

How modifications of China's energy data affect carbon mitigation targets

Heran Zheng¹, Yuli Shan¹, Zhifu Mi², Jing Meng³, Jiamin Ou¹, Heike Schroeder¹, and Dabo Guan^{1*}

1. Tyndall Centre for Climate Change Research, School of International Development, University of East Anglia, Norwich NR4 7TJ, UK
2. The Bartlett School of Construction and Project Management, University College London, London, WC1H 0QB, UK.
3. Department of Politics and International Studies, University of Cambridge, Cambridge CB3 9DT, UK.

Correspondence Email: Dabo.guan@uea.ac.uk (Dabo Guan)

Additional Information: The authors declare no competing financial interests.

Author contribution statement: H.Z., Z.M, Y.S, M.J., J.O designed the research; H.Z. wrote the main manuscript text; D.G., H.S conceived the research; and H.Z & Y.S provided the data and methods. All authors reviewed the manuscript.

Abstract

Frequent modifications to energy statistics have led to considerable uncertainty in China's ability to achieve its carbon mitigation targets. Here, we quantitatively measure the impact of energy data revisions on China's ability to achieve its mitigation targets. Our results indicate the following effects of data revisions: 1. Mitigation challenges have increased by 5%, and the achievement of national mitigation targets (as well as international pledges) might be postponed by two years. 2. Greater than expected carbon space or emission quota (from 22.94 to 31.31 Gt) will be obtained from 2015 to 2035. 3. CO₂ peak levels may become highly uncertain, with the uncertainty varying from 12% to 29%. In addition to national mitigation targets, data revision has profound implications for key industrial sectors. For example, raw coal consumption by the cement and iron and steel industries has long been underestimated, bringing uncertainty to the achievement of industrial mitigation targets. Our results reveal considerable uncertainty in China's energy data, and this uncertainty suggests that previous mitigation achievements have been overestimated and that the mitigation targets, carbon space values, and peak level estimates proposed by future mitigation schemes may not be reached.

Keywords: Mitigation; China; Uncertainty; Data revision; CO₂ inventory

1. Introduction

China's mitigation efforts have become increasingly important for meeting global decarbonisation targets because of China's increasing share of global primary energy consumption and total greenhouse gas (GHG) emissions (Liu, 2015; Shan et al., 2015; van Ruijven et al., 2012). Ambitious mitigation policies have been proposed to reduce the carbon emissions from China's carbon-intensive economy, and rigorous mitigation targets have been set to reduce carbon intensity (CO₂ emissions per unit gross domestic product (GDP)) by 40-45% by 2020 and 60-65% by 2030 compared with the 2005 level and to decrease peak carbon emissions by 2030 as promised in the 2014 China-US joint agreement. These ambitious mitigation targets cannot be achieved without a solid national emission inventory that comprehensively describes China's carbon status quo (Guan et al., 2012; Hong et al., 2016; Mi et al., 2017). Unfortunately, because of frequent revisions and inconsistent energy consumption data, China's emission inventory has suffered from considerable uncertainty, and the reliability of this inventory has long been criticised (Korsbakken et al., 2016; Qi and Wu, 2013; Wang, 2011). These inconsistent underlying energy statistics can lead to over- or underestimations of national CO₂ emissions and cause huge uncertainties in estimates of global emissions (Liu et al., 2015b; Marland et al., 2009), leading to errors in mitigation policies (Bruckner et al., 2014; Gregg et al., 2008; Guan et al., 2012).

Due to the importance of this problem, the inconsistency of energy data has been widely debated (Guan et al., 2012; Ma et al., 2014; Qi et al., 2016). Most studies have focused on the reasons underlying the uncertainty in emission inventories (e.g., under-reporting of energy consumption by small firms and data inflation to fit GDP growth), discussed how to improve the quality of energy data (e.g., employing satellite technology or institutional reform) via different methods or

investigated means to verify the reliability of these data in comparison with international sources (Akimoto et al., 2006; Guan et al., 2012; Korsbakken et al., 2016; Li et al., 2016; Liu, 2015; Sinton, 2001). Causes related to institutional factors might be too difficult to resolve in the short term, which also implies that ongoing mitigation efforts will be accompanied by uncertainty in the near future. This challenge mainly arises because in a political assessment system that prioritises GDP growth, GDP data are likely to be inflated, while energy data are often manipulated to match the inflated GDP growth (Guan et al., 2011; Guan et al., 2012; Li et al., 2016). Moreover, the impacts of frequent data modifications on the mitigation targets are poorly understood. Here, we quantify the uncertainty in the estimates of CO₂ emissions and the likelihood of achieving mitigation targets. We briefly illustrate the latest national energy data modification and compile CO₂ emission inventories based on the revised and original data. Using our compiled emission inventory, we quantitatively measure the impacts of the 2015 revision on two national mitigation pledges (the 40-45% and 60-65% mitigation targets noted above). Finally, we analyse the effects of the revisions at the sectoral level and their implications for sectoral mitigation.

2. Background: China's energy data revision

China has officially revised its energy statistics three times since 2000 (2006, 2010, and 2015) (Table 1). Such statistics modification is normally periodical in China, following the National Economic Census conducted every 5 years; the National Bureau of Statistics (NBS) uses data from the economic census to validate the historical statistical data collected from the hierarchical statistical system and make adjustments. Each revision has modified the energy balance sheets and final energy consumption by industrial sectors (Guan et al., 2012; Liu, 2015). However, NBS

does not officially disclose the reasons for revising energy data or how the data were revised. The revisions might be due to the application of new statistical methods or the validation of historical data within economic census data. We assume that new statistical rules or methods would be carried over until the next revision. For example, the new statistical rules and methods applied in the 2010 revision would be applied to statistics from 2008 to 2012. We consider that data revised in a given revision belong to the dataset up to that revision. For example, the 2015 revision revised data from 2000 to 2012, including the 2010 data. Hence, the 2010 revision affected data within the range from 2000 to 2012. To avoid confusion and facilitate discussion, the data scope of the present research begins in 2000, and energy data provided in the 2015 revision are considered 2015 data (including data from 2000 to 2014); energy data provided in the 2010 revision are considered 2010 data (including data from 2000 to 2012); data provided in the 2006 revision are considered 2006 data (including data from 2000 to 2007); and data provided before the 2006 revision are considered original data (including data from 2000 to 2003).

The data revision details are summarised in Table 1S.

The first energy data revision was conducted in 2006. Based on the first National Economic Census in 2004, NBS revised energy data from 1999 to 2003 in 2006. Compared with the original data, the 2006 data increased total energy consumption by an average of 5% from 1999 to 2003. A major change was observed in raw coal and other petroleum products. In the 2006 data, the former increased by an average of 4%, and the latter increased by nearly 4-fold in comparison with the original data. The second energy revision followed the second National Economic Census in 2008, and energy data from 2000 to 2007 were massively revised by NBS in 2010. The new 2010 data

revised total energy consumption upward by an average of 7% from 2000 to 2007, from 3% in 2007 to 10% in 2003 compared with the 2006 data. Compared with the 2006 data, the 2010 data mainly revised the historical consumption of raw coal and coke by average increases of 8% and 3%, respectively. The third data revision was conducted in 2015 following the third National Economic Census in 2013. This revision modified the energy data from 2000 to 2012, with an average increase in the total energy consumption of 2%. The massive revision occurred especially after 2005, as the discrepancy in total energy consumption between the 2015 data and the 2010 data increased constantly from a 4% gap in 2005 to an 11% gap in 2012. In the energy mix, the consumption of raw coal, other washing coal, coke and other gas in the 2015 data was substantially revised from 2000 to 2012, with average increases of 5.9% (1443 Mt), 9.4% (103 Mt), 9.3% (359 Mt), and 129% (360 Mt), respectively, higher than the 2010 data. Notably, the energy data after 2007 were substantially revised in the 2015 data. According to the change rates for raw coal, other washing coal, and coke during the period from 2007 to 2012, the rates between the 2015 data and the 2010 data increased by 9.1%, 17.3%, 11.6%, respectively.

Table 1. Comparison among the 2015 data, 2010 data, 2006 data and the original data

Item	Total Energy Consumption (Mtce)				Raw Coal (Mt)			
	2015 data	2010 data	2006 data	Original data	2015 data	2010 data	2006 data	Original data
2000	<u>1,159</u>	<u>1,205</u>	<u>1,101</u>	1,036	<u>1,047</u>	<u>1,107</u>	<u>1,022</u>	967
2001	<u>1,231</u>	<u>1,239</u>	<u>1,135</u>	1,085	<u>1,106</u>	<u>1,129</u>	<u>1,049</u>	1,017
2002	<u>1,330</u>	<u>1,318</u>	<u>1,217</u>	1,173	<u>1,212</u>	<u>1,209</u>	<u>1,108</u>	1,090
2003	<u>1,562</u>	<u>1,528</u>	<u>1,384</u>	1,318	<u>1,436</u>	<u>1,412</u>	<u>1,305</u>	1,253
2004	<u>1,799</u>	<u>1,768</u>	1,638		<u>1,644</u>	<u>1,615</u>	1,495	
2005	<u>2,034</u>	<u>1,964</u>	1,873		<u>1,856</u>	<u>1,774</u>	1,650	
2006	<u>2,243</u>	<u>2,151</u>	2,053		<u>2,053</u>	<u>1,953</u>	1,803	
2007	<u>2,412</u>	<u>2,292</u>	2,231		<u>2,207</u>	<u>2,088</u>	1,936	
2008	<u>2,484</u>	2,349			<u>2,277</u>	2,136		
2009	<u>2,671</u>	2,458			<u>2,448</u>	2,241		
2010	<u>2,861</u>	2,625			<u>2,590</u>	2,358		

2011	<u>3,141</u>	2,845	<u>2,886</u>	2,605
2012	<u>3,258</u>	2,939	<u>2,978</u>	2,669
2013	3,388		3,092	
2014	3,319		2,928	

Note: Mtce=Million tons coal equivalent; Mt=Million tons. Underlined data indicate the revised data for each dataset.

On the industrial level, the energy data revisions mainly revised energy consumption in energy-intensive industries related to raw coal consumption. The raw chemical and cement industries were the most affected. Comparing these industries in the 2015 revision with the 2010 revision, the raw coal consumption in the 2015 revision increased by 41% (434 Mt) and 21.6% (425 Mt) for the raw chemical and cement industries, respectively, from 2000 to 2012, which accounted for 53% of the total raw coal consumption gap from 2000 to 2012 (Figure 1S). These shifts in energy consumption revealed by the data revision indicated a more carbonised China, which directly affects the emissions and thereby poses a threat to the global mitigation initiative. China has set its own mitigation targets as part of its Nationally Determined Contributions (NDCs), which include two core pledges to reduce its carbon intensity by 40-45% by 2020 (2020 target) and by 60-65% by 2030 (2030 target). However, the mitigation schemes developed in 2009 and 2014 are based on the 2010 data; therefore, large uncertainties in China's mitigation policymaking and implementation might be generated from uncertain energy data, and these uncertainties further undermine China's ability to achieve its mitigation targets. To assess the impact of energy statistics revision on China's mitigation pledge, we focus on the energy data from the 2010 and 2015 revisions. Data from 2000 to 2014 in the two datasets are compared and analysed.

3. Materials and Methods

3.1 Energy inventory compilation and data source

All data were obtained from the China Energy Statistics Yearbooks for 2004 to 2015 (NBS, 2004-2015). The China Energy Statistics Yearbooks represent the only official energy data source and are published annually by the NBS. These reports include the national “Energy Balance Sheets” and “Energy Consumption by Sectors Sheets”, which provide detailed final energy consumption data for the whole country and by sector (Guan et al., 2012). The energy balance sheets and the sectoral energy consumption are modified after the National Economic Census, and the newly revised energy data are reported in the subsequent yearbook. As this paper focuses on the impact of the statistics revision in the 2014 yearbook on China’s ability to achieve its mitigation pledges, we compare two groups of energy data: (1) 2010 data (2000 to 2012), which included energy data from 2000 to 2008 from the China Energy Statistics Yearbook 2009 and energy consumption data from 2000 to 2012 from the China Energy Statistics Yearbooks from 2010 to 2013; and (2) 2015 data (2000 to 2014), which included revised energy data from 2000 to 2013 from the China Energy Statistics Yearbook 2014 and energy consumption data for 2014 from the China Energy Statistics Yearbook 2015. We used two versions of the energy data to compile the energy inventory from 2000 to 2014. To ensure consistency and comparability between the 2015 data (2000 to 2014) and 2010 data (2000 to 2012), we first extended the 2010 data to 2014 by assuming the same growth rate for 2012 to 2013 and 2013 to 2014 in the 2010 data as that in the 2015 data.

We adopted the sectoral energy consumption approach recommended by the IPCC (Intergovernmental Panel on Climate Change) to calculate the national territorial energy use, which

is different from the apparent energy consumption approach (Andres et al., 2014; Liu et al., 2015b; Shan et al., 2015). The latter approach is based on the mass balance of fuels for production, domestic and international trade, and stock change. Instead, the approach adopted here is based on energy production and trade data rather than on energy consumption (details can be found in Shan et al., 2015). The total energy consumption for each energy type is calculated using the following equation: total final consumption for each sector + energy used in processing and transforming (thermal power and heating supply) – losses – non-energy use. Following this approach, we prepared the national energy inventory for all the datasets. We collected all final energy consumption data (20 fuel types in total) for 47 socioeconomic sectors (42 of which are industrial sectors) from the China Energy Statistics Yearbooks. For the secondary energy type (thermal power and heating supply), the energy used in transforming was added to the corresponding sectors. For example, the total energy consumption for electricity generation is the final energy consumption in electricity generation (which is not used to generate electricity) plus the energy used in transforming from primary energy into electricity (transforming coal to electricity). After the losses and non-energy use are removed, the energy inventory can be presented for each energy type used in each socioeconomic sector. A detailed layout of the energy inventory is shown in Supplementary 2. We prepared energy inventories for the original, 2006, 2010 and 2015 datasets, which provide activity data for the subsequent CO₂ inventory.

3.2 CO₂ emission inventory

China publishes carbon per GDP intensity target achievements that can be used with GDP data to estimate "official" CO₂ emissions. In this study, the CO₂ inventories are based on the energy

inventories compiled above, which followed the IPCC national GHG inventory guidelines (IPCC, 2006; Peters et al., 2007; Shan et al., 2016). The emissions were calculated using the activity data (the amount of fossil fuels (physical units)) multiplied by the respective emission factor (EF) (Equation (1)):

$$CE = \sum \sum AD_{ij} \times EF_{ij} \quad (1)$$

where CE represents the total aggregated CO₂ emissions from different energy types *i* used by sector *j*. AD_{*ij*} (amount of fossil fuels *i* used in sector *j*) represents the fossil fuels combusted, measured in physical units, and EF_{*ij*} represents the emission factors for the fossil fuels *i* used in sector *j*. EFs can be separated into three parts: the net heating value of each fuel *i* (TJ per t fuel), which refers to the quantity of heat obtained per unit of fuel; the carbon content *c* of each fuel *i* (tC per TJ), which indicates the amount of carbon that could be released per heat unit during combustion; and the oxidisation rate *o* (%), which indicates the fraction of fuel *i* oxidised by each sector during combustion. The sub-factors are specific for the fuel type and sectors (Equation (2)):

$$CE = \sum \sum AD_{ij} \times n_i \times c_i \times o_{ij} \quad (2)$$

By aggregating the CO₂ emissions from different fossil fuels and sectors, we obtained the total CO₂ emissions. Although the default value was provided by the IPCC, different EFs were used because local fuel practices contribute to the uncertainty in CO₂ emissions (IPCC). In this paper, we refer to the EFs used in Liu's research (Liu et al., 2015b), in which the default EFs used by the IPCC were updated via surveys of coal mines. The results showed that Chinese emissions were overestimated by international institutes (such as IEA, EDGAR) by up to 14% in 2013. Following this approach, CO₂ emission inventories for each sector and each energy type were compiled; a layout is shown in Supplementary 2. All data can be accessed via China Emission Accounts and

Datasets (www.ceads.net), a free China energy data sharing platform. The CO₂ emissions for different datasets are shown in Figure 2. Based on the CO₂ emission inventory for each dataset constructed above, the historical carbon intensity can be calculated by CO₂ emissions/GDP. Historical GDP data were collected from the China Statistics Yearbooks from 2001 to 2015.

3.3 CO₂ emission projection

The Kaya identity is based on the famous IPAT equation

(Impact=Population×Affluence×Technology) used to develop identical equations for

anthropogenically driven forces (Equation 3) (Kaya, 1990), and the Kaya identity is used to

project future GHG emissions in many international projection systems, including the IPCC:

$$\text{Total emissions} = \text{Population} \times \left(\frac{\text{GDP}}{\text{population}} \right) \times \left(\frac{\text{Energy}}{\text{GDP}} \right) \times \left(\frac{\text{Emissions}}{\text{Energy}} \right) \quad (3)$$

The projection equation can be further simplified because of the strong correlation between GDP and CO₂ emissions (Blanco et al., 2014) as well as the essentially consistent population size in

short-term projections. Changes in CO₂ emissions can be driven by increases in economic

activities (reflected by the GDP) and changes in the carbon intensity of the economy. Thus,

emissions can be decomposed into a simplified Kaya identity (see Equation 4). This method is

simple but effective and has been used by Friedlingstein et al. (Friedlingstein et al., 2014). In this

paper, we follow the same projection method:

$$\text{Total emissions} = \text{GDP} \times \text{Carbon intensity} \quad (4)$$

Therefore, two parts must be projected: the GDP and the carbon intensity.

The first part is GDP projection. Future GDP data (constant price at 2000 levels) were

extrapolated based on the growth rate from China's 13th Five Year Plan (2016 to 2020), which

averaged 6.5% during the period (NDRC (National Development and Reform Commission), 2015). This growth rate is nearly in accordance with the GDP forecast by the World Bank (shown in Supplementary 2). We assumed that average GDP growth rate was 6% for 2021 to 2025, 5.5% for 2026 to 2030, and 5% for 2031 to 2035. This assumption is based on the trend in China's planned GDP growth rates; these rates were set as 7.5% for the 11th Five Year Plan (2006-2010), 7% for the 12th Five Year Plan (2011 to 2015), and 6.5% for the 13th Five Year Plan (2016 to 2020). Additional details are shown in Table 2 and Supplementary 2.

The second part is the carbon intensity. We assumed that China would maintain the mitigation policy implemented in its 12th Five Year Plan (2011 to 2015), with an average rate of decline of 3.2% annually in the future. We treat this trend as the typical scenario to evaluate the impact of the data revision in 2015 on achieving the 2020 and 2030 mitigation pledges. We made this assumption because the carbon intensity trajectory is largely affected by mitigation policies developed for the different five-year plans. In the 12th Five Year Plan, mitigation is a key national policy and is implemented in multi-level development plans. We employed a trend analysis (exponential regression) based on historical carbon intensity (2011 to 2014) to project the future trend and evaluate whether China can achieve its mitigation pledges under the mitigation policy of the 12th Five Year Plan.

To determine the uncertainty of China's carbon emission peak level, two other scenarios were introduced to compare with the basic scenario. (1) The accelerated scenario assumes that mitigation would be reinforced in the future; the carbon intensity is projected using the same method as in the 12th Five Year Plan scenario but is based on data obtained for the most recent 5

years. For example, to project carbon intensity in 2019, the carbon intensity from 2014 to 2018 was used. (2) The alternative scenario is derived from Green and Stern's research, which projects the peak emission time based on updated Chinese socioeconomic data. Their CO₂ projection assumes (Green and Stern, 2016) that the GDP growth rate from 2015 to 2020 will average 6.5% annually and will decrease to 5.5% from 2020 to 2025 (the rate is assumed to remain the same until 2035). From 2015 to 2020, the energy intensity decreases at a fixed annual rate of 4%, and the CO₂ intensity of energy decreases at a fixed rate of 1% and then increases to 1.5% thereafter. Compared with the other two scenarios, Green and Stern's scenario can be considered the strictest mitigation scenario, as the carbon intensity decline rate in this scenario is much higher than those in the others (e.g., 5.44% for 2020-2035 in Green and Stern's scenario and 4.59% in the 12th Five Year Plan scenario). We compared the CO₂ peak levels of different datasets in three scenarios to present how the data revision affects peak level changes. The details can be found in Supplementary 2.

In a sectoral mitigation analysis, we derived the sectoral CO₂ emissions (from 2005 to 2014) from the previously constructed CO₂ emission inventory of the 2015 data and 2010 data and collected sectoral GDP data from the China Statistics Yearbooks (2006-2015). Based on the sectoral CO₂ and GDP, the historical carbon intensity from 2005 to 2014 can be calculated before we project the sectoral carbon intensity using the trend analysis (in Supplementary 2). Notably, the sectoral carbon intensity for key sectors is projected from 2005 to 2020 only because mitigation policy was first included in sectoral economic plans in 2005; this intensity may present wide variations and might be difficult to precisely estimate over longer periods. Using the sectoral projection, we

evaluated the impacts of data revisions on achieving sectoral mitigation targets.

Table 2. Summary of Scenarios and Assumptions

Scenarios	Indicators		2016-2020	2021-2025	2026-2030	2031-2035	Description
12th Five Year Plan Scenario	Average GDP Growth		6.50%	6%	5.50%	5%	GDP assumption derived from the 13th Five Year Plan (6.5% for 2016-2020) and extrapolated to 2035 by subtracting 0.5% every 5 years. The carbon intensity is projected using an exponential regression based on intensity (2011-2015) for the 12th Five Year Plan scenario and on the last 5 years for the accelerated scenario.
	Carbon	2015 Data	-4.59%	-4.59%	-4.59%	-4.59%	
	Intensity	2010 Data	-4.82%	-4.82%	-4.82%	-4.82%	
Accelerated Scenario	Average GDP Growth		6.50%	6%	5.50%	5%	GDP and carbon intensity assumptions are derived from Green & Stern's research.
	Carbon	2015 Data	-5.11%	-4.99%	-4.99%	-5.00%	
	Intensity	2010 Data	-5.29%	-5.19%	-5.19%	-5.20%	
Green& Stern Scenario	Average GDP Growth		6.50%	5.5%	5.5%	5.5%	GDP and carbon intensity assumptions are derived from Green & Stern's research.
	Carbon	2015 Data	-4.96%	-5.44%	-5.44%	-5.44%	
	Intensity	2010 Data	-4.96%	-5.44%	-5.44%	-5.44%	

Note: The carbon intensity decline rate is an annual rate of decrease, and the GDP growth is the average rate for the respective period.

4. Results and Discussion

4.1 Challenges in reaching mitigation targets caused by data revisions

Uncertain energy data imply uncertainty in achieving mitigation targets. First, we update the carbon intensity based on different energy statistics from 2000 to 2014 and extend the trajectory to 2035. As shown in Figure 1, because of the data revision, the mitigation benchmark (carbon intensity of 2005) increased by 5%. Accordingly, the mitigation target required to reach the 2020 target increased from 19.47 to 20.49 Mt/10³ Yuan (CNY), and the target required to reach the 2030 target increased from 12.82 to 13.51 Mt/10³ CNY (the blue and red dashed lines in Figure 1 refer to the 40% and 60% reductions, respectively). Therefore, the overall mitigation requirements were increased (the black line and brackets in the figure refer to the required carbon intensity before and after revision, respectively). The uncertainty introduced by the revised energy statistics raises doubts about China's ability to achieve its mitigation pledges for 2020 and 2030. For example, the revisions suggest that the originally reported mitigation achievements might be inflated. Based on an extrapolation of the 2010 data, China had achieved a 29.9% carbon intensity reduction by 2014 (22.45 Mt/10³ CNY) compared with the 2005 level; however, under the revision, this figure changes to a 25.23% reduction (25.24 Mt/10³ CNY).

Under the assumption that the recent trends will continue, we extended the trend-based carbon intensity to 2035 (see Methods) (Figure 1) and projected that China can achieve the 40% carbon intensity reduction target (2020 target) by 2018, which represents a 41% carbon intensity reduction based on the 2010 data; however, the latest national data revision indicates that this target will not be met until 2020. This change may be attributed to the lower reduction rate of

carbon intensity indicated by the 2015 data. The 2010 data showed that the average Chinese carbon intensity from 2000 to 2014 decreased at a rate of 2.2% per year, whereas after the revision, the rate of reduction was 1.2%. Compared with the 2010 data for the same year, the lower reduction rate of the 2015 data leads to a higher carbon intensity, which causes the delay in meeting the mitigation targets. For the 2030 target, the 2010 statistics indicate that carbon intensity could be reduced by 60.7% by the end of 2026, whereas the revision indicates a delay in achieving the mitigation targets until 2028. A comparison between the 2015 data and 2010 data indicates that the 2015 data are associated with higher mitigation requirements (13.51 Mt/10³ CNY for the 2020 target and 20.26 for the 2030 target, 5% higher than the requirement for the 2010 data) but a lower mitigation rate (1.2% for the 2015 data; 2.2% for the 2010 data), contributing to the uncertainty in the mitigation targets and CO₂ trajectory.

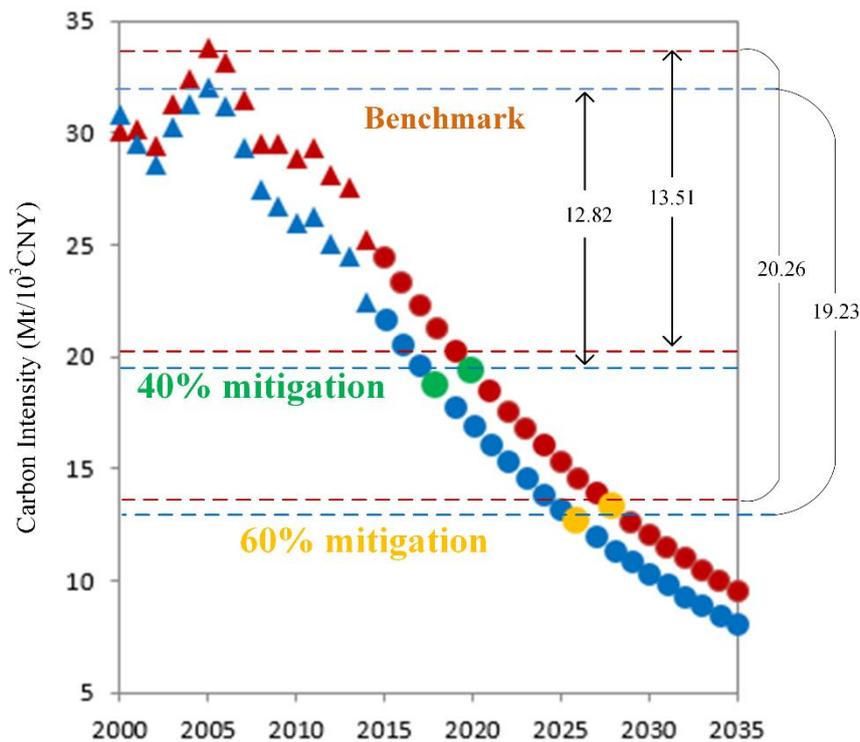


Figure 1. China carbon intensity trajectory (projection for 2015 to 2035). Triangles and circles

indicate historical data and projection data, respectively. Red and blue indicate the 2015 and 2010 data, respectively. The red and blue lines crossing the triangles indicate a mitigation benchmark (2005 carbon intensity level). The red dashed line indicates the mitigation target for the 2015 data, and the blue dashed line indicates the mitigation target for the 2010 data. The green dots represent when the 2020 mitigation target is achieved, and the yellow dots represent when the 2030 mitigation target is achieved. The black line and brackets indicate the changes in mitigation requirements. The black arrows are for the 2020 mitigation target, and the parentheses show the 2030 mitigation target. The unit of the Y-axis is Mt/10³ CNY. Note: CNY here is Chinese Yuan.

4.2 Carbon space and peak level changes

The revision of increased CO₂ emissions directly changed past CO₂ emissions in terms of the numbers and massively changed the trend slope of past emissions, which largely determined the future CO₂ trajectory and the achievement of mitigation targets. As the key feature of the NDCs, the CO₂ emission peak level has received widespread attention since late 2014, when the pledge was made. Using the simplest Kaya equation, we extended the CO₂ emission trajectory illustrated by the two datasets to 2035 to reveal how the data revision affects the peak levels. Although many factors may contribute to the CO₂ emission peak, mitigation policies play an important role in the peak levels. Because of the uncertain policy background, modellers employ scenario analyses to track China's CO₂ trajectory via assumptions for different portfolios of policies (Liu et al., 2015a; Mi et al., 2016; Zhang et al., 2016); however, the uncertainty in the energy data leads to additional uncertainty in the scenario analyses. To illustrate this uncertainty, we created an accelerated scenario (see Methods) and used Green and Stern's projection assumption (Green and Stern, 2016)

(see Methods) for CO₂ emissions for comparative purposes and to evaluate the impacts of uncertain data. We found that the peak level changes dramatically and ranges from 12.38% to 17.85% of peak level by 2010 data for different scenarios due to data revision. Following the CO₂ emission trend based on the 12th Five Year Plan (12th FYP), the CO₂ emissions should peak at 9.89 Gt in 2032; however, the 2015 data increase the peak level by 17.85% to 11.65 Gt in 2034 (Figure 2). In the accelerated scenario, the 2015 data indicate that China would reach the peak of 10.76 Gt CO₂ in 2030, whereas the 2010 data suggest that this figure will be 9.21 Gt CO₂ in 2028 (Figure 2). However, according to Green and Stern's method, the peak level would be 10.13 Gt and 9.08 Gt CO₂ for the 2015 and 2010 data, respectively, a difference of 12.38%. When considering only the uncertainty from the scenarios (without regarding data revision), the uncertainty would be 15% for the 2015 data and 9% for the 2010 data. To save the space and avoid confusion, we transit three scenarios of 12th Five Year Plan, accelerated scenario and Green and Stern's scenarios in to Scenarios 1, 2, 3 in the Figure 2 respectively. However, the uncertainty in the CO₂ peak might increase to 29%. Notably, the data revision significantly changes the past trend, especially in the 2011-2015 data series, which greatly affects the CO₂ trajectory. Although the 2015 data revision increased the CO₂ emissions compared with the 2010 data, this revision also indicates a slower carbon intensity reduction rate than the 2010 data, implying less CO₂ growth in the future. Therefore, the influence of data revision on the CO₂ trajectory is not only a numeric change, in which the 2015 data revised CO₂ emissions upward, but also changes the annual carbon intensity reduction rate during 2011-2015 from -4.82% to -4.59%. This difference affects the future CO₂ trajectory, especially for scenarios 1 and 2. Other studies have presented estimates of the peak level. Zhang et al. (2016) applied a C-GEM model, the multiregional simulation model for global

energy and economic systems, which is capable to capture the impact of policy by finding its effects on prices and goods, further people behaviours and then domestic economic activities. The research found that China's emissions would peak at 10 to 12 Gt CO₂ based on different scenarios. Mi et al. (2016) adopted the input-output model to project a peak level of 11.20 to 12.59 Gt based on different constraints. Liu et al. (2015a) used the Kaya identity model and estimated that the peak level might be 10.7 to 11.9 Gt in different scenarios.

The changes in the CO₂ trajectory generate additional under-reported CO₂ emissions, which means that China would gain additional carbon space (or emissions quota for mitigation targets) because of the data revision. After the 2015 revision, the gap between the CO₂ emissions calculated from the two energy datasets increased from 67 Mt to 1045 Mt every year from 2000 to 2014. During this period, CO₂ emissions cumulatively increased by 7.4 Gt, which accounted for 7.8% of the total emissions based on the new data compared with the cumulative emissions from the pre-revised data. This change suggests that the 7.4 Gt CO₂ was under-reported before the data update in 2015. In the future, the carbon space will likely present increased uncertainty because of the data revision. The results of all the scenarios indicate significant differences in the carbon space, which ranges from 22.94 to 31.31 Gt from 2015 to 2035 (36% uncertainty). Moreover, the uncertainty related to the additional emission space implies that the global carbon budget before the revision was underestimated; thus, the global CO₂ quota to reach the 2°C mitigation target is reduced (Friedlingstein et al., 2014).

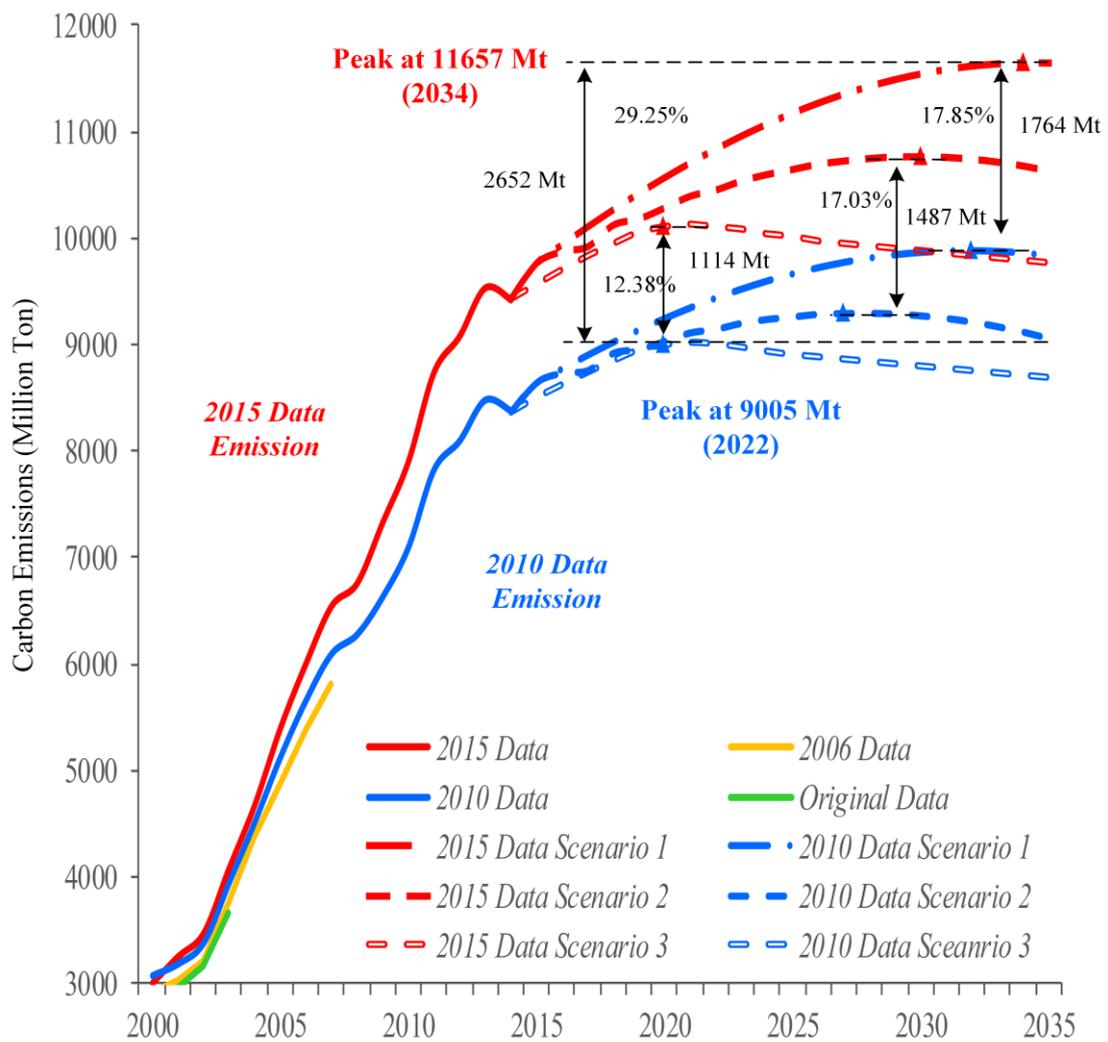


Figure 2 China's emission trajectory and projections (Unit: Gt CO₂).

Figure 2 compares the differences in peak level reached in the two datasets under the three scenarios. The peak levels reached by the 2015 data are 12.38% (1114 Mt), 17.3% (1487 Mt), and 17.85%(1764 Mt) higher than the peak levels projected by the 2010 data for the three scenarios, respectively. Scenario 1 is the 12th Five Year Plan scenario; Scenario 2 is the accelerated scenario; Scenario 3 is the Green and Stern scenario. In the 2010 data, the 2013 and 2014 emission data were extrapolated using the change rate of these two years in the 2015 data. Details can be found in the Methods section.

4.3 Implications for industrial mitigation

Because China's mitigation initiatives are disaggregated into energy-intensive sectors, the revised CO₂ emissions in the national inventory have resulted in uncertainty at the sectoral level. Together, three key industrial sectors consume more than 70% of the total energy: electricity supply (approximately 40%), non-metal mineral product manufacturing (14%), and ferrous metal smelting and pressing (20%). These sectors have the highest emissions and lowest emission efficiencies (high emissions/low output) (Chen and He, 2016; Liu et al., 2012; Wang and Liang, 2013). Mitigation policies for these sectors are highly important and directly determine the mitigation results; therefore, we focus on how the data revision affects these sectors. Because of the importance of these sectors to mitigation accounts, these sectors are required to publish sectoral action plans for reducing their emissions and CO₂ intensity (Wang et al., 2014). As indicated by the newly released 13th Five Year Plan (2016-2020), non-metal mineral product manufacturing aims to decrease its carbon intensity by 15% by 2020 and ferrous metal smelting and pressing aims to decrease its carbon intensity by 10% by 2020. Notably, carbon intensity for sector is the sectorial carbon emissions per unit sectorial GDP.

However, the 2015 data revision has a much greater effect on the steel and iron and cement industries than on the other sectors, which suggests that the historical energy consumption data for these two key sectors might be problematic. Because of the unique role of these sectors in the mitigation, any uncertainty in their energy data is important. The revision of energy data from 2000 to 2014 increased emissions from the iron and steel industry by an average of 17% (range from 5% to 31%), which was mainly induced by the energy required for steel production. The

emissions from cement production increased by 5% (range from -12% to 15%). During 2005 to 2012, the revised emissions increased by 12% each year (Table 2S). If we assume that the latest 2015 data are reliable, these findings would indicate a 21% underestimate for the steel industry and a 12% underestimate for the cement industry from 2005 to 2012 (Table 2S). The mitigation achievements of the iron and steel industry from 2005 to 2012 decreased from 45% to 35% because of the lower mitigation rate in the 2015 data, and the cement industry showed a slight decrease from 60% to 58%. The data revision in 2015 might make it more challenging to achieve mitigation targets. Based on the trend analysis, we extended the emissions to 2020 for the carbon intensity calculation. We found that the projected carbon intensity reduction from the iron and steel industry over the period of 13th Five Year Plan would decline significantly from 12% to 8%, while the carbon intensity reduction of the cement industry decreased from 34% to 28%. Based on the trends observed in the latest data, the sectoral mitigation target for the iron and steel industry might not be achieved.

Raw coal plays a dominant role in the energy structures of these two energy-intensive sectors. However, revision in raw coal consumption and its related emissions are not same for the two sectors. For the cement industry, raw coal-related emissions from 2000 to 2012 increased by an average of 14% after the revision, especially after 2005, since emissions were increased by an average of almost 30%. Subsequently, the total sectoral emission increased by an average of 5% from 2000 to 2012 and 12% after 2005 (details in Table 2S). The revision in raw coal consumed in the cement industry might indicate an underestimate of raw coal usage before 2015. However, there was an anomaly for the iron and steel industry between raw coal-related emissions and the sectoral emissions. From 2000 to 2008, coal-related emissions under the 2015 data were 10%

lower than those in the 2010 data, whereas the total sectoral emissions in the 2015 data were 15% higher than those in the 2010 data. After 2008, the changes in the coal-related emissions in the 2015 data were in accordance with those of the sectoral emissions but only accounted for 5% of the sectoral emission changes (Table 3S). As the dominant energy type in the iron and steel industry, the trend in coal-related emissions should have matched that of total emissions. The opposite change may have profound implications. For the steel industry, we found that the emissions from raw coal decreased while the emissions from coke and other gas increased after the revision, especially for other gas, which showed a three-fold growth (Table 2S). This finding may imply that a proportion of the coke and other gas used in the steel industry might have been categorised as raw coal in previous statistics, which would have overestimated the previous reliance of the steel industry on raw coal before 2008 and underestimated the raw coal consumption since 2008.

5. Conclusion and policy recommendations

CO₂ emissions are the main target of global emission mitigation, and the sheer magnitude of CO₂ emissions increases the importance of obtaining correct data because the uncertainties are closely correlated with the ability to achieve mitigation targets (Monni et al., 2004). This paper compares the difference in the 2015 energy data revision in China and shows how the large uncertainty impacts the achievement of national mitigation targets that are essential in global decarbonisation initiatives. After the energy statistics revisions, mitigation challenges increase by 5%, and achieving national mitigation targets (and international pledges) might be postponed by two years, from 2018 to 2020, to reach the 40% carbon intensity reduction target and from 2026 to 2028 to

reach the 60% carbon intensity reduction target. This delay is due to the slower carbon intensity reduction rate in the 2015 data. The 2015 data revision increased the past CO₂ emissions; therefore, extra carbon space (from 22.94 to 31.31 Gt) might be generated from 2015 to 2035, and CO₂ peak levels with the uncertainty varying from 12% to 29% might be induced by the revised energy statistics. In addition to the national mitigation targets, mitigation targets for key industrial sectors are affected by the data revision, in which raw coal consumption for the cement and iron and steel industries increased greatly. Although our study shows that achieving mitigation targets would not be derailed by the data revisions, the unexpected carbon space and lower carbon intensity reduction rate suggest that the mitigation challenges will exceed current estimates, especially for key mitigation sectors for which the data revision has altered sectoral mitigation prospects. Furthermore, the revisions have additional implications for global decarbonisation initiatives because the tremendous carbon space reported by the new data has long been underestimated. The remaining emission quota from 2015 with the 2°C goal (66% probability) is 1200 Gt CO₂. With the new data, extra carbon space in China might compromise the total remaining emission quota, increasing the challenges for other countries with shrinking emission quotas. This paper clearly shows that the uncertainties in the past will be reflected in uncertainties in projections of the future.

The revised data show inconsistencies in the energy data; however, they also show the progress in the energy statistics system, as the gap between the updated national data and aggregated provincial data is decreasing (Guan et al., 2012; Shan et al., 2015). It appears plausible that the energy accounting system will improve as the gap is reduced, but the current institutional arrangement of a bottom-up energy accounting system still relies on energy accounting at a lower

level, such as the city level, which requires highly accurate and reliable primary energy consumption data from manufacturers. Collecting these fundamental data is confronted with huge challenges such as local governments manipulating data for political benefits or a lack of control over small coal mines or factories, as described in previous research (Guan et al., 2012; Li et al., 2014; Zheng et al., 2014). In the current energy accounting institutions, more on-site surveys on energy data collection and accuracy checks with qualified labour would be helpful but costly. With the importance of China's energy statistics in the world, a well-established energy accounting system is urgently required to ensure consistency and accuracy instead of relying on National Economic Census data every 5 years to make adjustments. Alternative energy accounting approaches such as remote-sensing technology could be considered to monitor and verify CO₂ emissions.

Acknowledgements

All the data and results can be download freely from China Emission Accounts and Datasets (CEADs) at <http://www.ceads.net>. This work was supported by the National Key R&D Program of China (2016YFA0602604), the Natural Science Foundation of China (71533005, 41629501), the UK Economic and Social Research Council (ES/L016028/1), Natural Environment Research Council (NE/N00714X/1), British Academy Grant (AF150310), China Scholarship Council (No. 201606510016) and the joint Leverhulme Trust and Social Sciences Faculty Postgraduate Studentships at the University of East Anglia. We also acknowledge the editor and referees for their time and constructive suggestions.

References

- Akimoto, H., Ohara, T., Kurokawa, J. ichi, Horii, N., 2006. Verification of energy consumption in China during 1996-2003 by using satellite observational data. *Atmos. Environ.* 40, 7663–7667. doi:10.1016/j.atmosenv.2006.07.052
- Andres, R.J., Boden, T.A., Higdson, D., 2014. A new evaluation of the uncertainty associated with CDIAC estimates of fossil fuel carbon dioxide emission. *Tellus B* 66, 1–15. doi:10.3402/tellusb.v66.23616
- Blanco, G., Gerlagh, R., Suh, S., Barrett, J., de Coninck, H.C., Diaz Morejon, C.F., Mathur, R., Nakicenovic, N., Ofosu Ahenkora, A., Pan, J., Pathak, H., Rice, J., Richels, R., Smith, S.J., Stern, D.I., Toth, F.L., Zhou, P., 2014. Drivers, Trends and Mitigation, *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
- Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., Navarro, A. de la V., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., D, I., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wisser, R., Zhang, X., 2014. Energy Systems, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* pp. 511–597.
- Chen, W., He, Q., 2016. Intersectoral burden sharing of CO2 mitigation in China in 2020. *Mitig. Adapt. Strateg. Glob. Chang.* 21, 1–14.

doi:10.1007/s11027-014-9566-3

- Friedlingstein, P., Andrew, R.M., Rogelj, J., Peters, G.P., Canadell, J.G., Knutti, R., Luderer, G., Raupach, M.R., Schaeffer, M., van Vuuren, D.P., Le Quéré, C., 2014. Persistent growth of CO₂ emissions and implications for reaching climate targets. *Nat. Geosci.* 7, 709–715. doi:10.1038/ngeo2248
- Green, F., Stern, N., 2016. China's changing economy: implications for its carbon dioxide emissions. *Clim. Policy* 0, 1–15. doi:10.1080/14693062.2016.1156515
- Gregg, J.S., Andres, R.J., Marland, G., 2008. China: Emissions pattern of the world leader in CO₂ emissions from fossil fuel consumption and cement production. *Geophys. Res. Lett.* 35, L08806. doi:10.1029/2007GL032887
- Guan, D., Liu, Z., Geng, Y., Lindner, S., Hubacek, K., 2012. The gigatonne gap in China's carbon dioxide inventories. *Nat. Clim. Chang.* 2, 672–675. doi:10.1038/nclimate1560
- Guan, L., Sun, G., Cao, S., 2011. China's bureaucracy hinders environmental recovery. *Ambio* 40, 96–99. doi:10.1007/s13280-010-0112-6
- Hong, C., Zhang, Q., He, K., Guan, D., Li, M., Liu, F., Zheng, B., 2016. Variations of China's emission estimates response to uncertainties in energy statistics. *Atmos. Chem. Phys. Discuss.* doi:10.5194/acp-2016-459
- IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2006 IPCC Guidel. Natl. Greenh. Gas Invent. 3, 1–40.
- Kaya, Y., 1990. Impact of Carbon Dioxide emission control on GNP growth: Interpretation of proposed scenarios, in: Paper Presented to the IPCC Energy and

Industry Subgroup, Response Strategies Working Group.

- Korsbakken, J.I., Peters, G.P., Andrew, R.M., 2016. Uncertainties around reductions in China's coal use and CO₂ emissions. *Nat. Clim. Chang.* 6, 687–690. doi:10.1038/nclimate2963
- Li, H., Wu, T., Zhao, X., Wang, X., Qi, Y., 2014. Regional disparities and carbon “outsourcing”: The political economy of China's energy policy. *Energy* 66, 950–958. doi:10.1016/j.energy.2014.01.013
- Li, H., Zhao, X., Yu, Y., Wu, T., Qi, Y., 2016. China's numerical management system for reducing national energy intensity. *Energy Policy* 94, 64–76. doi:10.1016/j.enpol.2016.03.037
- Liu, Z., 2015. China's Carbon Emissions Report 2015. doi:<http://belfercenter.ksg.harvard.edu/files/carbon-emissions-report-2015-final.pdf>
- Liu, Z., Geng, Y., Lindner, S., Guan, D., 2012. Uncovering China's greenhouse gas emission from regional and sectoral perspectives. *Energy* 45, 1059–1068. doi:10.1016/j.energy.2012.06.007
- Liu, Z., Guan, D., Moor, S., Su, J., Zhang, Q., 2015a. Climate policy: Steps to China's carbon peak. *Nature* 522, 279–281.
- Liu, Z., Guan, D., Wei, W., Davis, S.J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R.J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T.A., Feng, K., Peters, G.P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., He, K., 2015b. Reduced carbon emission estimates from fossil fuel combustion and

- cement production in China. *Nature* 524, 335–338. doi:10.1038/nature14677
- Ma, B., Song, G., Zhang, L., Sonnenfeld, D.A., 2014. Explaining sectoral discrepancies between national and provincial statistics in China. *China Econ. Rev.* 30, 353–369. doi:10.1016/j.chieco.2014.07.004
- Marland, G., Hamal, K., Jonas, M., 2009. How uncertain are estimates of CO₂ emissions? *J. Ind. Ecol.* 13, 4–7. doi:10.1111/j.1530-9290.2009.00108.x
- Mi, Z., Meng, J., Guan, D., Shan, Y., Liu, Z., Wang, Y., Feng, K., Wei, Y.-M., 2017. Pattern changes in determinants of Chinese emissions. *Environ. Res. Lett.* 12, 74003. doi:10.1088/1748-9326/aa69cf
- Mi, Z., Wei, Y.-M., Wang, B., Meng, J., Liu, Z., Shan, Y., Liu, J., Guan, D., 2016. Socioeconomic impact assessment of China's CO₂ emissions peak prior to 2030. *J. Clean. Prod.* doi:10.1016/j.jclepro.2016.11.055
- Monni, S., Syri, S., Savolainen, I., 2004. Uncertainties in the Finnish greenhouse gas emission inventory. *Environ. Sci. Policy* 7, 87–98. doi:10.1016/j.envsci.2004.01.002
- NBS(NationalBureau ofStatistics), n.d. China Energy Statistical Yearbook. China Statistics Press, Beijing.
- NDRC(National Development and Reform Commission), 2015. Outline of China 13th Five Year Plan [WWW Document]. URL http://sh.xinhuanet.com/2016-03/18/c_135200400.htm (accessed 12.13.16).
- Peters, G., Weber, C., Liu, J., 2007. Construction of Chinese energy and emissions inventory (supporting information). Reports Work. Pap. from Norwegian Univ.

- Sci. Technol. Ind. Ecol. Progr. 1–21.
- Qi, Y., Stern, N., Wu, T., Lu, J., Green, F., 2016. China's post-coal growth. *Nat. Geosci.* 9, 564–566. doi:10.1038/ngeo2777
- Qi, Y., Wu, T., 2013. The politics of climate change in China. *Wiley Interdiscip. Rev. Clim. Chang.* 4, 301–313. doi:10.1002/wcc.221
- Shan, Y., Liu, J., Liu, Z., Xu, X., Shao, S., Wang, P., Guan, D., 2015. New provincial CO2 emission inventories in China based on apparent energy consumption data and updated emission factors. *Appl. Energy.* doi:10.1016/j.apenergy.2016.03.073
- Shan, Y., Liu, Z., Guan, D., 2016. CO2 emissions from China's lime industry. *Appl. Energy* 166, 245–252. doi:10.1016/j.apenergy.2015.04.091
- Sinton, J., 2001. Accuracy and reliability of China's energy statistics. *China Econ. Rev.* 12, 373–383. doi:10.1016/S1043-951X(01)00067-0
- van Ruijven, B.J., Weitzel, M., den Elzen, M.G.J., Hof, A.F., van Vuuren, D.P., Peterson, S., Narita, D., 2012. Emission allowances and mitigation costs of China and India resulting from different effort-sharing approaches. *Energy Policy* 46, 116–134. doi:10.1016/j.enpol.2012.03.042
- Wang, C., Lin, J., Cai, W., Liao, H., 2014. China's carbon mitigation strategies: Enough? *Energy Policy* 73, 47–56. doi:10.1016/j.enpol.2014.05.041
- Wang, X., 2011. On China's energy intensity statistics: Toward a comprehensive and transparent indicator. *Energy Policy* 39, 7284–7289. doi:10.1016/j.enpol.2011.08.050
- Wang, Y., Liang, S., 2013. Carbon dioxide mitigation target of China in 2020 and key

economic sectors. *Energy Policy* 58, 90–96. doi:10.1016/j.enpol.2013.02.038

Zhang, X., Karplus, V.J., Qi, T., Zhang, D., He, J., 2016. Carbon emissions in China: How far can new efforts bend the curve? *Energy Econ.* 54, 388–395. doi:10.1016/j.eneco.2015.12.002

Zheng, H., Wang, X., Cao, S., 2014. The land finance model jeopardizes China's sustainable development. *Habitat Int.* 44, 130–136. doi:10.1016/j.habitatint.2014.05.008

Table Caption

Table 1 Comparison between 2015 data, 2010 data, 2006 data and Original data

Note: Mtce=Million tons coal equivalent; Mt=Million tons. Underlined data indicate the revised data for each dataset.

Table 2 Summary of Scenarios and Assumptions

Note: The carbon intensity decline rate is an annual rate of decrease, and the GDP growth is the average rate for the respective period.

Figure Caption

Figure 1. China carbon intensity trajectory (projection for 2015 to 2035). Triangles and circles indicate historical data and projection data, respectively. Red and blue indicate the 2015 and 2010 data, respectively. The red and blue lines crossing the triangles indicate a mitigation benchmark (2005 carbon intensity level). The red dashed line indicates the mitigation target for the 2015 data, and the blue dashed line indicates the mitigation target for the 2010 data. The green dots represent when the 2020 mitigation target is achieved, and the yellow dots represent when the 2030 mitigation target is achieved. The black line and brackets indicate the changes in mitigation requirements. The black arrows are for the 2020 mitigation target, and the parentheses show the 2030 mitigation target. The unit of the Y-axis is $\text{Mt}/10^3$ CNY. Note: CNY here is Chinese Yuan.

Figure 2 China's emission trajectory and projections (Unit: Gt CO₂).

Figure 2 compares the differences in peak level reached in the two datasets under the three scenarios. The peak levels reached by the 2015 data are 12.38% (1114 Mt), 17.3% (1487 Mt), and 17.85%(1764 Mt) higher than the peak levels projected by the 2010 data for the three scenarios, respectively. Scenario 1 is the 12th Five Year Plan scenario; Scenario 2 is the accelerated scenario; Scenario 3 is the Green and Stern scenario. In the 2010 data, the 2013 and 2014 emission data were extrapolated using the change rate of these two years in the 2015 data. Details can be found in the Methods section.