Title

Black carbon emissions and reduction potential in China: 2015—2050

Authors

Wang, Wenjun
Khanna, Nina
Lin, Jiang
et al.

Publication Date

2023-03-01

DOI

10.1016/j.jenvman.2022.117087

Journal of Environmental Management 329 (2023) 117087

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Black carbon emissions and reduction potential in China: 2015–2050

Wenjun Wang [a], Nina Khanna [b,*], Jiang Lin [a,b], Xu Liu [b,c]

[a] *University of California, Berkeley, Berkeley, CA, 94720, USA*
[b] *Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA*
[c] *National School of Development, Peking University, Beijing, 100871, China*

ARTICLE INFO

Keywords:
Black carbon
Climate change
China

ABSTRACT

Black carbon is a product of the incomplete combustion of carbonaceous fuels and has significant adverse effects on climate change, air quality, and human health. China has been a major contributor to global anthropogenic black carbon emissions. This study develops a black carbon inventory in China, using 2015 as the base year, and projects annual black carbon emissions in China for the period 2016–2050, under two scenarios: a Reference scenario and an Accelerated Reduction scenario. The study estimates that the total black carbon emissions in China in 2015 were 1100 thousand tons (kt), with residential use being the biggest contributor, accounting for more than half of the total black carbon emissions, followed by coke production, industry, agricultural waste burning, and transportation. This study then projects the total black carbon emissions in China in 2050 to be 278 kt in the Reference scenario and 86 kt in the Accelerated Reduction Scenario. Compared to the Reference scenario, the Accelerated Reduction scenario will achieve much faster and deeper black carbon reductions in all the sectors. The dramatic reductions can be attributed to the fuel switching in the residential sector, faster implementation of high-efficiency emission control measures in the industry, transportation, and coke production sectors, and faster phase-out of agricultural waste open burning. This analysis reveals the high potential of black carbon emission reductions across multiple sectors in China through the next thirty years.

1. Introduction

Black carbon (BC) is a product of the incomplete combustion of carbonaceous fuels, such as fossil fuels and biomass. It is a major contributor to global warming, an air pollutant, and a well-established health hazard. BC particles are very effective at absorbing solar radiation and converting it to heat. The per unit of mass warming impact of BC on climate is 460–1500 times stronger than that of carbon dioxide (CO_2) (Climate & Clean Air Coalition, 2021). When deposited on ice and snow, BC reduces the ability of the surface to reflect sunlight, thus heating the surface and accelerating the melting of snow and ice (Climate & Clean Air Coalition, 2021). Submicron BC particles may spread over distances of hundreds to thousands of kilometers. BC is a component of PM2.5, which is associated with millions of deaths annually (Bond et al., 2013; Vohra et al., 2021). The small diameter of BC particles allows for deep penetration into the lungs, causing significant human health risks, including higher blood pressure (Baumgartner et al., 2014), spreading infectious diseases (Hussey et al., 2017), and increasing the risk of death (Li et al., 2016). The BC particles can also significantly degrade optical depths and visibility (Novakov and Rosen, 2013). In addition, BC is deposited on plant leaves (increasing their temperature), reduces sunlight that reaches the Earth, and modifies rainfall patterns, therefore it affects agricultural productivity and ecosystem health. The lifetime of BC in the atmosphere ranges from only days to weeks (Climate & Clean Air Coalition, 2021). Since BC does not last long in the atmosphere, efforts to reduce it can benefit the climate, human health, agriculture, and ecosystems within a relatively short period of time.

China has been a major contributor to global anthropogenic BC emissions due to its large population, substantial fuel consumption, and oftentimes inefficient combustion conditions (Climate & Clean Air Coalition, 2021). Recently, rapid economic development has led to marked changes in fuel consumption, not only the total amount but also remarkable shifts in structure and efficiency. Dependence on coal has been decreasing. From 1965 to 2015, the proportion of coal in total fuel consumption dropped from 87.1% to 63.7% (Dong et al., 2017). Besides, recent policies to reduce greenhouse gas (GHGs) and other air pollutants favor combustion efficiency improvement and better emission control

---

* Corresponding author.
E-mail address: xzheng@lbl.gov (N. Khanna).

https://doi.org/10.1016/j.jenvman.2022.117087
Received 13 June 2022; Received in revised form 14 December 2022; Accepted 17 December 2022

technologies. China also plans to increase its efforts to mitigate climate change in the next 15 years. For example, in the "Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions," the central government set a goal of decreasing the emission intensity (emission amount per unit of gross domestic product, or GDP) of CO_2 by 60%–65% by 2030, relative to the 2005 level (National Development and Reform Commission, 2015). Mitigation strategies for BC can complement these CO_2-focused climate change mitigation efforts and could be an important component of a global climate change response strategy. Actions to reduce BC are crucial to slowing the rate of warming in the near term, reducing the loss of snow and ice in the Arctic (Backman et al., 2021), limiting global temperature rise to below 1.5 °C, thus helping protect China's population and economy from the effects of devastating climate change while supporting China's decarbonization targets and the newly announced targets for 2030 carbon peaking and 2060 carbon neutrality. Therefore, a more accurate and updated BC inventory and future trend projection are needed.

A series of studies have been conducted to estimate BC emissions in China. Streets et al. (2001) developed a provincial-level BC emission inventory for China, using 1995 as the base year. They then, in 2003, developed more updated emission inventories, using 2000 as the base year, for various air pollutants in China, including BC. After that, a series of emission inventories that included BC were developed for China (Cao et al., 2006; Lei et al., 2011; Qin and Xie, 2011; 2012; Wang et al., 2012; Zhang et al., 2013; Ni et al., 2014), Asia (Ohara et al., 2007; Zhang et al., 2009; Li et al., 2017), and on the global level (Bond et al., 2004; Lamarque et al., 2010; Klimont et al., 2017; Xu et al., 2021). Some bottom-up global emission inventories of air pollutants and greenhouse gases also report estimations for China's BC emissions. These inventories include the Evaluating the CLimate and Air Quality ImPacts of Short-livEd Pollutants (ECLIPSE) v5a, the Community Emissions Data System (CEDS), and The Emissions Database for Global Atmospheric Research (EDGAR) v5.0. The existing studies and emission inventories provide a valuable basis for understanding historical BC emissions in China for various time periods. However, most historical emission estimations include high uncertainty mainly due to the large variations in the BC emission factors (EF_{BC}) being used, as seen by the wide ranges in estimations from different studies or emission inventories.

In addition to historical BC estimates, a few other studies have analyzed and projected the future BC emission trends in China. Streets et al. (2001) predicted BC emissions in China in 2020 based on data from the RAINS-Asia model. Wang et al. (2012) predicted BC emissions in China for 2008–2050 for baseline and low-carbon scenarios based on fuel consumption data from an outdated National Long-term Development Plan (2008–2050) (National Development and Reform Commission and Development Research Center of the State Council, 2009) with high uncertainty mainly due to the lack of sufficient EF_{BC} measurements. Lu et al. (2019) predicted China's BC emissions in 2020 and 2030 by assuming certain relative changes in energy consumption level and BC emission factors. These BC emission projections suffer from high uncertainty due to large variations in BC emission factors reported in the literature and the lack of direct measurements of BC emission factors, especially in rapidly growing countries such as China. These studies did not attempt to provide an independent and systematic projection of China's future energy consumption and the potential changes in the fuel mix, which directly affects BC emissions; nor did these studies consider China's most recent policies such as emission standards and residential coal to gas/electric programs, and their potential impacts on future BC emissions.

This study utilizes the latest reported experimental work on direct measurements and modeling of EF_{BC} in China and takes into consideration the latest technological and policy developments related to BC reductions. By using detailed integrated energy modeling of China's energy transition that accounts for existing and potential new energy trends and BC emission control policies, our analysis provides updated projections that help reduce the uncertainty in future BC emission estimates. Unlike other existing studies that are outdated (Wang et al., 2012) or only include BC projections out to 2030 (Li and Qi, 2011), our bottom-up model captures the impact of the latest energy and technological trends on BC emissions across all economic sectors and uses two scenarios of plausible but very different pathways to project BC emissions for 2015 through 2050. The Reference scenario and Accelerated Reduction scenario used in this study capture the uncertainties associated with both energy and environmental policy implementation and technological development. Both scenarios are designed to reflect the relevant government policies, e.g., five-year plans (FYPs) and various emission standards, with different paces of policy implementation and energy and emissions control technology adoption through different fuel consumption and EF_{BC} projections. Through scenario analysis, a possible range of BC emissions in China is provided out to a longer time horizon (2050) and notable differences in the sectoral potential of BC emission reductions are identified.

The rest of this paper proceeds as follows. Section 2 introduces our methodology, data, and scenario designs for estimating BC emissions in China. Section 3 reports on and discusses the BC emission inventory in China in the base year and the projected BC emissions and relative contributions of various sectors over the period 2015–2050, under two different scenarios. Section 4 offers conclusions.

2. Methodology and data

We estimated and projected BC emissions in China from 2015 to 2050 as a product of bottom-up fuel consumption projections and the corresponding emission factors (EFs), using the following equation:

$$E = \sum_j \sum_k C_{j,k} EF_{j,k}$$

where E is the total annual BC emissions; C is the fuel consumption data; EF is the emission factors; and the subscripts j, k represent a certain fuel type and sector, respectively.

This analysis takes into account five major sectors and three minor sectors that emit BC. The five major sectors are residential, industry, coking, agricultural waste burning, and transportation. The residential sector is further divided into the urban residential sector and the rural residential sector, where the rural residential sector involves biomass (e.g., firewood, crop residues) burning for cooking and heating purposes. The three minor sectors are natural gas flaring, municipal solid waste (MSW) open burning, and the power sector. For each sector, we calculated the BC emissions by fuel type. The fuels of interest that emit BC include coal, oil, gas, and biomass. For each fuel type in each sector, we used emission factors summarized from the most recent literature while taking into account the adoption of certain emission control technologies that may decrease future emission factors. More details on this will be presented in the following subsections.

2.1. Construction of the base year inventory

The base year fuel consumption data were calibrated with nationally reported statistics on China's energy balance from China's National Bureau of Statistics, while fuel consumption projections were based on scenario results from the national bottom-up, energy end-use China 2050 DREAM model. Agricultural waste burning in this study refers to the open burning of agricultural residues (excluding forest and savannah burning). We used the average of the annual agricultural waste open burning activity levels in China reported by the existing literature (Shi et al., 2017 and Li and Wang, 2013) as the base year activity level. Natural gas flaring data is taken from remote-sensing-based estimation reported by Global Gas Flaring Reduction Initiative (GGFR). MSW open burning activity data is estimated using 3% of total municipal solid waste generated in China as an upper bound estimate since 97% of MSW is disposed to solid waste disposal sites (Hoornweg et al., 2005).

We adopted the EFs mainly from previous inventory studies and reported measurements to estimate BC emissions in China for 2015. Newly reported direct measurements of EFs and region-specific EFs were adopted when available. For example, the emission factor for coal in the industry sector has been updated to account for the latest BC emission removal efficiency of 69%. The removal efficiency was determined as follows. According to a survey by Yao et al. during the revision of the *Emission Standard of Air Pollutants for Boiler*, 85 of the 95 coal-fired boilers measured have installed a dust removal device, of which 96% have a removal efficiency greater than 80%. Thus, a conservative approximation of the overall removal efficiency is (85/95) × 96% × 80% ≈ 69%. Lu et al. (2019) adopted a 75% removal rate for the industrial sector, which is similar to our approximation here. As emission control technologies develop and are adopted widely, the overall removal efficiency is projected to increase considerably in the near future. We will describe more about the projected changes in the next subsection. The EFs used in this study and the related references are listed in Table 1. More details are described in Appendix A.

2.2. Projection of future emissions

2.2.1. Modeling methodology

To project future BC emissions in China for the period 2016–2050, we used fuel-specific energy consumption projections from a bottom-up energy end-use model coupled with our analysis and projections of possible changes in EFs due to technological and policy development that affect BC emissions. Scenario analysis is used to project different energy development and BC emissions control pathways to identify BC reduction potential in specific sectors.

The analysis of energy development pathways uses fuel consumptions results from the Berkeley Lab's China 2050 Demand Resource Energy Analysis Model (DREAM), a national bottom-up energy end-use model that includes energy demand, supply, and transformation sectors. This model is an application of the Low Emissions Analysis Platform (LEAP) developed by the Stockholm Environmental Institute. The China 2050 DREAM model includes a demand module consisting of five demand subsectors (residential buildings, commercial buildings, industry, transport, and agriculture) and a transformation module consisting of energy production, transmission and distribution subsectors. As a bottom-up energy end-use model, key drivers of energy consumption (e.g., physical activity drivers such as population and vehicle stock, economic drivers such as GDP) and energy intensity trends by end-use resulting from technology choices and energy efficiency improvement are used to project fuel consumption within a given sector. For example, private car stock is projected as a function of GDP growth based on international trends, while the fuel consumption of private cars is calculated based on assumed technology choices (e.g., gasoline versus diesel cars), and fuel consumption trends per vehicle type based on market data and expected improvements from fuel economy standards and technological improvements.

This model enables detailed consideration of technological development such as industrial production, equipment efficiency, residential appliance usage, vehicle ownership, power sector efficiency, lighting and heating usage as a way to evaluate China's energy and emission reduction development paths. Nationally published statistics are used to calibrate historical activity levels, and national energy balances are used to calibrate the model's base year energy consumption by fuel and by sector.

In doing so, the model is able to simulate the impact of technological changes and existing and potential policies and programs on the projected consumption of specific fuels for each demand sector under defined scenarios. Previously published reports and papers have presented in-depth discussions of the overall modeling methodology, key sectoral drivers, and modeling parameters, as well as the assumptions and basis for future projections of energy demand drivers (Zhou et al. 2013, 2018, 2019, 2022; Khanna et al., 2019; Lin et al., 2019). Previous

Table 1
Black carbon emission factors for China in 2015.

Sectors	Fuel type	EFs (g/kg)	EFs from References
Residential	Raw coal	3.36	3.7[c], 3.32[d], 3.05[e]
	Briquette	0.06	0.12[c], 0.004[d], 0.004–0.09[e]
	Liquefied petroleum gas (LPG)	0.067	0.067[f]
	Natural gas	0.0001	0.0001[f]
	Biogas	0.0001	0.0001[j,q]
	Firewood	0.84	1.0[c], 0.59[g], 0.41[h], 1.49[i], 0.7[j]
Industry	Coal	0.10[a]	0.32[a,c]
	Coke	0.03136	0.03136[f]
	Gasoline	0.067	0.07[c], 0.06525[f]
	Kerosene	0.117	0.117[f]
	Diesel	0.25	0.25[c]
	Heavy fuel oil	0.36	0.36[c]
	LPG	0.067	0.067[f]
	Gases	0.0001	0.0001[f]
Coking	Coking	0.32	0.32[f]
Agricultural Waste Burning	Agricultural waste	0.68	0.6[k], 0.75[l]
Transportation	Light-duty gasoline vehicles (LDGV)	0.016	0.016[m]
	Light-duty gasoline trucks (LDGT1)	0.021	0.021[m]
	Mid-duty gasoline trucks (LDGT2)	0.029	0.029[m]
	Heavy-duty gasoline trucks (HDGV)	0.023	0.023[m]
	Gasoline private cars, fleet cars, and taxis	0.0058	0.0058[o]
	Gasoline motorcycles	0.0075	0.0075[o]
	Light-duty diesel vehicles (LDDV)	0.18	0.18[m]
	Heavy-duty diesel trucks (HDDV)	0.31	0.31[m]
	Light-duty diesel trucks (LDDT)	0.46	0.46[m]
	Diesel private cars, fleet cars, and taxis	0.168	0.168[o]
	Diesel rail	1.1	1.1[j,n]
	Diesel water	1.1	1.1[j,n]
Power	Coal	0.002	0.0029[j], 0.0001–0.032[c], 0.003–0.32[n], 0.002[o], 0.0015[p], 0.0013[q]
	Diesel	0.027	0.02646[f], 0.028[p]
	Natural gas	0.0001	0.0001[f,j], 0.00002[p]
Natural Gas Flaring	Natural gas	1.6 (g/m^3)[b]	0.5–1.75 (g/m^3)[b,k]
Municipal Solid Waste Open Burning	Municipal solid waste	0.65	0.65[k]

*** For all other sectors and fuels, we used the average of the EFs reported in the References.

****More details on the EFs are available in Appendix A.

[a] The EF reported in the reference did not consider removal efficiency. The EF used in this paper is adjusted by a 69% removal efficiency according to the result of a survey by Yao et al. during the revision of the Emission Standard of Air Pollutants for Boiler, where they found 85 of the 95 coal-fired boilers measured have installed a dust removal device, of which 96% have a removal efficiency greater than 80%.

[b] Klimont et al., (2017) used different EFs for natural gas flaring in different regions around the world. This paper adopts the baseline EF for non-OECD countries.

[c] Streets et al., (2001).

[d] Chen et al., (2006).

[e] Chen et al., (2009).
[f] Bond et al., (2004).
[g] Andreae and Merlet (2001).
[h] Reddy and Venkataraman (2002); OM/OC ratio assumed as 1.3.
[i] Li et al., (2009).
[j] Ni et al., (2014).
[k] Klimont et al., (2017).
[l] Cao et al., (2008).
[m] Song et al., (2012)
[n] Cao et al., (2006).
[o] Qin and Xie (2011).
[p] Lu et al., (2019).
[q] Zhang et al., (2013).

applications of this model on different sectoral analyses and national energy and emission pathways have been evaluated by others (Bellevrat, 2012, Li and Qi, 2011) and validated through multi-model comparisons (Zhang et al., 2013). For this study, the most recent energy transition scenario analysis using the 2050 DREAM model is used as the basis for fuel consumption changes with updated energy calibration through 2018–19, and consideration of newly announced policies through 2020 (Zhou et al., 2022). This recent scenario analysis was also validated through comparison with other deep decarbonization scenarios for China in Khanna et al., (2021).

2.2.2. Scenario analysis

Using the model, projected fuel consumption for specific energy-using activities that lead to BC emissions in the urban and rural residential, transport, power, coking, and industry sectors are extracted for two specific scenarios: a Reference Scenario of current policies and an Accelerated Reduction scenario with faster energy transition and greater BC mitigation efforts.

Under the Reference scenario, current energy policies in place and limited autonomous technological improvement are assumed to continue to have an effect on reducing total demand and continuing the transition to cleaner fuels, but no additional new policies beyond what have already been announced are assumed through 2050. The detailed assumptions about changes in each energy demand sector can be found in Zhou et al. (2022).

For BC emissions mitigation, a similar storyline holds, in that no new mitigation policies or measures are assumed to occur before 2050. As a result, EFs in the residential sector are assumed to be constant over the period 2015–2050. EFs in the industrial sector are determined by assuming full compliance with the Emission Standard of Air Pollutants for Boilers (GB 13271–2014) will be achieved by 2035. More specifically, full compliance with the standard implies a 100% adoption rate of high-efficiency (>99%) emission control technologies for all coal-fueled boilers, or equivalently, a 97% reduction in coal's EF by 2035 compared to the 2015 level. Full compliance also requires reductions in the EFs of heavy oil and other oil products to match the EF of diesel. For years between 2015 and 2035, we used linear interpolation to calculate the annual emission factors for each fuel type. For 2035–2050, the emission factors were assumed to be constant. The EF of coking was determined by assuming full compliance with the Emission Standard of Pollutants for Coking Chemical Industry (GB 16171–2012) will be achieved by 2035, which implies a 48% reduction in the EF of coking. Similarly, we used linear interpolation to calculate the annual emission factors between 2015 and 2035 and assumed the emission factor remains constant between 2035 and 2050. Finally, for the transportation sector, we adopted the EF projections for the business-as-usual (BAU) (for the rest of China) scenario in Song et al. (2012) for 2015–2030, and we assumed the EFs for different types of vehicles remain constant between 2030 and 2050.

The Accelerated Reduction Scenario assumes that the maximum technically feasible shares of commercially available energy efficiency and renewable energy supply are adopted by 2050, resulting in lower energy demand as well as a faster transition away from fossil fuels toward electricity and low carbon fuels (Zhou et al., 2022). For instance, in the rural residential sector, there are both faster energy efficiency improvements for coal and biomass stoves, and also phase-out of coal stoves for heating and cooking by 2050 as a result of fuel switching programs and electrification policies. Similarly, there are also efficiency improvements that reduce total fuel consumption, as well as increased electrification across all sectors that displaces the consumption of fossil fuels with higher black carbon EFs (see Table S1).

In addition to these changes in energy consumption, EFs for BC are also assumed to decrease faster in most sectors[1] over time due to the earlier adoption of mitigation measures as a result of new policies. In the industrial sector, full compliance with the standard (GB 13271–2014) is assumed to be achieved by 2030, —five years earlier than that is assumed in the Reference scenario—due to accelerated policy implementation and enforcement. For the coking sector, instead of assuming full compliance with the standard (GB 16171–2012), we assumed that, by 2035, all coke ovens would meet the minimum emission levels observed from industrial surveys in 2015, which implies a 90% reduction in the EF. For natural gas flaring, we first estimate a flaring to production ratio using the observed data from 2015 to 2020 and then applied this ratio to the projected natural gas production from the China DREAM model to project natural gas flaring activity for the next 30 years. In addition to changes in activity (i.e., natural gas flared) as a result of different energy development pathways, we assume the BC emission factor to be constant at 1.6 g/m^3 in the Reference scenario but declining gradually to the OECD-countries-level of 0.57 g/m^3 by 2035 in the Accelerated Reduction scenario. For the transportation sector, we adopted the EF projections by Song et al. (2012) for the EURO V/VI scenario for 2015–2030, which characterized the case where the standards, the Limits and Measurement Methods for Emissions from Light-Duty Vehicles (CHINA 5 & 6), and Limits and Measurement Methods for Emissions from Diesel Fueled Heavy-Duty Vehicles (CHINA V and CHINA VI) will be fully implemented. We assumed the EFs for different types of vehicles would remain unchanged between 2030 and 2050, as China VI has already significantly lowered key pollutants.

Non-energy BC emission sources include agricultural waste burning and municipal solid waste burning. For agricultural waste burning, the amount of agricultural waste burned is assumed to gradually phase out by 2050 under the Reference Scenario and gradually phase out by 2035 in the Accelerated Reduction scenario. Compared to the Reference scenario, the Accelerated Reduction scenario is projected to achieve a 35% reduction in municipal solid waste generation by 2035 based on newly announced policies for waste reduction and sorting in China (National Development and Reform Commission and Ministry of Housing and Urban-Rural Development, 2017). A constant 3% fraction is applied to the projected municipal solid waste generation to calculate the municipal solid waste burning.

Table 2 summarizes the projected BC emission factors reductions under the Reference Scenario and the Accelerated Reduction Scenario.

3. Results and discussion

3.1. BC emissions in China in 2015

The total BC emissions in China in 2015 were estimated to be 1100 kt. Total emissions, as estimated in this study for 2015, were similar to those reported in EDGAR v5.0 (2022) (1314 kt in 2015) and recent work by Xu et al. (2021) (1230 kt in 2017) for similar timeframe, but lower than that reported by CEDS (2018) (2534 kt in 2014). Although the

---

[1] The EFs in residential, agricultural waste burning, power and MSW open burning sectors are assumed to be the same for both scenarios as mitigation measures/technologies to reduce per unit BC emissions in these sectors are not widely available or applied.

Table 2
Projected black carbon emission factors reductions.

Scenarios	Sectors		EF Reduction Compared to 2015	Year Achieved
Reference	Residential		–	–
	Industrial	Coal	97%	2035
		Heavy fuel oil	31%	2035
		Gasoline, Kerosene, Diesel, Coke, LPG, Gases	–	–
	Coking		48%	2035
	Transportation	Light-duty gasoline vehicles (LDGV)	43%	2030
		Light-duty gasoline trucks (LDGT1)	58%	2030
		Mid-duty gasoline trucks (LDGT2)	49%	2030
		Heavy-duty gasoline trucks (HDGV)	35%	2030
		Gasoline private cars, fleet cars, and taxis	–	–
		Gasoline motorcycles	–	–
		Light-duty diesel vehicles (LDDV)	27%	2030
		Heavy-duty diesel trucks (HDDV)	37%	2030
		Light-duty diesel trucks (LDDT)	41%	2030
		Diesel private cars, fleet cars, and taxis	73%	2030
		Diesel rail	–	–
		Diesel water	–	–
	Agricultural Waste Burning		–	–
	Power		–	–
	Natural Gas Flaring		–	–
	Municipal Solid Waste Open Burning		–	–
Accelerated Reduction	Residential		–	–
	Industrial	Coal	97%	2030
		Heavy fuel oil	31%	2030
		Gasoline, Kerosene, Diesel, Coke, LPG, Gases	–	–
	Coking		90%	2035
	Transportation	Light-duty gasoline vehicles (LDGV)	87%	2030
		Light-duty gasoline trucks (LDGT1)	90%	2030
		Mid-duty gasoline trucks (LDGT2)	90%	2030
		Heavy-duty gasoline trucks (HDGV)	87%	2030
		Gasoline private cars, fleet cars, and taxis	–	–
		Gasoline motorcycles	86%	2030
		Light-duty diesel vehicles (LDDV)	85%	2030
		Heavy-duty diesel trucks (HDDV)	87%	2030
		Light-duty diesel trucks (LDDT)	88%	2030
		Diesel private cars, fleet cars, and taxis	73%	2030
		Diesel rail	–	–
		Diesel water	–	–
	Agricultural Waste Burning		–	–
	Power		–	–
	Natural Gas Flaring		64%	2035
	Municipal Solid Waste Open Burning		–	–

timeframes are different with temporal changes in China's BC emissions, the results from this study are within the same magnitude of those reported in the earlier studies by Streets et al. (2003) (1049 kt BC emissions in 2000), Ohara et al. (2007) (1137 kt in 2003), Ni et al. (2014) (963 kt in 2007) and lower than by Cao et al. (2006) (1499 kt in 2000), Zhang et al. (2009) (1811 kt in 2006), Klimont et al. (2017) (1925 kt in 2010). The variations between studies for a given timeframe are largely due to the updated EFs for residential fuels, industrial activities, and motor vehicles, and the inclusion of updated removal efficiency for BC emissions from the industrial sector. It is worthy to note that significant uncertainty remains for BC emissions inventory and estimates of current emissions, due to the lack of more recent and China-based EFs measurements, as well as uncertainties in fuel consumption data. This uncertainty in BC emissions estimate is well documented in the literature (e.g., Wang et al., 2012; Klimont et al., 2017; Lu et al., 2019). More EF measurements in China, especially in the industrial and coke production sectors, could help to improve the accuracy of the inventory in the future.

Contributions from the residential, industry, coke, agricultural waste burning, transportation, power, natural gas flaring, and municipal solid waste burning were estimated to be 708, 97, 166, 65, 55, 3, 3, and 3 kt, respectively. Residential use of fuels, including coal, firewood, crop residues, and others was the biggest contributor to BC emissions in China in 2015, accounting for more than half (64%) of the total BC emissions, and 95% of those occurred in rural areas. This share estimate is close to the majority of the share reported in the literature, e.g., Li et al. (2016) (55% in year 2010), Lu et al. (2019) (57% in year 2010), Wang et al. (2012) (54% in year 2007), Ni et al. (2014) (71% in year 2007) and Cao et al. (2006) (62% in year 2000). Note that in these papers, biomass was estimated separately from the residential sector and in our paper, biomass is included in the residential sector. Thus, to make comparison, we sum up the shares of biomass and residential sector and reported the total. For example, Li et al. (2016) estimated the share of residential sector to be 49% and the share of biomass to be 6%, thus the sum of the two accounts for 55% of the total BC emissions in year 2010. There are some other papers that reported significantly higher or lower residential sector share than the majority of literature. For example, Streets et al. (2001) and Streets et al. (2003) reported 89% in 1995 and 85% in 2000, respectively. Lu et al. (2019) did not include biomass in their calculation and estimated the share of residential sector to be 21% in 2015.

Coke production and industry ranked the second and the third highest in BC emissions, respectively, accounting for 24% of total BC emissions in sum. For these two sectors, coal consumption was the predominant source of BC emissions. The share of the industrial sectors (the sum of coke production and industry) estimated in this paper is similar to but lower than the majority of those reported in previous works as this paper included an updated removal efficiency for the industrial sector. More specifically, the majority of shares of industrial sectors reported in the literature ranges from 27% to 36%, e.g., Li et al. (2016) (30% in 2010), Lu et al. (2019) (27% in 2010), Qin and Xie (2012) (39% in 2009), Wang et al. (2012) (33% in 2007), Cao et al. (2006) (36% in year 2000). Some paper reported significantly higher or lower industrial shares, e.g., Lu et al. (2019) (63% in 2015), Streets et al. (2001) (7% in 1995) and Streets et al. (2003) (8% in 2000).

The transportation sector accounted for 5% of the total BC emissions. In the transportation sector, BC emissions were primarily from diesel consumption (97%); gasoline was only responsible for a small portion (3%) of the total. This low contribution share of transportation is very different from those in developed countries, where the transportation sector is estimated to be the largest source of BC emissions (Bond et al., 2004). Agricultural waste burning contributed another 6% of the total BC emissions. Power, natural gas flaring, and municipal solid waste burning together account for the remaining 1% of the base year BC emission. Relative contributions of various sources of BC emissions in China in 2015 are shown in Fig. 1. A summary of the total BC emissions in China in various base years and the associated sectoral contributions reported in the literature is shown in Appendix A (Table S4).

3.2. Projections of BC emissions in China

BC emissions in China from 2016 to 2050 were projected under the Reference and the Accelerated Reduction scenarios. It is estimated that BC emissions in 2050 will be 278 kt in the Reference scenario and significantly lower at 86 kt in the Accelerated Reduction scenario. Under the Reference scenario, the total BC emissions in China will decrease gradually over time during the projection period as emissions from all the sectors will keep decreasing during this period. The residential sector will remain the biggest contributor to BC emissions in China from 2016 to 2050. BC emissions from the residential sector are projected to be 189 kt in 2050, reduced by 73% compared to their 2015 level. The industry, coke production, transportation sectors, agricultural waste burning, power, and natural gas flaring are projected to emit 15, 34, 37, 0, 0, and 0.1 kt BC in 2050, respectively, achieving reductions of 84%, 80%, 32%, 100%, 100%, and 98%, respectively, relative to 2015. The reductions will mainly result from the use of better emission control technologies, such as high-efficiency dust collectors and exhaust systems and gradual phase-out of agricultural waste burning. Reduction in fuel consumption as a result of incremental energy efficiency improvements and some fuel switching to cleaner fuels will also play important roles. BC emissions and relative contributions of various sources under the Reference scenario are shown in Fig. 2.

Under the Accelerated Reduction scenario, the emissions will decrease more rapidly over the period 2016–2050 and will reach totals of 849, 457, 231, and 86 kt in 2020, 2030, 2040, and 2050, respectively, and achieve reductions of 92% in 2050 relative to 2015. Emissions from all the five major sectors (residential, coking, industrial, agricultural waste burning, and transportation) will keep decreasing rapidly over the period 2016–2050. The residential and industrial sectors, coke production, agricultural waste burning, transportation, power, natural gas flaring, and municipal solid waste open burning will reach totals of 60, 9, 3, 0, 12, 0, 0, 2 kt, respectively, in 2050 and achieve reductions of 91%, 91%, 98%, 100%, 78%, 100%, 100%, and 37%, respectively, relative to 2015. The residential sector will remain the biggest contributor to China's BC emissions over this period. Within the residential sector, more than 90% of BC emissions occurred in rural areas, due primarily to coal and biomass stove used for heating and cooking. Compared to the Reference scenario, the Accelerated Reduction scenario achieves much faster and deeper reductions in all the sectors considered. The dramatic reductions can be attributed mostly to the fuel switching in the rural residential sector and faster implementation of high-efficiency emission control measures in the industry, transportation, and coke production sectors. The projection reveals the high potential of BC emission reductions in China in the next few decades, with the largest reduction potential coming from residential, agricultural waste burning, and coking sectors. BC emissions and the relative contributions of various sources under the Accelerated Reduction Scenario are shown in Fig. 3.

The relative contributions of changes in fuel consumption and reductions in EFs to the differences between the Accelerated Reduction scenario and the Reference scenario are shown in Table 3. The contribution of changes in fuel consumption is calculated by assuming the EFs

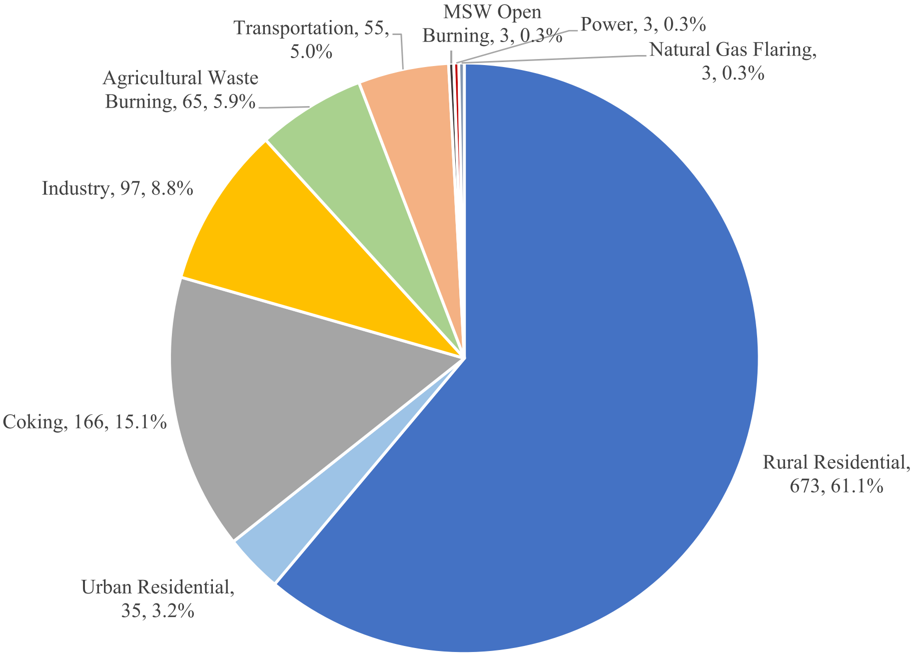

Fig. 1. BC emissions (Unit: kt) and contributions of different sectors in China in 2015.

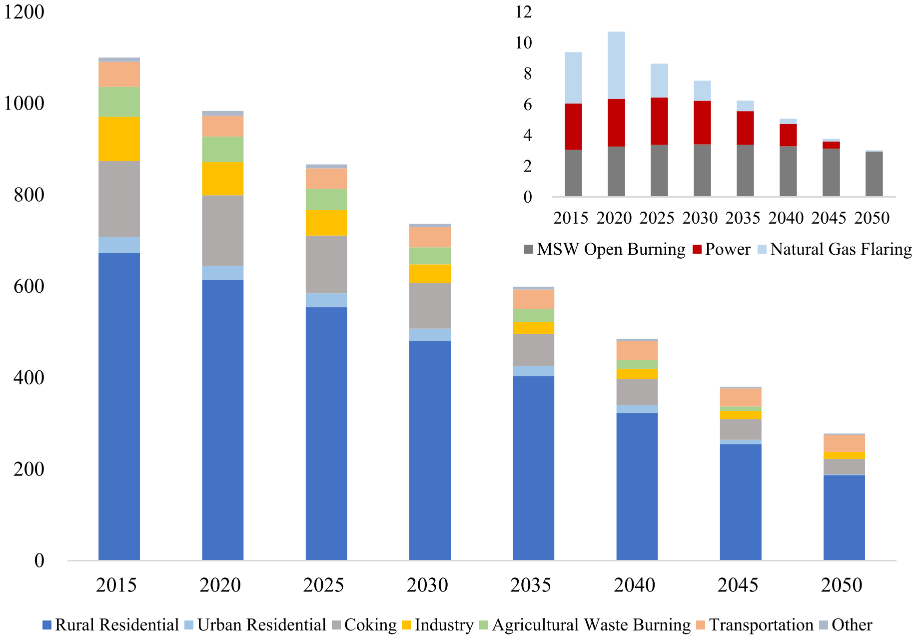

Fig. 2. BC emissions (Unit: kt) and contributions of different sectors in China under the Reference scenario, from 2015 to 2050.

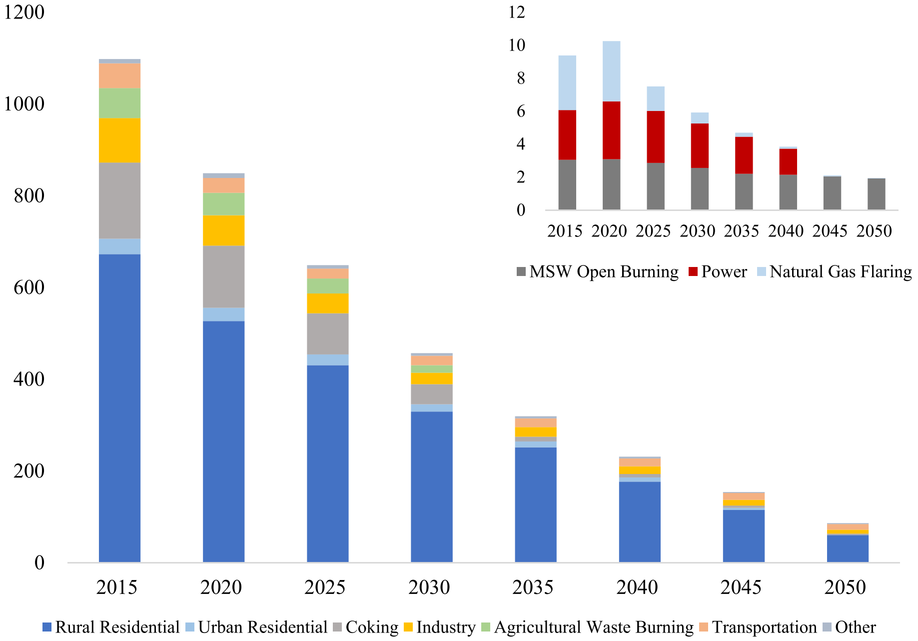

Fig. 3. BC emissions (Unit: kt) and contributions of different sectors in China under the Accelerated Reduction scenario, from 2015 to 2050.

are the same as those in the Reference scenario. In this case, the only source of the differences in BC emissions is the change in fuel consumption. The contribution of reductions in EFs is then calculated as (one minus the contribution of changes in fuel consumption). In 2030, about 75% of all BC reductions are driven by changes in fuel consumption. The number later increased to 93% in 2050. By sector, fuel switching has the biggest impact on reducing BC from the residential sector, while emission standards mandating specific technologies have a greater impact on the industry, coking, and transportation in 2030. After 2030, the contribution of these emission standards then declines dramatically over time as their impacts on reducing EFs have already been realized. As of 2050, only 42% of BC reductions in coking and no more than 1% of BC reductions in industry and transportation come from reductions in EFs.

4. Conclusions and policy implications

This study developed a more robust and up-to-date BC inventory for China, using 2015 as the base year, with updated annual projections for BC emissions in China for the time period 2016–2050 under two scenarios: the Reference scenario and the Accelerated Reduction scenario. The study estimated the total BC emissions in China were 1100 kt in 2015, with residential use being the biggest contributor, accounting for more than half (64%) of the total BC emissions, followed by the coke production, industry, agricultural waste burning, and transportation sectors. This study projected total BC emissions in China in 2050 to be 278 kt in the Reference scenario and 86 kt in the Accelerated Reduction scenario. Under the Reference scenario, the BC emissions will decrease gradually from 2016 to 2050, mainly as a result of China's existing

Table 3
BC reductions in the accelerated reduction scenario and contributions of changes in fuel consumption and reductions in EFs.

Year	Sectors	Total Reductions[a] (kt)	Contribution of Changes in Fuel Consumption[b] (%)	Contribution of Reductions in EFs[b] (%)
2030	Residential	162.0	100	0
	Industrial	15.2	38	62
	Coking	56.4	25	75
	Agricultural Waste Burning	21.0	100	0
	Transportation	23.5	22	78
	Power	0.1	100	0
	Natural Gas Flaring	0.6	0	100
	MSW Open Burning	0.9	100	0
	Total	279.7	75	25
2050	Residential	128.3	100	0
	Industrial	6.6	100	0
	Coking	30.9	58	42
	Agricultural Waste Burning	0.0	100	0
	Transportation	24.8	100	0
	Power	0.0	100	0
	Natural Gas Flaring	0.1	0	100
	MSW Open Burning	1.0	100	0
	Total	191.7	93	7

[a] Reductions are calculated as the differences in BC emissions between the Reference scenario and the Accelerated Reduction scenario.

[b] Contribution of changes in fuel consumption is calculated by assuming the EFs are the same as those in the Reference scenario. In this case, the only source of differences in BC emissions is a change in fuel consumption. The contribution of reductions in EFs is calculated as (one minus the contribution of changes in fuel consumption).

policies and efforts toward emission control and transition to clean energy. Under the Accelerated Reduction scenario, emissions from all the five major sectors will decrease rapidly from 2016 to 2050. Compared to the Reference scenario, the Accelerated Reduction scenario achieves much faster and deeper reductions in all the sectors considered, with the largest BC reductions in residential, coking and transportation sectors. The dramatic reductions can be attributed mostly to fuel switching in the residential sector and faster implementation of high-efficiency emission control measures in the industry, transportation, and coke production sectors.

Although there is currently a lack of policies focused directly on BC, China has employed various strategies focused on improving air quality, including residential fuel-switching programs and emission standards for mobile vehicles, industrial boilers, and coking ovens. In addition to improving air quality, these have also been demonstrated to be effective in reducing related BC emissions. For the residential sector, China took extraordinary steps to switch out inefficient and polluting small coal boilers for heating and promote the substitution of coal with natural gas and electricity, in the run-up to the nation's 2017 deadline set in the Air Pollution Prevention and Control Action Plan (2013) for achieving major reductions in ambient fine particulate matter ($PM_{2.5}$), substantially reducing BC at the same time (State Council of the PRC, 2013). Filter-based standards for new diesel cars and heavy-duty diesel trucks from the latest China VI emission standards will significantly cut BC emissions by >95% (along with other forms of ultrafine particulates.) Emission standards for industrial boilers and coking ovens, if implemented fully, will also lead to drastic BC emission reductions. In addition, the use of shore power by ships at ports has been vigorously promoted by the Ministry of Transport in various policies focused on shore-based power use, to reduce air and noise pollution from ships in the port area (MOT of the PRC, 2017a; MOT of the PRC, 2017b; MOT of the PRC, 2019a; MOT of the PRC, 2019b). Using shore power by ships at ports also reduces BC emissions from shipping fuel use while docked at ports. By the end of 2019, more than 5400 shore power facilities have been built across the country, covering more than 7000 berths (MOT of the PRC, 2020).

To further reduce BC emissions in the near future, more supporting policies and mitigation measures are needed in China. First, and most important, since the rural residential sector will continue to be the biggest contributor to BC emissions in China, promoting fuel switching and expanding the clean heating and cooking programs in the rural residential sector is essential. This will require addressing some of the implementation challenges that have emerged with the recent programs, and with more attention given to small coal stoves, woodburning stoves, and fireplaces. Enforcing full compliance with existing national emission standards for mobile vehicles, boilers, and ovens is also of vital importance, and expanding emission standards for diesel-power vehicles to include off-road vehicles can further help reduce BC emissions. For shipping, as the current utilization rate of most shore power utilities is well below 10% (Zhu, 2020), promoting the use of established shore power utilities is challenging, yet necessary.

This study uses data from some newly reported experimental work on direct measurements of EF_{BC} in China and published national energy consumption data, which helps to reduce the uncertainty in BC emissions estimates. However, the lack of direct measurement or modeling of EF_{BC} is still the major source of uncertainties in our BC emission estimation. Future work on EF_{BC} measurements is greatly needed and could play a key role in developing more accurate historical emission inventories that can provide a robust foundation for future projections. Moreover, this analysis is focused on a national scale, but BC emissions and concentrations can vary significantly across regions. More detailed BC emissions measurements and estimation at more granular geographical scales will be needed to better understand the air quality and human health implications of BC mitigation measures. Such analysis could help improve the current understanding of the geographical distribution of BC emissions and provide a basis for informing subnational and region-specific policy development.

Credit author statement

Wenjun Wang: Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Nina Khanna: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Project administration, Jiang Lin: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition, Xu Liu: Data curation, Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the Institute for Governance & Sustainable Development (IGSD) and the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The authors would also like to thank Gabrielle Dreyfus for her review of an earlier version of this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.117087.

References

Andreae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochem. Cycles 15 (4), 955–966.

Backman, J., Schmeisser, L., Asmi, E., 2021. Asian emissions explain much of the arctic black carbon events. Geophys. Res. Lett. 48 (5) e2020GL091913.

Baumgartner, J., Zhang, Y., Schauer, J.J., Huang, W., Wang, Y., Ezzati, M., 2014. Highway proximity and black carbon from cookstoves as a risk factor for higher blood pressure in rural China. Proc. Natl. Acad. Sci. USA 111 (36), 13229–13234.

Bellevrat, E., 2012. Which decarbonisation pathway for China? Insights from Recent Energy-Emissions Scenarios. IDDRI report. Available from: https://www.iddri.org/sites/default/files/import/publications/wp1812_eb_decarbonisation-china-2050.pdf.

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. J. Geophys. Res. Atmos. 109 (D14).

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., 2013. Bounding the role of black carbon in the climate system: a scientific assessment. J. Geophys. Res. Atmos. 118 (11), 5380–5552.

Cao, G., Zhang, X., Zheng, F., 2006. Inventory of black carbon and organic carbon emissions from China. Atmos. Environ. 40 (34), 6516–6527.

Cao, G., Zhang, X., Wang, Y., Zheng, F., 2008. Estimation of emissions from field burning of crop straw in China. Chin. Sci. Bull. 53 (5), 784–790.

Chen, Y., Zhi, G., Feng, Y., Fu, J., Feng, J., Sheng, G., Simoneit, B.R., 2006. Measurements of emission factors for primary carbonaceous particles from residential raw-coal combustion in China. Geophys. Res. Lett. 33 (20).

Chen, Y., Zhi, G., Feng, Y., Liu, D., Zhang, G., Li, J., Sheng, G., Fu, J., 2009. Measurements of black and organic carbon emission factors for household coal combustion in China: implication for emission reduction. Environ. Sci. Technol. 43 (24), 9495–9500.

Climate & Clean Air Coalition, 2021. Black Carbon. https://www.ccacoalition.org/en/slcps/black-carbon. (Accessed 27 January 2022). accessed.

Dong, K.Y., Sun, R.J., Li, H., Jiang, H.D., 2017. A review of China's energy consumption structure and outlook based on a long-range energy alternatives modeling tool. Petrol. Sci. 14 (1), 214–227.

EDGARv5.0 air pollutants, https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP (accessed 29 March 2022).

Hoesly, R.M., Smith, S.J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J.J., Vu, L., Andres, R.J., Bolt, R.M., Bond, T.C., et al., 2018. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). Geosci. Model Dev. (GMD) 11 (1), 369–408.

Hoornweg, D., Lam, P., Chaudhry, M., 2005. Waste Management in China: Issues and Recommendations. *Urban Development Working Papers No. 9*. East Asia Infrastructure Department, World Bank.

Hussey, S.J., Purves, J., Allcock, N., Fernandes, V.E., Monks, P.S., Ketley, J.M., Andrew, P.W., Morrissey, J.A., 2017. Air pollution alters Staphylococcus aureus and Streptococcus pneumoniae biofilms, antibiotic tolerance and colonisation. Environ. Microbiol. 19 (5), 1868–1880.

Khanna, N., Fridley, D., Zhou, N., Karali, N., Zhang, J., Feng, W., 2019. Energy and CO2 implications of decarbonization strategies for China beyond efficiency: modeling 2050 maximum renewable resources and accelerated electrification impacts. Appl. Energy 242, 12–26.

Khanna, N., Zhou, N., Price, L., 2021. Pathways toward Carbon Neutrality: A Review of Recent Studies on Mid-Century Emissions Transition Scenarios for China. California-China Climate Institute Report. https://ccci.berkeley.edu/sites/default/files/GTZChina-Sept2021-FINAL.pdf. (Accessed 4 April 2022). accessed.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., Schöpp, W., 2017. Global anthropogenic emissions of particulate matter including black carbon. Atmos. Chem. Phys. 17 (14), 8681–8723.

Lamarque, J.F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M.G., 2010. Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmos. Chem. Phys. 10 (15), 7017–7039.

Lei, Y., Zhang, Q., He, K.B., Streets, D.G., 2011. Primary anthropogenic aerosol emission trends for China, 1990–2005. Atmos. Chem. Phys. 11 (3), 931–954.

Li, H., Qi, Y., 2011. Comparison of China's carbon emission scenarios in 2050. Adv. Clim. Change Res. 2 (4), 193–202.

Li, F., Wang, J., 2013. Estimation of carbon emission from burning and carbon sequestration from biochar producing using crop straw in China. Trans. Chin. Soc. Agric. Eng. 29 (14), 1–7.

Li, X., Wang, S., Duan, L., Hao, J., Nie, Y., 2009. Carbonaceous aerosol emissions from household biofuel combustion in China. Environ. Sci. Technol. 43 (15), 6076–6081.

Li, Y., Henze, D.K., Jack, D., Henderson, B.H., Kinney, P.L., 2016. Assessing public health burden associated with exposure to ambient black carbon in the United States. Sci. Total Environ. 539, 515–525.

Li, C., Yan, F., Kang, S., Chen, P., Han, X., Hu, Z., Zhang, G., Hong, Y., Gao, S., Qu, B., Zhu, Z., 2017. Re-evaluating black carbon in the Himalayas and the Tibetan Plateau: concentrations and deposition. Atmos. Chem. Phys. 17 (19), 11899–11912.

Lin, J., Khanna, N., Liu, X., Teng, F., Wang, X., 2019. China's non-CO 2 greenhouse gas emissions: future trajectories and mitigation options and potential. Sci. Rep. 9 (1), 1–10.

Lu, Y., Wang, Q.G., Zhang, X., Qian, Y., Qian, X., 2019. China's black Carbon Emission from Fossil Fuel Consumption, vol. 212. Atmospheric Environment, pp. 201–207, 2015, 2020, and 2030.

Port Shore Power Construction, Usage, and Next Steps, 2020.

Ministry of Transport of the People's Republic of China, 2017a. Shore Power Layout Plan of Ports.

Ministry of Transport of the People's Republic of China, 2017b. Guide of Application for Shore-Based Power Supply Project Award Funds for Berthed Ships in 2016-2018.

Ministry of Transport of the People's Republic of China, 2019b. Port and Ship Shore Power Management Measures.

National Development, Reform Commission and Development Research Center of the State Council, 2009. 2050 China Energy and CO2 Emissions Report. Science Press, Beijing.

National Development and Reform Commission and Ministry of Housing and Urban-Rural Development 2017. Implementation Plan of Domestic Waste Classification System. http://www.gov.cn/zhengce/content/2017-03/30/content_5182124.htm. (Accessed 28 January 2022) Accessed.

Ni, M., Huang, J., Lu, S., Li, X., Yan, J., Cen, K., 2014. A review on black carbon emissions, worldwide and in China. Chemosphere 107, 83–93.

Novakov, T., Rosen, H., 2013. The black carbon story: early history and new perspectives. Ambio 42 (7), 840–851.

Ohara, T.A.H.K., Akimoto, H., Kurokawa, J.I., Horii, N., Yamaji, K., Yan, X., Hayasaka, T., 2007. An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. Atmos. Chem. Phys. 7 (16), 4419–4444.

Qin, Y., Xie, S.D., 2011. Estimation of county-level black carbon emissions and its spatial distribution in China in 2000. Atmos. Environ. 45 (38), 6995–7004.

Qin, Y., Xie, S.D., 2012. Spatial and temporal variation of anthropogenic black carbon emissions in China for the period 1980–2009. Atmos. Chem. Phys. 12 (11), 4825–4841.

Reddy, M.S., Venkataraman, C., 2002. Inventory of aerosol and sulphur dioxide emissions from India: I—fossil fuel combustion. Atmos. Environ. 36 (4), 677–697.

National Development and Reform Commission, 2015. Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%27s%20First%20NDC%20Submission.pdf. (Accessed 28 January 2022) Accessed.

Ministry of Transport of the People's Republic of China, MOF of the PRC, NDRC of the PRC, NEA of the PRC, SGCC, CSG, 2019a. Notice on Jointly Promoting Shore Power Use Among Berthed Ships at Ports.

Shi, Z.L., Jia, T., Wang, Y.J., Wang, J.C., Sun, R.H., Wang, F., Li, X., Bi, Y.Y., 2017. Comprehensive utilization status of crop straw and estimation of carbon from burning in China. Journal of China Agricultural Resources and Regional Planning 38 (9), 32–37.

Song, W.W., He, K.B., Lei, Y., 2012. Black Carbon Emissions from On-Road Vehicles in China, vol. 51. Atmospheric environment, pp. 320–328, 1990–2030.

State Council of the People's Republic of China, 2013. Air Pollution Prevention and Control Action Plan.

Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.H., Yarber, K.F., 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. Journal of Geophysical Research: Atmospheres 108 (D21).

Streets, D.G., Gupta, S., Waldhoff, S.T., Wang, M.Q., Bond, T.C., Yiyun, B., 2001. Black carbon emissions in China. Atmos. Environ. 35 (25), 4281–4296..

Vohra, K., Vodonos, A., Schwartz, J., Marais, E.A., Sulprizio, M.P., Mickley, L.J., 2021. Global Mortality from Outdoor Fine Particle Pollution Generated by Fossil Fuel Combustion: Results from GEOS-Chem, vol. 195. Environmental Research, 110754.

Wang, R., Tao, S., Wang, W., Liu, J., Shen, H., Shen, G., Wang, B., Liu, X., Li, W., Huang, Y., Zhang, Y., 2012. Black carbon emissions in China from 1949 to 2050. Environ. Sci. Technol. 46 (14), 7595–7603.

Xu, H., Ren, Y.A., Zhang, W., Meng, W., Yun, X., Yu, X., Li, J., Zhang, Y., Shen, G., Ma, J., Li, B., 2021. Updated Global Black Carbon Emissions from 1960 to 2017: Improvements, Trends, and Drivers. Environmental Science & Technology.

Zhang, Q., Streets, D.G., Carmichael, G.R., He, K.B., Huo, H., Kannari, A., Klimont, Z., Park, I.S., Reddy, S., Fu, J.S., Chen, D., 2009. Asian emissions in 2006 for the NASA INTEX-B mission. Atmos. Chem. Phys. 9 (14), 5131–5153.

Zhang, N., Qin, Y., Xie, S., 2013. Spatial distribution of black carbon emissions in China. Chin. Sci. Bull. 58 (31), 3830–3839.

Zhou, N., Fridley, D., Khanna, N.Z., Ke, J., McNeil, M., Levine, M., 2013. China's energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model. Energy Pol. 53, 51–62.

Zhou, N., Khanna, N., Feng, W., Ke, J., Levine, M., 2018. Scenarios of energy efficiency and CO 2 emissions reduction potential in the buildings sector in China to year 2050. Nat. Energy 3 (11), 978–984.

Zhou, N., Price, L., Yande, D., Creyts, J., Khanna, N., Fridley, D., Lu, H., Feng, W., Liu, X., Hasanbeigi, A., Tian, Z., 2019. A roadmap for China to peak carbon dioxide emissions and achieve a 20% share of non-fossil fuels in primary energy by 2030. Appl. Energy 239, 793–819.

Zhou, N., Khanna, N., Zhang, J., Lu, H., Price, L., Fridley, D., Ke, J., Feng, W., Shen, B., Lin, J., Levine, M., 2022. China Energy Outlook 2022. Lawrence Berkeley National Laboratory (Forthcoming), Berkeley.

Zhu, Y., 2020. *More construction, less utilization: why is it Difficult to increase shore power?* Finance. sina.com.cn. https://finance.sina.com.cn/wm/2020-05-13/doc-iircuyvi2910619.shtml. (Accessed 28 January 2022). Accessed.