results of this article are only meaningful to China, the methodology proposed in this article can be used for reference by other countries, in order to regulate the responsibilities and rights of countries regarding carbon reduction.

5. Conclusion

In order to improve the cost-effectiveness of CO_2 emission reduction, this study establishes a CER model, which consists of two parts: the optimization model and the game model. It aims to explore the positive impact of inter-regional cooperation and incentive mechanism on the total cost savings of CO_2 abatement. The key findings of the study are: (1) By utilizing regional differences in MACs, inter-regional cooperation can significantly save the total costs of CO_2 abatement compared to that before optimized cooperation; (2) based on the Shapley value for the allocation of the total costs saving to the region, each region can be allocated fair cooperation benefits, thus realizing the win-win situation of the cooperation.

It is necessary for the governments to establish a cooperative emission reduction model. Regions with high MACs, such as East China and South China, should be actively encouraged to participate in the cooperation to reduce their high abatement costs by transferring the abatement tasks to the low-cost regions. Those regions with lower MACs, such as North China and Northwest, should share the emission reduction burden of other regions as much as possible within their own emission reduction capacities. It will bring greater economic benefits to the low-cost regions by receiving substantial transferred compensation.

This article only provides a quantitative method for promoting regional cooperation to reduce total CO_2 abatement costs in theory. In the future, more research should focus on how to ensure the operation of regional cooperation compensation mechanisms. Relying solely on the central government to promote inter-regional cooperation is clearly not enough, and a bottom-up market approach is necessary to ensure the long-term and efficient operation of regional cooperation. Studying how to apply economic means, such as carbon trading or carbon taxation, to mobilize the enthusiasm of stakeholders is the key to supporting the implementation of this research result.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

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