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Regional allocation of CO_2 emissions allowance in China by 2020: A ZSG-DEA model based investigation

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Abstract: The mitigation efforts of China are increasingly important for meeting global climate target since the rapid economic growth of China has led to an increasing share in the world's total CO_2 emissions, and nowadays, China has become the world's largest CO_2 emitter. This paper sets out to explore the approach for realizing China's national mitigation targets submitted to UNFCCC as part of the Copenhagen Accord and the Cancún Agreements; that is, to reduce the intensity of CO_2 emissions per unit of GDP by 40-45% by 2020, as well as reducing the energy intensity and increasing the share of non-fossil fuel in primary energy consumption, through a study of regional allocation of CO_2 emissions allowance over China's provinces. This paper first argues that the realization of the mitigation targets of China to reduce emission intensity and energy intensity essentially represent a total amount of CO_2 emissions allowance allocation and energy consumption control problem, and a multi-objective optimization method will be more appropriate to solve this problem. Then an improved zero sum gains data envelopment analysis (ZSG-DEA) optimization model is proposed, which could simultaneously deal with the constant total amount of CO_2 emission allowance allocation and energy consumption reassignment through the efficiency measure, iterative computation, and input variable adjustment process. In addition, several scenarios of China's regional economic and social development, CO_2 emissions, and energy consumption by 2020 under the Chinese mitigation action plans are presented. Based on these scenarios and through the implementation of the allocation model, a new efficient CO_2 emissions allowance allocation scheme on a provincial level for China's 30 regions is proposed, in which five provinces of Ningxia, Inner Mongolia, and Shanxi etc. have to shoulder heavier mitigation burden in terms of emission intensity and energy intensity reductions, and the burdens on other five provinces of Anhui, Jiangxi, and Jiangsu etc. are comparatively lighter. Furthermore, the remaining 20 Chinese provinces all take mediumly ranked emission intensity and energy intensity reduction burdens.

Keywords: allowance allocation, CO_2 emissions, energy intensity, non-fossil fuel, ZSG-DEA

1 Introduction

Despite the major energy efficiency improvements achieved during the last decade, the rapid development of the economy, which has undergone extensive industrialization, and conversion technologies, have substantially increased China's primary energy demand and caused serious environmental problems at the regional levels in the country due to harmful emissions such as greenhouse gas (GHG), SO_2, NO_x and particulate matter. Nowadays, China has become the

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greatest consumer of energy and emitter of CO_2 in the world (Hu and Lee, 2008; Li, 2010; Wang and Watson, 2010; Wang et al., 2012). Furthermore, with the growing emphasis on international environmental issues from public and government, China has already faced enormous pressures in the international negotiation on CO_2 emissions control and climate change mitigation.

Up to March 2010, following the Copenhagen climate conference, forty-two industrialized countries and forty-three developing countries, including all major emitting countries, had submitted their emission reduction or emission control pledges and action plans for 2020 to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat as part of the Copenhagen Accord, and all of these emission reduction and control proposals were later included in the Cancún Agreements (as analyzed by van Ruijven et al., 2012). Den Elzen et al. (2011a,b) had assessed the effect of these pledges and actions on GHG emissions, and concluded that they are "not as straightforward as they seems". The Kyoto protocol Annex I countries have defined emission reduction targets relative to different base years, as well as the non-Annex I countries (including China) have proposed commitments in terms of overall intensity targets associated with detailed domestic actions. As Den Elzen et al. (2011b) and ven Ruijven et al. (2012) mentioned, the mitigation efforts of China are increasingly important for meeting global climate target, for China's rapid economic growth has led to an increasing share in the total GHG emissions of the world. However, since the income level (GDP per capita) of China is still much lower than that of the industrialized countries, and China has historically contributed less to world's current GHG concentrations than the industrialized countries did, China, at the current stage, is not eager to take on ambitious and absolute emission reduction target. Alternatively, China had proposed a mitigation action plan consists of reducing CO_2 emissions intensity (i.e. CO_2 emissions per unit of GDP) by 40% to 45% by the year of 2020 based on the 2005 level, which was 2.99 tonnes of CO_2 per ten thousand $RMB_{¥2005}$, and increasing the share of non-fossil fuels in primary energy consumption to around 15% by 2020. This mitigation action plan was internationally submitted to the UNFCCC as part of the Copenhagen Accord and the Cancún Agreements. In addition, as part of China's national plan, the energy intensity (i.e. energy consumption per unit of GDP) reduction target was continuously proposed in China's 11^{th} Five-Year Plan (20% reduction by 2010 compared to 2005) and 12^{th} Five-Year Plan (16% reduction by 2015 compared to 2010) of energy saving and emission reduction.

To realize sustainable development, improve energy utilization efficiency, and protect the environment, the central government of China has put forward a strategic target of constructing an environment-friendly and resource-saving society. Therefore, the 40-45% emission intensity reduction target, 15% non-fossil fuel share target, and the energy intensity reduction targets were all formally announced by the State Council of China, and were listed in the National Economic and Social Development Medium- and Long-term Plans so as to be given a legal force.

While the authorities at the provincial level (provinces, autonomous regions, and municipalities) have been required to adjust their economic growth mode and restructure their policies, this may not guarantee that local efforts on energy saving and emission reduce are in line with the national target. Lack of accountability for reduction efforts at the provincial level may lead to poor implementation of national policy. Therefore, it is particularly important for China efficiently to disaggregate the national target into the provincial target for each province. In addition, given the diversity of economic and social developments in different Chinese administrative regions, regional allocation of CO_2 emissions allowance requires an effective and efficient method to measure the relevant parameters at regional level such as emission intensity, energy intensity, energy consumption structure (i.e. shares of coal, petroleum, natural gas and non-fossil fuels in primary energy consumption), and energy and/or emission efficiency which could be evaluated through the application of Data Envelopment Analysis (DEA) based optimization models and the utilization of regional GDP, population, energy consumption and CO_2 emissions data. This explains the necessity for efficiency analyses and scientific assessments of the regional allocation of CO_2 emissions allowance over provinces in China.

The aim of this paper is to disaggregate China's national CO_2 emissions intensity reduction target at the regional level, i.e., to allocate China's national CO_2 emission allowance over Chinese provinces by 2020. Since the energy intensity reduction target and the share of non-fossil fuels in primary energy consumption increase target are parts of China's national mitigation plan, both of the issues are taken into account in our study when allocating the CO_2 emissions allowance. In this study, we first discuss the total emission control problem and analyze the existing emission allowance allocation approach. Then we utilize an improved zero sum gains data envelopment analysis (ZSG-DEA) model, which belongs to optimization method and could deal with constant total amount resources allocation problem, to allocate China's CO_2 emission allowance over provinces. Based on several specified scenarios of the economic and social development of China and its 30 regions in 2020, an ideally efficient resource reallocation scheme is presented. After that, the CO_2 emissions allowance allocation results and the related values of emission intensity, energy intensity, and share of non-fossil fuels for China by 2020 are discussed and compared both at the national and the provincial levels.

The remainder of this paper is organized as follows. Section two identifies the potential problems of total CO_2 emissions control and critically analyzes the main approaches to CO_2 emissions allowance allocation in the literature. In the third section, the CCR-DEA model and the original ZSG-DEA model are introduced, and then the improved ZSG-DEA model for emission allowance allocation in China is proposed. Section four first presents the historical data of China's economic and social development, and then proposes one baseline scenario and three reference scenarios, in which the data on China's national and regional GDP, population, energy consumption and CO_2 emissions are projected, for energy and emission performance evaluation and emission allowance allocation. Section five first illustrates the implementation of the proposed ZSG-DEA model and the iteration and adjustment process of the reallocation, presents the regional emission allowance allocation results, and then gives a comparison and discussion on the emission intensity and energy intensity reduction burdens for China's 30 regions by 2020. The sensitivity analysis of the regional CO_2 emissions allowance allocation based on different scenarios is also presented in Section five. The final section concludes the paper.

2 Literature review: total emission control and emission allowance allocation approaches

CO_2 emissions allowance trading is an effective mechanism for emission control, and the initial emission allowance allocation is the key to and premise of this trading. Various emission allowance allocation approaches have been proposed to cope with emission control at international level. Before the Kyoto Protocol, Grubler et al. (1994) proposed that the emission allowance allocation should follow the principle that all countries should be assigned an equal GHG emission reduction rate. Allocating emission allowance equally among countries, coupled with the ability to trade those allowances, is a simple scheme; yet it is fraught with inequities as it ignores the inherent relation between emissions and population or human activities. Westing

(1989) suggested land area as a measurement for allocating emission rights. This straightforward basis has a number of advantages, such as the stability of national land area as a measure, ease of measurement and application, no requirement for monitoring, and avoidance of verification difficulties; however, it favours large but sparsely-populated countries and discriminates against small, densely-populated countries. Grubb (1990) suggested a modified form of per capita allocation, signifying that everyone should have an equal right to an identical emissions quota. Per capita emissions are perceived to be more equitable than the method mentioned previously; however this basis by itself is inadequate, as national governments and not individuals eventually need to pay for global remediation efforts. Any index based solely on this approach would require unacceptably large reductions in industrial countries or entail massive transfer payments to developing countries. Several researchers have proposed an alternative approach, known as the cumulative emission per capita concept (Ding et al., 2010; Yu et al., 2011), which advocates the philosophy of equal or converging per-capita cumulative emission rights over time. This index includes a measure of historical responsibility; however it has to overcome the political and practical difficulties of determining responsibility prior to the modern era.

Given the limitation of the aforementioned simple allocation index, a series of more comprehensive and complicated allocation methods were proposed. For example, Phylipsen et al. (1998) presented a Triptych sectoral approach to distribute the emission reduction burdens among EU Member States. This emission reduction allocating method is based on technological criteria at the sector level, and accounting for important national circumstances. As decomposing emission allowances according to sectors enables a close link to real-world emission reduction strategies, the Triptych sectoral approach is therefore more concrete than previous approaches. The efforts to refine Triptych sectoral approach are also found in current literature. Groenenberg et al. (2001) extended the Triptych approach to the global differentiation of emission reduction, while Den Elzen et al. (2006, 2008) further proposed a multi-stage commitment approach, which allows the delayed participation of developing countries. Some researchers argue that the choice of index should emphasize both the contraction of anthropogenic CO_2 emissions and equitable distribution among countries, leading to the total budget of CO_2 (Bohringer and Welsch, 2004; Ekholm et al., 2009). Compared with other approaches, the contraction and convergence scheme is a preferable and more rational and far-sighted solution, as emission rights are allocated not just across countries, but individually. However, Bohringer and Welsch (2004) asserted that this scheme could potentially increase the transaction costs of emission control and reduction, and international monitoring and decrease public welfare in many countries worldwide.

The approaches mentioned above aim to increase the transparency and equity of the emission allowance allocation among countries, emphasizing the mitigation of contradictions between developed and developing countries in terms of the emission reduction issue. Little attention has been paid to allocating emission allowance within a specific country. Thus, the existing research to some extent ignores the potential challenges of the regional allocation of emission rights. Given the continuing assessment of CO_2 emissions and increasing number of countries participating in emission reduction, research should emphasize not only sharing the burden among countries, but also equitable and rational distribution within countries. For example, the diversity of developments and emission performance in different provinces may challenge the regional reallocation of emission allowance in China. Few, if any, published researches have addressed this research gap. Based on a newly developed comprehensive index combining three indicators for CO_2 emissions control capacity, responsibility and potential, Yi et al. (2011) proposed a CO_2 emissions intensity allocation model, which was applied to allocate the CO_2 reduction targets for provinces in China. However, their emission intensity allocation model is restricted when dealing with problems of total amount emission allowance allocation. Wei et al. (2011) measured the CO_2 reduction potential and abatement capacity of China's 29 provinces over the period 1995-2007 by taking into account both equity and efficiency principles and using a slack-based measure model. However, as they themselves state in their paper, they do not discuss the emission allowance allocation but only the share of the burden among China's provinces.

In this paper, we consider that the Chinese government's commitment to reducing CO_2 emissions intensity by 40-45% is essentially a total amount of emission control target. Since the growth mode, economic and social development, natural resources endowment, and energy-using efficiency of different regions differ greatly, it will be difficult directly to disaggregate the national target of CO_2 emissions intensity reduction into the provincial target for China's 30 regions. Furthermore, the Chinese government has also proposed targets for reducing energy intensity and increasing the share of non-fossil fuel consumption, which should also be achieved by 2020 in association with the emission intensity reduction process. Therefore, in this paper, we translate the target for emission intensity and energy intensity reduction into the target for total emission and total energy consumption control, based on several specified scenarios of the economic and social developments of China and its provinces by 2020, and further allocate the emission allowance based on the target for total emission and total energy consumption control. Given that the constraints of total CO_2 emissions, total energy consumption constraints and the share of non-fossil fuel consumption need to be satisfied simultaneously, we point out that a use of multi-objective optimization method will be more appropriate.

As a non-parametric approach, Data Envelopment Analysis (DEA) has been widely used in the resource allocation problem (Korhonen and Syrjanen, 2004), especially the allocation problem with a fixed total amount of input or output. It is considered that Cook and Kress (1999) proposed the first model, under the DEA framework, that deals with the fixed input allocation problem in which the input allocation was based on a concept that the efficiency score of each decision making unit (DMU) should remain unchanged. Here, the efficiency score is the optimal objective value of DEA model and denotes the efficiency level of each DMU. Unit 1 efficiency score indicates that the related DMU is measured as efficient, and if the score is less than 1, the related DMU is considered inefficiency. If a DMU is measured as efficient, it means that compared with other DMUs under evaluation, this DMU performs best with the lowest consumption of inputs or highest production of outputs. Cook and Kress (1999)'s approach was based on output-oriented version of the CCR-DEA model (Charnes et al., 1978), in which the objective of DEA model is to minimize the weighted combination of input variables with the constraint that the weighted combination of output variables is assigned unit, and the constant returns to scale case is assumed. Cook and Zhu (2005) extended this method to cases that the input-oriented CCR-DEA model was utilized, in which the objective of DEA model is to maximize the weighted combination of output variables. Beasley (2003) presented several DEA models to solve the same fixed input resources allocation problem with the consideration that the average efficiency scores of DMUs in an organization should be maximized. Lozano and Villa (2004) and Lozano et al. (2009) also conducted research on such problems of the emission permits allocation. In their study, a centralized point of view was adopted in DEA method to correspond to the three objectives: maximizing aggregated desirable production, minimizing the consumption of input resources, and minimizing undesirable total emissions. By introducing the zero sum game concepts in to the DEA method, Gomes and Lins (2008) developed a zero sum gains data envelopment analysis (ZSG-DEA) model which was used to reallocate CO_2 emissions allowance among the Annex I parties and Non-Annex I countries of Kyoto Protocol. Also by using ZSG-DEA model, Serrao (2010) proposed a model to efficiently reallocate agricultural greenhouse gas emissions among 15 EU countries. Since the DEA based method has been successfully and effectively applied in the resource allocation problem, in this paper we choose a DEA based approach for the CO_2 emissions allowance allocation over the provinces in China.

One of the key issues related to the CO_2 emissions allowance allocation under the DEA framework is how to deal with the CO_2 emissions which are considered to be undesirable outputs of a productive process, and the production of CO_2 should be minimized. There are several approaches to modelling such types of undesirable outputs in the DEA context; for instance, dealing the undesirable outputs through a weak disposability reference technology by assuming the undesirable outputs and desirable outputs are generated in the same production process (Färe et al., 1989; Zhou et al., 2006); applying the directional distance function to simultaneously increase the desirable outputs and decrease the undesirable outputs (Chung et al., 1997; Färe et al., 2007; Lozano and Gutierrez, 2008; Zhou et al., 2012); translating the undesirable outputs into desirable outputs mathematically under the classification invariance (Seiford and Zhu, 2002); and treating the undesirable outputs as inputs (Reinhard et al., 2000; Zhang et al., 2008). Furthermore, Sueyoshi et al. (2010) and Sueyoshi and Goto (2011a, 2011b, 2011c) proposed a DEA model using the range-adjusted measure which combined the undesirable and desirable outputs in a unified treatment. Since the regional CO_2 emissions allowance is a sub-divided quota of the total emission control target of China, which can essentially be considered as a distribution of the resource to each region, the approach proposed in this paper therefore realistically treats the undesirable outputs of the CO_2 emissions allowance as inputs.

3 Methodology for regional allocation of CO_2 emissions allowance

3.1 CCR-DEA model and zero sum gains DEA (ZSG-DEA) model

The CCR-DEA model first proposed by Charnes et al. (1978) has the following formulation.

$$
\begin{aligned}
& E_{\text{CCR}} = \min \theta \\
& s.t. \ \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rk}, r = 1,\ldots s, \\
& \quad \sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ik}, i = 1,\ldots m, \\
& \quad \lambda_j \geq 0, \ j = 1,\ldots n.
\end{aligned}
\tag{1}
$$

In model (1), θ is the CCR-DEA efficiency measure of the kth DMU under evaluating, and E_{CCR} is the optimized efficiency score for DMU_k. x_{ij} and y_{rj} are the inputs and outputs values, respectively, of each DMU_j, and x_{ik} and y_{rk} are the inputs and outputs values for the under evaluating DMU_k. λ_j are the intensity variables associated with each DMU_j for connecting the inputs and outputs. In model (1), there are n DMUs, and each of them has s inputs and m outputs.

The original CCR-DEA model assumes complete inputs or outputs independence, which indicates that the inputs or outputs of a given DMU do not affect the inputs or outputs of any other DMU. However, in some situations that the total amount of a specific input or output is fixed, this assumption of independence does not exist. In this situation, if an inefficient DMU tries to become efficient through increasing its production, then the other units must decrease their production so as to maintain the constant sum of demand (Gomes et al., 2008; Gomes and Souza, 2010). Similar situation appears in the performance evaluation of CO_2 emissions control and energy consumption control problems that the total allowance of CO_2 emissions and the total amount of energy consumption need to be fixed.

To take this point in consideration, Lins et al. (2003) proposed a new ZSG-DEA method, which represents a similar situation to a zero sum game. In such a situation, all that is gained (or lost) by one of the DMUs must be lost (or gained) by the other DMUs, which means that the net sum of gains must be equal to zero. In other words, when the inefficient DMU is searching for its efficient projection, it has to lose a certain quantity of input or receive a certain amount of output alternatively. As the total output or input fixed, the other DMUs must receive that amount of input or lose that quantity of output alternatively. This alternative approach distinguishes itself from traditional DEA approaches, as the searching for the projection on the efficient frontier of any DMU will lead the change of the efficient frontier.

With such characteristics, the ZSG-DEA model could be applied to the evaluation problems that the independence of inputs (or outputs) does not exist, and the total amount control of inputs (or outputs) does exist; CO_2 emissions allowance efficiency measurement being a typical example (Gomes and Lins, 2008; Lin and Ning, 2011).

The original ZSG-DEA model proposed by Gomes and Lins (2008) is based on input-oriented radial CCR-DEA model, in which all of the input variables are adjusted with same proportion, and the constant returns to scale setting need to be guaranteed. Furthermore, in their case, the DMUs search for their projections on the efficient frontier with only one constant total amount of input: CO_2 emissions. However, in this research, we consider more than one input which have constant total amount, and the quantity of each of them may decrease with different proportion when the specified DMU is searching for efficiency. In addition, we consider that the constant returns to scale setting is valid when each and every DMU is operating at an optimal scale and the application of variable returns to scale setting will be more appropriate. Because the observed DMU in this research are different in size and stay at different development stage, the presumption that all DMUs under analysis are already operating at an optimal scale may not exist. Therefore, based on Gomes and Lins (2008)'s approach, we present the following modified non-radial ZSG-DEA model.

$$
\begin{aligned}
& E_{\mathrm{ZSG}} = \min \sum\nolimits_{i=1}^{m} w_i \theta_i \\
& s.t. \ \ \sum\nolimits_{j=1}^{n} \lambda_j y_{rj} \ge y_{rk}, r = 1, \dots s, \\
& \quad \sum\nolimits_{j=1}^{n} \lambda_j x_{ij} \left(1 + \frac{x_{ik}(1-\theta_i)}{\sum\nolimits_{j=1, j \ne k}^{n} x_{ij}} \right) \le \theta_i x_{ik}, i = 1, \dots m, \qquad (2) \\
& \quad \sum\nolimits_{i=1}^{m} w_i = 1, w_i \ge 0, i = 1, \dots m, \\
& \quad \lambda_j \ge 0, \ j = 1, \dots n.
\end{aligned}
$$

In model (2), θ_i is the ith input related ZSG-DEA efficiency measure of DMU_k under the constraint that the sum of the ith input must be fixed, w_i is the normalized user-specified weight for θ_i, and E_{ZSG} is the unified weighted average efficiency for DMU_k. x_{ij} and y_{rj} are the inputs and outputs values, respectively, and x_{ik} and y_{rk} are the inputs and outputs values for the under evaluating DMU$_k$. λ_j is the contribution of DMU$_j$ to the efficient projection.

The under evaluated DMU$_k$ in model (2) is the object unit that is attempting to decrease its inputs, thus θ_i is the decrease rate for its ith input. Therefore, $x_{ik}(1\text{-}\theta_i)$ is the decrease on the ith input for DMU$_k$, and the amount of the decrease needs to be distributed to the other n-1 DMUs so as their ith input will increase. This process makes sure that the decrease of DMU$_k$ equals to the increase of the other DMU$_j$ ($j\neq k$), and the sum of the ith input is constant. One strategy to distribute $x_{ik}(1\text{-}\theta_i)$ to other DMUs is that, the increase on the ith input for the other DMUs are proportional to their levels of the initial ith input, and the proportion for DMU$_j$ is $x_{ij} \Big/ \sum_{j=1,\, j\neq k}^{n} x_{ij}$. Thus, after the redistribution, the ith input of DMU$_j$ becomes $x_{ij}\left(1+x_{ik}(1-\theta_i) \Big/ \sum_{j=1,\, j\neq k}^{n} x_{ij}\right)$.

The above ZSG-DEA model is formulated to promote the allocation of the input with a constant total amount, when the inefficient DMUs are searching for efficiency. After this inputs redistribution process, all the DMUs will be projected to a new efficient frontier and therefore all DMUs will become efficient. Compared with the original DEA efficient frontier, the newly formed ZSG-DEA efficient frontier will be at a lower level. This is because that the originally efficient DMUs have to be assigned some quantity of input or must lose a certain amount of output to compensate for the amount of input loss or the quantity of output gain of the originally inefficient DMUs. As mentioned in Gomes and Lins (2008), this redistribution strategy is appropriate and reasonable when a regulatory agent is exist and has the ability to influence the DMUs' behavior of allocating resources so as to make all DMUs become efficient.

3.2 A non-radial ZSG-DEA model for CO_2 emissions allowance allocation in China

In this study, we aim to obtain a ZSG-DEA efficient frontier which could appropriately represent an efficient regional allocation of CO_2 emissions (undesirable output), total energy consumption and non-fossil fuel consumption (normal inputs) in the context of CO_2 emissions intensity reduction and energy intensity reduction in China by 2020.

Therefore, we first set a projection of a total amount of emission allowance and energy consumption of China by 2020 (baseline scenario set in section 4.2) based on the commitment to reducing CO_2 emissions intensity by 40-45%. Then we initially allocate the emission allowance based on the percentage for each region's emission out of the total emission of the whole country, which is obtained from the average quantities from 2006 to 2010. Thus, the initial allocation could be seen as representing a basis for further reallocation through ZSG-DEA model.

Using the ZSG-DEA model, we aim to achieve an efficient allocation, which means that all regions which lie on the new ZSG-DEA frontier will become DEA efficient by adjusting the amounts of CO_2 emissions and energy consumptions among different regions of China. In order to reflect the demographic and economic characteristics of each region during allocation, the output variables we used in the modified ZSG-DEA model are gross domestic product (*GDP* in billion RMB) based on the price of 2005, and population (*POP* in millions of inhabitants). The input variables used are total energy consumption (*TE* in million tonnes of coal equivalent, i.e. tce), CO_2 emissions (CO_2 in million tonnes), and non-fossil energy consumption (*NF* in million tce). Here, the term of coal equivalent is a reference unit for the energetic evaluation of various energy carriers, and according to the conversion factors from energy physical unit to calorific value provided in China's national standard (GB/T 2589-2008): General principles for calculation of total production energy consumption (SAC, 2008), 1 kilogram coal equivalent corresponds to a value specified as 29.3 million joules (or 7,000 kilocalories). All three inputs have constant total amounts which need to be reallocated among China's regions. The associated ZSG-DEA allocation model (3) is shown below.

$$
\begin{aligned}
E_{\mathrm{ZSG}}^{'} &= \min w^{TE}\theta^{TE} + w^{CO_2}\theta^{CO_2} + w^{NF}\theta^{NF} \\
s.t.\ & \sum\nolimits_{j=1}^{n}\lambda_j y_j^{GDP} \geq y_k^{GDP}, \\
& \sum\nolimits_{j=1}^{n}\lambda_j y_j^{POP} \geq y_k^{POP}, \\
& \sum\nolimits_{j=1}^{n}\lambda_j x_j^{TE}\left(1+\frac{x_k^{TE}(1-\theta^{TE})}{\sum\nolimits_{j=1,j\neq k}^{n} x_j^{TE}}\right) \leq \theta^{TE} x_k^{TE}, \\
& \sum\nolimits_{j=1}^{n}\lambda_j x_j^{CO_2}\left(1+\frac{x_k^{CO_2}(1-\theta^{CO_2})}{\sum\nolimits_{j=1,j\neq k}^{n} x_j^{CO_2}}\right) \leq \theta^{CO_2} x_k^{CO_2}, \\
& \sum\nolimits_{j=1}^{n}\lambda_j x_j^{NF}\left(1+\frac{x_k^{NF}(1-\theta^{NF})}{\sum\nolimits_{j=1,j\neq k}^{n} x_j^{NF}}\right) \leq \theta^{NF} x_k^{NF}, \\
& w^{TE}+w^{CO_2}+w^{NF}=1, w^{TE}, w^{CO_2}, w^{NF}>0, \\
& \lambda_j \geq 0, j=1,...n.
\end{aligned}
\tag{3}
$$

In model (3), θ^{TE}, θ^{CO_2}, and θ^{NF} represent the efficiency of total energy consumption, the efficiency of CO_2 emissions allowance allocation, and the efficiency of non-fossil fuel consumption, respectively. w^{TE}, w^{CO_2}, and w^{NF} are corresponding normalized user-specified weights of these efficiencies. We consider that all of the three efficiencies have identical importance when evaluating the unified ZSG-DEA efficiency E'_{ZSG}; thus all three weights are set to be 1/3.

The definition of unified efficiency E'_{ZSG} proposed in Model (3) suggests that, of regions with the same total energy consumption level, same CO_2 emissions level, and same non-fossil energy consumption level, the one produces higher GDP and sustains more population is measured to be more efficient. Alternatively, of those regions with similar values of GDP and population, the most efficient one is that with the lowest energy consumption level and CO_2 emissions level.

3.3 Research framework and main assumptions

In order to give a more clear interpretation of our regional emission allowance allocation model and its adjustment and reallocation process, we additionally illustrate the research framework in Figure 1 to indicate our projection, computation and analysis steps, as well as the main assumptions of our modelling and analysis.

First of all, we propose that China's target on CO_2 emissions intensity reduction is essentially a total amount of emission control target, and the disaggregation of emission intensity reduction of China is essentially an emission allowance allocation problem among different Chinese regions. Thus, in this study, we need to translate the intensity target into a total amount target before conducting the regional emission allowance allocation.

Second, since Chinese government also proposed other mitigation action plans associated with emission intensity reduction plan, we assume here that the realization of energy intensity reduction target and share of non-fossil fuel increase target should also be taken into account when allocating CO_2 emissions allowance. Also, we need to first translate the energy intensity target and share of non-fossil fuel target into total amount targets, and then assign them among Chinese provinces. In addition, there may exist overlap effects between the emission intensity target and energy intensity target, as well as between the emission intensity target and the share of non-fossil fuel target, therefore, we need to additionally analysis how these three targets overlap for the final emission intensity reduction.

Third, in order to translate the intensity target into total amount target, we propose a baseline scenario of China's growth by 2020, in which the national GDP, population, total energy consumption, CO_2 emissions, and non-fossil fuel consumption are projected according to the assumptions of GDP annual growth rate, population growth rate, central government's energy intensity reduction target, emission intensity reduction target, and share of non-fossil fuel increase target. Except the population projection, we assume that all the other projection in our baseline scenario are based on the GDP projection (because the major targets in China's mitigation action plans are set as unit GDP intensity targets), and the adjustments on China's GDP growth will lead to various energy consumption and CO_2 emissions projections. Thus, other than the baseline scenario, we also propose three reference scenarios to reflect the low, mid-high, and high economic growth situations of China by 2020.

Fourth, based on the historical data of regional economic and social developments, energy consumptions and CO_2 emissions status of Chinese 30 provinces, the projected national GDP, population, total energy consumption, total CO_2 emissions allowance, and total non-fossil fuel consumption of China by 2020 are initially assigned or allocated among Chinese 30 regions. Here, we assume that the percentages of regional GDP and regional population of each Chinese region in the total GDP and total population of China in 2020 are similar to those percentages of 2006-2010's average levels of each region, which indicate that the growth pattern and development status of each Chinese region will not essentially change during the next decade. Similarly, when initially allocating the emission allowance and the related energy consumption among different regions, the average percentage levels of these values during 2006-2010 are utilized.

Fifth, CCR-DEA model (1) are applied to measure the original efficiency levels of Chinese 30 regions based on the projected and initially allocated values, and then ZSG-DEA model (3) are utilized to adjust the allocated emission allowances among different regions. After several times of iteration, when all regions are projected to the ZSG-DEA efficient frontier and are measured as CCR-DEA efficient, the final emission allowance allocation scheme is confirmed. Meanwhile, the reassignment of total energy consumption target and non-fossil fuel consumption target will also be confirmed simultaneously.

At last, based on the emission allowance allocation scheme, the emission intensity, energy intensity, share of non-fossil fuels of each Chinese region can be further calculated and the intensity reduction burdens for each region can be analyzed and compared. Furthermore, based on the other three reference scenarios, the sensitivity analysis on emission allowance allocation can be presented for low, baseline, mid-high, and high economic growth settings for China and its 30 regions by 2020.

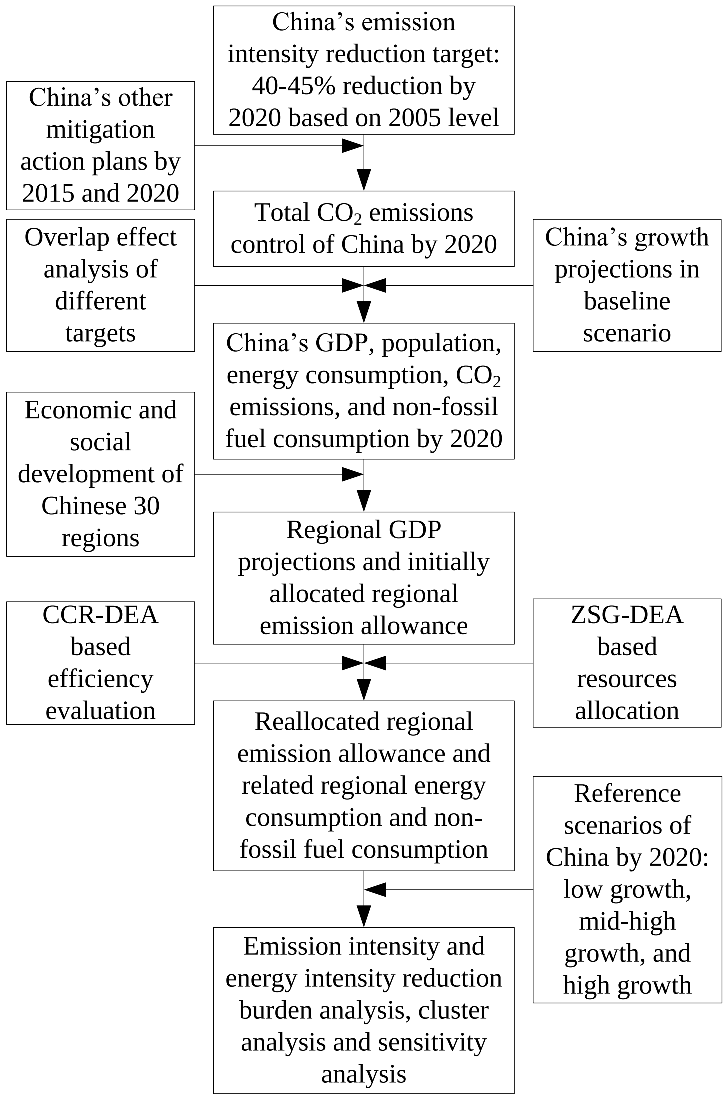

Figure 1 Research framework of emission allowance allocation over provinces in China

4 Data and scenarios

4.1 Historical values of 2005

The values of China's GDP, population, and total energy consumption in 2005, collected from the China Statistical Yearbook (NBS, 2006a) and the China Energy Statistical Yearbook (NBS, 2006b), are 19895.8 billion $RMB_{¥2005}$, 1280.5 million inhabitants, and 2623.2 million tonnes of coal equivalent (tce), respectively.

Here, we calculate China's total CO_2 emissions of 2005 by using the default emission indicators provided in IPCC (2006) and the conversion factors from energy physical unit to calorific value provided in China's national standard (GB/T 2589-2008): General principles for calculation of total production energy consumption (SAC, 2008). Since the resources endowment, energy consumption structure and energy utilization efficiency of different Chinese regions differ greatly, in order to reflect the regional differences on CO_2 emissions, we firstly disaggregate the total fossil fuel energy consumption of each Chinese region into sub-item energy consumptions (i.e. raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, and natural gas) according to the provincial energy balance pivot tables (NBS, 2006b). Then, these sub-item energy consumptions are converted into calorific value according to the conversion factors (SAC, 2008). Thirdly, the sub-item energy consumption based calorific values of each Chinese region are further translated into its CO_2 emissions. Because there has been no large scale survey on CO_2 emissions of China at the provincial level, the specific emission factors for each type of energy in each China's region could not be obtained from the published official reports or statistics, we here utilized the default IPCC CO_2/calorific value factors (IPCC, 2006) for the emission calculation. In addition, considering the differences on regional energy resource quality and energy utilization efficiency, a fine adjustment on the default emission factors used for different Chinese regions were conducted so as to reflect these differences between different Chinese regions. That is, for the regions with comparatively higher energy intensities (calculated based on 2005 data) in China, the upper bound value of the emission factors are applied; for the regions with comparatively lower energy intensities, the lower bound value of the emission factors are used; and other regions whose energy intensities were middle ranked among Chinese 30 regions in 2005, the default emission factors are utilized. Finally, the sub-item energy consumption based CO_2 emissions are accumulated into the regional total CO_2 emissions and the national total CO_2 emissions of China, which was 5951.5 million tonnes CO_2 in 2005.

We also calculated China's non-fossil fuel consumption of 2005 as 168.7 million tce, according to the data published in the China Energy Statistical Yearbook (NBS, 2006b). When calculating the regional non-fossil fuel consumption, we firstly collect the following data in the provincial energy balance pivot tables under the items of "moving in electricity from other provinces", "indigenous primary electricity production", and "sending out electricity to other provinces", and "other energy". Then we calculate the non-fossil fuel part of the moving in electricity for each region. Since each region's moving in electricity includes the composition which comes from the consumption of non-fossil fuels (hydro power, nuclear power and wind power), and each region gets the moving in electricity mainly through the national power grid of China, we here use the share of non-fossil fuel electricity production in total electricity production, which was 18% on average for China in 2005, to approximately calculate the non-fossil fuel part of the moving in electricity for each region. Thirdly, we calculate the non-fossil fuel parts of the indigenous primary electricity and sending out electricity. The indigenous primary electricity production mainly comes from hydro power and wind power for every Chinese region and the share of indigenous primary electricity production in total electricity production for most Chinese regions were quite low and were utilized for local consumption. But there were four exceptions: Yunnan, Sichuan, Qinghai, and Hubei, which had large amount of indigenous primary electricity productions and large parts of these electricity productions are sent out to other Chinese regions for consumption. To avoid double counting, the sending out electricity parts are subtracted from the indigenous primary electricity productions for the above four regions. Fourthly, the non-fossil fuel part of the moving in electricity and the non-fossil fuel part of the indigenous primary electricity (excluding sending out primary electricity for the above four regions) are summed up and converted into coal equivalent according to the regional conversion factor of each Chinese region in 2005 which was in the range of 292-425 g/kWh (CEC, 2007). In addition, the data under the item of other energy in the provincial energy balance pivot table are also calculated as part of the non-fossil fuel consumption of each Chinese region. Finally, all the non-fossil fuel consumptions calculated above are accumulated to be the total non-fossil fuel consumptions of Chinese regions in 2005.

Based on the above values of China's GDP, total energy consumption, total CO_2 emissions, and total non-fossil fuel consumption, the national energy intensity, emission intensity, and share of non-fossil fuels in primary energy consumption of China in 2005 can be confirmed which are 1.32 (tce/ten thousand $RMB_{¥2005}$), 2.99 (tCO_2/ten thousand $RMB_{¥2005}$), and 6%, respectively. Furthermore, these values for China's 30 administrative regions were also calculated and presented in Table 1. Four regions of Tibet, HongKong, Macao and Taiwan are excluded because of the data absence.

Table 1 Regional values of GDP, population, energy and emission of China and its 30 regions in 2005

Regions	GDP (billion RMB at 2005 rates)	Population (million)	Total energy consumption (million tce)	CO_2 emissions (million tonnes CO_2)	Non-fossil fuel consumption (million tce)	Energy intensity (tce/ten thousand RMB)	CO_2 emissions intensity (tCO_2/ten thousand RMB)	Share of non-fossil fuels in primary energy consumption
Beijing	697.0	15.4	55.2	110.5	2.6	0.79	1.59	5%
Tianjin	390.6	10.4	41.2	99.3	0.5	1.05	2.54	1%
Hebei	1001.2	68.5	197.5	507.1	3.7	1.97	5.07	2%
Shanxi	423.1	33.6	123.1	307.1	1.8	2.91	7.26	1%
Inner Mongolia	390.5	23.9	96.4	266.5	1.2	2.47	6.83	1%
Liaoning	804.7	42.2	146.9	334.2	4.3	1.82	4.15	3%
Jilin	362.0	27.2	59.6	162.7	3.8	1.65	4.49	6%
Heilongjiang	551.4	38.2	80.3	172.2	2.7	1.46	3.12	3%
Shanghai	924.8	17.8	80.7	179.7	1.4	0.87	1.94	2%
Jiangsu	1859.9	74.8	169.0	425.0	2.1	0.91	2.29	1%
Zhejiang	1341.8	49.0	120.3	254.4	14.1	0.90	1.90	12%
Anhui	535.0	61.2	65.2	162.7	1.0	1.22	3.04	2%
Fujian	655.5	35.4	61.6	133.4	10.3	0.94	2.04	17%
Jiangxi	405.7	43.1	42.9	104.1	3.5	1.06	2.57	8%
Shandong	1836.7	92.5	236.1	579.3	2.6	1.29	3.15	1%
Henan	1058.7	93.8	146.3	337.2	3.0	1.38	3.18	2%
Hubei	659.0	57.1	98.5	197.2	11.3	1.49	2.99	11%
Hunan	659.6	63.3	91.1	191.6	10.9	1.38	2.90	12%
Guangdong	2255.7	91.9	177.7	352.8	19.5	0.79	1.56	11%
Guangxi	398.4	46.6	49.8	112.1	8.5	1.25	2.81	17%
Hainan	89.8	8.3	8.2	16.1	0.5	0.91	1.79	6%
Chongqing	346.8	28.0	43.6	83.4	6.1	1.26	2.40	14%
Sichuan	738.5	82.1	113.0	171.1	19.4	1.53	2.32	17%
Guizhou	200.5	37.3	64.3	155.8	5.5	3.21	7.77	9%
Yunnan	346.2	44.5	60.2	145.5	12.1	1.74	4.20	20%
Shaanxi	393.4	37.2	54.2	113.9	1.8	1.38	2.89	3%
Gansu	193.4	25.9	43.7	89.3	7.1	2.26	4.62	16%
Qinghai	54.3	5.4	16.7	21.4	4.8	3.07	3.94	29%
Ningxia	61.3	6.0	25.1	52.8	0.8	4.10	8.61	3%
Xinjiang	260.4	20.1	55.1	113.2	1.7	2.11	4.35	3%
China	19895.8	1280.5	2623.2	5951.5	168.7	1.32	2.99	6%

4.2 Projection values in scenarios of 2020

The scenarios of China's economic growth, population, energy consumption and CO_2 emissions by 2020 are given as follows. First of all, according to the research of the

Development Research Center of the State Council of China (Wang, 2005) and the EIA (2009), the annual GDP growth rate of China during the period of 2011 to 2020 is 5.3% and 6.4% (in the low economic growth scenarios) and 8% and 7.4% (in the high economic growth scenarios), respectively. Here, we first assume that the annual GDP growth rate during 2010-2020 is 6.4% in our baseline scenario; thus the projection for China's GDP by 2020 is 68.3 trillion RMB (at 2005 rates) or 81.2 trillion RMB (at 2010 rates). In addition, for further sensitivity analysis, we also set another three economic growth scenarios other than the baseline scenario, which are low growth scenario, mid-high growth scenario, and high growth scenario with the annual GDP growth rate of 5.3%, 7.4%, and 8%, respectively, during 2011 and 2020.

Secondly, according to the research of the United Nations Department of Economic and Social Affairs, China's population by 2020 will be 1.43 billion (UNDESA, 2008). We use this population projection in our four scenarios.

Thirdly, in the IEA (2009b), the projection baseline of China's CO_2 emissions is 9.6 billion tonnes, and the number in the reference scenario of the ERI (2009a) is 10.2 billion tonnes. Since China aims to reduce its emission intensity by 40-45% by 2020 compared to 2005, and considering the projection of GDP for 2020 set above in the baseline scenario, the target emission intensity by 2020 should be 1.65-1.79 (tonnes CO_2/ten thousand $RMB_{¥2005}$). In this study, we consider a high emission intensity decrease rate of 45% and choose the target emission intensity value of 1.65 (tonnes CO_2/ten thousand $RMB_{¥2005}$). Therefore, the constant total CO_2 emissions control target of China for 2020 in the baseline scenario is 11.2 billion tonnes, which is 1.6 billion tonnes more than that in the baseline of the IEA (2009b), and 1 billion tonne more than that in the reference scenario of the ERI (2009a). In addition, this figure is above the 450 ppm CO_2 equivalent scenario, in which China's CO_2 emissions are projected to be 8.4 billion tonnes (IEA, 2009b).

In China's 11th Five-Year Plan (2006-2010), a goal of reducing energy intensity by 20% was set and was almost achieved, since the latest government report issued in 2011 indicated that China's energy intensity has decreased by 19.1% by the end of 2010 based on 2005 level. In addition, in the 12th five-Year Plan (2011-2015), a new goal of 16% energy intensity reduction was proposed. Here, we consider that during the 12th and 13th Five-Year Plans (2011-2020), the energy intensity will continuously decrease but with a decreasing rate lower than 20%. Since the energy intensity decrease is highly related with the decrease of emission intensity, and the targets of energy intensity reduction and emission intensity reduction are overlapping to a certain extent (as analyzed by den Elzen et al., 2011b), in order to set the energy intensity reduction rate appropriately and reasonably, we initially assume the energy intensity reduction rate to be 16% and 15% during 2011-2015 and 2016-2020, respectively, and then analysis the possible overlap effects between these two intensity reduction targets so as to further confirm whether our energy intensity reduction rate setting is appropriate.

In 2005, China's total energy consumption was 2623.2 tce, in which the shares of four major sub-item energy consumptions of coal, petroleum, natural gas, and non-fossil fuels (hydro power, nuclear power and wind power) in primary energy consumption were 70%, 20%, 3%, and 7%, respectively. In 2010, the above four shares changed to 68%, 19%, 4%, and 9%, respectively. According to the baseline scenario and assuming the 16% and 15% energy intensity reduction rates during 2011-2015 and 2016-2020, respectively, the energy intensity of China in 2020 will be 0.94 (tce/ten thousand $RMB_{¥2005}$), which is 29% below the 2005 level, and therefore the total energy consumption of China in 2020 will be 6427.7 tce. Since the Chinese government has put forward a series programs and policies to adjust the economic growth mode so as to promote energy efficiency, and to optimize the energy consumption structure was considered the key approach in the efforts of energy efficiency promotion and given priority in the 12th five-Year Plan and the Comprehensive Work Plan of Energy Saving and Emission Reduction (SCC, 2011), here we mainly focus on the energy consumption structure adjustments and related CO_2 emissions changes when analyzing the overlap effect. We first consider a basic projection of the shares for coal, petroleum, natural gas, and non-fossil fuels in 2020: 57%, 20%, 8%, and 15%, respectively, referring the research of ERI (2009b). Under this projection, up to 2020, the share of high carbon intensity energy (coal) will decrease by 13% compared with 2005 level, and the shares of clean energy (natural gas) and non-fossil fuels will respectively increase by 5% and 8% during the same period. This basic projection reflects a normal energy consumption structure adjusting process according the current status of Chinese economic growth and the implementation of current energy management policies. Then, we consider a conservative projection, in which the shares of the four major sub-item energy consumptions in 2020 are assumed similar to their levels in 2010: 68%, 19%, 4% and 9%, respectively. This conservative projection reflects a negative situation that the energy consumption structure will hardly be optimized in the next decade. Furthermore, an optimistic projection is assumed, and the shares of the four major sub-item energy consumptions will be 52%, 18%, 10%, and 20% respectively. It is notable that, under this optimistic projection, the share of coal in primary energy consumption will be remarkably reduced and the gap caused by this reduction will be filled in by the increasing consumptions of natural gas and renewable energy, and the shares of them will significantly increase by about 7% and 13%, respectively, compared with the 2005 levels.

The above three projections could be seen as the normal level, lower bound and upper bound of China's energy consumption structure in 2020, and based on these projections, we further calculate the related CO_2 emissions of China in 2020 according to the region specific and energy item specific emission factors we utilized above when calculating China's total CO_2 emissions in 2005. The calculation results indicate that under the conservative projection and the basic projection, China's emission intensity reduction rates of 2020 to 2005 will be 3.8% and 7.9% below the baseline emission intensity reduction rate (45%), which means that under these two projections the overlap effect of energy intensity reduction target hardly affect the emission intensity, since it does not lead to additional emission reductions nor a higher decrease in emission intensity beyond 45%. Under the optimistic projection, the energy intensity reduction target is projected to overlap with the emission intensity reduction target, but the overlap effect is not obvious. According to our calculation, the optimistically projected final emission intensity reduction rate is just 0.1% beyond the 45% baseline rate. Because the overlap effects between these two intensity reduction targets are insignificant both under the normal level and the lower/upper bound of energy consumption structures, we could confirm that the settings of energy intensity reduction (i.e. 16% and 15% decreases during 2011-2015 and 2016-2020 respectively) for China in the baseline scenario is appropriate. As a matter of fact, the 29% energy intensity reduction target is exactly the guarantee of the realization of 45% emission intensity reduction target.

The above analysis also indicates that, considering the current economic growth mode and energy consumption structure of China, the 45% emission intensity reduction target and the 29% energy intensity reduction target are well matched, and they do not evidently overlap with each other. Although these two targets are highly related, the energy intensity reduction target should not be omitted when allocating the emission allowance, since the disaggregation of the emission intensity reduction target is not directly related to the effort of energy consumption structure optimization and energy efficiency promotion, but the disaggregation of energy intensity reduction target could clearly indicate the energy management target for each Chinese region, and guide the energy saving and emission control policy making of local government.

Furthermore, according to the National Renewable Energy Development Medium- and Long-Term Plans (NDRC, 2007), by 2020, the percentage of the non-fossil fuel consumption in the primary energy consumption should come up to 15%. Thus, non-fossil fuel consumption is projected to be 964.2 million tce by 2020 in our baseline scenario. It should be noticed that, in the above three projections of energy consumption structure in 2020, the shares of non-fossil fuels in primary energy consumption are set to 15% (basic level), 9% (lower bound), and 20% (upper bound). The basic level is the national target and reflects the most possible situation of the consumption of non-fossil fuels in 2020 under the current status of China's economic development and energy policies. The lower bound and the upper bound respectively reflect the less possible pessimistic situation and optimistic situation, that in the former one, the share of non-fossil fuels will stay on its 2010 level for the next decade, and in the latter one, the share will double its 2010 level. Similar to the overlap effect analysis above, according to our calculation of CO_2 emissions under these three projections, the share of non-fossil fuel increase target also will not evidently overlap for the final emission reductions. Because the 15% share of non-fossil fuel target proposed by the government is covered by the 45% emission intensity reduction target and is considered one of the key efforts to decrease energy intensity and promote energy efficiency, thus, the non-fossil fuel target of 2020 in our baseline scenario also will not lead to obvious higher decrease in emission intensity.

To sum up, in our baseline scenario, the projected values under the five criteria of GDP, population, total energy consumption, CO_2 emissions, and non-fossil fuel consumption for China in 2020 are 68278.2 billion $RMB_{¥2005}$, 1430 million people, 6427.7 million tce, 11233.3 million tonnes CO_2, and 964.2 million tce, respectively. All of the projection values for China for 2020 are initially distributed among its 30 regions according to each region's shares of these values under the above five criteria in the total amount for the whole country based on the historical average values of 2006 to 2010. For example, the average share of CO_2 emissions of Hebei in the total CO_2 emissions of China during 2006-2010 was 8.09%, thus, Hebei is then initially allocated 8.09% share of China's total CO_2 emission allowance in 2020. The projected and initially allocated regional values of GDP, population, energy consumption, CO_2 emissions, and non-fossil fuel consumption for China's 30 regions are presented in Table 2.

Table 2 Projections of regional GDP, population, energy and emission of China and its 30 regions by 2020 (baseline scenario)

Regions	GDP (billion RMB at 2005 rates)	Population (million)	Total energy consumption (million tce)	CO_2 emissions (million tonnes CO_2)	Non-fossil fuel consumption (million tce)
Beijing	2302.2	18.9	121.6	162.1	14.7
Tianjin	1438.5	12.9	104.3	183.2	2.6
Hebei	3308.3	76.7	465.4	908.4	21.2
Shanxi	1386.7	37.6	295.0	551.7	10.2
I. Mongolia	1540.3	26.5	266.6	628.9	7.1
Liaoning	2825.0	47.2	339.2	672.9	24.4
Jilin	1311.8	29.9	135.4	286.3	21.7

Heilongjiang	1821.2	41.9	188.9	299.0	15.5
Shanghai	3047.7	21.4	190.9	284.4	7.9
Jiangsu	6495.9	84.1	423.9	782.3	12.0
Zhejiang	4492.3	56.4	285.7	476.9	80.6
Anhui	1831.7	66.6	158.4	325.6	5.9
Fujian	2301.7	39.5	157.1	255.8	58.8
Jiangxi	1379.6	48.1	103.5	206.1	19.9
Shandong	6333.2	103.2	583.3	1046.2	14.6
Henan	3635.8	103.0	357.6	683.0	17.4
Hubei	2293.4	62.5	246.2	409.0	64.7
Hunan	2301.8	70.1	238.2	361.5	62.1
Guangdong	7671.1	105.9	444.8	625.3	111.5
Guangxi	1392.0	52.0	124.8	217.7	48.7
Hainan	307.9	9.3	21.6	32.7	2.9
Chongqing	1231.3	31.1	124.0	174.0	35.0
Sichuan	2550.4	89.0	290.5	340.5	111.1
Guizhou	678.7	40.7	135.8	273.0	31.6
Yunnan	1134.2	49.7	144.1	268.6	69.2
Shaanxi	1414.5	41.0	141.3	246.0	10.4
Gansu	626.2	28.5	100.9	159.9	40.4
Qinghai	185.3	6.1	42.5	43.7	27.6
Ningxia	206.3	6.8	61.5	112.3	4.6
Xinjiang	833.4	23.2	134.7	216.1	9.8
China	68278.2	1430.0	6427.7	11233.3	964.2

Since we also proposed another three reference scenarios for sensitivity analysis of emission allowance allocation, the projected values under those five criteria for China in 2020 are further presented in Table 3.

Table 3 Projections of China's GDP, population, energy and emission by 2020 (reference scenarios)

Scenario	GDP (billion RMB at 2005 rates)	Population (million)	Total energy consumption (million tce)	CO_2 emissions (million tonnes CO_2)	Non-fossil fuel consumption (million tce)
Low growth	61538.8	1430.0	5793.2	10124.5	869.0
Mid-high growth	74973.6	1430.0	7058.0	12334.9	1058.7
High growth	79268.9	1430.0	7462.3	13041.5	1119.3

5 Results and discussions of CO_2 emissions allowance allocation in China by 2020

5.1 CO_2 emissions allowance allocation over China's 30 regions

The DMUs considered in this study are 30 administrative regions of China. Firstly, we want to verify which regions under the initial projections by 2020 are efficient or inefficient. Then, we need to know what will be the efficient allocation for CO_2 emissions allowance, i.e., how the constant total amount of emission allowance should be reallocated over China's 30 regions in the context of CO_2 emissions intensity reduction commitment, as well as the energy intensity reduction and share of non-fossil fuel increase targets by 2020.

The second to the fifth column of Table 4 presents the initial value of three inputs (total energy consumption, CO_2 emissions allowance, and non-fossil fuel consumption for China's 30 regions by 2020), and the initial CCR-DEA efficiency of each region calculated through model (1). The CCR-DEA efficiency denotes each region's performance of producing desirable GDP output and sustaining population through consuming energy input and emitting undesirable CO_2 output as by product. These three inputs, which have a constant total amount, are further adjusted by using the ZSG-DEA efficiency of model (3). After five iterations and adjustments, the reallocation of CO_2 emissions allowance over different regions in China by 2020 were obtained and shown in the seventh column of Table 4. Table 4 also presents the adjusted total energy consumption (the sixth column), non-fossil fuel consumption (the eighth column) and the final ZSG-DEA efficiency (the ninth column) after the reallocation. The ZSG-DEA efficiency indicates each region's performance of GDP producing and population sustaining with the consumption of total amount fixed energy and the utilization of total amount controlled emission allowance. It can be seen that all regions achieve efficiency (i.e. gained unit 1 efficiency score) and lie on the new ZSG-DEA frontier after the reallocation.

Table 4 Allocated values and efficiency scores of Chinese regions by 2020 (baseline scenario)

Regions	Initial values				Adjusted values (after five iterations and adjustments)			
	Total energy consumption (million tce)	CO_2 emissions (million tonnes CO_2)	Non-fossil fuel consumption (million tce)	Initial CCR-DEA efficiency	Total energy consumption (million tce)	CO_2 emissions allowance (million tonnes CO_2)	Non-fossil fuel consumption (million tce)	Final ZSG-DEA efficiency after reallocation
Beijing	121.6	162.1	14.7	1.000	163.6	221.4	40.1	1.000
Tianjin	104.3	183.2	2.6	1.000	140.4	250.2	7.2	1.000
Hebei	465.4	908.4	21.2	0.495	331.7	657.3	22.2	1.000
Shanxi	295.0	551.7	10.2	0.382	145.7	293.7	10.2	1.000
I. Mongolia	266.6	628.9	7.1	0.401	143.2	275.2	8.9	1.000
Liaoning	339.2	672.9	24.4	0.463	261.0	500.1	16.0	1.000
Jilin	135.4	286.3	21.7	0.514	130.9	258.9	8.7	1.000
Heilongjiang	188.9	299.0	15.5	0.633	182.2	360.6	12.1	1.000
Shanghai	190.9	284.4	7.9	1.000	256.9	388.4	21.7	1.000
Jiangsu	423.9	782.3	12.0	1.000	570.4	1068.4	32.9	1.000
Zhejiang	285.7	476.9	80.6	0.679	340.0	475.2	85.6	1.000
Anhui	158.4	325.6	5.9	1.000	213.1	444.6	16.1	1.000
Fujian	157.1	255.8	58.8	0.653	185.5	266.9	47.9	1.000
Jiangxi	103.5	206.1	19.9	1.000	139.2	281.5	54.4	1.000
Shandong	583.3	1046.2	14.6	0.814	581.9	1112.3	35.5	1.000
Henan	357.6	683.0	17.4	0.747	387.4	784.8	27.3	1.000
Hubei	246.2	409.0	64.7	0.517	209.4	316.8	56.4	1.000
Hunan	238.2	361.5	62.1	0.581	218.9	338.8	58.4	1.000
Guangdong	444.8	625.3	111.5	0.829	590.8	832.4	149.8	1.000
Guangxi	124.8	217.7	48.7	0.716	162.6	258.9	40.8	1.000
Hainan	21.6	32.7	2.9	1.000	29.1	44.6	7.9	1.000
Chongqing	124.0	174.0	35.0	0.558	109.8	164.7	29.4	1.000
Sichuan	290.5	340.5	111.1	0.636	277.5	425.7	75.4	1.000
Guizhou	135.8	273.0	31.6	0.522	130.1	271.4	9.8	1.000
Yunnan	144.1	268.6	69.2	0.564	155.0	239.1	41.7	1.000
Shaanxi	141.3	246.0	10.4	0.702	151.9	308.5	10.8	1.000
Gansu	100.9	159.9	40.4	0.505	89.1	137.5	23.9	1.000
Qinghai	42.5	43.7	27.6	0.297	18.9	29.0	5.2	1.000
Ningxia	61.5	112.3	4.6	0.243	23.1	47.6	1.7	1.000
Xinjiang	134.7	216.1	9.8	0.445	88.3	178.6	6.2	1.000
Total	6427.7	11233.3	964.1	-	6427.7	11233.3	964.1	-
Mean	-	-	-	0.663	-	-	-	1.000

In Table 4, seven regions are shown to be efficient under the evaluation of the CCR-DEA model (1): Beijing, Tianjin, Shanghai, Jiangsu, Anhui, Jiangxi, and Hainan. The allowance of these efficient regions accounts for 24% of the total emission allowance of 2020. The remaining 23 regions are all inefficient ones and the worst performing region is Ningxia with an efficiency score of 0.243. The average efficiency score of all these 30 regions is 0.663. A comparative analysis can be made through Table 4. Analyzing, for instance, the DMUs of Beijing and Guangxi, it can be found that, although these two regions have approximately the same quantities of total energy consumption, CO_2 emissions, and non-fossil fuel consumption, Beijing is more efficient than Guangxi, since its GDP is 65% higher. Similarly, Jiangxi and Guizhou have almost the same quantity of total energy consumption and CO_2 emissions, but Jiangxi produces twice as much GDP as Guizhou and sustains more population, which implies that Guizhou is less efficient than Jiangxi.

Using the ZSG-DEA model (3), a new ZSG-DEA frontier is provided with the reallocation of CO_2 emissions allowance over China's 30 regions. As mentioned previously, after the reallocation, all regions become efficient. The promotion of the average total energy consumption efficiency θ^{TE}, average CO_2 emissions efficiency θ^{CO_2}, and average non-fossil fuel consumption efficiency θ^{NF}, as well as the unified efficiency E'_{ZSG} during the five iterations are illustrated in Figure 2, which indicates a rapid increase of ZSG-DEA efficiency scores. It should be noted that not all of these regions are Pareto efficient, as some regions have positive slacks in output variable of GDP. However, there will be no positive slacks associated with input variables of CO_2 emissions and energy consumption. That is because the ZSG-DEA model we proposed imposes a fixed total amount of each of these inputs, which means that no decrease of inputs without bounds can occur.

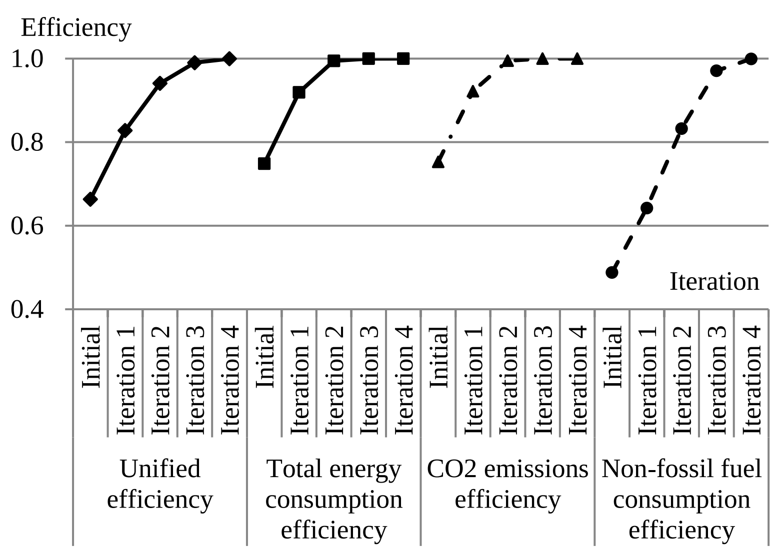

Figure 2 Promotion process of average efficiency through iterations and adjustments

During the process of the five iterations, different regions have different adjustments of their allocated CO_2 emissions allowances, as illustrated in Figure 3. The CO_2 emissions allowances of 13 regions (Beijing, Tianjin, Heilongjiang, Shanghai, Jiangsu, Anhui, Jiangxi, Henan, Guangdong, Guangxi, Hainan, Sichuan, and Shaanxi) experience an obvious increase after the reallocation and the most evident increases (+36%) take place in those regions which were evaluated as efficient under the initial CCR-DEA efficiency from model (1), e.g., Beijing, Shanghai, Jiangxi, etc. There are also 10 regions whose CO_2 emissions allowances decrease after the reallocation: Hebei, Shanxi, Inner Mongolia, Liaoning, Hubei, Yunnan, Gansu, Qinghai, Ningxia, and Xinjiang. The most obvious CO_2 emissions allowance decrease is on Ningxia (-57%), followed by Inner Mongolia (-56%) and Shanxi (-46%). The adjustments of CO_2 emissions allowances of the remaining 7 regions (Jilin, Zhejiang, Fujian, Shandong, Hunan, Guizhou, and Chongqing) are slight that none of the adjustments exceeds ten percent.

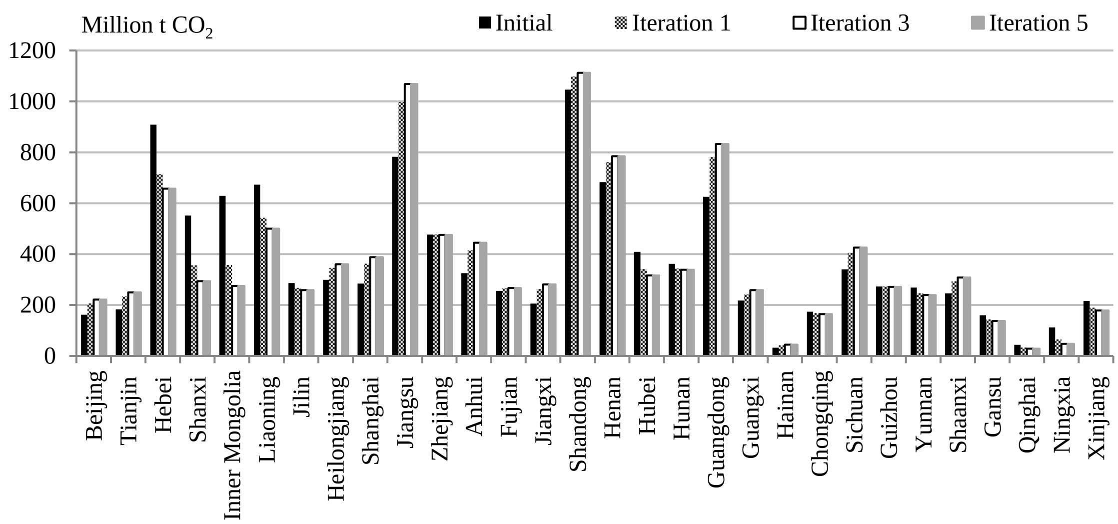

Figure 3 Adjustment process of regional CO_2 emissions allowance

5.2 Discussions and comparative analysis

From a general viewpoint, the results from the ZSG-DEA model can be considered as an reasonable scheme for the CO_2 emissions allowance allocation and as a first step for the allowance trade process in that, ideally, if some high-performing regions (e.g., Shandong, Henan, Guangdong, and Guangxi whose initial CCR-DEA efficiencies are all above 0.7) aim to become efficient in terms of energy consumption efficiency, CO_2 emissions efficiency, and unified efficiency, they will increase their emission values at the expense of decreasing the emission values of other regions. Conversely, for some of the other low-performing regions (e.g., Ningxia, Inner Mongolia, Shanxi, and Qinghai, whose initial CCR-DEA efficiencies are all below or around 0.4), the way to become efficient is to decrease their emission values in order to provide the opportunity of emission value increase to other regions. Furthermore, those regions that are initially evaluated as CCR-DEA efficient (e.g., Beijing, Shanghai, Jiangxi, Hainan etc.) continue to be efficient after the reallocation process, in which their emission values are also increased. Therefore, we could say that when allocating the constant total amount of resources, the ZSG-DEA approach will "benefit" the regions that operate at the optimal scale of operation or approximately optimal scale of operation. However, on the contrary, this approach will "punish" the regions that are far from the optimal scale of operation.

We further calculate three indices of energy intensity, CO_2 emissions intensity, and share of non-fossil fuels in primary energy consumption for each region in 2005 (based on historical data) and by 2020 (under the total amount control baseline scenario and after the reallocation process). The results are respectively presented in the last three columns in Table 1 and the second to the fourth columns of Table 5. A complementary analysis is further implemented from Table 5 (shown in last three columns) and Figure 4 and 5 that, in terms of energy intensity, the sharpest falls from 2005 to 2020 take place in Ningxia, Qinghai, Inner Mongolia, and Shanxi, and the rates of decrease for these regions are all above 60%. During the same period, the energy intensity decline of Guangdong is the least, followed by Jiangsu, Shanghai, Anhui and Jiangxi, whose decreasing rates are all below 10%. In addition, for Hainan, it is acceptable but not recommended that it can increase its energy intensity for about 3% according to the ZSG-DEA adjustment process, since Hainan's energy efficiency is highly ranked among China's 30 regions and its energy consumption structure is more balanced with comparatively lower share of coal consumption but higher share of clean and renewable energy consumptions.

Table 5 Energy intensity, emission intensity, and share of non-fossil fuels in 2020 and their changes compared with 2005 levels of China and its 30 regions (baseline scenario)

Region	Energy intensity (tce/ten thousand RMB)	CO_2 emissions intensity (tCO_2/ten thousand RMB)	Share of non-fossil fuels in primary energy consumption	Energy intensity change	CO_2 emissions intensity change	Share of non-fossil fuels change
Beijing	0.71	0.96	24.51%	-10.3%	-39.3%	428%
Tianjin	0.98	1.74	5.11%	-7.4%	-31.6%	358%
Hebei	1.00	1.99	6.68%	-49.2%	-60.8%	255%
Shanxi	1.05	2.12	6.97%	-63.9%	-70.8%	382%
I. Mongolia	0.93	1.79	6.18%	-62.3%	-73.8%	382%
Liaoning	0.92	1.77	6.14%	-49.4%	-57.4%	111%
Jilin	1.00	1.97	6.65%	-39.4%	-56.1%	4%
Heilongjiang	1.00	1.98	6.67%	-31.3%	-36.6%	98%
Shanghai	0.84	1.27	8.43%	-3.4%	-34.4%	391%
Jiangsu	0.88	1.64	5.77%	-3.3%	-28.0%	363%
Zhejiang	0.76	1.06	25.18%	-15.6%	-44.2%	115%
Anhui	1.16	2.43	7.57%	-4.5%	-20.2%	378%
Fujian	0.81	1.16	25.80%	-14.2%	-43.0%	54%
Jiangxi	1.01	2.04	39.05%	-4.5%	-20.5%	381%
Shandong	0.92	1.76	6.10%	-28.5%	-44.3%	462%
Henan	1.07	2.16	7.06%	-22.9%	-32.2%	239%
Hubei	0.91	1.38	26.95%	-38.9%	-53.8%	134%
Hunan	0.95	1.47	26.68%	-31.2%	-49.3%	124%
Guangdong	0.77	1.09	25.36%	-2.2%	-30.6%	131%
Guangxi	1.17	1.86	25.11%	-6.6%	-33.9%	47%
Hainan	0.95	1.45	27.23%	3.7%	-19.2%	340%
Chongqing	0.89	1.34	26.73%	-29.1%	-44.4%	90%
Sichuan	1.09	1.67	27.17%	-28.9%	-28.0%	58%
Guizhou	1.92	4.00	7.57%	-40.2%	-48.5%	-12%
Yunnan	1.37	2.11	26.88%	-21.4%	-49.8%	34%
Shaanxi	1.07	2.18	7.11%	-22.1%	-24.7%	112%
Gansu	1.42	2.20	26.83%	-37.0%	-52.5%	66%
Qinghai	1.02	1.57	27.23%	-66.8%	-60.3%	-6%
Ningxia	1.12	2.31	7.35%	-72.7%	-73.2%	128%
Xinjiang	1.06	2.14	7.03%	-49.9%	-50.7%	125%
China	0.94	1.65	15.0%	-28.9%	-45.0%	133%

As shown in Figure 4, for CO_2 emissions intensity, Ningxia and Inner Mongolia both experience the sharpest fall (-73%) from 2005 to 2020, followed by Shanxi, Hebei and Qinghai, whose emission intensity decreasing rates are all above 60%. The results in Figure 5 show that Ningxia, Inner Mongolia, Shanxi, and Qinghai have to take higher burdens of achieving both the emission intensity reduction and the energy intensity reduction targets of more than 60% by 2020. However, for the regions of Anhui, Jiangxi, Jiangsu, Sichuan, Shaanxi, and Hainan, both of these burdens are considerably lower and the reduction targets for them are all below 30%. The remaining regions all have medium reduction burdens, and for most of these regions, the energy intensity reduction rates are comparatively lower than the emission intensity reduction rates.

In 2020, there are 14 regions whose shares of non-fossil fuels in primary energy consumption are higher than the national average (15%), and 11 of these are regions in the south or southwest of China, and are rich in hydropower; e.g., Yunnan, Sichuan, Guangxi and Hubei. The other regions, such as Qinghai and Gansu, are in northwestern China where the wind power is abundant.

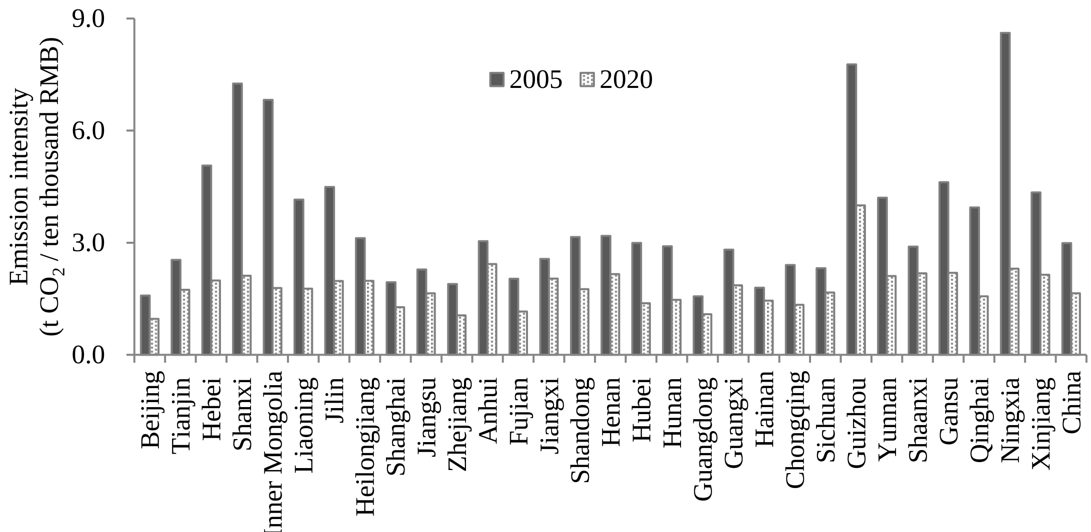

Figure 4 Emission intensity reductions of China and its 30 regions (2020 to 2005)

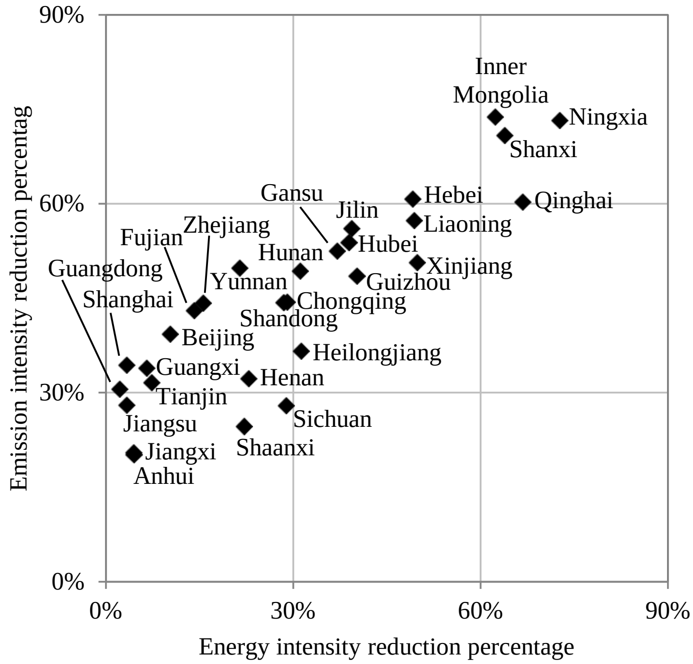

Figure 5 Energy and emission intensity reduction percentages for Chinese regions (2020 to 2005)

We further classify China's 30 regions into three clusters of low, medium and high burdens of reductions according to their percentages of energy intensity reduction and emission intensity reduction. The classifications are shown in Figures 6 and 7, respectively.

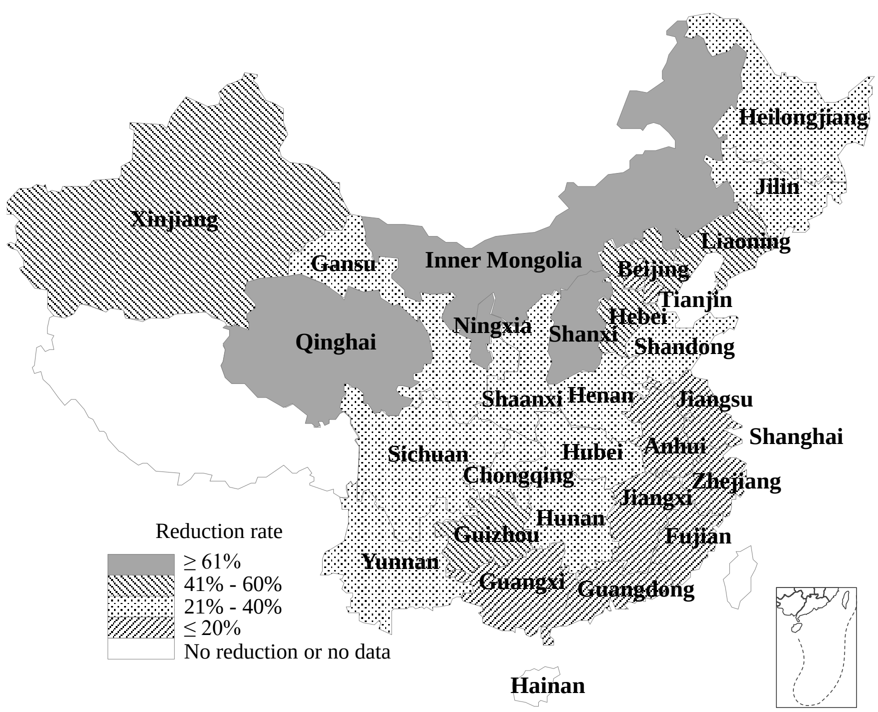

Figure 6 Cluster analysis map of energy intensity reduction level for China's 30 regions

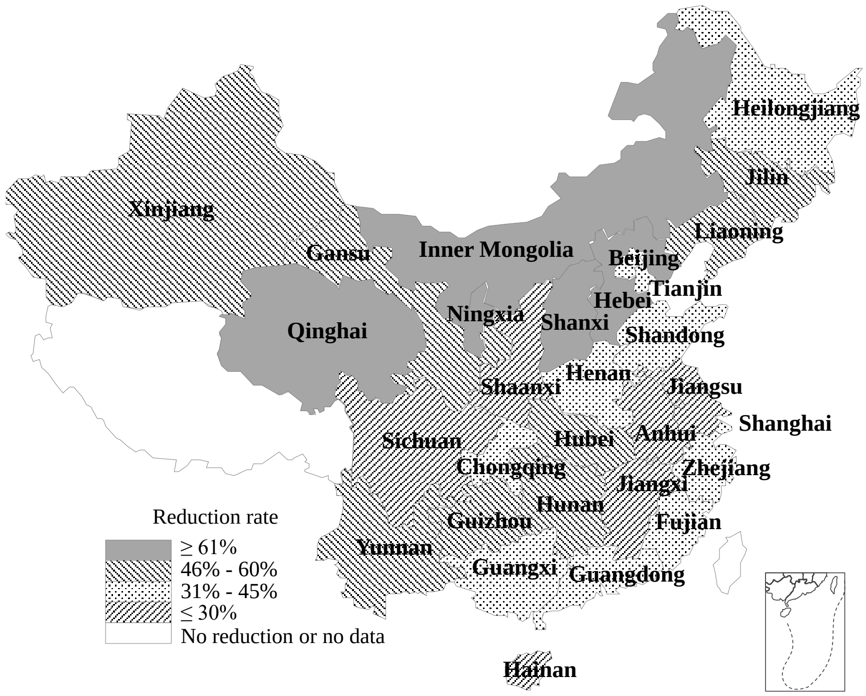

Figure 7 Cluster analysis map of emission intensity reduction level for China's 30 regions

For the energy intensity reduction, four provinces shoulder high reduction burdens, with a reduction percentage of more than 60%. These four are all northwestern provinces (Inner Mongolia, Ningxia, Qinghai) or northern province (Shanxi) of China and their average reduction percentage is 66%. Four regions have medium-high reduction burdens (with a reduction percentage between 40% and 60%). Two of these regions (Liaoning, Hebei) are located on the east coast of China, and the other two are both central and western provinces (Xinjiang, Guizhou). The average reduction percentage for them is 47%. There are another eleven provinces shoulder medium-low reduction burdens whose reduction percentages are between 20% and 40%. Most of them are central and west Chinese regions. And the remaining ten regions have low reduction burdens (with a reduction percentage below 20%). Most of these regions are in east area of China and their average reduction percentage is only 7%.

For emission intensity reduction, three northwestern provinces and two northern provinces will take high reduction burdens, with an average reduction percentage of 68%. Four eastern provinces and two western provinces will shoulder low reduction burdens, with an average reduction percentage of 23%. The remaining nineteen provinces have to take medium-high or medium-low reduction burdens. Of these medium-high reduction regions, Liaoning and Jilin come from northeastern China, as well as Hubei and Hunan come from central China, which are all Chinese heavy industry bases. And of those medium-low reduction regions, four municipalities of Beijing, Tianjin, Shanghai and Chongqing, as well as Zhejiang, Shandong and Guangdong are all considered the most well economically and socially developed regions in China.

In general, the CO_2 emissions allowance allocation scheme shows that the regions with high initial CCR-DEA efficiencies will take low reduction burdens; according to our calculations there are 7 such regions, which are mainly provinces in eastern China. These provinces have experienced the most rapid economic growth and social development in China in the past 30 years, and their energy intensity and emission intensity in 2005 are below China's average level. Conversely, the regions with low initial CCR-DEA efficiencies have to shoulder high reduction burdens. There are 4 such provinces in our allocation scheme which are all provinces in western China. Compared to eastern and central China, western China has a low population density and high resource reserves, but the least developed economy and society, and the energy intensity and emission intensity of these provinces in 2005 are higher than the average value of China.

Since we have set another three economic growth scenarios of low growth (5.3% annual GDP growth rate), mid-high growth (7.4% annual GDP growth rate), and high growth (8% annual GDP growth rate) reference scenarios, we further calculate three projections for China's GDP by 2020 as shown in Table 6. Compared with the projection in baseline scenario, China's GDP in 2020 will decrease 6739 billion $RMB_{¥2005}$ in low growth scenario, and respectively increase 6695 or 10990 billion $RMB_{¥2005}$ in mid-high growth or high growth scenarios.

Correspondingly, to realize the 45% emission intensity reduction target, the CO_2 emissions of China in 2020 will be 10124 million tonnes, 12334 million tonnes, and 13041 million tonnes (shown in Table 6 and Figure 8) in low growth, mid-high growth, and high growth scenarios, respectively. It means that to keep the emission intensity of 1.65 (tCO_2/ten thousand $RMB_{¥2005}$) in 2020, China's total CO_2 emissions in low growth scenario could be 9.87% below the baseline total emissions, but will be 9.81% or 16.10% above the baseline total emissions in mid-high growth or high growth scenarios. Furthermore, compared with the 2010 level, China's total CO_2 emissions will respectively increase by 724, 1833, 2935, and 3641 million tonnes by 2020 in the low growth, baseline, mid-high growth, and high growth scenarios. The projected total CO_2 emissions by 2020 in all the four scenarios are above the 450 ppm CO_2 equivalent scenario that China's CO_2 emissions should be 8400 million tonnes (IEA, 2009b).

Table 6 Projected GDP, energy consumption and CO_2 emissions of China by 2020 (reference scenarios)

Scenario	Low growth scenario	Mid-high growth scenario	High growth scenario
GDP (billion RMB at 2005 rates)	61538.8 (-6739.3)	74973.6 (+6695.4)	79268.9 (+10990.8)
Total energy consumption (million tce)	5793.2 (-634.4)	7058.0 (+630.3)	7462.3 (+1034.7)
CO_2 emissions (million tonnes CO_2)	10124.5 (-1108.8)	12334.9 (+1101.6)	13041.5 (+1808.2)
Non-fossil fuel consumption (million tce)	869.0 (-95.2)	1058.7 (+94.5)	1119.3 (+155.2)

Note: numbers in the parentheses indicate the decrease (-) or increase (+) volumes compared with the baseline scenario

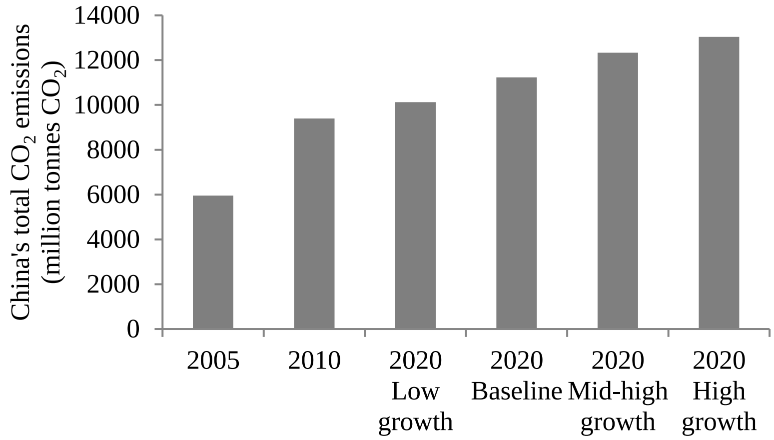

Figure 8 China's total CO_2 emissions of 2005, 2010 and 2020 in different scenarios

In addition, China's total energy consumption and non-fossil fuel consumption by 2020 in the reference scenarios are also calculated and documented in Table 6. The total energy consumption will be 634 million tce less than or 630 million tce and 1034 million tce more than the baseline total energy consumption in low growth, mid-high growth, and high growth scenarios, respectively. And the non-fossil fuel consumption by 2020 in low growth scenario will be 95 million tce less than that in baseline scenario, and 94 million tce or 155 million tce more than the baseline non-fossil fuel consumption in mid-high growth scenario or high growth scenario, respectively. The corresponding projected regional GDP and reallocated CO_2 emissions allowance, total energy consumptions and non-fossil fuel consumptions of China's 30 regions in these three reference scenarios are further documented in Appendix Table A1.

6 Conclusions

Nowadays, China has become the greatest energy consumer and CO_2 emitter in the world. Since the rapid economic growth of China in the latest decade has led to an increasing share in the world's GHG emissions, the mitigation efforts of China are increasingly important for meeting global climate target. Recently, China had proposed a mitigation action plan consists of reducing the CO_2 emissions intensity and increasing the share of non-fossil fuels in primary energy consumption, and submitted it to the UNFCCC as part of the Copenhagen Accord and the Cancún Agreements. In addition, the energy intensity reduction target was also proposed as part of China's national plan during both the 11th and 12th Five-Year Plans. In this study, we point out that China's CO_2 emissions intensity reduction target is essentially a total emission control and emission allowance allocation problem, and the realization of this target is highly associated with China's other mitigation plans of energy intensity reduction and share of non-fossil fuel consumption increase. Although each Chinese province have been required to adjust their economic growth mode and energy consumption structure, as well as restructure their energy and emission policies, it may not guarantee that the regional efforts on energy saving and emission reduce can meet the national mitigation target. Therefore, it is particularly important for China to rationally and effectively disaggregate the national mitigation targets into the provincial targets, i.e. to reasonably allocate the national total emission allowance over China's provinces, and simultaneously assign the national total energy consumption and non-fossil fuel consumption targets among Chinese provinces.

Based on several specified scenarios of China's economic and social development, and considering the mitigation targets announced by Chinese government of decreasing energy intensity and emission intensity, as well as increasing the share of non-fossil consumption, this study proposes a modified ZSG-DEA model to allocate the constant total amount of CO_2 emissions allowance over China's 30 provinces by 2020. Through the efficiency measure, iteration and adjustment process of ZSG-DEA model, a new ideally efficient CO_2 emissions allowance allocation scheme at the provincial level for China is proposed.

The allocation result first shows that the ZSG-DEA model can be seen as an effective method for the CO_2 emissions allowance allocation in that it benefits the high-performing regions and punishes the regions far from optimal scale of operation. Furthermore, based on the allocation result, the indices of energy intensity, emission intensity, and share of non-fossil fuels in primary consumption for China and its 30 regions by 2020 are calculated, which indicate that the provinces of Ningxia, Inner Mongolia, Shanxi, and Qinghai have to shoulder heavier burdens of achieving both the emission intensity reduction and the energy intensity reduction targets of more than 60%; the burdens on the provinces of Anhui, Jiangxi, Jiangsu, Sichuan, Shaanxi, and Hainan are comparatively light that are all below 30%; and the remaining Chinese regions all have medium reduction burdens between 30% and 60%.

Since the CO_2 emissions allowance allocation approach for China at the provincial level proposed in this paper provides only an initial and ideal reallocation scheme, we suggest that at least one future improvement regarding the application of ZSG-DEA model should be considered. Because different regions may have different natural resource endowments and be at different stages of economic and social development, when allocating the mission allowance to these regions, specific restrictions on the intensity variables assigned to each region (i.e. the contribution of each region to efficient projection) should be included, in order to lead to a more reasonable and flexible reallocation scheme in which the characteristics of different regions could be better reflected. In addition, the carbon leakage effect also plays a role in the energy and emission efficiency measure and the CO_2 emissions allowance allocation over provinces in China. However, in the current study we are not able to take into account this effect in our medelling, or analyze its macro-economic effects under our allocation model framework. Therefore, it is considered another important potential improvement of this study in the future.

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Appendix

Table A1 Projected or reallocated values of GDP, energy consumption and CO_2 emissions allowance of China's 30 regions by 2020 (reference scenarios)

	GDP (billion RMB at 2005 rates)			**Total energy consumption (million tce)**			**CO_2 emissions (million tonnes CO_2)**			**Non-fossil fuel consumption (million tce)**		
	Low growth scenario	Mid-high growth scenario	High growth scenario	Low growth scenario	Mid-high growth scenario	High growth scenario	Low growth scenario	Mid-high growth scenario	High growth scenario	Low growth scenario	Mid-high growth scenario	High growth scenario
Beijing	2075.0	2528.0	2672.8	147.5	179.6	189.9	199.6	243.1	257.1	36.1	44.0	46.6
Tianjin	1296.5	1579.6	1670.1	126.6	154.2	163.0	225.5	274.7	290.5	6.5	7.9	8.3
Hebei	2981.7	3632.7	3840.8	299.0	364.3	385.1	592.4	721.7	763.1	20.0	24.3	25.7
Shanxi	1249.8	1522.6	1609.9	131.3	160.0	169.1	264.7	322.5	341.0	9.2	11.2	11.8
I. Mongolia	1388.3	1691.4	1788.3	129.1	157.3	166.3	248.1	302.2	319.5	8.0	9.7	10.3
Liaoning	2546.1	3102.0	3279.7	235.2	286.6	303.0	450.8	549.2	580.6	14.4	17.6	18.6
Jilin	1182.3	1440.4	1522.9	118.0	143.8	152.0	233.4	284.3	300.6	7.9	9.6	10.1
Heilongjiang	1641.4	1999.8	2114.3	164.2	200.0	211.5	325.0	396.0	418.7	10.9	13.3	14.1
Shanghai	2746.9	3346.6	3538.3	231.6	282.1	298.3	350.1	426.5	451.0	19.5	23.8	25.1
Jiangsu	5854.7	7132.9	7541.5	514.1	626.3	662.2	962.9	1173.1	1240.3	29.7	36.2	38.2
Zhejiang	4048.9	4932.8	5215.4	306.5	373.4	394.8	428.3	521.8	551.7	77.2	94.1	99.4
Anhui	1650.9	2011.3	2126.6	192.1	234.0	247.4	400.7	488.2	516.2	14.5	17.7	18.7
Fujian	2074.5	2527.4	2672.2	167.2	203.7	215.4	240.5	293.0	309.8	43.1	52.6	55.6
Jiangxi	1243.4	1514.8	1601.6	125.5	152.9	161.6	253.7	309.1	326.8	49.0	59.7	63.1
Shandong	5708.1	6954.2	7352.7	524.4	638.9	675.5	1002.5	1221.4	1291.3	32.0	39.0	41.2
Henan	3276.9	3992.3	4221.0	349.1	425.3	449.7	707.3	861.8	911.1	24.6	30.0	31.7

Hubei	2067.0	2518.3	2662.5	188.7	229.9	243.1	285.5	347.9	367.8	50.8	61.9	65.5
Hunan	2074.6	2527.6	2672.4	197.3	240.3	254.1	305.4	372.0	393.3	52.6	64.1	67.8
Guangdong	6913.9	8423.3	8905.9	532.5	648.7	685.9	750.2	914.0	966.4	135.0	164.5	173.9
Guangxi	1254.6	1528.5	1616.1	146.6	178.6	188.8	233.4	284.3	300.6	36.8	44.8	47.4
Hainan	277.5	338.1	357.5	26.3	32.0	33.8	40.2	49.0	51.8	7.1	8.7	9.2
Chongqing	1109.8	1352.0	1429.5	99.0	120.6	127.5	148.4	180.8	191.2	26.5	32.2	34.1
Sichuan	2298.7	2800.5	2961.0	250.1	304.7	322.2	383.7	467.5	494.2	67.9	82.8	87.5
Guizhou	611.7	745.2	787.9	117.2	142.8	151.0	244.6	298.0	315.1	8.9	10.8	11.4
Yunnan	1022.2	1245.4	1316.8	139.7	170.3	180.0	215.5	262.6	277.6	37.6	45.8	48.4
Shaanxi	1274.9	1553.2	1642.2	136.9	166.8	176.3	278.1	338.8	358.2	9.7	11.9	12.5
Gansu	564.4	687.6	727.0	80.3	97.8	103.4	123.9	151.0	159.6	21.5	26.2	27.7
Qinghai	167.0	203.5	215.2	17.1	20.8	22.0	26.1	31.9	33.7	4.6	5.7	6.0
Ningxia	185.9	226.5	239.5	20.8	25.4	26.8	42.9	52.3	55.2	1.5	1.9	2.0
Xinjiang	751.1	915.1	967.6	79.6	97.0	102.6	161.0	196.2	207.4	5.6	6.8	7.2
China	61538.8	74973.6	79268.9	5793.2	7058.0	7462.3	10124.5	12334.9	13041.5	869.0	1058.7	1119.3