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China's non-fossil fuel CO_2 emissions from industrial processes

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HIGHLIGHTS

- China's non-fossil fuel CO_2 emissions from industrial processes are calculated in 2003–2018.
- The CO_2 emissions from ten industrial processes in 2016 reach 5% of China's total emissions.
- The CO_2 emissions from industrial processes show fast increase before 2014, and fluctuate in 2014–2018.
- The 466 Mt CO_2 is close to total CO_2 emissions from Brazil, the world top 11 emitter.

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ABSTRACT

China is the largest contributor of global CO_2 emissions, to date more than quarter of the world total CO_2 is from China. Well known on the fossil fuel combustion and cement production as the major emission sources, however, "non-fossil fuel CO_2 emissions" are rarely reported by literature (except the emission from cement production). As China becomes the center for global manufacturing, it is critical to understand the magnitude and dynamics of China's non-fossil fuel CO_2 emissions so effective mitigation policy can be addressed. Here we collected data for all kinds of industrial processes CO_2 emissions, and based on available data we calculated the CO_2 emissions from the production of lime, plate glass, ammonia, calcium carbide, soda ash, ethylene, ferroalloys, alumina, lead and zinc in 2003–2018. We found that China's CO_2 emissions from these ten industrial processes reached 466 Mt CO_2 in 2016, which is equivalent to 5% of China's total CO_2 emissions (9000 Mt CO_2) from fossil fuel combustion and cement production process. The 466 Mt CO_2 is approximate to total fossil fuel CO_2 emissions from Brazil, the world top 11 CO_2 emitter. The CO_2 emissions from these ten industrial production processes show a fast increase before 2014, and fluctuate in 2014–2018. Quantifying such emission is critical for understanding the global carbon budget and developing a suitable climate policy given the significant magnitude and recent dynamics of China's non-fossil fuel CO_2 emissions.

1. Introduction

CO_2 emissions from human activities are considered as the major driver for anthropogenic climate change [1–4]. Among all kinds of Greenhouse Gas emissions [5], the contribution of CO_2 emission alone to global warming is 76% [6], combustion of carbon based fossil fuels (coal, oil and natural gas) and the production of cement [7] are the major sources for human induced CO_2 emissions. Global agencies list the data of CO_2 emission from fossil fuel combustion and the production of cement for countries as the baseline for climate change negotiation and policy implementation [8–19]. Table 1 listed the major international agencies that reporting the CO_2 emissions for countries. IEA [13,14] and EIA [12] estimated China's CO_2 emissions from fossil fuel combustion, while CDIAC [9] and CEADs [17] calculated CO_2 emissions from fossil fuel combustion and cement product. In addition to the emissions from fossil fuel combustion and cement production, EDGAR [15,16] considered CO_2 emissions from steel industrial process.

However, CO_2 emission can be generated from the physical and chemical transition of industrial production processes [20], such as the production of mineral products (e.g., lime, soda ash, asphalt roofing), chemical products (e.g., ammonia, nitric acid) and metal products (e.g., iron, steel and aluminum) [21]. Such emissions are less frequently reported by current international carbon emission datasets. More importantly, whether to include these emission sources could possibly result in the significant difference of the CO_2 emission dataset for certain countries, such as China that the amount of emissions from industrial production process are considerable [8,22,23].

Especially, as the world largest developing country, China plays a

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Table 1
Comparison of international emission datasets.

Agency	IEA (International Energy Agency)	EDGAR (Emission Database for Global Atmospheric Research)	CDIAC (Carbon Dioxide Information Analysis Centre)	EIA (U.S. Energy Information Administration)	CEADs (China Emission Accounts and Datasets)
Period	1960–2016 (OECD) 1971–2016 (non-OECD)	1970–2017	1751–2014	1980–2016	1997–2015
Data sources	IEA energy databases [13]	Fossil fuel consumption: IEA energy balance statistics (1970–2015) BP statistics (2016–2017) cement, lime, ammonia and ferroalloys production: USGS statistics urea production and consumption: IFA statistics gas used from flaring: GGFR/NOAA steel production: worldsteel cement clinker production: UNFCCC	1751–1950: Etemad et al. (1991) [52], Andres et al. (1999) [53] 1950 - now: UN Energy Statistics Yearbook, U.S. Department of Interior's Geological Survey (cement production), EIA (1994), Rotty (1974), and data provided by G. Marland (gas flaring)	International Energy Statistics	China Energy Statistical Yearbooks
Emission Factor	2006 IPCC Guidelines for National Greenhouse Gas Inventories	2006 IPCC Guidelines for National Greenhouse Gas Inventories	N/A	EIA estimates	Liu et al. (2015) [54]
Method	2006 IPCC Guidelines for National Greenhouse Gas Inventories	2006 IPCC Guidelines for National Greenhouse Gas Inventories	Marland and Rotty (1984) [55], Boden et al. (1995) [56] and Andres et al. (1999) [53]	N/A	2006 IPCC Guidelines for National Greenhouse Gas Inventories
Uncertainty	5% (OECD) 10% (non-OECD)	± 5% (OECD) ± 15% (non-OECD)	8.4%	N/A	−15 ~ 25% (95%CI)
Scope	Fossil fuel combustion	Fossil fuel use (combustion, flaring), industrial processes (cement, steel, chemicals and urea) and product use	Fossil-fuel burning, cement production, and gas flaring	Energy consumption	Energy-related emissions (17 fossil fuels in 47 sectors) and process-related emissions (cement production)
Latest Emission in China	9,481 MtCO2 (2018)	10877.22 MtCO2 (2017)	10602.54 MtCO2 (2014)	10,593 MtCO2 (2016)	9,644 MtCO2 (2015)

Table 2
Classifications of industrial process emissions by the IPCC.

IPCC classification		NDRC2012	Liu et al., 2016	this study
2	Industrial processes			
2A	Mineral industry			
2A1	cement production			
2A2	Lime Production			
2A3	Glass Production			
2A5	Other Process			
2B	Chemical industry			
2B1	Ammonia production			
2B2	Nitric acid production			
2B3	Adipic acid production			
2B4	Caproiactam, Glyoxal and glyoxylic acid			
2B5	Carbide production			
2B6	Titanium dixoxide production			
2B7	Soda ash production			
2B8	Petrochemical and carbon black production			
2B8a	Methanol			
2B8b	Ethylene			
2B8f	Carbon black			
2B9	Fluorides production			
2C	Metal Industry			
2C1	Iron and steel production			
2C2	Ferroalloys production			
2C3	Aluminum production			
2C4	Magnesium production			
2C5	Lead production			
2C6	Zinc production			
2D	Non-energy productions from fuel and solvent use			
2E	Electronics industry			
2G	Product is used as a substitute for ozone-depleting substances			
2H	Other manufacturing			

significant role in global actions on climate change mitigation in terms of mitigating the CO_2 emissions. China's carbon emission from fossil fuel burning and cement production reached 9.43 Gt CO_2 in 2017, the highest among the world [24]. To date more that quarter of the global total CO_2 emissions are contributed by China. 90% of China's energy consumption is supplied by fossil fuels, results in the high carbon intensive of the economy. On the other hand, China now is the global center of manufacturing, more than 50% of global production of coal, iron, steel and cement are produced by China and supply for global consumers [25–27]. About 25% of China's emission is associated with the consumption activates abroad [28]. China's dominate position in global manufacturing make it critical for understand the global status of CO_2 emissions [29]. Particularly, whether included the emissions from industrial processes in addition to cement production will result in remarkable difference of China's emission data reporting [30,31].

Cement production is the most major source of CO_2 emissions from industrial processes. CDIAC reported that CO_2 emissions from cement production in China reached 1243 Mt CO_2/yr (https://cdiac.ess-dive.lbl.gov) in 2014. CO_2 emissions from cement will reduce to 856–957 Mt in 2020 considering the reduction of cement production and the decreasing of emission factor due to the improvement of production technology [32]. In addition, China contributes almost half of global iron and steel production and the exports of steel are the largest in the world [33]. China's total crude steel output reached 807 million tons in

2016, accounting for above 40% of world steel production (world steel association). The iron and steel industry is the third largest source of CO_2 emissions from China's industrial processes [33] and CO_2 emissions from iron and steel reached 1134 million tons CO_2 in 2011 [34]. In addition to the emission from cement, iron and steel production, previous studies show that the CO_2 emissions from lime production was 60 million tons CO2 in 2012 [35]. It is clear that whether to consider the non-fossil fuel CO_2 emissions from industrial processes will result in the significant difference (up to 15%) of CO_2 emission reporting in China [13,16,17,36].

Moreover, NDRC (National Development and Reform Commission) reported that "non-fossil fuel" CO_2 emissions from four industrial processes, such as ammonia, fluorides, ferroalloys and aluminum production in 2012. It is noted that the inventory of NDRC did not show the evolution trend of CO_2 emissions. Due to the rapid economic growth and strong dependence on fossil fuel in energy requirements, fossil fuel CO_2 emissions showed rapid increasing after the 21 century [37,38]. It is noted that China's fossil fuel CO_2 emissions showed relatively stable trend since 2012 and rose again after 2018 [39]. However, the evolution trend of China's "non-fossil fuel" CO_2 emissions are rarely reported by literature.

Therefore, estimating of CO_2 emissions from China's industrial production is critical for understanding the global carbon budget and developing a suitable climate policy. Moreover, the CO_2 emissions from the other products including glass, lime, ammonia, aluminum, calcium carbide and soda ash was 233 million tons in 2013, which is equivalent to the total CO_2 emissions of Spain [40]. Therefore, CO_2 emissions from lime and the other industrial production have a significant impact on quantitative estimation of total CO_2 emissions from China.

However, the studies in term of recent CO_2 emissions from the industrial processes except for cement production and iron and steel production are rarely. The CO_2 emissions from cement products and iron and steel products are not included in this study because recent quantitative estimates of CO_2 emissions have been published. Owing to recent quantitative estimates of CO_2 emissions from cement products and iron and steel products have been published.

Hence, here we focus on the comprehensive investigation of CO_2 emissions from industrial processes in addition to cement, iron and steel production. As China becomes the center for global manufacturing, it is critical to understand the magnitude and dynamics of China's non-fossil fuel CO_2 emissions so effective mitigation policy can be addressed. In this study we calculate ten industrial production, such as lime, plate glass, ammonia, calcium carbide, soda ash, ethylene, ferroalloys, aluminum, lead and zinc in 2003–2018, to our best knowledge, China's CO_2 emissions from ethylene, ferroalloys, lead and zinc production are calculated for the first time.

2. Methodology

The CO_2 emissions from industrial processes refer to CO_2 released from the processes of chemically or physically transform materials into industrial products. According to the IPCC classification [13], industrial processes include eight major emission source: Mineral industry (2A), chemical industry (2B), metal industry (2C), non-energy products from fuels and solvent use (2D) and other industry (2H). The detailed classifications are provided in Table 2.

IPCC points out "non-fossil fuel" CO_2 emissions from more than 30 industrial processes, but given China's major industrial processes and the limitation of data availability, in this study, we calculated the CO_2 emissions from 9 types of major industry production processes (yellow mark in Table 2): 2 in Mineral industry: lime production and plate glass production; 3 in chemical industry: ammonia production, calcium carbide production, and soda ash production; 4 in metal industry: ferroalloys production, aluminum production, lead and zinc production.

The IPCC's Guidelines for National Greenhouse Gas inventories suggested three methodologies to calculate emissions from industrial process. The Tier 1approach and the Tier 2 approach both estimate emissions based on production and emissions factors, with the difference that the global average emission factor used in Tier 1 approach and the country-specific emission factor used in Tier 2 approach. The Tier 3 approach estimates the emissions based on the carbon inputs. The calculation process requires a material flow analysis of the entire production supply chain. Hence, the Tier 3 approach requires the greatest volume of data. For the purpose of data feasibility, CO_2 emissions from lime production and calcium carbide were calculated by the Tier 2 approach, and CO_2 emissions from the rest of industrial process were calculated by the Tier 1.

The emission is calculated according to the following equation:

$$E = AD_i \times EF_i$$

where, E is emission, the unit is tons per year, AD represents the activity data, which are the amount of industry products at the national level (mass unit: tons). EF is the emission factor, which represents the amount of CO_2 released for each unit of product. For CO_2 emission, the unit of EF is ton CO_2 per ton product.

The emissions from the production processes of lime, plate glass, ammonia, calcium carbide, soda ash, ethylene, ferroalloys, aluminum, lead and zinc production are list as the following:

(1) Lime production:

Lime, also known as calcium oxide, is formed by heating limestone, which results in CO_2 emissions.

The reaction is as follows:

$$CaCO_3(\text{limestone}) + \text{heat} \rightarrow CaO + CO_2$$

Limestone in the above reaction can be replaced by dolomite to produce dolomitic lime and release CO_2, which is in accordance with the following reaction:

$$CaMg(CO_3)_2(\text{dolomite}) + \text{heat} \rightarrow CaO{\cdot}MgO(\text{dolomitic lime}) + 2CO_2$$

(2) Plate glass production:

$$CaCO_3 \rightarrow CaO + CO_2$$

$$MgCO_3 \rightarrow MgO + CO_2$$

(3) Ammonia production:

Hydrogen production:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

Hydrogen and nitrogen production:

$$CH_4 + \text{air} \rightarrow CO + 2H_2 + 2N_2$$

(4) Calcium carbide production:

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaO + 3C \rightarrow CaC_2 + CO$$

$$2CO + O_2 \rightarrow 2CO_2$$

(5) Soda ash production:

$$2Na_2CO_3{\cdot}NaHCO_3{\cdot}2H_2O = 3Na_2CO_3 + 5H_2O + CO_2$$

(6) Ethylene production:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

(7) Ferroalloys production:

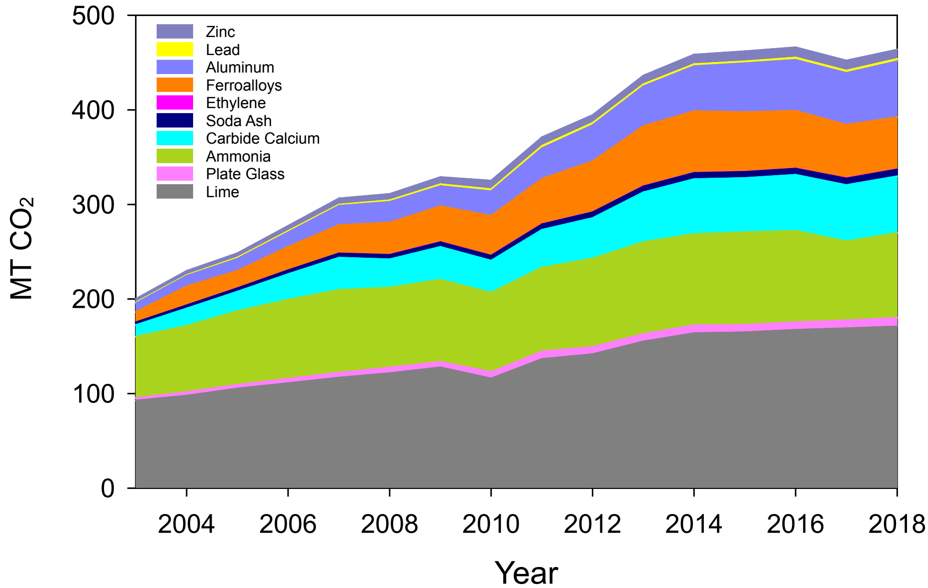

Fig. 1. Industrial process CO_2 emissions from the production of lime, plate glass, ammonia, calcium carbide, soda ash, ethylene, ferroalloys, alumina, lead and zinc in 2003–2018.

Ferroalloys are alloys of iron and one or more metals, including silicon, magnesium, chromium, molybdenum, vanadium, and tungsten. Ferroalloys production refers to a metallurgical reduction process that leads to significant CO_2 emissions.

(8) Aluminum production:

$2AL_2O_3 + 3C \rightarrow 4AL + 3CO_2$

(9) Lead production:

Lead production consists of primary and secondary production processes. There are two primary processes for the lead production: sintering/smelting process and direct smelting process. In the sintering/smelting process, lead concentrates are mixed with recycled sinter, lime rock and silica, oxygen, and high-lead-content sludge to produce a sinter roast that consists of lead oxide and other metallic oxides. The sinter roast and ores containing other metal, air, smelting by-products and metallurgical coke reduce lead oxide and produce CO_2 emissions by heating. In the direct smelting process, the production of the sinter roast is skipped, the lead concentrates and other material are melted and oxidized directly. The major raw material of secondary production process is lead acid batteries, which is reduced to lead and produce CO_2 during the smelting process.

(10) Zinc production:

Zinc production includes primary production process and secondary production process. In China, the two main primary zinc production process are the pyrometallurgical process and the hydrometallurgical process. The pyrometallurgical technique uses the metallurgical coke or coal as reductant to produce zinc and release CO_2 emissions. No non-energy CO_2 emissions during the hydrometallurgical process thus the detail of hydrometallurgical technique is not described in this study. The secondary zinc production process refers to the recovery of zinc from various materials, which involves zinc concentration, sintering, smelting and refining processes. It results in CO_2 emissions if some carbonaceous are seen as reductant during the concentration processes.

3. Data sources

The activity production data for lime is collected from the Chinese Building Materials Industry Yearbook from 2003 to 2016. The production of calcium carbide from 2003 to 2016 is archived in the China Industrial Statistics Yearbook 2017 (T-14). The activity production data for plate glass, aluminum, ferroalloys, lead and zinc from 2003 to 2018, soda ash and ammonia from 2003 to 2017 is all available from the website (http://data.stats.gov.cn) of China's National Bureau of Statistics (NBS). Emission factors are used in this study, except for lime and calcium carbide production from the IPCC guidelines for national greenhouse gas inventories. CO_2 emission factors of lime production and calcium carbide were collected from the NDRC reports for China's national greenhouse gas inventories [41–43].

4. Results

Based on the abovementioned methodology, as well as activity data and emission factors collected from statistical yearbook, NBS [44] and guidelines of IPCC and NDRC [42,43], we calculated the CO_2 emissions from the production of lime, plate glass, ammonia, calcium carbide, soda ash, ethylene, ferroalloys, aluminum, lead and zinc for the period 2003–2018. The trend of CO_2 emissions from these ten industrial processes can be divided into two phases during the studied period: the rapid growth state from 2003 to 2013 (Phase I) and stable emission state from 2014 to 2018 (Phase II). The substantial feature of Phase I is the rapid growth of emissions. In the Phase I, the total CO_2 emissions from ten industrial production were 200 Mt CO_2 in 2003 but 436 Mt CO_2 in 2013 (Fig. 1), more than 2 times increase within ten years. The average annual growth rate of CO_2 emissions reached 8%. In the Phase II, the total CO_2 emissions from ten industrial production archived 466 Mt CO_2 in 2016 (Fig. 1), which increased by 6% compared to 2013. The average annual growth rate of CO_2 emissions from industrial processes was 1% during the Phase II (2013–2018), which was one-eighth of the average annual growth rate during the period of Phase I. A downward trend of emissions even was shown during the period (2016–2017). Therefore, we call Phase II a relatively stable fluctuation period of emissions.

The emissions from the production of lime, ammonia, calcium carbide, ferroalloys and aluminum constitute above 90% of total emissions from the 10 industrial processes. Lime production was leading sources of CO_2 emissions from ten industrial processes. In 2003, CO_2 emissions from lime production were 93 Mt CO_2 and increased to 168 Mt CO_2 in 2016, which is 2 times less than the CO_2 emissions of lime in 2003. The

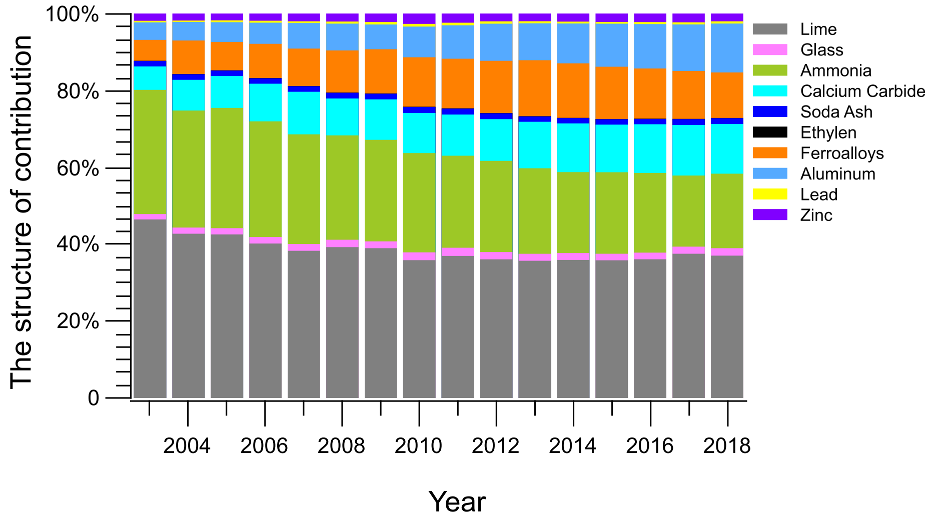

Fig. 2. The contribution of the ten industrial processes to industrial process CO_2 emissions during 2003–2018 period.

contribution of lime production to total CO_2 emissions from 10 industrial processes reached 46% in 2003, but fell to 36% in 2016 (Fig. 2). According to the Almanac of the Chinese Building Materials Industry 2002–2017 [44], lime production showed a steady growth due to smooth operations of the macro economy. After 2003, the growth rate of CO_2 emissions from lime production slowed down. The main reason was the increasing emphasis on environmental protection and energy conservation, which result in the closure of little shaft kiln.

Ammonia production has been the second largest source of CO_2 emissions from 10 industrial processes. The CO_2 emissions from ammonia production was 65 Mt CO_2 (Fig. 1), accounting for 32% of total CO_2 emissions from 10 industrial processes in 2003. The CO_2 emissions from ammonia production reached 84 Mt CO2 in 2017, a less 2 times increase within fifteen years. After 2013, the contribution of ammonia production to total CO_2 emissions from 10 industrial processes fell to 20% (Fig. 2). A smooth increasing trend of emissions from ammonia production is due to relatively stable development of China's agriculture [21].

In 2003, the CO_2 emissions from calcium carbide production, ferroalloys production and aluminum production were all around 10 Mt CO_2, and the contribution rates of total CO_2 emissions from 10 industrial processes were around 5%. In 2013, the CO_2 emissions from these three sources have exceeded 50 Mt CO_2, which is equivalent to a fivefold increase within ten years. After 2013, the emissions from calcium carbide production, ferroalloys production and aluminum production entered a relatively stable state, the sum of emissions from these three sectors constituted 37% of total emissions from the ten industrial processes (Fig. 2). Note that the highest growth rate was in the CO_2 emissions of calcium carbide, ferroalloys and aluminum production during Phase I. In contrast, the lowest growth rate was in the CO_2 emissions of lime and ammonia production during Phase I. The CO_2 emissions from plate glass, soda ash, ethylene, lead and zinc are at a relatively low level, which was only 10 Mt CO_2 in 2003. In 2018, the sum of emissions from the rest five industrial processes reached 28 Mt, accounting for 6% of total emissions from ten industrial processes.

Considering the rapid development of industrialization and urbanization, industrial sectors have become the largest energy consumers [45,46]. China's industrial processes consume industrial products while releasing CO_2 emissions. However, China's development of industry is disproportionate in terms of CO_2 emissions, thus China's CO_2 emissions are facing increasing international pressure [33]. In order to explore the relationship between China's development of industry and CO_2 emissions, we compared the increase of gross of secondary industry (red line, Fig. 3) and the increase of CO_2 emissions (columns, Fig. 3). We selected gross of secondary industry as an economic indicator rather than GDP because CO_2 emissions intensity is nonlinearly related to GDP, but positively correlated with the GDP ratio of the secondary industry [47].

Before 2006, the increase of gross of secondary industry (red line, Fig. 3) and the increase of CO_2 emissions (columns) remained synchronized and showed no significant gap. After 2006, the increase of gross of secondary industry (red line, Fig. 3) and the increase of CO_2 emissions (columns) from industrial processes shows an increasing discrepancy after 2006.

There may be two reasons for the relative decoupling of secondary industry and "non-fossil fuel" CO_2 emissions from industrial processes: policy impact and technological progress.

In 2011, the Ministry of Industry and Information Technology of China issued "the '12th Five-Year' Development Plan". This plan targeted to reduce CO_2 emissions per unit GDP by 17% [48]. In 2015, the National Development and Reform Commission pointed out that the CO_2 reduction target of "the '12th Five-Year' Development Plan" had been achieved by adjusting industrial structure, improving energy efficiency and optimizing energy structure [49]. Compared with "the '12th Five-Year' Development Plan", the CO_2 emission reduction target of "the '13th Five-Year' Development Plan" is more challenging, which aim to reduce CO_2 emissions per unit GDP by 18%. The gap of the increase of gross of secondary industry (red line, Fig. 3) and the increase of CO_2 emissions (columns) from industrial processes were further increased after 2015.

On the other hand, technological progress may also provide a partial explanation for the decoupling development of the increase of gross of secondary industry (red line, Fig. 3) and the increase of CO_2 emissions (columns, Fig. 3) from industrial processes, for example, technological progress can invent more substitutions for energy-intensive construction materials. Technological progress has different effects on fossil fuel CO_2 emissions and non-fossil fuel CO_2 emissions. For fossil fuel CO_2 emissions, the impact of technological progress on emission reductions is affected by "rebound effect" since fossil fuel CO_2 emissions from energy requirements. But "rebound effect" from technological progress has little impact on non-fossil fuel CO_2 emissions, therefore, technological progress may be more effective in reducing non-fossil fuel CO_2 emission from industrial processes [50].

5. Discussion

The previous study indicated that CO_2 emissions from five industrial processes, such as plate glass, soda ash, ammonia, calcium carbide and alumina, were 233 Mt CO_2 in 2013 [21]. Our results showed that CO_2 emissions from ten industrial processes are nearly 2 times as high as the

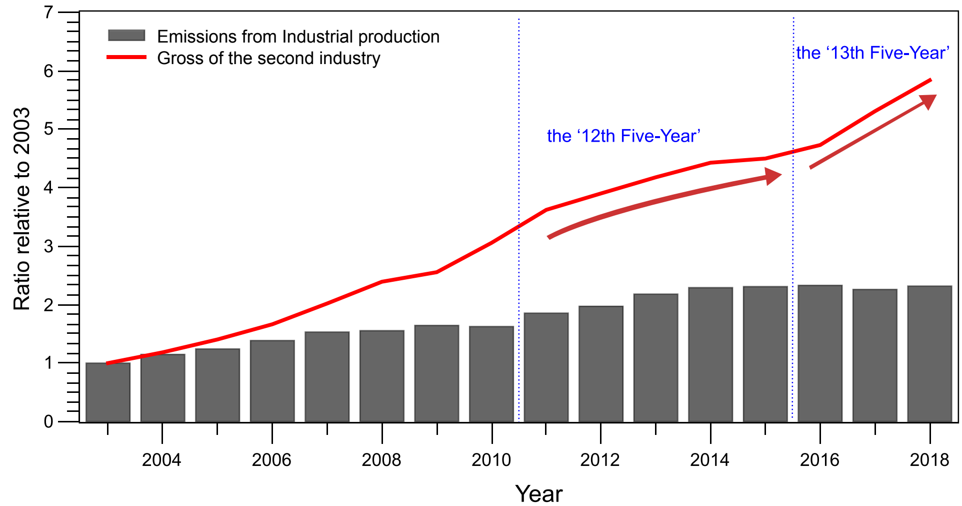

Fig. 3. The annual growth of CO_2 emissions from ten industrial production (column) and gross of the secondary industry (red line) during the period of 2003–2018.

previous study because additional five industrial production, such as lime, ferroalloys, ethylene, lead and zinc are included in this study. All the results show that CO_2 emissions from industrial process are significant enough that is needed to be considered by current emission inventories, and whether the CO_2 emissions from industrial processes will increase or not will considerably contribute to the possible peak of global total emissions. Understanding CO_2 emissions from more industrial products can improve the accuracy of China's CO_2 emissions inventory and assess the impact of China's CO_2 emissions on global carbon budget.

The CO_2 emissions from the industrial production processing of lime, lime, plate glass, ammonia, calcium carbide, soda ash, ferroalloys, aluminum, lead and zinc were 466 Mt CO_2 in 2016, exceeding the total annual CO_2 emissions of developed countries such as Spain, Italy and Australia, even higher than total fossil fuel CO_2 emissions from Brazil, the world top 11 CO_2 emitter (Fig. 4). The cumulative industrial emissions of manufacturing the 10 products were 5.7 Gt CO_2, which is twice the total annual emissions of India in 2017 (2.5 Gt CO_2 from EDGAR) and exceeds the total annual CO_2 emissions of the United States in 2017 (5.1 Gt CO_2). However, such emissions are not reported by current international emission datasets or by China's national emission inventories that are reported to the UN.

However, China has developed a series of policies, enhancing air pollution issues in recent years. The production of fossil fuel and CO_2 emissions from fossil fuel combustion both show a stable trend after 2014 in China. However, considering the quickly development of China's economic and large-scale infrastructure, the production of fossil fuel and CO_2 emissions from fossil fuel combustion is predicted to rise again after 2018 [39,40].

Recent dynamics of the industrial production shows the decrease of major industrial products in the period from 2014 to 2016, which matches well with the emission decrease. However, the recent growth rate of industrial products rebounded (Fig. 5), suggesting the possible rapid increase of the emissions from industrial production processes in near future. During the first three months in 2019, nearly all the industrial production excluding the zinc reached the highest on Mar. 2019 compared to 2008. After a decline in 2015, the production of plate glass, lead and ferroalloys started to rebound since 2016 while the trend of aluminum, soda ash and have been increasing. Compared to the production on Mar. 2019 with that in 2008, the production of ferroalloys (+1.93), aluminum (+1.85) and increase faster than cement (+1.78), which may drive the corresponding emissions to grow larger. Considering a high possibility of future growth of non-fossil fuel CO2 emissions from industry, it is necessary to continue to implement strong CO_2 reduction policy. In addition, technological innovations in the industrial sector should be encouraged to develop alternatives to energy-

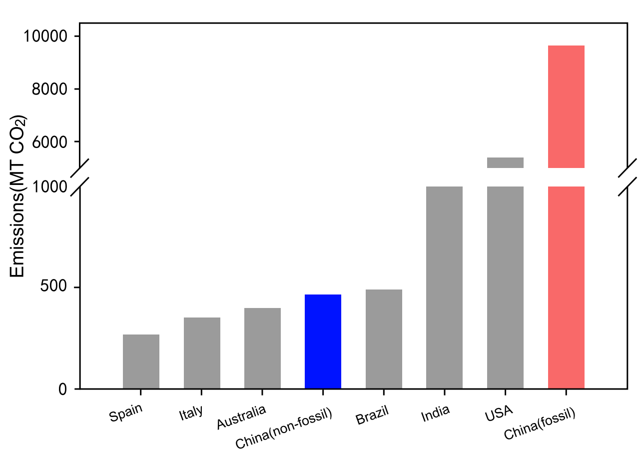

Fig. 4. CO_2 emissions from China's industrial process and cement production, and the total carbon emission from several developed countries in 2016 (data based on EDGAR).

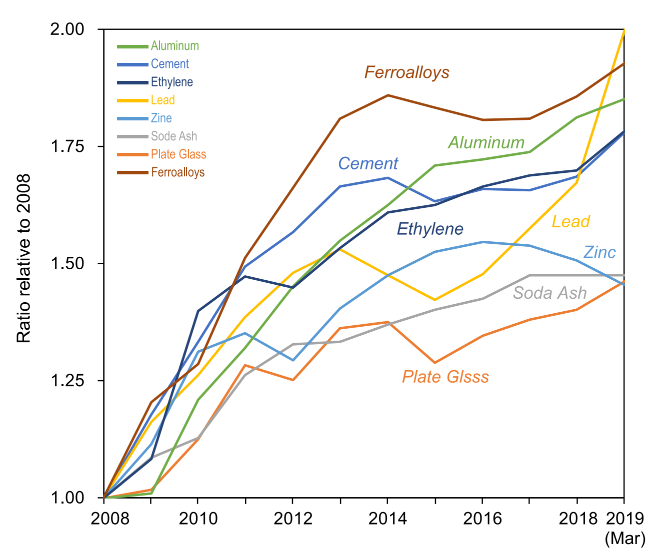

Fig. 5. The annual cumulative growth of the production for cement, plate glass, soda ash, ferroalloys, aluminum, lead and zinc between 2008 and 2018 and Mar. 2019 specifically.

intensive materials to inhibit CO_2 emission.

For the limitation of data of emission factors, it is difficult to estimate the uncertainty of non-fossil fuel CO_2 from industrial progresses. Given the considerable uncertainty regarding the estimation of non-fossil CO_2 from industrial processes production, more precise estimation and in-situ studies based on bottom-up data sources should be prioritized in the future. In addition, non-fossil fuel CO_2 from industrial processes may have spatial heterogeneity considering the obvious regional differences in China's economic development and industrialization level. Non-fossil fuel CO_2 from industrial on regional or even city scale should be estimated in the future [51]. Moreover, quantitative impact of technological progresses on non-fossil fuel CO_2 emissions has important implications on future China's emissions reductions.

6. Conclusion

In this study, we conducted investigation and calculation of the CO_2 emissions from the production of lime, plate glass, ammonia, calcium carbide, soda ash, ferroalloys, alumina, lead and zinc from 2003 to 2018. Results suggested that China's CO_2 emissions from these ten industrial processes reached 466 Mt CO_2 in 2016, which is equivalent to 5% of China's total CO_2 emissions (9000 Mt CO_2) from fossil fuel combustion and cement production processes. The 466 Mt CO_2 is higher than total fossil fuel CO_2 emissions from Brazil, the world top 11 CO_2 emitter. The CO_2 emissions from these ten industrial production processes show a fast increase before 2014, and fluctuate in 2014–2018. The results indicated that quantifying such emission is critical for understanding the global carbon budget and developing a suitable climate policy given the significant magnitude and recent dynamics of China's non-fossil fuel CO_2 emissions.

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