

Article

Scenario Analysis of CO₂ Reduction Potentials from a Carbon Neutral Perspective

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Abstract: As a major emitter of CO₂, China needs to take responsibility for slowing down global warming. In this paper, the potential carbon emission intensity of provinces is firstly calculated using the non-radial directional distance function under the group- and meta-frontier techniques, and then six scenarios based on two factors (economic development and carbon intensity) are set up to estimate the emission reduction potential of China and each province. Considering the goal of carbon neutrality, the calculation of CO₂ emission reduction potential quantifies the amount of emissions that can be reduced and the amount of emissions that should be balanced. Additionally, the degree of difficulty in achieving abatement potential is also calculated. The findings are as follows: First, assuming that the economic growth rate is reduced to 4.4% (achieving the second “100-year goal”) and each province adopts the most advanced low-carbon technologies, China could reduce carbon emissions by 5970.56 Mt compared to 2019 levels. To achieve net-zero emissions, the remaining 3824.2 Mt of carbon emissions should be removed by carbon reduction technologies. Second, the effect of slowing down economic growth and decreasing carbon intensity varies greatly among provinces. Hebei and Shandong should be prioritized as they have the greatest potential for emission reductions under both scenarios. Third, it is more difficult for Beijing, Shanghai, Hubei, Hunan, Inner Mongolia Autonomous Region, Chongqing, and Sichuan to achieve the abatement potential and they require more effort to reduce the same amount of carbon emissions compared to other provinces. The study provides a reference for achieving carbon neutrality and helps provinces to develop differentiated emission reduction strategies.

Keywords: emission reduction potential; economic growth slowdown; carbon intensity; net-zero emissions; non-radial directional distance function; scenario analysis



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1. Introduction

Due to China’s industrial and energy structure, the rapid economic growth has consumed a large amount of energy, which is also accompanied by high CO₂ emissions. From 1990 to 2020, the share of global CO₂ emissions in China increased from 10% to 30.7% [1]. On a per capita basis, China’s per capita carbon emissions exceeded the world average in 2010 and were around 6.4 tons per capita in 2020, ranking around 15th in the world [2]. Greenhouse gases are widely recognized as the primary drivers of global warming. In 2016, China officially joined the Paris Agreement, and countries have agreed that “by the end of the century, the Earth’s warming must be constrained to 2 °C and further to 1.5 °C” [3]. To achieve more ambitious climate mitigation goals, the global community must reach a state of carbon neutrality from the middle to the end of the century [4]. Recognizing its significant role as a major contributor to CO₂ emissions, China has embraced its responsibility in mitigating global warming and has established a series of goals aimed at reducing CO₂ emissions [5,6]. China committed in 2015 to achieve a 60% to 65% reduction in emission intensity by 2030 compared to 2005 levels [7]. In 2020, China further committed to achieving a carbon peak by 2030 and carbon neutrality by 2060 [8]. Carbon neutrality

refers to a state where the amount of carbon dioxide emitted is offset by the amount of CO₂ absorbed from the atmosphere. The analysis of the CO₂ reduction potential quantifies the amount of CO₂ emissions that can be reduced which will help China to achieve its carbon emission and carbon emission intensity goals, and considering carbon neutral targets, it also can calculate the amount of CO₂ emissions that should be offset. Research on CO₂ reduction potential is extensive, including different countries, regions, industries, and enterprises [9–15]. For example, Li and Wei [16] aim to estimate the CO₂ emission efficiency and the potential emission reduction of the Paris Agreement contracting countries for the period of 1991–2014. Other scholars have studied the impact of policies on emission reductions and thus calculated the reduction potential, for instance, Ma, et al. [17] set up four simulation scenarios to evaluate and predict the contribution of land intensification to regional carbon neutrality. This paper estimates the carbon emissions that can be reduced and the emissions that need to be offset by carbon reduction technologies in China and its provinces from the perspective of carbon neutrality, which can provide a reference for the provincial governments in China to formulate carbon reduction policies.

Diverse methods have been applied to estimate the potential for mitigating CO₂ emissions. The Logarithmic Mean Divisia Index (LMDI) is a prevalent method that evaluates the factors that affect CO₂ emissions and calculates the possible reductions by taking into account the degree of variation in these factors. For instance, Song, et al. [18] utilized the LMDI methodology to identify the main drivers of CO₂ emissions within the transport sector of China and then generated a theoretical mitigation model based on these drivers to assess the potential for CO₂ emission abatement. The efficiency method is also used to measure the CO₂ emission reduction potential, which is usually based on the optimal energy efficiency or carbon emission efficiency, and the reduction potential is measured by calculating the difference between the current situation and the optimal situation, such as Akan and Akan [19] and Xia, et al. [20], who used single-factor energy efficiency as an indicator to measure the reduction potential, and some scholars also use total factor energy efficiency to measure the reduction potential [21]. The total factor efficiency of CO₂ emission is based on the total factor productivity theory, which comprehensively evaluates the efficiency by considering the production process of carbon dioxide and the substitution relationship between diverse input variables simultaneously [22,23]. Jin, et al. [24] and Zhang, et al. [25] also used different DEA models to measure the carbon emission efficiency and then further studied the emission reduction potential. This paper uses the DEA method to obtain the reduction potential by calculating the total factor production technology frontier. In contrast to other methods, this method takes production technologies into account and is calculated on the basis of the most advanced production technologies currently available.

According to the above literature review, there are some limitations in the analysis of emission reduction potential. Firstly, slower economic growth and the reduction of carbon emission intensity are important reasons for carbon emission reduction [26,27], and most of the studies on emission reduction potential have only calculated the potential when the emission efficiency is improved through the DEA method, and they have not considered the emission reduction effect of the slowdown of economic growth. Since 2011, China's economic growth rate has continued to slow down, in addition to the domestic and international cyclical environment, and there are also factors of China's own structural changes in the economy, representing a shift in the economy's potential growth rate from a high to a medium-high rate, which is a basic characteristic of the new normal economy. And in the long term with the expansion of the total economic volume and economic structure changing, the growth rate of the economy will continue to fall back. Therefore, when calculating the potential for emission reduction, it is more appropriate to take into account the combined effect of lower emission intensity and slower economic growth. Second, fewer studies have examined the potential for emission reductions from a carbon neutral perspective and quantified the amount of emissions that need to be offset by carbon reduction technologies. Finally, there is also less discussion on the degree of difficulty in realizing the emission reduction potential, which varies from region to region due to

the large differences in low-carbon technologies. For example, even if two regions have the same potential, the region with a lower level of technology may face greater barriers and need to invest more time and effort to realize its potential. Therefore, an indicator to measure the degree of difficulty in realizing the emission reduction potential is needed, which can help provinces to set more realistic emission reduction targets.

Motivated by this, the first contribution of this paper is to consider the mitigation effects of slower economic growth and lower emission intensity at the same time, setting up six scenarios based on possible changes in economic growth and carbon intensity and estimating the mitigation effects under different scenarios. The second contribution is to quantify the amount of CO₂ reductions that can be achieved and the amount that should be balanced out by technologies such as carbon capture, utilization, and storage (CCUS) from a carbon neutral perspective. The third contribution is the proposal of a technical feasibility index to estimate the degree of difficulty in reducing emissions potential at the national and provincial levels, an assessment that can help to set emission reduction targets that are both achievable and realistic.

2. Methodology

2.1. Group-Frontier and Meta-Frontier Technologies

In the field of Data Envelopment Analysis (DEA), the non-radial directional distance function (NDDF) is a widely used method for evaluating the efficiency of total factor carbon dioxide emissions and identifying the potential for emission reduction [28–31]. Zhou, Ang and Wang [28] provided a formal definition of NDDF. In traditional studies, DMUs (decision-making units) were supposed to have the same technology of production and use the common technology frontier. In reality, the assumption of common production technology is no longer justified when substantial technological disparities exist in different categories or classifications of DMUs [32]; thus, technology heterogeneities among groups were considered [33–35]. Compared to the traditional radial directional distance function, the NDDF allows for non-proportional variations between different input and output factors. This enables the model to better accommodate real-world scenarios and accurately reflect complex production processes [36,37]. Considering heterogeneity in different regions, this study employed the group- and meta-frontier improved NDDF proposed by Cheng, et al. [38] to estimate the CO₂ emissions efficiency, because it overcomes the problem that the meta-frontier is not always able to encompass all of the group frontier.

Supposing that N decision-making entities exist, every entity employs capital stock (k), energy (e), and labor (l) as inputs during the manufacturing procedure, leading to the generation of expected output GDP (y) and adverse output CO₂ (c) [38]. N decision-making units are classified by the relevant standards, and then H groups are obtained. The group frontier technology is expressed as follows [39]:

$$T^g = (k, l, e, y, c) : (k, l, e) \text{ be able to produce } (y, c) \quad (1)$$

According to the production theory, set T should satisfy null-jointness assumptions, the strong disposability of desirable outputs and inputs, and weak disposability of undesirable outputs, implying that any reduction in undesirable outputs must be accompanied by a proportional reduction in desirable outputs [40]. The assumption is made that the set T is bounded and closed, which indicates that there is a finite upper limit to the amount of output that can be produced given a fixed amount of inputs [41,42]. Hayami [43] was the first to introduce the concept of a meta-frontier. Meta-frontiers emphasize the heterogeneity of production technologies with different DMUs reflecting size, type, region, and other inherent attributes. All DMUs are then divided into groups based on different sources of technological heterogeneity. Each group can form a production frontier, i.e., a group frontier.

Finally, a new production frontier, the meta-frontier, is further defined by incorporating all group-frontier technologies. The meta-frontier technology can be expressed as follows [39]:

$$T^m = \{T^{g1} \cup T^{g2} \cup \dots \cup T^{gh}\} \quad (2)$$

Due to the variability of socio-economic development in provinces, technological heterogeneity significantly exists among regions [44]. The construction of the common production frontier for all provinces fails to adequately capture the technological disparities that exist among different regions. Therefore, based on socio-economic development of different regions in China, the 30 provinces are divided into four groups by the National Bureau of Statistics of China, namely the Northeast region, Central region, Western region, and Eastern region (Table S1). T^g and T^m represent group- and meta-frontier technology respectively, where T^m is enveloping T^g of four groups.

2.2. Potential Emission Intensity Based on Non-Radial Directional Distance Function

Zhou, Ang and Wang [28] proposed a formal definition of the non-radial directional distance function (NDDF) which takes undesirable outputs into account. The NDDF is as follows:

$$\overrightarrow{ND}(k, l, e, y, c; g) = \sup \left\{ \omega^T \beta : (k, l, e, y, c + g \times \text{diag}(\beta)) \in T \right\} \quad (3)$$

The direction vector g is denoted as $g = (-g_k, -g_l, -g_e, g_y, -g_c)$. Negative signs in g indicate the decreasing direction (inputs and undesired outputs), while positive signs indicate the increasing direction (desired outputs). $\omega = (\omega_k, \omega_l, \omega_e, \omega_y, \omega_c)^T$ is the normalized weight vector associated with inputs and outputs, which was set to $(1/9, 1/9, 1/9, 1/3, 1/3)$, $\text{diag}(\beta)$ denotes the diagonal matrix, and $\beta = (\beta_k, \beta_l, \beta_e, \beta_y, \beta_c) \geq 0$ is the scale factor vector, indicating the set of factors that affect the individual inefficiency for each input (output).

$\overrightarrow{ND^g}(k, l, e, y, c; g)$ denotes the group NDDF with the following values:

$$\begin{aligned} \overrightarrow{ND^g}(k, l, e, y, c; g) &= \max \omega_k \beta_k^g + \omega_l \beta_l^g + \omega_e \beta_e^g + \omega_y \beta_y^g + \omega_c \beta_c^g, \\ \text{s.t. } \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t k_n^t &\leq (1 - \beta_k^g) k, \\ \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t l_n^t &\leq (1 - \beta_l^g) l, \\ \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t e_n^t &\leq (1 - \beta_e^g) e, \\ \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t y_n^t &\leq (1 + \beta_y^g) y, \\ \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t c_n^t &\leq (1 - \beta_c^g) c, \\ \lambda_n^t &\geq 0, \beta_y^g \geq 0, 0 \leq \beta_k^g, \beta_l^g, \beta_e^g, \beta_c^g < 1, n = 1, 2, 3, \dots, N^r, r = 1, 2, 3, \dots, R, t = 1, 2, 3, \dots, T \end{aligned} \quad (4)$$

In this formula, k_n^t denotes the capital of province n in period t , while N^r denotes the N DUMs of group r . This paper assumes that the production technology is constant and returns to scale ($\lambda_n^t \geq 0$). PEI^g represents the possible intensity of carbon emissions subject to the technology of a group frontier. According to the above obtained inefficiency values of GDP and CO₂, PEI^g is calculated as follows:

$$PEI^g = \frac{(1 - \beta_c^g) c}{(1 + \beta_y^g) y} \quad (5)$$

$\overrightarrow{ND^m}(k, l, e, y, c; g)$ denotes the meta-frontier NDDF with the following values [38]:

$$\begin{aligned} \overrightarrow{ND^m}(k, l, e, y, c; g) = & \max \omega_k \beta_k^m + \omega_l \beta_l^m + \omega_e \beta_e^m + \omega_y \beta_y^m + \omega_c \beta_c^m, \\ \text{s.t. } \sum_{r=1}^R \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t k_n^t & \leq (1 - \beta_k^m) (1 - \beta_k^g) k, \\ \sum_{r=1}^R \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t l_n^t & \leq (1 - \beta_l^m) (1 - \beta_l^g) l, \\ \sum_{r=1}^R \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t e_n^t & \leq (1 - \beta_e^m) (1 - \beta_e^g) e, \\ \sum_{r=1}^R \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t y_n^t & \leq (1 - \beta_y^m) (1 - \beta_y^g) y, \\ \sum_{r=1}^R \sum_{t=1}^T \sum_{n=1}^{N^r} \lambda_n^t c_n^t & \leq (1 - \beta_c^m) (1 - \beta_c^g) c, \\ \lambda_n^t \geq 0, \beta_y^m \geq 0, & 0 \leq \beta_k^m, \beta_l^m, \beta_e^m, \beta_c^m < 1, t = 1, 2, 3, \dots, T, r = 1, 2, 3, \dots, R, n = 1, 2, 3, \dots, N^r \end{aligned} \quad (6)$$

PEI^m represents the possible intensity of carbon emissions subject to the technology of a meta-frontier. Based on the above obtained inefficiency values of CO_2 and GDP, PEI^m is calculated according to the following:

$$PEI^m = \frac{(1 - \beta_c^m)(1 - \beta_c^g)c}{(1 + \beta_y^m)(1 + \beta_y^g)y} \quad (7)$$

The actual emission intensity (AEI) is obtained from the formula $AEI = CO_2/GDP$. Carbon emission intensity decreasing indicates a reduction in CO_2 emissions per unit of GDP. With an improvement in technology, AEI first can be improved to PEI^g and further improved to PEI^m ($PEI^g \geq PEI^m$). PEI^g and PEI^m can be obtained according to Equations (6) and (7), respectively.

2.3. The Degree of Difficulty in Achieving Emissions Abatement Potential

In the scenario of decreasing carbon intensity, even if the emission reduction potential of different regions were known, the difficulty of achieving the corresponding potential varies due to the differences in low-carbon technologies among provinces. It is easier for regions to learn from neighboring regions to improve their low-carbon technologies. Therefore, within the same group of regions, it is relatively easy to improve their technology to the group-frontier technology by learning from the neighboring regions within the group, which we call the easily achievable potential (EA), which can be calculated by Equation (8). It is relatively difficult for regions to improve their technology to the meta-frontier technology and achieve greater potential because it means that the region needs to learn technology from areas far away from itself, which requires more effort and time, which we call the not easily achievable potential (NEA), and it can be calculated by Equation (9). This article uses the index proposed by Xiao, Zhou, Zhang, Wang, Shan and Ren [13] to assess the difficulty of realizing the reduction potential of each province, as shown in Equation (10). In formula (10), we introduce the technical feasibility index (TF) as the ratio between the not easily achievable reduction potential (NEA) and the total emission reduction potential. The latter refers to the sum of easily achievable (EA) and challenging emission reduction potentials (NEA). Hence, the technical feasibility index (TF) varies between 0 and 1, with higher values indicating greater challenges in reducing CO_2 emissions. In the condition that $AEI - PEI^m = 0$ and $PEI^g - PEI^m = 0$, the technical feasibility index (TF) is 0. The former is where DUMs situated in the meta-frontier technology exhibit no potential for abatement, and the latter is where the DUMs' meta-frontier technology overlaps with the group-frontier technology and there is only an inefficiency value for the group.

$$EA = GDP \times (AEI - PEI^g) \quad (8)$$

$$NEA = GDP \times (PEI^g - PEI^m) \quad (9)$$

$$TF = \frac{NEA}{NEA + EA} = \begin{cases} \frac{PEI^g - PEI^m}{AEI - PEI^m}, & AEI - PEI^m \neq 0 \\ 0, & AEI - PEI^m = 0, PEI^g - PEI^m = 0 \end{cases} \quad (10)$$

3. Design of Scenarios

The carbon emissions are as follows:

$$CO_2 = GDP \times EI = GDP \times \frac{CO_2}{GDP} \quad (11)$$

Carbon emissions are determined by GDP and carbon emission intensity (EI). According to the economy and intensity factors, the scenario design encompasses three main components: baseline, economic growth slowdown, and the decline in carbon intensity. The baseline is the benchmark for comparing the emission level with a series of scenarios; the slowdown of economic growth includes the growth rate slowing down by 1% and the growth rate being 4.4%. The scenarios of carbon intensity decline are set up for the carbon emission efficiency increases in the group frontier and meta-frontier. Based on the above, six scenarios were formulated to assess the impact of slower economic growth and the lower emission intensity (as shown in Table 1). The baseline for these scenarios is defined by the levels of CO₂ emissions and emission intensity in 2019. Scenarios A1 and A2 calculate the abatement effect of a slowdown in economic growth, with emission intensity assumed to be constant. Scenario A1 aims to explore the emission mitigation impacts of marginal change (1%) of the slowdown of economic growth. According to the study of Sheng and Zheng [45], A2 is set as an economic growth rate of 4.4%. The “Two Hundred Years” goal is the core of the Chinese Dream of the Great Rejuvenation of the Chinese Nation, with the first 100-year goal being achieved soon and the second 100-year goal on the way. In order to make a good medium- and long-term development plan, there is an urgent need to quantify the second 100-year goal. Sheng and Zheng [45] tried to quantify the level of economic development one hundred years after the founding of the new China, they discussed what level of quantification is acceptable and feasible, and then backwardly extrapolated to find out how much economic growth is needed to support China’s modernization from 2021 to 2049 in order to achieve this level. The study shows that in order to achieve the second centennial goal, the average annual GDP growth rate from 2021 to 2049 needs to remain above 4.4%. Therefore, Scenario A2 of this paper is set to have a GDP growth rate of 4.4% [45]. Under two distinct scenarios of enhanced carbon emission efficiency, Scenarios B1 and B2 investigate the potential changes in carbon intensity as well as the potential for reducing CO₂ emissions. Scenario B1 represents the reduction potential if DMUs’ technology reaches the group-frontier technology. Subsequently, in Scenario B2, DMUs have the opportunity to further enhance their technology to reach the meta-frontier level. It is worth noting that optimal efficiency improvement is attained through the utilization of the best technology of production presently accessible in China. However, this should be subject to technological change, as future technological advancements may result in even greater efficiency improvement. Scenarios C1–C2 explore the collaborative mitigation effects of slower economic growth and lower carbon intensity. The maximum mitigation potential can be achieved in Scenario C2 when the economic growth rate is 4.4% and carbon efficiency increases to the meta-frontier technology (the carbon intensity is PEI^m). Combining the marginal effect of economic slowdown (A1) with B1 and B2 may not serve as a reference for actual emission reduction, so we do not discuss the effect of combining them together. In this paper, we just want to examine the marginal effect of economic slowdown to provide readers with an understanding of the emission reductions brought about by economic factors. The combination of A2 with B1 and B2 can serve as a reference for the actual emission reduction in China, because A2, B1, and B2 are all scenarios that China may achieve in the future.

Table 1. Scenarios set by intensity and economic changes.

Baseline: The level of carbon emissions or emission intensity in 2019
Scenario A1: GDP growth dropped by 1%
Scenario A2: GDP growth rate is 4.4%
Scenario B1: Carbon intensity reduced to PEI^g (improve efficiency to the best practice of group-frontier technology)
Scenario B2: Carbon intensity reduced to PEI^m (improve efficiency to the best practice of meta-frontier technology)
Scenario C1: Combination of scenarios A2 and B1
Scenario C2: Combination of scenarios A2 and B2

Potential carbon emissions (PCO_2) and potential change in CO_2 emissions ($PCCO_2$) can be obtained through Equations (12) and (13), respectively.

$$PCO_2 = PGDP \times PEI \quad (12)$$

$$PCCO_2 = CO_2 - PCO_2 \quad (13)$$

4. Variable Selection and Data Sources

Due to the different focuses of studies, researchers use different inputs and outputs to calculate environmental efficiency. For example, natural resources, labor, and capital are often used as inputs; GDP is often used as a good output; and some polluting gases or water are often used as bad outputs, such as carbon dioxide, sulfur dioxide, sewage, etc. This study focuses on the assessment of CO_2 emission efficiency, similar to the studies by Wang, et al. [46], so three inputs (energy, labor, and capital stock), an expected output GDP, and an adverse output carbon emissions were chosen.

Carbon emissions were obtained from the CEADs database, which estimates CO_2 emissions for 30 provinces of the country using the IPCC sectoral method. The data on individuals in employment (l) and gross domestic product (y) were obtained from provincial statistical yearbooks. To determine the capital stock (k), we utilized the method of perpetual inventory, which was obtained from formula (14).

$$K_t = I_t + (1 - \delta)K_{t-1} \quad (14)$$

In period t , K_t represents the capital stock, I_t stands for fixed assets investment, and δ denotes the depreciation rate. In the period $t - 1$, K_{t-1} represents the capital stock. For this study, we adopted a depreciation rate of 9.6% based on Zhang [47]. Additionally, all monetary variables were adjusted to constant prices in the year 2000. The data on fixed assets investment were acquired from the China Statistical Yearbooks.

5. Empirical Analysis and Results

5.1. CO_2 Emission Intensity of Regions

Figure 1 shows the trend and comparison of AEI during 2000–2019 in the four regions. Firstly, the AEI of the four regions shows a decreasing trend, indicating that it takes less and less CO_2 to achieve the same GDP. Among them, the eastern region has the lowest level, dropping sharply from $2.49 \text{ t}/10^4 \text{ RMB}$ in 2000 to $1.29 \text{ t}/10^4 \text{ RMB}$ in 2019. In contrast, the western region has a higher AEI, falling from $4.01 \text{ t}/10^4 \text{ RMB}$ in 2000 to $2.6 \text{ t}/10^4 \text{ RMB}$ in 2019 (Figure 1).

Figure 2 compares AEI with PEI^g and PEI^m of the four regions in China during 2000–2019. Among the three indexes, AEI exhibited the highest value across all four regions. By utilizing the optimal technology within the group, AEI can be minimized to the extent of PEI^g . Conversely, PEI^m is the smallest value since meta-frontier technology encompasses all frontier technologies within the group. In addition, the red and yellow lines in the eastern region are overlapping, indicating that the eastern region adopts the most advanced production technologies within China.

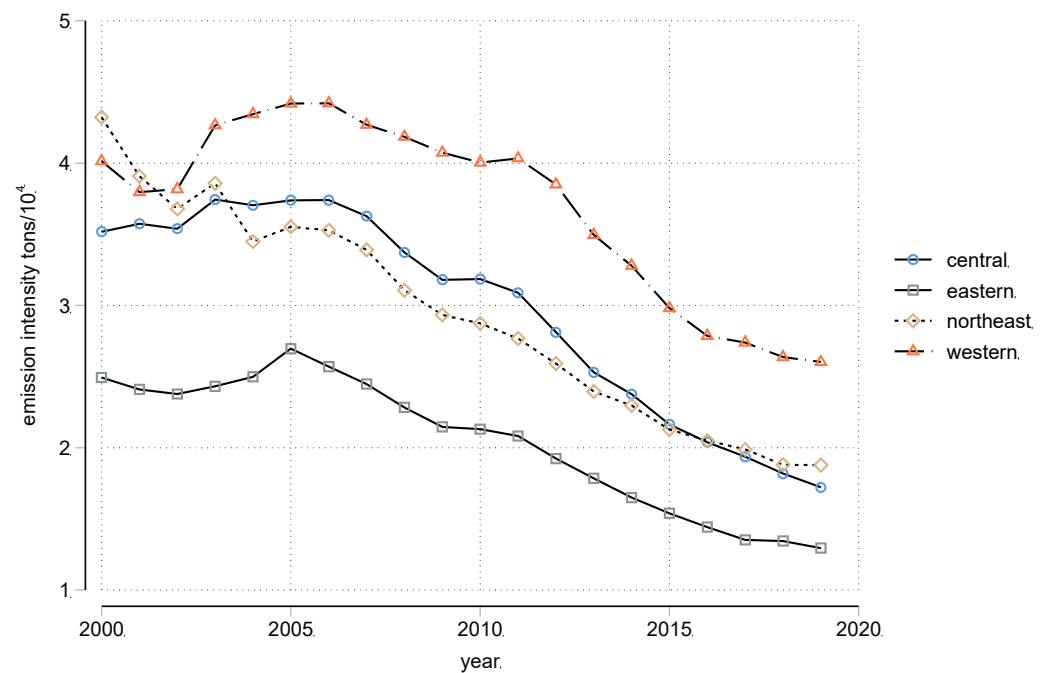


Figure 1. AEI of four regions in China during 2000–2019.

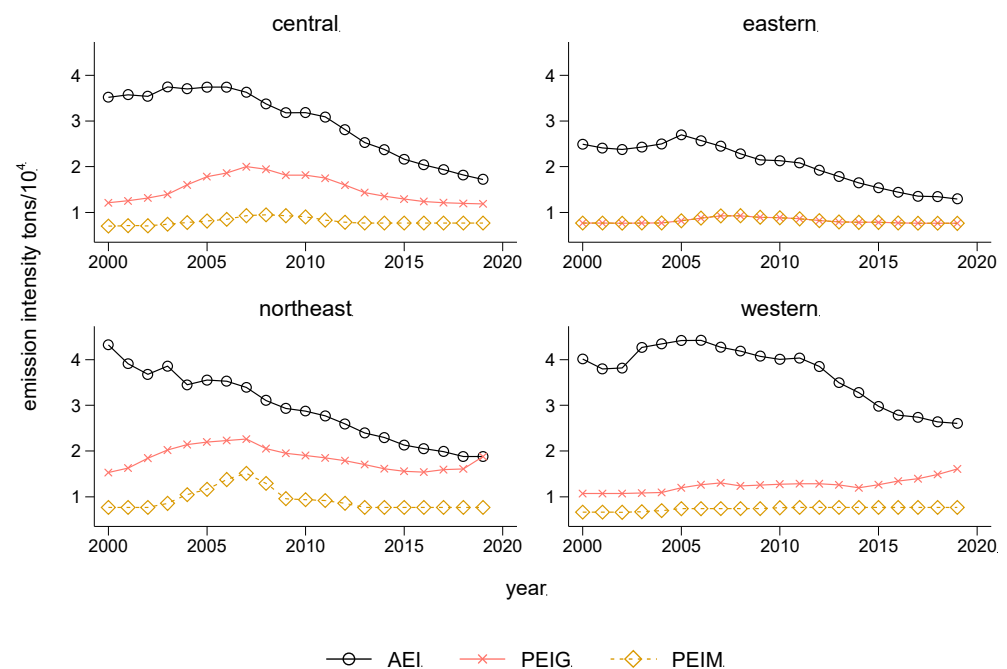


Figure 2. The emission intensity of four regions in China during 2000–2019.

5.2. Potential Carbon Emission Intensity at the National Level

In 2015, the Chinese government made a commitment to achieve a 60% to 65% reduction in carbon emission intensity by 2030 compared to the levels observed in 2005 [7]. In 2019, the actual emission intensity in China had decreased by about 43.98% from the 2005 level (Table 2), which indicates that the implementation of a range of environmental regulations and governmental reforms has had a favorable impact on the reduction in carbon dioxide emissions, but more time and effort are still needed to achieve the 60% to 65% targets. The potential carbon intensity of China under Scenarios B1 and B2 is shown in Table 2, and the potential reduction in carbon intensity is calculated.

Table 2. The potential emission intensity under two different scenarios in China.

Classification	Scenario	Emission Intensity (tons/10 ⁴ RMB)	The Percentage Decrease in Emission Intensity Compared to 2005
Actual emission intensity in 2005		3.3733599	
Baseline (2019)		1.8897158	43.98%
Potential carbon intensity	B1	1.1694709	65.33%
	B2	0.74989311	77.77%

In the B1 scenario, the carbon intensity in the nation can be effectively decreased to a comparatively low level of 1.169 t/10⁴ RMB, as shown in Table 2, and the emissions intensity could be 65.33% lower than in 2005 (Table 2). To achieve the B1 scenario, China needs to facilitate the technological advancement of all provinces to align with the highest level within their respective groups. With the implementation of meta-frontier technology, the carbon intensity stands at 0.750 t/10⁴ RMB, suggesting that China has the potential to reduce its emission intensity by an additional 0.420 t/10⁴ RMB. Under Scenario B2, the emissions intensity could be 77.77% lower than in 2005 (Table 2), at which point all provinces should adopt the most advanced technology.

5.3. Potential for Reducing Carbon Emissions

Carbon neutrality refers to the net-zero emission of CO₂. This equilibrium can be attained by either minimizing CO₂ emissions or employing various technologies, such as carbon capture, utilization, and storage (CCUS), to remove emissions from the atmosphere. Lower carbon intensity and slower economic growth can assist in reducing carbon emissions, which can mitigate the technical pressure of decarbonization. Figure 3 illustrates the potential for reducing national CO₂ emissions across different scenarios. The findings are presented relative to the emission levels in 2019, which serve as the reference point. In China, the emission reference point was approximately 9794.76 Mt. Scenario A1 in Figure 3 demonstrates the potential for achieving a reduction of 92.31 Mt in CO₂ emissions, indicating that a reduction in CO₂ emissions of about 0.94% is related to a 1% slowdown in China's GDP growth rate. China should maintain an economic growth rate of 4.4% in order to achieve the second "100-year goal2, and under Scenario A2, it is possible to achieve a reduction of 157.86 Mt (equivalent to 1.61% of total emissions) (Figure 3) in China's CO₂ emissions. The average abatement potential of carbon emissions is 124.44 Mt per province and 3733.17 Mt for the entire country under Scenario B1 (Figure 3). The average reduction in CO₂ emissions could be 196.93 Mt per province and 5907.92 Mt for the whole country under Scenario B2 (Figure 3). For Scenario C1, the country could reduce its CO₂ emissions by 3830.86 Mt. To accomplish a state of carbon neutrality, the remaining 5963.9 Mt carbon emissions would need to be offset in some way. On average, each province has an abatement potential of approximately 127.7 Mt CO₂, and negative emission technologies need to offset around 198.8 Mt CO₂ emissions per province (Figure 3). Based on the results under Scenario C2, China's second "100-year target" of 4.4% economic growth and every province achieving the highest level of performance in meta-frontier technology, the reduction potential could reach 5970.56 Mt (Figure 3). Scenario C2 indicates that it is necessary to offset the remaining 3824.2 Mt emissions to achieve net-zero carbon emissions. These findings help to quantify the need for negative emission technologies under different scenarios in China.

Table 3 compares the CO₂ reduction potential among the 30 provinces under different scenarios. The reduction potential quantifies the extent to which carbon emissions are reduced at the 2019 level. To facilitate a more effective comparison, the abatement results were standardized using the min-max normalization method, transforming them into a scale of 0–1. This normalization allows for easier interpretation and evaluation of the results across different scenarios [48]. Larger standardized results mean better emission reductions.

Since the economic development strategies of different provinces vary, in this part, only Scenarios A1, B1 and B2 are applied to calculate provincial reduction potential (Table 3).

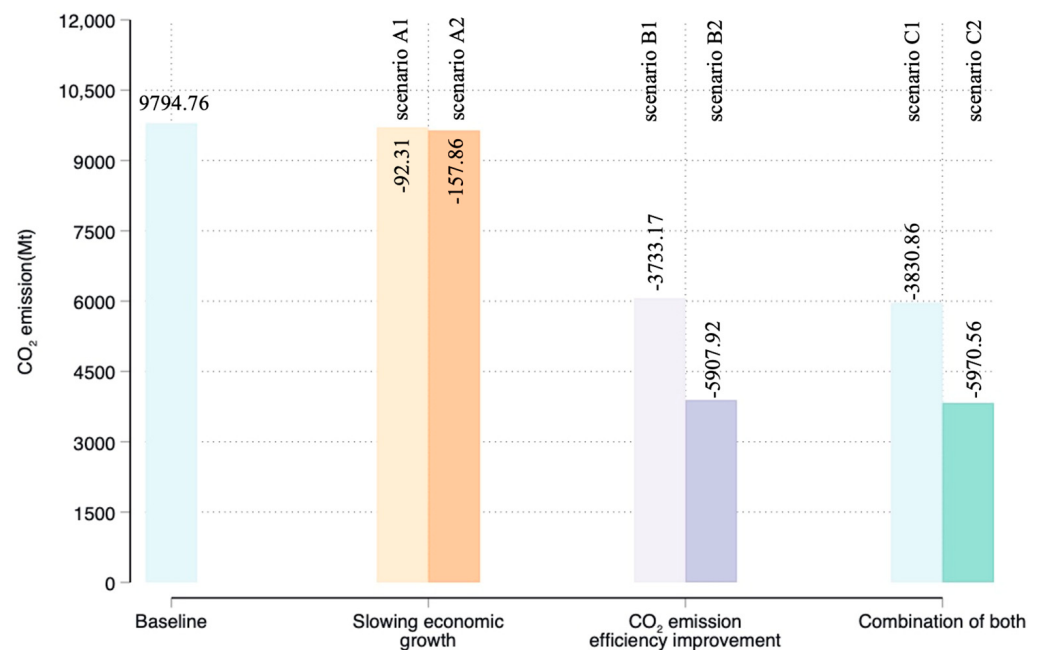


Figure 3. Abatement carbon emissions potential in different scenarios.

In our analysis results, implementing measures to slow down economic growth proves to be an effective abatement strategy for Shandong. Being a major industrial province and also a major CO₂ emitter in China, its industrial GDP accounted for 39.8% of total GDP in 2019. A 1% reduction in Shandong's economic growth rate is associated with an 8.88 Mt reduction in emissions, accounting for 0.95% of total emissions. Meanwhile, provinces with higher reduction potential in the A1 scenario include Hebei, Jiangsu, and Inner Mongolia, all of which have a large share of secondary industries in their economic structure and emit more CO₂. For example, Hebei is the largest steel producer in China, with crude steel production reaching 240 million tons in 2019, accounting for nearly a quarter of China's and nearly an eighth of the world's production. In contrast, Hainan's economic growth slowdown has the smallest effect on emission reduction. In 2019, Hainan's tertiary industry accounted for 59%, which played a decisive role in its economic development. The second industry accounted for a small proportion of 20.7%, and Hainan's CO₂ emissions in 2019 are low at 43.07 million tons. Therefore, when the economic growth slows down, the effect on CO₂ emission reduction is limited (0.41 Mt) (Table 3).

In the strategies to decrease carbon intensity, Shandong and Hebei have a higher reduction potential under Scenario B1, and they are both in the eastern region, indicating that they have a larger carbon intensity in the eastern region and have more potential for improvement. They can learn some technologies from other provinces in the eastern region to improve carbon efficiency and further reduce CO₂ emissions. Beijing and Shanghai in the eastern region; Liaoning, Jilin, and Heilongjiang in the northeast region; and Sichuan, Chongqing, and Inner Mongolia in the western region have lower reduction potential under the B1 scenario, indicating that these provinces have lower carbon intensity in their respective regions and have higher emission reduction technologies compared to other provinces in the group, so there is less reduction potential when increasing carbon efficiency to the frontier of the group. The northeast region contains only three provinces, namely Liaoning, Jilin, and Heilongjiang, indicating that all three provinces are at the front of their group. In the B2 scenario, Hebei and Inner Mongolia have a greater potential to reduce emissions, partly because of their own larger carbon emissions and also because they are farther away from the meta-frontier and have a greater potential for reducing emissions

when improving their carbon efficiency to the meta-frontier. Beijing and Shanghai in the B2 scenario have the lowest abatement effect not only because of their own lower carbon emissions but also their high carbon efficiency, as their technology is on the meta-frontier. In the process of achieving China's carbon emission reduction targets, Hebei and Shandong provinces can be targeted as they have a greater potential to reduce emissions under both the economic growth slowdown and carbon intensity decline scenarios.

Table 3. Carbon emissions (Mt) and abatement results under different scenarios among various provinces.

Province	Baseline Emissions	A1 Emissions	A1 Effect	B1 Emissions	B1 Effect	B2 Emissions	B2 Effect
Beijing	89.18	88.34	0.05	89.18	0	89.18	0
Tianjin	158.47	156.95	0.13	112.52	0.1	112.52	0.07
Hebei	914.21	905.65	0.96	454.99	0.95	224.67	1
Shanxi	564.86	559.54	0.58	233.19	0.69	74.46	0.71
Inner Mongolia	794.28	786.73	0.84	794.28	0	105.95	1
Liaoning	533.39	528.33	0.55	533.39	0	193.3	0.49
Jilin	203.66	201.68	0.19	203.66	0	87.78	0.17
Heilongjiang	278.21	275.54	0.27	278.21	0	133.29	0.21
Shanghai	192.91	191.09	0.17	192.91	0	192.91	0
Jiangsu	804.59	797.01	0.85	470.57	0.69	470.57	0.48
Zhejiang	381.41	377.84	0.37	293.77	0.18	293.77	0.13
Anhui	408.06	404.27	0.4	252.14	0.32	163.5	0.35
Fujian	278.11	275.52	0.26	217.25	0.13	217.25	0.09
Jiangxi	242.31	240.06	0.22	174.89	0.14	113.23	0.19
Shandong	937.12	928.23	1	454.77	1	454.77	0.7
Henan	460.63	456.33	0.46	406.51	0.11	263.17	0.29
Hubei	354.75	351.45	0.34	354.75	0	229.67	0.18
Hunan	310.64	307.75	0.29	310.64	0	198.23	0.16
Guangdong	569.12	563.76	0.58	489.42	0.17	489.42	0.12
Guangxi	246.72	244.39	0.23	148.91	0.2	105.71	0.2
Hainan	43.07	42.66	0	24.35	0.04	24.35	0.03
Chongqing	156.25	154.78	0.13	156.25	0	102.32	0.08
Sichuan	315.16	312.23	0.3	315.16	0	223.72	0.13
Guizhou	261.13	258.72	0.24	241.6	0.04	58.66	0.29
Yunnan	185.96	184.24	0.15	133.99	0.11	95.11	0.13
Shaanxi	296.27	293.48	0.28	153.21	0.3	100.33	0.28
Gansu	164.49	162.94	0.13	62.43	0.21	44.31	0.17
Qinghai	51.75	51.27	0.01	43.02	0.02	14.56	0.05
Ningxia	212.41	210.42	0.19	51	0.33	13.25	0.29
Xinjiang	455.27	450.99	0.46	170.99	0.59	60.6	0.57

5.4. The Degree of Difficulty in Realizing Emissions Abatement Potential

The presence of diverse low-carbon technologies among provinces introduces variability in the level of difficulty associated with achieving equivalent CO₂ emission reductions. Figure 4 shows the constituents of the abatement potential for the 30 provinces. Emission abatement potential is divided into easily achievable (EA) and not easily achievable reduction potential (NEA) depending on whether the province reaches the technology of the group frontier or the meta-frontier. The lowest means that the lowest carbon emissions can be achieved in realizing its reduction potential. Nationally, 2867.41 Mt of the 2019 abatement potential comes from the not easily achievable category and is caused by inter-regional technology gaps, accounting for 29.27% of China's total emissions in 2019.

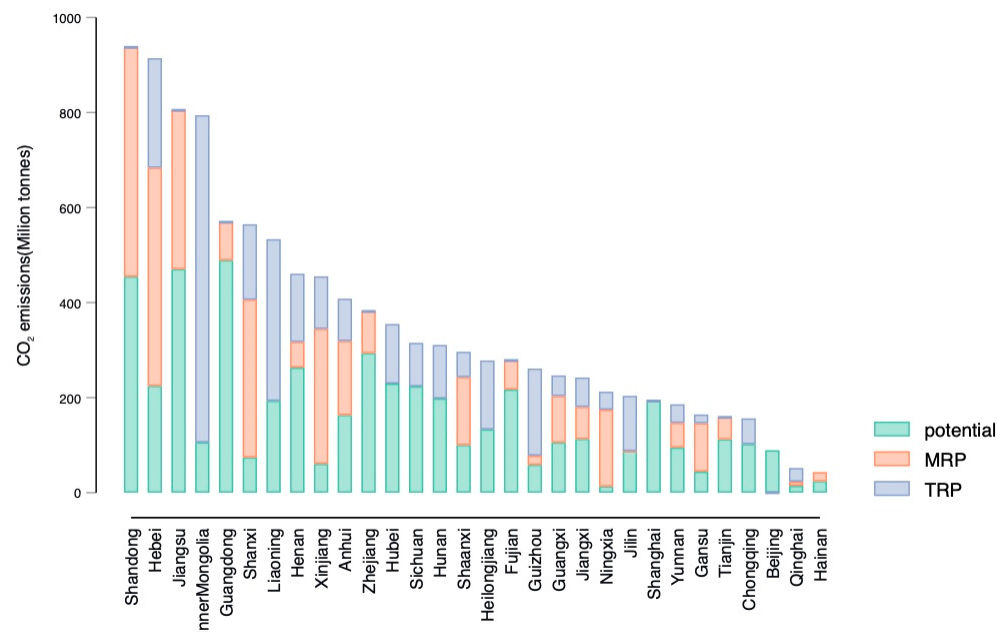


Figure 4. Constituents of carbon emissions in 2019.

The degree of difficulty in achieving emissions abatement potential can be calculated based on the easily achievable and not easily achievable reduction potential of each province, as depicted in Figure 4. The scatter plot in Figure 5 shows the technology feasibility index (TF) of the reduction potential for 30 provinces. Certain provinces have the potential to reduce carbon emissions at comparable levels, but the degree of difficulty in achieving abatement potential varies. As an example, Jiangsu and Liaoning exhibit the capacity to achieve reductions in carbon emissions of 334.02 Mt and 340.09 Mt, respectively. However, achieving this reduction potential is more challenging for Liaoning, as its TF value is equal to 1, while Jiangsu's TF value is 0. In comparison, Jiangsu is more likely to realize its potential. Furthermore, Hebei and Inner Mongolia, being major CO₂ emitting provinces, have reduction potentials of 689.54 Mt and 688.33 Mt, respectively. Nevertheless, Inner Mongolia's TF value is equal to 1, indicating that additional efforts are required to achieve emission reductions compared to Hebei. This difference highlights the need for considering the not easily achievable reduction potential when setting emission reduction targets. Provinces with higher TF values, such as Liaoning and Inner Mongolia, require more extensive efforts to achieve their emission reduction goals. The provinces with a TF value of 1 include Beijing, Shanghai, Hubei, Hunan, Inner Mongolia Autonomous Region, Chongqing, Sichuan, Liaoning, Jilin, and Heilongjiang. Both Beijing and Shanghai have an EA and NEA of 0, indicating that they are on both the group frontier in the eastern region and also on the meta-frontier, so their abatement technology is optimal and their abatement potential is zero with no change in technology, and a more recent technological innovation is needed to increase their abatement potential. Several provinces, including Zhejiang, Tianjin, Jiangsu, Fujian, Shandong, Guangdong, and Hainan, have a TF value of zero, suggesting that these provinces can reduce their carbon emissions without overcoming the technological gap between the different groups because their group-frontier technologies are the same as the meta-frontier technologies. That is to say, these provinces can realize their potential for reducing emissions by aligning with the most advanced technology available within their respective groups. On a nationwide scale, the TF value stands at 0.4849, implying that 48.49% of the abatement potential is not easy to achieve, and 51.51% is comparatively more attainable. Nevertheless, in order to effectively address the remaining 48.49%, China must prioritize the diffusion of technology and bridge the existing technology gap.

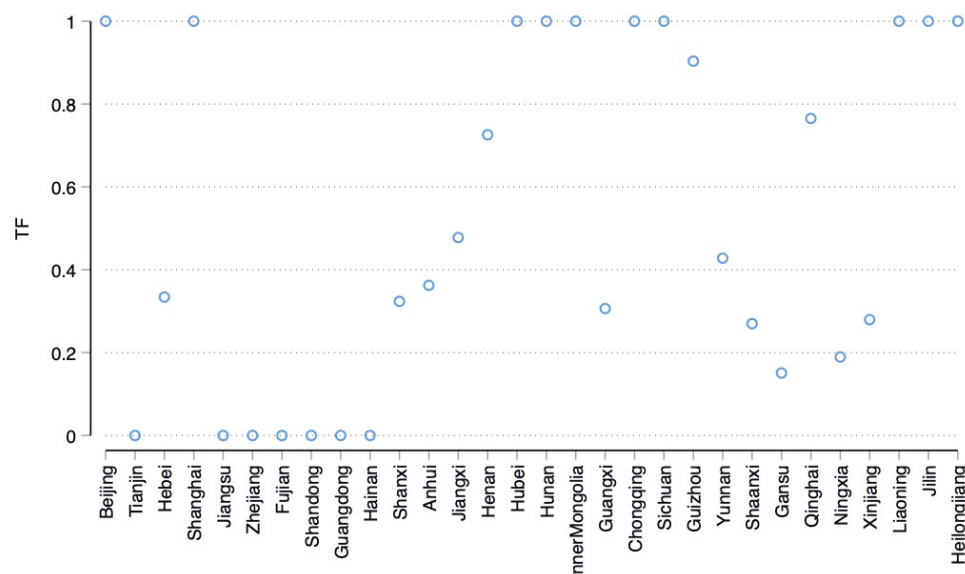


Figure 5. Technical feasibility of reducing CO₂ emissions in 2019.

6. Conclusions

This study proposes a framework for scenario analysis that takes into account both the slowing down of economic growth and the reduction in emission intensity and evaluates the CO₂ emission reduction potentials of China and 30 provinces under a carbon neutral perspective. Additionally, the degree of difficulty in achieving emissions abatement potential is evaluated.

The research indicates that in order to accomplish net-zero emissions, by reducing China's economic growth rate to 4.4% (taking into account China's second centennial goal) and increasing its emissions efficiency to the level of best practice (Scenario C2), China could reduce its CO₂ emissions by 5970.56 megatons (Mt) compared to 2019 levels, with the remaining 3824.2 Mt of CO₂ requiring carbon abatement technologies to offset. Furthermore, if all provinces adopt the most advanced technology (B2), the intensity of carbon emission in China could be decreased by as much as 77.77% compared to the 2005 level. The effect of reducing emissions through slower economic growth and lower CO₂ intensity varies significantly across provinces. The slowdown of economic growth is more effective for some provinces with more CO₂ emissions and a larger proportion of secondary industries, such as Shandong, Hebei, Jiangsu, and Inner Mongolia. Conversely, it is less effective in provinces with lower emissions and a higher share of tertiary industries, such as Hainan. In the process of achieving emission reduction targets in China, Hebei and Shandong provinces can be the key targets due to their substantial potential for emissions reduction under both the scenarios of slower economic growth and lower carbon intensity.

In the analysis of regional heterogeneity, the degree of difficulty in achieving emissions abatement potential significantly differs across regions, primarily because of considerable variations in the implementation of carbon-reducing innovations. In provinces with greater technical barriers, such as Beijing, Shanghai, Hubei, Hunan, Inner Mongolia Autonomous Region, Chongqing, and Sichuan, the value of TF is one, indicating that they need greater efforts to reduce potential emissions. In particular, Beijing and Shanghai, already at the forefront in terms of emission reduction technology, require new low-carbon technology to obtain more room for emission reduction. They should take a leading role in driving emission reduction technology advancements in China. China's TF value of 0.4849 indicates that 51.51% of the potential is relatively easy to realize. Nevertheless, in order to tackle the remaining 48.49% of potential emissions, it is essential to facilitate the widespread adoption of technologies and bridge the technological disparity among regions.

The findings from our study provide valuable insights. Firstly, in order to reach a state of zero net carbon emissions, it is essential to focus on reducing CO₂ emissions from

production and consumption activities while simultaneously implementing strategies to effectively offset CO₂ emissions. The analysis conducted in this study offers quantitative assessments of the potential emissions abatements and the adoption of negative- and zero-carbon technologies across different scenarios. Secondly, provinces with high technical feasibility (TF) levels, including Beijing, Shanghai, Hubei, Hunan, Inner Mongolia Autonomous Region, Chongqing, and Sichuan, should be given more time to achieve their emission reductions, because they need to make more effort to reduce emissions. Closing the technology gap between regions could be a solution to reduce TF, and it is crucial to adopt advanced low-carbon technologies not only at the local level but also on a broader spatial scale. It is imperative to establish a robust system for technology diffusion in order to expedite the widespread adoption of technologies across larger geographical areas. Beijing and Shanghai already have the best low-carbon technologies in the country, so new technologies are needed to increase their reduction potential. Furthermore, other provinces would also benefit from technology diffusion.

The limitation of this study is that the calculation of efficiency makes no distinction between different industries, as different industries have different technological frontiers. In future research, an exploration of specific sub-industries could be undertaken. Another limitation is that we have estimated the emission reduction potential at the provincial level, and the reduction potential can be calculated at the city level to obtain more specific and detailed results in future.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su16104274/s1>, Figure S1: Illustration of meta-frontier technology and group-frontier technologies; Table S1: Region division of China.

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