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When does the Turning Point in China's CO_2 Emissions Occur? Results Based on the Green Solow Model

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Abstract
In recent years, the surge in China's CO_2 emissions has caused increasing international concern. In this paper, we investigate whether and when the turning point in China's CO_2 emissions would occur. A simple yet powerful neoclassical Green Solow Model (GSM) is utilized herein as the main forecasting tool. To verify the capability of this framework to address China's economy, a key prediction of the GSM – the convergence in per capita CO2 emissions across Chinese provinces – is empirically verified. By assigning reasonable values to the GSM's key parameters, the trajectories of total CO_2 emissions are projected for the three regions of China and the whole country. The forecast results show that under the benchmark scenario, China's total CO_2 emissions would peak approximately in the year 2047. According to the sensitivity analysis, carbon efficiency is the most important determining factor for whether a turning point in total CO2 emissions may occur.

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1. Introduction

As the main greenhouse gas (GHG), carbon dioxide (CO_2) is considered to be the most important cause of global warming. In recent years, due to rapid economic growth, China's CO_2 emissions have increased rapidly. According to the estimations of the Carbon Dioxide Information Analysis Center (CDIAC), China's CO_2 emissions had expanded by more than three-fold within two decades, from 2461 million tons in 1990 to 8241 million tons in 2010. Since 2007, China has overtaken the U.S. as the world's largest CO_2 emitter. Moreover, in 2010, China's total CO_2 emissions accounted for approximately a quarter of the world's total emissions; emissions from China represented as much as 68% of the total increase in global CO_2 emissions between 2000 and 2010.[1] Figure 1 depicts China's CO_2 emissions and its share of global emissions since 1990. For comparison, China's share of world GDP in the same period is also included in the figure. From 1990 to 2011, China's share of world GDP rose by 7.8%, from 1.63% to 9.39%, whereas China's CO_2 emissions proportion increased by 13.7%, from 10.95% to 24.65%, during the same period.

[Figure 1 is here]

The fact that China's share of world CO_2 emissions grew faster than its share of world GDP partly reflects China's extensive growth during the two decades from 1990-2011, which relied heavily on energy consumption and generated increasing levels of pollution.[2] Because the conventional extensive growth model has brought mounting tensions to resources and the environment, it has proven to be unsustainable and needs to be shifted to a more

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[1] See http://articles.timesofindia.indiatimes.com/2013-04-15/pollution/38555480_1_renewable-energy-emissions-international-climate-negotiations.

[2] Besides the surging CO_2 emissions, the fog and haze (whose main component is Fine Particulates Matter, or PM2.5) that stroke the North and East of China frequently since 2012 are additional types of representative air pollutants. For more information about haze and fog in China, see http://usa.chinadaily.com.cn/china/2013-12/08/content_17159665.htm and http://www.forbes.com/sites/ywang/2013/12/06/eastern-china-hit-by-severe-air-pollution/.

intensive growth pattern, typically identified with more efficient energy consumption and lower pollution emissions. Meanwhile, international pressure to shift the pattern of growth has also increased, in terms of pressure to control GHG emissions and mitigate global warming. Given China's remarkable share of global CO_2 emissions and its rapid growth (see Figure 1), the international community's concern over China's CO_2 emissions is increasing.

Despite the necessity to control CO_2 emissions and the Chinese government's commitment to so, there is a vigorous debate within academic circles and the international community at large about how rapidly CO_2 emissions in China could be reduced, if at all.[3] Given China's high volume of CO_2 emissions and its current growth trend, the key questions of concern for the international community and academics include: When will the turning point in China's CO_2 emissions occur, if at all? If there is a turning point, how high will the emission peak be? Additionally and more importantly, under what circumstances will the turning point exist? Will it occur as a natural outcome of China's economic development or as a consequence of government intervention? In order to answer these questions convincingly, the theory of the CO_2 Environmental Kuznets Curve (CKC) is utilized and examined herein. Literally speaking, CKC is a special case of the Environmental Kuznets Curve (EKC), which was first introduced by Grossman and Kruger (1991) to describe a hypothesized U-shaped relationship between various indicators of environmental degradation and income per capita: In the early stage of economic development, pollution increases and the environment deteriorates; however, beyond a certain level of income per capita, pollution

[3] Some recent actions of the Chinese government suggest that China is indeed determined to join international environmental lobbies in reducing CO_2 emissions. After launching ambiguous programs to cut the CO_2 intensity of GDP through the allocation of concrete reduction goals to every province in 2009 and 2011, it has been reported that China is considering setting a total cap on its CO_2 emissions during the next five-year period 2016-2020, which would be the first time in the history such an action is undertaken. For more information, see http://www.reuters.com/article/2014/06/03/china-climatechange-idUSL3N0OK1VH20140603.

decreases and the environment improves.

As stressed in survey papers such as Stern (2004) and Dinda (2004), the existing empirical EKC literature contains problems in both empirical and theoretical aspects. In the empirical aspect, it is already well known that the empirical results from EKC analyses (including the positions of the turning points of the studied pollutants) are highly sensitive to the regression specifications, the variables used as the regressors, and even the sample size. The differences in empirical results from EKC analyses are so large that there has as yet been no consensus regarding whether the EKC relationship is valid. For instance, although the empirical studies of Cole et al. (1997), Schmalensee et al. (1998), Galeotti and Lanza (2005) and Auffhammer and Carson (2008) support the existence of a CKC, Agras and Chapman (1999), Roca and Alcántara (2001), Azomahou et al. (2006) and He and Richard (2009) all claim that the empirical results do not favor the existence of a turning point in CO_2 emissions. Torras and Boyce (1998) verify that the emission peak only exists for certain types of pollutants. Galeotti et al. (2006) find evidence supporting the existence of a CKC only in OECD nations. Some studies have even reported the relationship between pollutants and income to follow various shapes such as a "U", "inverted-U", "N" or "inverted-N" (e.g., Holtz-Eakin and Selden, 1995; Moomaw and Unruh, 1997; Torras and Boyce 1998; Duarte et al. 2013). Moreover, as Wagner (2008) have noted, nearly all these empirical studies on CKC have been subject to several major econometric complications such as ignoring the nonlinear transformations of integrated regressors and the cross-sectional dependence in the panel context. In a recent study, Itkonen (2012) claims that recent studies estimating the CKC by adding energy consumption as a control variable are subject to model misspecifications related to the econometric methodology and data definition used. On the theoretical side, a growing body of literature has emerged to provide theoretical explanations for the inverted-U shaped EKC, including Stokey (1998), Andreoni and Levinson (2001), Brock and Taylor (2005, 2010). However, very few of these theoretical explanations can be used to guide empirical estimations directly. The empirical EKC/CKC literature to date has basically examined the EKC/CKC as a purely empirical relationship, which is also one important reason why different empirical studies vary considerably in their forms of estimation and their results. The latest development in EKC/CKC estimations involves utilizing more advanced methodologies and/or specific regression specifications. Some representative studies include: Azomahou et a. (2006) and Nguyen-Van (2010), which utilized nonparametric and semiparametric panel data analyses to investigate the EKC for CO_2 emissions and energy consumption, respectively; Fouquau et al. (2009), which used a threshold panel specification to estimate EKC for energy demand; Duarte et al. (2013), which employed a panel smooth transition approach to examine EKC for water use; and Jobert et al. (2014), which applied a Bayesian shrinkage approach to estimate a country-specific EKC from panel data. However, although the utilization of new methodologies could improve the quality of estimations to some extent, some fundamental problems involved with the EKC framework, as Stern (2004) and Dinda (2004) claim, still exist.

Given the potential problems and flaws in EKC estimation and other empirical forecasting models, we refrain from making forecasts on the basis of empirical frameworks in this study.[4] Instead, our forecast is conducted utilizing the "Green Solow Model" (GSM) as

[4] Other empirical models available for forecasts include IPAT, STIRPAT and ImPACT (York et al. 2003). However, these models also suffer from similar empirical and theoretical problems as the empirical EKC method. Moreover, because these models generally suppose that the impact of income on the environment is linear, the occurrence of a turning point for pollutant emissions highly depends on some specific assumptions of future income and other factors that could influence the environment. Usually, these assumptions are rather arbitrary, which to a great extent affects the reliability of the forecast results.

the main theoretical tool. Developed by Brock and Taylor (2010), the GSM is a neoclassical theoretical framework that incorporates pollutant emissions into the textbook Solow model. Under the GSM framework, the projection of China's CO_2 emissions can be completely determined when some key parameters in the model are fixed. The inverted-U shaped CKC can be observed if certain conditions of the key parameters are met. Concretely speaking, the contribution of this paper is twofold. First, the prediction of the GSM that there would exist convergence in per capita CO_2 emissions across Chinese provinces is verified with China's provincial panel data. The convergence not only confirms the applicability of GSM to China but also implies that China's provincial CO_2 emissions tend to stabilize, which is a necessary condition for the existence of a turning point in China's total CO_2 emissions in the long run. Although some studies have found evidence supporting the convergence of some pollutants, including CO_2, across countries (Chang and Lee, 2008; Ordás Criado et al., 2011), this study represents the first time that the convergence in per capita CO_2 emissions across Chinese provinces is verified. Second, using reasonable values for the GSM's key parameters for the three regions of China (eastern, central and western), the projections of China's CO_2 emissions between 2011 and 2080 are forecasted based on the predictions for the three regions with the GSM framework.[5] The results indicate that China's total CO_2 emissions would peak approximately in the year 2041 in the benchmark scenario.

The rest of this paper proceeds as follows. In section 2, the framework of the GSM and its relationship with the EKC are briefly introduced. In section 3, an empirical study is

[5] There are currently 23 provinces, four Centrally Administered Municipalities, and five autonomous regions in China. Since these entities are administratively equal, for convenience we use the term "province" throughout this paper. According to the classification scheme of the National Bureau of Statistics (NBS), the Eastern region includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan; the Central region includes Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan; the Western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shannxi, Gansu, Qinghai, Ningxia and Xinjiang.

conducted to examine a key prediction of the GSM, that there is a convergence in per capita CO_2 emissions across Chinese provinces. In section 4, after the values of the key parameters of the EKC are determined for the three regions, the trajectories of CO_2 emissions for these regions and the country as a whole are forecasted. Some international comparisons are also implemented to check the reasonableness of the forecast results. Finally, section 5 concludes and suggests directions for further studies.

2. The Green Solow Model

The GSM was originally developed by Brock and Taylor (2010). As the model's name reveals, the GSM inherits the basic elements of the textbook Solow Model developed by Solow (1956). The only differences in the GSM are the introduction of CO_2 emissions as an unwanted by-product and exogenous technology progress in pollution abatement.[6] The core equations that describe the dynamics of capital stock and pollutant emissions are as follows.

$$\frac{\dot{k}}{k}=(1-\theta)sk^{\alpha-1}-(\delta+n+g_B) \tag{1}$$

$$\frac{\dot{e}_C}{e_C}=\left(g_B+\alpha\frac{\dot{k}}{k}\right)-g_A \tag{2}$$

$$\frac{\dot{E}}{E}=\left(n+g_B+\alpha\frac{\dot{k}}{k}\right)-g_A \tag{3}$$

where k denotes the capital stock per effective worker, e_C represents the pollution emissions per capita, and E represents total CO_2 emissions. The variables s, δ, n, g_B and g_A represent saving rate, depreciation rate, population growth rate, productive technology growth rate, and the growth rate for carbon efficiency. The variable α is the production elasticity of capital stock, and θ is the ratio of investment in CO_2 abatement to total GDP. Eq. (1) describes the

[6] The assumptions of exogenous technology progress in both goods production and abatement are indeed strong. The benefit of making such strong assumptions is that the model becomes relatively simple and easier to calculate.

dynamics of capital stock. Similar to the textbook Solow model, the increase in capital stock per effective worker ($\dot{k}$) is the difference of actual investment $(1-\theta)sk^{\alpha}$ and break-even investment $(\delta+n+g_B)k$. Eq. (2) interprets the dynamics of per capita CO_2 emissions. Under the model, per capita CO_2 emissions would increase at the same rate as exogenous productive technology progress and decrease at a rate matching the exogenous improvement in carbon efficiency, which explains the term g_B in the parentheses and $-g_A$ outside the parentheses, respectively. Additionally because the GSM treats CO_2 emissions as the by-product of the output, a change in output would also affect the growth rate of per capita CO_2 emissions; therefore, the second term in the brackets ($\alpha\,\dot{k}/k$) is introduced. Eq. (3) describes the dynamics of total CO_2 emissions. Compared with Eq. (2), there is an additional term n – the population growth rate – in Eq. (3). Additional details and the derivations of these equations can be found in Brock and Taylor (2010).

The GSM utilizes a simple neoclassical growth framework to analyze how pollution evolves alongside the process of economic development. The most important conclusion of the GSM is that the inverted-U shaped EKC exists only when $n+g_B<g_A$; otherwise, pollution emissions will continuously increase over time without any turning point.[7] This conclusion is intuitively depicted in the left panel of Figure 2.

[Figure 2 is here]

As shown in the upper half of the left panel of Figure 2, when $n+g_B<g_A$, the horizontal line corresponding to $\dot{E}/E=0$ crosses the vertical axis at $\frac{g_A-n-g_B}{\alpha}>0$; therefore, the total emissions peak at time T, ahead of the time T* when the economy arrives at the steady

[7] An implicit assumption for this analysis is that the original capital stock, k(0), is lower than the steady-state level, k*. This assumption is verified by the development history of OECD countries and major developing countries over the last two centuries because no economy has ever experienced long-term decline in capital stock per capita.

state because T* is actually the time when $\dot{k}/k = 0$. In this case, the turning point of CO_2 emissions would occur before the economy enters the steady state; therefore, the inverted-U shaped EKC would exist. In contrast, as shown in the right panel of Figure 2, if $n+g_B>g_A$, then $\frac{g_A - n - g_B}{\alpha} < 0$, and CO_2 emissions would not reach a maximum before the economy reaches the steady state at time T*. In this case, the total emissions would monotonously increase along the transition path before T* as the economy approaches the steady state; after time T* the emissions would still continue growing at a steady rate. As a result, if $n+g>g_A$ the inverted-U shaped EKC would not be observed.

3. Empirical tests for a GSM prediction: convergence in per capita CO_2 emissions across provinces

An important prediction of the GSM is that there will be convergence in per capita emissions of the pollutants if $n+g_B<g_A$ when the inverted-U shaped EKC exists. Because the purpose of this research is to utilize the GSM as a theoretical framework to investigate whether there will be a turning point in total CO_2 emissions, the convergence of provincial CO_2 emissions should first be tested. The reason for this test is threefold. First, as Ordás Criado et al. (2011) note, in the long run, the growth is sustainable only when the pollutants' pollution levels are stabilized. As a result, if the convergence does not exist, the provincial per capita CO_2 emissions would not finally reach a steady level because the provinces where per capita CO_2 emissions grew faster would keep growing more rapidly in terms of per capita CO_2 emissions. In other words, the existence of the convergence is a necessary condition for the occurrence of a turning point in CO_2 emissions (Jobert et al., 2010). Second, the existence of convergence in the per capita CO_2 emissions across Chinese provinces indicates that the

actual data for China are applicable to the GSM framework. Therefore, the GSM can indeed be utilized to forecast China's CO_2 emissions. Third, the values of certain important parameters such as output elasticity of capital stock (α) can be calculated based on the estimation results for the convergence, which makes forecasts based on the GSM more objective and reasonable.

3.1. Methodology

Parallel to the convergence in economic growth rate derived from the textbook Solow model, a direct prediction of the GSM is a convergence in per capita CO_2 emissions across provinces. This prediction asserts that an economy with lower initial per capita CO_2 emissions tends to experience faster growth in per capita CO_2 emissions than economies with higher initial per capita CO_2 emissions. Concretely, this "catch-up" process can be described by the following equation, which is directly derived from the set-ups of the GSM:[8]

$$\frac{1}{N}\ln\left(e_{it}^{c}/e_{it-N}^{c}\right)=\beta_0+\beta_1\ln\left(e_{it-N}^{c}\right)+\beta_2\ln\left(s_i\right)+\beta_3\ln\left(1-\theta_i\right)+\beta_4\ln\left[\left(n+g_B+\delta\right)_i\right]+\varepsilon_{it} \tag{4}$$

$$\beta_0=g_B-g_A+1/N\left(1-e^{-\lambda N}\right)log\left(\overline{\Omega_{t-N}B_{t-N}}\right)$$

$$\beta_1=-1/N\left(1-e^{-\lambda N}\right)$$

$$\beta_2=\left[\alpha/\left(1-\alpha\right)\right]\cdot 1/N\left(1-e^{-\lambda N}\right)$$

$$\beta_3=\left[\alpha/\left(1-\alpha\right)+\epsilon-1\right]\cdot 1/N\left(1-e^{-\lambda N}\right)$$

$$\beta_4=-\beta_2$$

$$\varepsilon_{it}=1/N\cdot\left(1-e^{-\lambda N}\right)?og\left(\Omega_{i,t-N}B_{i,t-N}/\overline{\Omega_{t-N}B_{t-N}}\right)+\sigma_{it}$$

where i represents the ith economy, N is the number of years in the sample, $\lambda = [1 - \alpha][n + g_B + \delta]$ is the convergence rate toward the steady state, and $\Omega_{i,t-N}B_{i,t-N}$ is the product of

[8] A full derivation can be found in the early version of the discussion paper of Brock and Taylor (2010).

abatement technology level and productive technology level, representing the synthesized technology level of the ith economy. $\overline{\Omega_{t-N}B_{t-N}}$ is the average value of the synthesized technology levels for all economies at time t-N. ϵ is a parameter of a concrete abatement function a(θ). σ_{it} is an i.i.d error term. All the other variables and parameters have been defined in section 2.

Eq. (4) can be used to test the convergence. If the key coefficient, β_1, is estimated to be negative as predicted by theory, then the convergence in per capita CO_2 emissions across provinces during the sample period is verified. Because other explanatory variables such as ln(s) and ln(n+g_B+δ) are introduced in Eq. (4), the conditional convergence is tested.

Eq. (4) is usually estimated by ordinary least squares (OLS) with cross-section data. However, the commonly known problem of heterogeneity would cause the OLS estimates to be biased.[9] In addition, the limited freedom of the cross-section data may also affect the reliability of the estimation result. In order to effectively tackle the heterogeneity problem and make full use of the potential of our data sample, as suggested by Weeks and Yao (2003) and Ding and Knight (2009), Eq. (4) is reorganized into the following Eq. (5) with a lagged dependent variable on the right-hand side:

$$\ln\left(e_{it}^{c}\right)=\gamma_0+\gamma_1\ln\left(e_{it-N}^{c}\right)+\gamma_2\ln\left(s_i\right)+\gamma_3\ln\left(1-\theta_i\right)+\gamma_4\ln\left[\left(n+g_B+\delta\right)_i\right]+\mu_{it} \qquad (5)$$

$$\gamma_0=N\beta_0;\quad \gamma_1=1+N\beta_1;\quad \gamma_2=N\beta_2;\quad \gamma_3=N\beta_3;\quad \gamma_4=N\beta_4;\quad \mu_{it}=N\varepsilon_{it};$$

Then, we set N=1 and utilize the dynamic panel data to estimate Eq. (5). In Eq. (5), a

9 Brock and Taylor (2010) handle this heterogeneity problem by assuming that a country with higher productive technology B may have a lower emission technology level Ω at the same time, so that the product of the two, BΩ, might be similar across different countries. However, this assumption is more likely to be valid in our case than in the empirical study carried out by Brock and Taylor themselves, because we investigate different provinces within the same country whereas Brock and Taylor employ a cross-country data set. The heterogeneity of technological sophistication across provinces is probably less than that among different countries.

positive coefficient of $ln(e^{c}_{it-N})$ less than 1 is indicative of the existence of conditional convergence. Because Eq. (5) incorporates dynamics and could control for endogeneity using GMM, we use Eq. (5) as the benchmark equation in the empirical study. There are generally two estimation methods for dynamic panel data, namely the first-differenced GMM and the system GMM. Because the latter has a superior finite sample property and is consistent even when there are measurement errors and endogenous right-hand-side variables, in the context of empirical growth research, we employ the panel data system GMM estimator as our prior estimator.[10]

3.2 Data

3.2.1 Chinese provincial CO_2 emissions

Because there are no official statistics available till date for CO_2 emissions in China, we have to estimate the provincial emissions ourselves. The estimation is conducted according the Eq. (6) below. The first item in the square bracket represents the CO_2 emissions from fossil fuel combustion, which are estimated according to IPCC (2006). The second item, CE, represents the CO_2 emissions generated from cement production.[11]

$$EC_i = \sum_{j=1}^{m}\left[\left(F_{ij}\cdot CF_{ij}\cdot CC_{ij} - SC_{ij}\right)\cdot OF_{ij}\right] + CE_i \qquad (6)$$

The meanings of the parameters in Eq. (6) are as follows: the subscript i represents province i and the subscript j, the energy of type j; m is the number of energy types. EC denotes the CO_2 emissions, F is the fuel consumption, CF is the fuel's calorific factor, CC is the

[10] According to first-differenced GMM, the regression equation is first differenced to eliminate the effect of initial efficiency, and the lagged levels of the right-hand-side variables are then used as instruments in the first-differenced equations. However, Bond et al. (2001) point out that the first-differenced GMM estimator is subject to a large downward finite sample bias, particularly when the number of time series observations is small. They instead recommend a system GMM estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998).

[11] Wei et al. (2010) first utilized the method suggested by IPCC (2006) to estimate Chinese provincial CO_2 emissions from fossil fuel combustion. According to the estimations of Carbon Dioxide Information Analysis Center (CDIAC) and Liu et al. (2009), the CO_2 emissions from cement production account for approximately 10-15% of total CO_2 emissions in China. These emissions occur mainly during the decomposition of carbonates ($CaCO_3 = CaO + CO_2$ and $MgCO_3 = MgO + CO_2$). Therefore the CO_2 emissions from cement production are also included in the estimation.

fuel's potential carbon emission factor, SC is the fuel's carbon sequestration, OF is the fuel's fraction of carbon oxidized. As mentioned previously, CE represents the CO_2 emissions from cement production. For each fuel type, the values of CF, CC and OF suggested by IPCC (2006) are used directly.

The consumptions of various types of fuels are taken from the *China Energy Statistic Yearbook (1996-2012)*. Because the provincial carbon-sequestration productions are unavailable, we simply ignore the item SC_{ij}.[12] The provincial cement production data are obtained from the China Economic Information Network. Because provincial consumption data are not available prior to 1995, the time span of our sample period is from 1995 to 2011.[13] Figure 3 shows the ranking of provinces sorted by per capita CO_2 emissions in the first available year, 1995. It can be observed from Figure 3 that during our sample period 1995 - 2011, provinces with lower per capita CO_2 emissions (such as Yunan, Guangxi and Hainan) had experienced faster growth in per capita CO_2 emissions than provinces with higher per capita CO2 emissions (such as Shanghai, Tianjin and Beijing), suggesting that a convergence in per capita CO_2 across provinces most likely exists.

[Figure 3 is here]

3.2.2 Other data

The textbook Solow model is for a closed economy, in which the savings rate is equal to the investment rate. However, considering China's huge scale of foreign business, this assumption does not hold. Instead, following Weeks and Yao (2003) and Ding and Knight

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[12] Ignoring the carbon-sequestration products would not significantly influence the estimation results because China's carbon-sequestration industry is relative small; therefore the calculations conducted by other researchers similarly all neglect this item.

[13] Tibet is excluded simply because of the unavailability of its energy consumption data. Because Chongqing City became a new municipality only in 1997, in our database we therefore merged Chongqing into Sichuan province. Due to data unavailability for the Ningxia Hui autonomous region between 2000 and 2002 and for Hainan Province in 2000, the CO_2 emissions for these two provinces in corresponding years are obtained using a simple interpolation method.

(2009), the fixed-asset investment rate is used as the value of s in Eqs. (4) and (5).

There has previously been considerable controversy over the estimation of the capital depreciation rate, δ. Some scholars prefer to take a constant value of δ for all provinces (Zhang and Zhang, 2003; Guo and Jia, 2004, etc.). However, because the difference in δ is an important cause of the difference in growth rates and CO_2 emissions across provinces, we calculate provincial capital depreciation rates using real capital stock data estimated by He et al. (2007).

For the population growth rate n, we use the growth rate of the provincial residential population rather than the registered population because the residential population makes direct contribution to local economic development and CO_2 emissions, whereas under the current household registration system, the migrant workers working and living in a province are usually still registered at their birth places elsewhere.

The value of productive technology progress, g_B, is also highly controversial. Although some studies report no statistically significant technology progress in China (such as Kong et al. 1999; Wu, 2000), most studies estimate technology progress to be positive in China during the post-reform period (such as Young, 2003; Cao, 2007). The estimated technology progress in productivity since the mid-1990s has been relatively stable and fluctuates within a small range between 1% and 2%.[14] For the nationwide technology progress, we set g_B=1.5%. Because the eastern region has the highest rate of technology progress, whereas the western region is estimated to have the lowest rate (Wang et al., 2006), we set the technology progress rates for eastern, central, and western China at 1.8%, 1.5% and 1.2%,

[14] In an influential paper, Mankiw et al. (1992) assume that the value for initial goods technology differs across countries by at most an idiosyncratic error term. They implemented an augmented Solow model which incorporated human capital in it and find reasonably good estimation results. Therefore this assumption is not absolutely rootless, and the technology difference across provinces within a country must be smaller than that across countries.

respectively.[15]

The parameter θ represents CO_2 abatement cost as a ratio of GDP. Due to the unavailability of data on the specific investment for CO_2 emission abatement, we simply take the average ratio of total investment in environmental protection to GDP during the sample period as the value of θ.[16] Because θ is accessible only after 2002, and because the value of θ is relatively stable for each province (the variation range for θ is usually less than 1%), we combine ln(1-θ) in Eqs.(4) and (5) into the constant term.[17]

3.3 Estimation results

In order to test the convergence nationwide and within regions, we estimate dynamic Eq. (5) with the data from all provinces and the provinces in the three regions, respectively. The results are presented in Table 1. In order to test the potential influences of endogeneity, the estimates of traditional fixed effects (FE) and system GMM (S-GMM) are both reported.

[Table 1 is here]

In Table 1, we can clearly observe that the coefficients of $\ln(e_t^c)$ are indeed significantly positive and lower than 1 for China and its three regions, implying that a conditional β-convergence in per capita CO_2 emissions exists across the provinces within the whole country as well as within each region.

An interesting finding is that the implied convergence rates of per capita CO_2 in the central and western regions of China are greater than that in the eastern region, suggesting that the intra-area differences in per capita CO_2 emissions in the central and western

[15] Although the concrete numbers for the growth rates of technological progress in different regions of China are to some extent arbitrary, the basic principles of these settings are consistent with the empirical findings that a convergence in economic development does not exist across the three regions in China (Peng, 2005).

[16] It should be admitted that the treatment is a compromise as the most relevant data are not available; nevertheless this treatment is still to some extent reasonable. Because many environmental protection programs are synthesized, it is usually difficult to distinguish what exact proportion of the environmental investment is for a specifically targeted pollutant.

[17] A further unit root test shows that the series ln(1-θ) is stationary. The p-value of the Levin-Lin-Chu test for panel data unit root is 0.015; therefore, at the 5% significance level we can refuse the hypothesis that ln(1-θ) has a panel data unit root.

provinces are considerably larger than within eastern provinces. The existence of convergence also implies that the provincial per capita CO_2 emissions tend to stabilize in a long run, which creates the possibility for the occurrence of a turning point in total CO_2 emissions for the three regions as well as for the whole country. The existence of convergence in per capita CO_2 emissions also provides some hints to policy makers on how to set up differential policies to control for regional growth of CO_2 emissions in a more reasonable and efficient way: provinces with relatively high CO_2 emissions per capita should be assigned tougher targets for emissions reductions and faster reduction rates, while the provinces with relatively low carbon intensity should be allowed to cut emissions at a lower rate.

4. Forecasting China's CO_2 emissions

4.1 Parameters settings

Given the regional gaps in economic development and remarkable differences in the patterns of energy consumption and CO_2 emissions between the three regions of China, it is more reasonable to project China's CO_2 emissions based on forecasts for each region. As stressed by You (2013), forecasting using disaggregated information (e.g., Auffhammer and Carson, 2008) can improve the accuracy of the forecasts because regional heterogeneity can be taken into account. We project CO_2 emissions for the eastern, central and western regions, individually, and then forecast for the whole country by adding the projected regional emissions together. In order to make reasonable and reliable forecasts, the settings of the related parameters in the GSM (α, s, δ, θ, n, g_A, and g_B) are critical. In this subsection we discuss the proper values for these parameters for each region of China.

The output elasticity of capital stock, α, can be estimated based on the regression results for the convergence analysis (see Table 1). We take the values of implied α for the three regions on the basis of system GMM estimates because the GMM method accounts for the potential endogeneity problem and therefore produces more reliable estimates. Specifically, the values of α for eastern, central and western regions are chosen as 0.69, 0.69 and 0.71, respectively. This choice is consistent with previous studies estimating that α ranges between 0.55 and 0.85 for China's economy (Chow and Lin, 2002; Cao, 2007; Li and Zeng, 2009).[18] The value for saving rate (s), depreciation ratio (δ) and the share of CO_2 abatement cost to GDP (θ) are the same as discussed previously for the estimation of convergence.

As defined, g_B is the productivity growth rate. According to our calculations from the empirical estimation section, the values of g_B for the eastern, central and western regions are 1.8%, 1.5% and 1.2%, respectively.

The exogenous growth rate in carbon efficiency, g_A, is a key parameter for determining whether the inverted-U shaped EKC exists. A natural idea is to set g_A as the rate at which the CO_2 emission intensity of GDP decreases over time. However, this treatment has two main flaws. First, the decrease in CO_2 emission intensity cannot fully reflect an advance in carbon efficiency. For instance, even if the carbon efficiency remains unchanged, when the non-energy factor inputs of the economy (such as labor and capital) grow faster than the energy input, the CO_2 emission intensity would decrease, and vice versa. Second, the level of CO_2 emission intensity of GDP is to some extent influenced by economic cycles. For example, during China's economic boom period between 1995 and 1998, CO_2 emission intensity

[18] Note that the estimated value of α is remarkably higher for China than for western countries. For instance, Duffy and Papageorgiou (2000) and Altras (2004) both estimated α to be below 0.4. Because α reflects the importance of capital stock in economic growth, the relatively higher estimated value of α reveals the fact that capital stock plays the role of a growth engine for China's economic development.

decreased relatively rapidly, whereas during the economic downturn from 2008 to 2011, the overall CO_2 emission intensity hardly declined, and even rose slightly in some provinces. Despite these flaws, in the medium and long run, the evolvement of CO_2 intensity would still reflect the effects of technology progress in carbon efficiency. As a result, in this study we take the annual rate of decrease in CO_2 intensity during 1995 and 2007 as a reference rather than an exact value for g_A. The corresponding rates for the eastern, central and western regions for the period 1995-2007 are 4.0%, 4.3% and 3.0%, respectively.[19] Another reference for g_A is the changes in government staff devoted to environmental protection, as suggested by He and Wang (2012).[20] Utilizing the data from the China Statistical Yearbooks on Environment (1996-2012), the average annual growth rates of the government staff specialized in environmental protections are calculated to be 4.2%, 5.3% and 5.6% for the eastern, central and western regions, respectively. We simply take the average of these two references for g_A as the benchmark values of g_A in corresponding regions. Therefore, for the eastern, central and western regions the values of g_A are set to 4.1%, 4.8% and 4.3%, respectively. It is noteworthy that the difference between the two references of g_A for the western region is considerably larger than that for the eastern and central areas. Considering the fact that g_A is crucial for the potential existence of a turning point in CO_2 emissions,

[19] Comparatively, the annual rates of CO_2 intensity decreases for three regions during 2007-2011 are much lower: 1.9% and 2.0% for the eastern and central regions, respectively, whereas the western region in fact saw a slight increase in CO_2 intensity. It should be noted that this period coincided with the international financial crisis. In 2008, Chinese government launched a 4000 billion yuan (570 billion US dollars according to the exchange rate at that time) stimulus package to cushion economic growth. Since then, heavy investment has been put into high pollution and high energy consumption industries such as steel and cement. From 2008 to 2011, energy consumption grew much faster than labor force and capital, which caused a remarkably lower growth rate for CO_2 emissions. As a result, the slower rate of decrease in CO_2 intensity after 2007 is more likely a reflection of the influences of the international financial crisis on the Chinese economy instead of decreased efficacy of carbon efficiency or abatement technology.

[20] He and Wang (2012) argue that the number of government staff that are devoted to environmental protection could be treated as a proxy for the strength of environmental regulation and protection. As Price et al. (2011) and Leggett (2012) point out, the rapid growth of China's CO_2 emissions is partly due to lack of sufficient administrative supervision. As a result, an increase in the number of officials specialized for environmental protection would to some extent reflect an improvement in the enforcement of CO_2 abatement measures and other environmental protection policies and regulations, which would therefore be likely to increase China's carbon efficiency. Notably, the idea of utilizing the number of staff specified in a certain industry as a proxy to measure technology progress in that industry is borrowed from Romer (1990), who defined the technology progress rate as proportional to the population working in the R&D sector.

different possible values of g_A are tested in the sensitivity analysis in the next section.

During the sample period between 1995 and 2011, the growth rates for the residential population in eastern, central and western regions were 1.2%, 0.26% and 0.33%, respectively. Although China has recently eased its one child policy that has been in place over two decades, the relatively low population growth is expected to persist.[21] Considering the fact that the regional differences between eastern and inland provinces will most likely be reduced over time, there are predicted to be fewer workers migrating from inland provinces to coastal areas for higher-paying jobs. As a result, the population growth rate of the eastern region may be slightly lower than its average annual growth rate in the last two decades, whereas the population growth rates of the central and western regions may be slightly higher than their respective historical average levels. Therefore, we set the population growth rates (n) in eastern, central and western regions at 0.8%, 0.3% and 0.4%, respectively.[22]

Finally, the initial future economic growth rates projected for the three regions are set at the average growth rates during our sample period between 1995 and 2011. Based on the initial growth rate of GDP per capita, the dynamics of initial capital stock per effective worker in each region could be calculated according to the production function and the dynamic equation Eq.(1) for capital stock.

To summarize, the values of the parameters for China's three regions in the benchmark

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[21] See, for example, http://www.newsweek.com/2014/01/24/one-child-policy-one-big-problem-china-245118.html and http://www.bbc.co.uk/news/world-asia-china-25533339.

[22] Because the population proportions of eastern, central and western regions were approximately 40%, 32% and 28% during our sample period between 1995 and 2011, the settings for the population growth rates in the three regions suggest that the population growth rate for the whole country would be about 0.53% for the first few years in the forecast period. According to the 2010 National Population Census, the average annual rate of natural population growth in China was approximately 0.57% between 2000 and 2010, which is consistent with the implied population growth rate considering that the declining trend in the population growth rate may continue. Therefore our settings for population growth rates for the three regions of China are reasonable.

scenario are shown in Table 2. It should be noted that for each region, the condition for the existence of a turning point in CO_2 emissions, $n+g_B<g_A$, is satisfied. Therefore, CO_2 emission peaks will occur in all regions of China, suggesting that an overall turning point in China's CO_2 emissions will appear at some time in the future.[23]

[Table 2 is here]

4.2 Forecast results

Once the key parameters of the GSM and the initial GDP growth rates are fixed, the dynamics of China's CO_2 emissions as well as economic growth are completely determined according to Eqs. (1)-(3). Before the forecast is conducted, the credibility of the GSM framework is first examined. The sample period is split into two subperiods (1995-2006 and 2007-2011), and the in-sample forecasts of CO_2 emissions for the three regions and the whole country are made for the last five years of the sample period (2007-2011). The in-sample forecast results are close to the actual emissions, and the relative errors of forecast (the ratio of forecast error to the actual data) are within 5% in most years for the three regions and the whole country.[24] The in-sample forecast results verify the credibility of the fit of the model to the actual data; therefore, it can be used to make an out-of-sample forecast. Figure 4 plots the projected total CO_2 emissions for the three regions and for China as a whole from 2011 to 2100 (black lines in Figure 4).

[Figure 4 is here]

As shown in Figure 4, in the benchmark scenario, the turning point in total CO_2

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[23] One caveat regarding the setting of parameters is that although the values of n, g_B, and g_A for each region are assigned based on statistics or estimates from the literature, these parameters are essentially exogenously determined. As a result, the reasons why these parameters are chosen such that the sustainable growth condition is met cannot be interpreted within the GSM framework. This is because the GSM is essentially a neoclassical growth model, in which n, g_B, and g_A are exogenous parameters.

[24] Due to space limitations, the in-sample forecast results are not given here but are available upon request.

emissions will occur in the year 2047, and the emission peak will reach 22.62 billion tons at that time. Because the forecast results are highly dependent on the values of key parameters in the GSM, it is necessary to perform a sensitivity analysis based on the choices of some important parameters over the range of possible values. Because the condition for existence of a turning point is that $g_B+n<g_A$, we focus on these three key parameters. In order to take the uncertainty into full consideration, we allow for variation as much as 50% from the benchmark scenario level. Specifically, we make repeated calibrations with one of the three key parameters changing ±10%, ±25% and ±50% while keeping other two parameters unchanged. For each scenario, we examine whether and when the turning point in total CO_2 emissions occurs and the corresponding total CO_2 emissions at that point. The results for the sensitivity analysis are reported in Table 3.

[Table 3 is here]

As shown clearly in Table 3, the time at which the turning point occurs is most sensitive to the growth rate in carbon efficiency (g_A). A decrease in g_A by 10% would delay the occurrence of the emission peak by nearly a decade. If the g_A is 50% lower than the benchmark level, the turning point would not occur before 2100.[25] Comparatively, the other two parameters' changes do not alter the timing and level of the emission peak significantly.[26,27]

[25] In this scenario, the central region would still see its emissions peak before 2100, but the western and eastern regions would not experience any emission peaks before 2100. Specifically, for the eastern region, because $g_B+n-g_A=0.0055>0$, the turning point in CO_2 emissions does not exist, and the CO_2 emissions would continuously grow over time. More precisely, the turning point collapses once g_A declines by 37%.

[26] According to the suggestions of an anonymous reviewer, the forecasts based on provincial data are also made to contrast the forecasts based on regional data. The calibration results indicate that the two forecasts have similar trends for the three regions and for the whole country. At the national level, the forecast based on provincial data predicts that the turning point in total CO_2 emissions will occur in 2049 with the emissions peaking at 23.92 billion tons. Compared with the predictions under the benchmark scenario based on regional data, the turning point occurs two years later, and the emissions peak is 1.32 billion tons greater (5.8% of the benchmark emission peak). Therefore, the influence of provincial heterogeneity on the accuracy of the prediction is limited.

[27] We have also compared our results with the experiences of some representative economies that have experienced the peak of CO_2 emissions and the forecasts of some other researchers. Due to limit of length, these contents are not given in

5. Conclusion

As China's economy boomed, China's total CO_2 emissions proliferated at a dramatic rate. Since 2007, China has already become the largest CO_2 emitter in the world; and in 2010 China contributed nearly a quarter of global total CO_2 emissions. The surge in China's CO_2 emissions has caused increasing international concern, and the domestic pressures from an increasing gap in energy demand and the deteriorating environment are also forcing the Chinese government to shift economic growth patterns to be more intensive and curb CO_2 emissions. Despite the Chinese government's reiteration of this goal and implementation of policies to control CO_2 emissions, skeptics doubting whether China can effectively hold CO_2 emissions in check still exist at home and abroad.

In order to address the concerns about whether and when the turning point in China's CO_2 emissions will occur, the emissions should be forecasted in a reasonable and reliable way. A commonly used forecasting method is the EKC. However, due to some major problems in both theoretical and empirical aspects, the EKC is not directly employed for forecasting in this research. Instead, the prediction herein is based on a computable theoretical framework – the GSM. The GSM inherits the basic characteristics of the textbook Solow model and incorporates CO_2 emissions as an undesirable by-product. If the forces contributing to increasing CO_2 emissions (including the scale effects caused by economic growth and population increases) grow less rapidly than the forces contributing to emissions reductions (abatement technology progress and investment in emission reduction), the emissions would stabilize at some time and then eventually decrease.

In order to examine whether the GSM framework is applicable to China's economy, a

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the paper but are available online.

direct prediction of the GSM – that per capita CO_2 emissions converge across provinces – is tested. Utilizing fixed effects and system GMM methods, the convergence in CO_2 per capita across provinces across the whole nation as well as within three distinct regions of China is verified. The existence of convergence also implies that provincial per capita CO_2 emissions tend to stabilize in the long run, which is a prerequisite for the existence of a turning point in CO_2 emissions.

Considering the remarkable differences in development levels and energy consumption patterns across China's different regions, the national CO_2 emissions are forecasted using disaggregated regional information. After assigning reasonable values to the key parameters of the GSM for the three regions, the respective CO_2 emissions between 2011 and 2100 for the eastern, central and western regions of China are projected. The predicted national CO_2 emissions are the sum of the three regions' projected emissions. In the benchmark scenario, the turning point in China's total CO_2 emissions would occur approximately in 2047, and the corresponding total emissions and per capita emissions would be approximately 22622 million tons and 13891 kilograms, respectively.

According to the sensitivity analysis, carbon efficiency is the most important factor in determining the existence of a CO_2 emission peak. Other conditions being equal, a decrease in the progress rate of carbon efficiency (g_A) by 37% would cause the collapse of the turning point, whereas a 10% increase in g_A would cause the turning point to occur 6 years earlier than that in the benchmark scenario. As a result, enhancing the efficiency of energy usage and CO_2 emissions and accelerating the technology progress of CO_2 abatement techniques are vitally important for ensuring that the turning point in China's CO_2 emissions occurs as early as possible.

Despite the merits of our forecast results based on the GSM, there is still ample room for further improvement of the GSM framework in both theoretical and empirical aspects. For instance, the assumptions of exogenous productive technology progress and carbon efficiency could be relaxed. In addition, energy could be introduced in the production function as a separate input, so that the effect of the change in energy structure on CO_2 emissions could be elaborately examined. These improvements represent possible future research directions that could provide a more sophisticated GSM framework and more reasonable and reliable forecast results.

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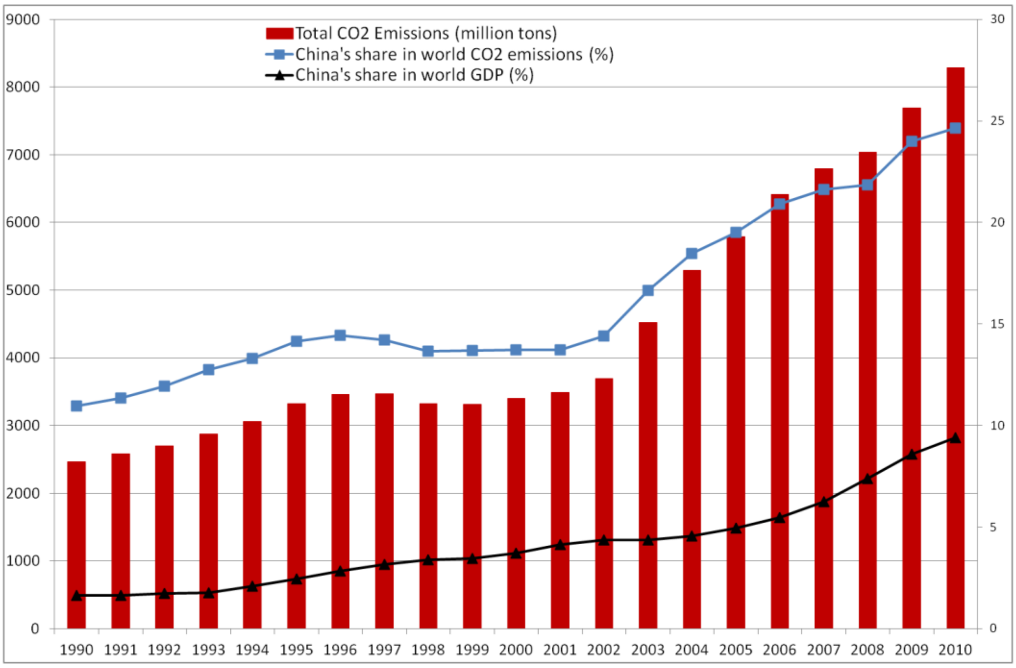
Figure 1. China's total CO_2 emissions (left scale), its share of global emissions (right scale), and its share of world GDP (right scale) since 1990



Source: China's total CO_2 emissions data are from the CDIAC. Global GDP data are from the World Bank Database. The ratios of China's CO_2 emissions and China's GDP to the global levels are calculated by the authors.

Figure 2. The GSM and its Relationship with EKC

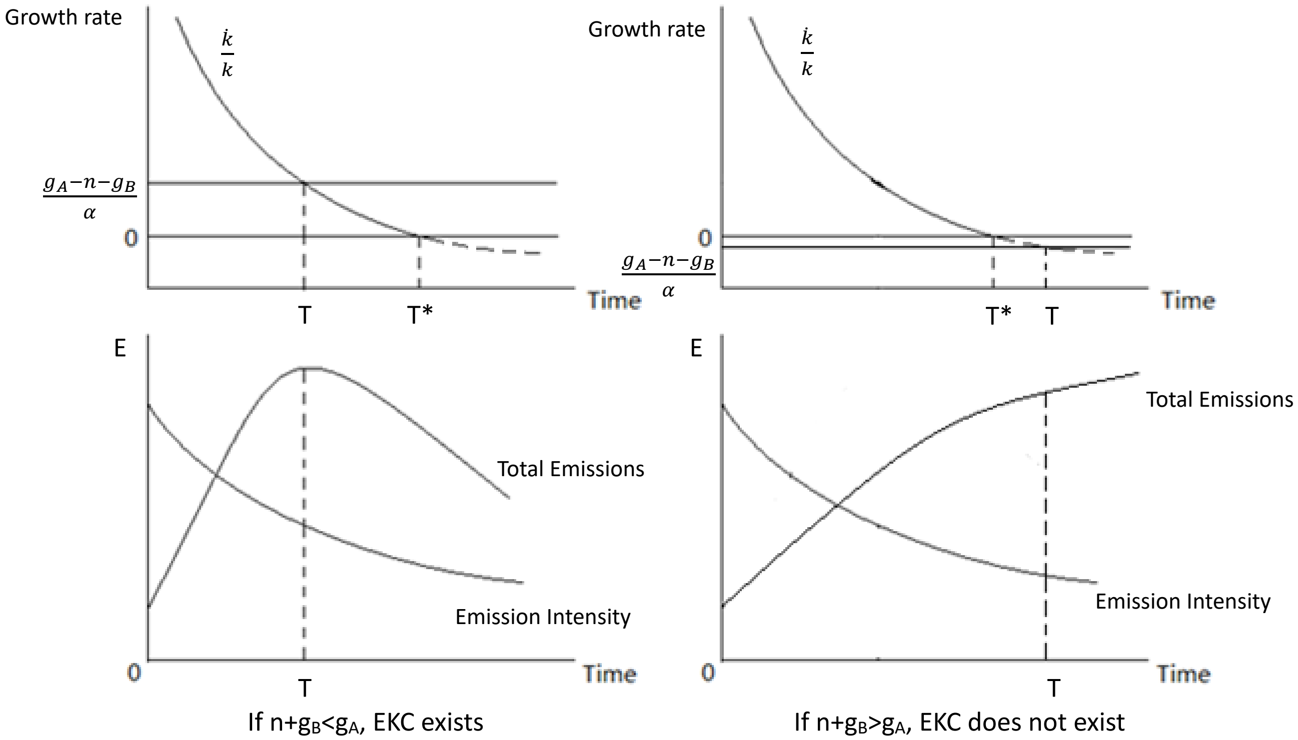
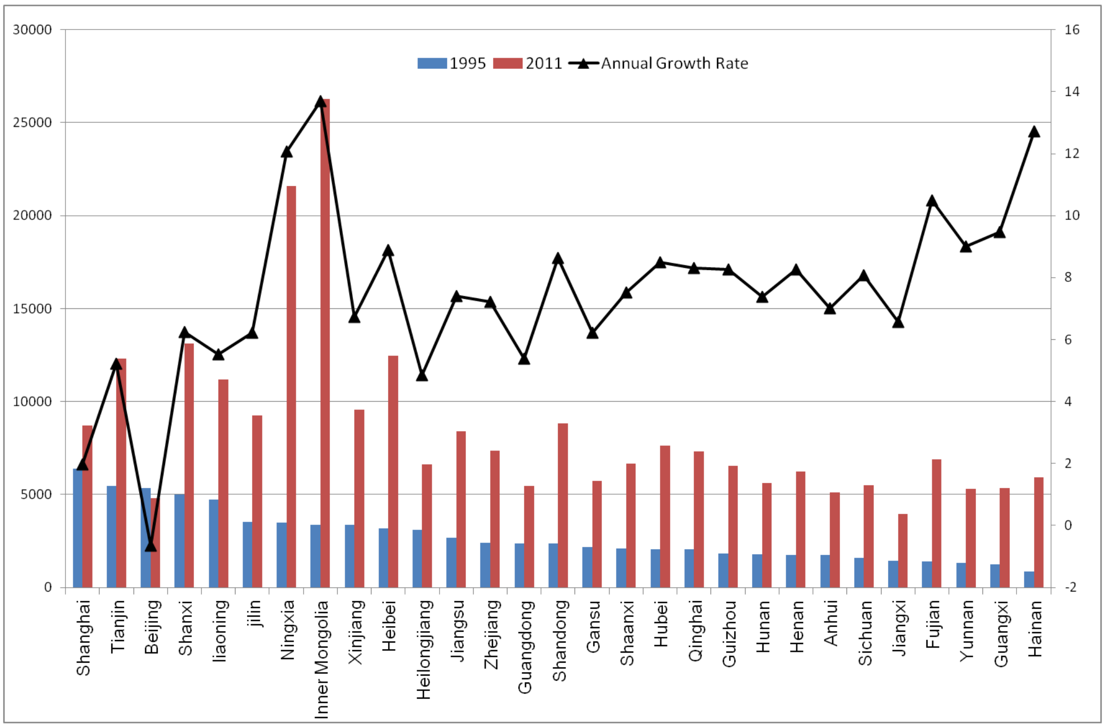
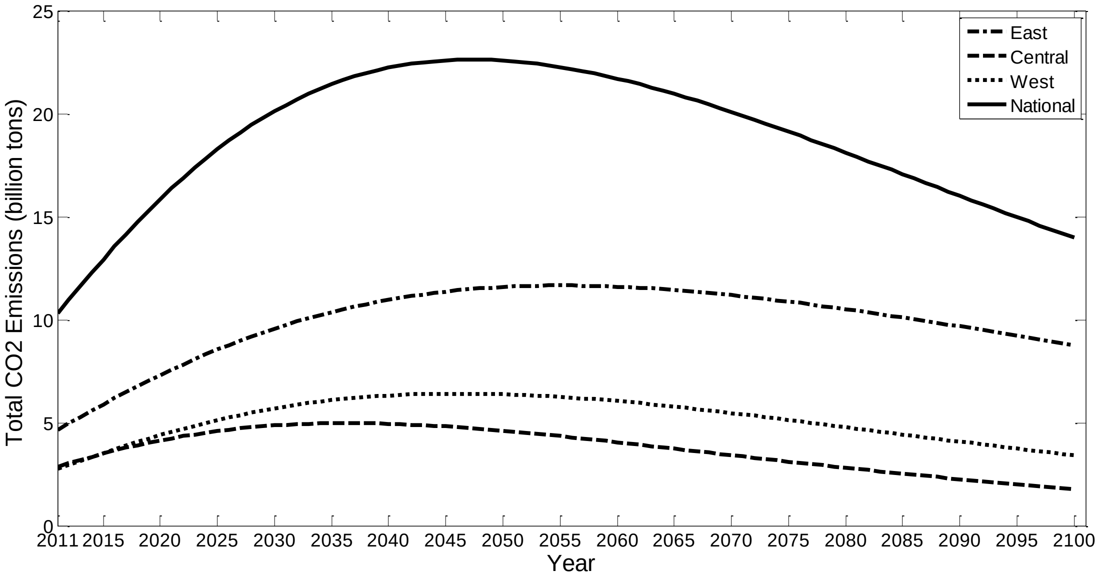


Figure 3. 1995 and 2011 provincial per capita CO_2 emissions (kilos) and average annual growth rate over sample period (%)



Source: The provincial CO_2 emissions are calculated according to Eq. (17), provincial population data are from China Statistic Yearbooks (1996-2012), and the provincial per capita CO_2 emissions along with their corresponding growth rates are calculated by the authors.

Figure 4. China's projected national and regional total CO_2 emissions from 2011 to 2100 in the benchmark scenario



Note: The different lines represent the projections of CO_2 emissions for the eastern, central and western regions, and the country as a whole, as shown in the legend.

Table 1. Estimation results of Eq. (5) for the whole country and the three regions

Region	National		Eastern		Central		Western	
Variable	FE	S-GMM	FE	S-GMM	FE	S-GMM	FE	S-GMM
$\ln(e_{t-1}^{c})$	0.956***	0.959***	0.983***	0.931***	0.894***	0.923***	0.902***	0.916***
	(0.021)	(0.030)	(0.027)	(0.109)	(0.059)	(0.333)	(0.031)	(.163)
ln(s)	0.158***	0.174***	0.129***	0.154	0.174**	0.173	0.266***	0.210
	(0.027)	(0.048)	(0.040)	(0.163)	(0.060)	(0.263)	(0.036)	(0.152)
$\ln(n+g_B+\delta)$	-0.041*	-0.027	0.007	-0.044	-0.087*	-0.054	-0.044***	0.073
	(0.021)	(0.027)	(0.030)	(0.087)	(0.039)	(0.083)	(0.012)	(0.185)
R^2	0.982		0.982		0.981		0.980	
Implied λ	4.50%	4.22%	1.72%	7.15%	11.2%	8.01%	10.3%	8.77%
Implied α	0.78	0.81	0.88	0.69	0.62	0.69	0.73	0.71
Obs./ instruments	464	464/63	176	176/63	128	128/63	160	160/63
A-B test for AR(1)		0.000		0.016		0.061		0.025
A-B test for AR(2)		0.357		0.185		0.612		0.138
Hansen Test		1.000		1.000		1.000		1.000

Notes: Robust standard errors are given in parentheses. All test results are given as p-values. FE and S-GMM stand for fixed effects and system GMM methods, respectively. Following Ding and Knight (2009), in the system GMM estimations, $\ln(e_{t-1}^{c})$ is treated as a predetermined variable; ln(s) and ln(n+gB+δ) are treated as endogenous variables. Implied convergence rate λ and the output elasticity of capital stock α are calculated according to the definitions of coefficients γ1 and γ2 in Eq. (5). Significance at the 1%, 5% and 10% levels is indicated by *, **, and ***, respectively.

Table 2 Model parameterizations of the benchmark scenario

	α	s	σ	θ	n	g_A	g_B	γ_0
East	0.69	0.45	4.63%	1.19%	0.8%	4.1%	1.8%	10.0%
Central	0.69	0.54	4.64%	0.97%	0.3%	4.8%	1.5%	10.5%
West	0.71	0.59	3.87%	1.25%	0.4%	4.3%	1.2%	11.0%

Note: γ_0 represents the per capita GDP growth rate at the initial time of the projection (2011).

Table 3. Calibration results for the different scenarios in the sensitivity analysis

Parameter	Scenario (change percentage)	Time of turning point in national CO_2 emissions	Peak national CO_2 Emissions (bn tons)
	+10%	2049	23.29
	+25%	2053	24.44
	+50%	2060	26.93
g_B	**-10%**	2046	22.02
	-25%	2043	21.22
	-50%	2040	20.09
	+10%	2048	23.04
	+25%	2050	23.70
	+50%	2052	24.92
n	**-10%**	2046	22.22
	-25%	2045	21.66
	-50%	2043	20.79
	+10%	2041	19.62
	+25%	2034	16.54
	+50%	2026	13.50
g_A	**-10%**	2055	26.88
	-25%	2075	37.88
	-50%	No turning point before 2100	NA

Note: In each alternative scenario, a specific parameter is altered while all the other parameters are kept constant.