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National carbon emissions from the industry process: Production of glass, soda ash, ammonia, calcium carbide and alumina

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ABSTRACT

China has become the world's largest carbon emitter. Its total carbon emission output from fossil fuel combustion and cement production was approximately 10 Gt CO_2 in 2013. However, less is known about carbon emissions from the production of industrial materials, such as 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). Carbon emissions from the production processes of these industrial products (in addition to cement production) are also less frequently reported by current international carbon emission datasets. Here we estimated the carbon emissions resulting from the manufacturing of 5 major industrial products in China, given China's dominant position in industrial production in the world. Based on an investigation of China's specific production processes, we devised a methodology for calculating emission factors. The results indicate that China's total carbon emission from the production of alumina, plate glass, soda ash, ammonia and calcium carbide was 233 million tons in 2013, equivalent to the total CO_2 emissions of Spain in 2013. The cumulative emissions from the manufacturing of these 5 products during the period 1990–2013 was approximately 2.5 Gt CO_2, more than the annual total CO_2 emissions of India. Thus, quantifying the emissions from industrial processes is critical for understanding the global carbon budget and developing a suitable climate policy.

1. Introduction

Climate change is one of the greatest challenges facing humankind today [1–3]. Human-induced carbon emissions are the major greenhouse gas emissions that drive anthropogenic climate change [2,4]. Carbon emissions can be generated by fossil fuel combustion, industrial production processes, waste treatment and land use change [5]. Fossil fuel combustion and cement production are the most significant sources of human-induced carbon emissions that have been reported by international datasets [6–9]. Cement production in particular is the largest source of industrial production emissions and has been widely reported. The amount of emissions from fossil fuel combustion and cement production are also considered baseline amounts for planning mitigation actions and allocating the mitigating responsibilities [10,11]. In addition to fossil fuel combustion and cement production, the manufacturing of mineral, chemical and metal products can generate carbon emissions [5], as chemical and physical transformations of materials can release CO_2. The IPCC lists several types of industrial products (see Table 1) the chemical or physical production of which can release carbon emissions. For example, global emissions from cement production were approximately 2000 Mt CO_2 in 2013 [9].

A more comprehensive understanding of the emissions from industrial processes is required (except for cement production, which has been widely reported; the calculation of emissions from the cement production process can be seen in our previous studies [12]). First, the sources of emissions from industrial processes can be diverse. In addition to the different types of industrial products that could produce CO_2, the different stages of the industrial process can emit CO_2. For example, carbon emissions from cement production refer to the direct emissions from the calcination process for clinker production (2A1 in IPCC classification). Direct primary energy combustion and indirect electricity consumption also occur during this process; emissions from these processes can be categorized as emissions from energy combustion (1A2 in IPCC classification). Carbon emissions from cement production arise from the production of clinker, which is the major component of cement. In the production of clinker, the calcination of calcium carbonate ($CaCO_3$) releases CO_2 emissions, but CO_2 can also be released during the calcination of cement kiln dust (CKD). Thus,

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Table 1
Classifications of industrial process emissions by the IPCC.

IPCC classification	
2: Industrial processes	Calculated in this study
2A: Mineral industry	
2A1: Cement production	
2A2: Lime production	
2A3: Glass production	■
2A4: Other carbonation process	
2A5: Other process	
2B: Chemical industry	
2B1: Ammonia production	■
2B2: Nitric acid production	
2B3: Adipic acid production	
2B4: Caprolactam, glyoxal and glyoxylic acid production	
2B5: Carbide production	■
2B6: Titanium dioxide production	
2B7 Soda ash production	■
2B8: Petrochemical and carbon black production	
2B8a: Methanol	
2B8b: Ethylene	
2B8f: Carbon black	
2B9: Fluorides production	
2B10: Other	
2C: Metal industry	
2C1: Iron and steel production	
2C2: Ferroalloys production	
2C3: Aluminum production	■
2C4: Magnesium production	
2C5: Lead production	
2C6: Zinc production	
2C7: Other	
2D: Non-energy products from fuels and solvent use	
2D1: Lubricant use	
2D2: Paraffin wax use	
2D3: Solvent use	
2D4: Other	
2E: Electronics industry	
2G: Product is used as a substitute for ozone-depleting substances	
2H: Other manufacturing	
2H: Other	

Shaded cells are the industries that been calculated in this study.

precisely estimating the carbon emissions from cement production also requires the estimation of the carbon emissions from the production of clinker and the CKD, for which the complexity and difficulty of calculation increases. Second, the emission factors used for the calculation are highly dependent on the technology used for production, and this technology is specific to time zone and to region, thus causing difficulties for compiling the national emission factors for calculating emissions from industrial processes. Finally, the global relocation of manufacturing from the developed countries to the emerging economies introduces challenges for emission calculations, given the incomprehensive statistics system of industrial production and the lack of sufficient information regarding the technology level of developing countries.

This study aims to present a quantitative estimation of national carbon emissions from industrial production processes. We focus on China, now the world's top consumer of primary energy and emitter of carbon emissions. Its rapid economic development and industrialization processes [13,14] have made China the world's top consumer of primary energy and emitter of greenhouse gases [15]. In 2013, the total carbon emissions generated by China was already higher than the combined emissions of the U.S. and the EU [16]. Moreover, China has assumed the dominant position in global manufacturing [17], as its production of iron, steel, coke, cement and glass constitute greater than 50% of global production [18]. Emissions from cement production have been reported by international agencies such as CDIAC [19] and EDGAR [9]. However, to our knowledge, emissions from other industrial processes including those for 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), have not been reported in the literature.

Many types of industrial processes could release carbon emissions, including but not limited to the production of iron and steel, metallurgical coke, cement, aluminum, soda ash, titanium dioxide, lime, carbonates ammonia, petrochemicals, glass, zinc, phosphoric acid, lead, silicon carbide and nitric acid. We investigated the manufacturing of 22 industrial products (iron, steel, finished steel, titanium, coke, cement, plate glass, sulfuric acid, soda ash, caustic soda, ammonia, ethylene, calcium carbide, agrochemicals, nitrogen, phosphorus, chemical pesticides, non-ferrous metal, refined copper, aluminum, alumina and lima). We calculated the emissions of five industry processes based on the available data concerning both production and emission factors.

Supported by the nationwide investigation of the factory-level technologies that aim to calculate the emission factors, this research used the national emission factors reported by the National Development and Reform Commission (NDRC) [20] to calculate the emissions of 5 major industrial production processes, namely those of alumina, plate glass, soda ash, ammonia and calcium carbide. We also calculated the emissions resulting from the production of iron and steel; however, such emissions are categorized as emissions from energy consumption (1A2 in IPCC classification), given the fact that the emissions were generated during the coke combustion that was used as a reducing agent. Our calculation thus does not incorporate the emissions from iron and steel production.

2. Methodology

Carbon emissions from industrial production refer to the CO_2 released from the physical–chemical process of transforming raw materials into industrial products. The fossil fuels used in this transformation stage are considered the carbon emissions from fossil fuel combustion performed by the industrial sectors and are not considered as the industrial process emissions. For example, emissions from the calcination of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$) are considered industrial process emissions. By contrast, emissions from fossil energy usage during the calcination process are considered energy-related emissions.

According to the IPCC's Guidelines for National Greenhouse Gas Inventories, industrial process emissions result from several types of industrial production: 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 1.

In this study, we calculated the emissions from 5 types of major industry production processes. On the one hand, these emissions are not reported in existing emission data sets; on the other hand, the openly accessible data sources can be supported by the calculation.

The IPCC [5] suggested three basic methodologies to estimate industrial process emissions. The Tier 1 approach, also known as the reference approach, is an output-based approach that estimates emissions based on the production volume and the default emission factors. The emissions factors refer to the emission amounts per production unit, which amounts vary depending on the production processes; the global average emission factors will be used in the Tier 1 approach, and the emissions are estimated by the mass production amount and the mass of emissions per production unit (global average value). The Tier 2 approach is also an output-based approach, but estimates emissions based on production and country-specific information for correction emission

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factors. The calculation process in this approach is similar to the Tier 1 approach, except the global average emission factors are replaced by country-specific values. The Tier 3 approach is an input-based carbonate approach that 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, we adopted the Tier 1 approach. Our calculation is based accordingly on the following equation:

$$\text{Emission} = \text{Activity data}_i * \text{Emission factor}_i \quad (1)$$

Activity data are the amount of industry products at the national level (mass unit: tons). The emission factors (unit: ton CO_2/ton product) is the national average ratio of the amount of CO_2 released for each unit of product. The emission released during the production process of glass, soda ash, ammonia and calcium carbide and alumina are listed as the following:

(1) *Glass production:* When glass raw materials have been melted, the limestone ($CaCO_3$), dolomite $Ca(CO_3)$, $Mg(CO_3)$ and soda ash (Na_2CO_3) produce CO_2:

$$CaCO_3 \rightarrow CaO + CO_2 \quad (2)$$

$$MgCO_3 \rightarrow MgO + CO_2 \quad (3)$$

(2) *Soda Ash production:* Soda ash comprises primarily sodium carbonate (Na_2CO_3). CO_2 is emitted during the production of Na_2CO_3, thus the carbon emissions can be estimated by multiplying the quantity of soda ash consumed by the default emission factor for sodium carbonate:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O = 3Na_2CO_3 + 5H_2O + CO_2 \quad (4)$$

(3) *Ammonia production:* Ammonia (NH_3) in the form of major industrial chemical products is synthesized by hydrogen and nitrogen, while both the production processes will release CO_2 as a byproduct:
Hydrogen production:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (5)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (6)$$

Hydrogen and nitrogen production:

$$CH_4 + \text{air} \rightarrow CO + 2H_2 + 2N_2 \quad (7)$$

Ammonia synthesis:

$$N_2 + 3H_2 \rightarrow 2NH_3 \quad (8)$$

(4) *Calcium carbide production:* Calcium carbide (CaC_2) is created by heating calcium carbonate ($CaCO_3$) to produce calcium oxide (CaO) and the carbonization process of calcium oxide (CaO). Both processes will release CO_2.

$$CaCO_3 \rightarrow CaO + CO_2 \quad (9)$$

$$CaO + 3C \rightarrow CaC_2 + CO \quad (10)$$

$$2CO + O_2 \rightarrow 2CO_2 \quad (11)$$

(5) *Alumina production:* During the alumina production process, CO_2 is emitted from the consumption of carbon anodes while transforming alumina oxide into alumina metal:

$$2Al_2O_3 + 3C = 4Al + 3CO_2 \quad (12)$$

3. Data sources

The activity production data for alumina, plate glass, soda ash, ammonia and calcium carbide are all openly available from the National Statistics Yearbook for 2014 (Table 13-12, Output of Industrial Products) [18], which is compiled by China's National Bureau of Statistics (NBS). The NBS is also the official source of the industrial, social and economic data that used for creating international datasets such as the datasets provided by the IEA [21,22], World Bank [22] and the IMF. The data on energy consumption and industry production provided by the NBS is also reported by the China National Greenhouse Gas Inventory [23] and has been used for National Communication of Climate Change [24]. The emission factors used in this study are from the IPCC guidelines for national greenhouse gas inventories and the NDRC reports for China's national greenhouse gas inventories [20], which are also consistent with National Communication of Climate Change [24] (see Fig. 1).

4. Results

On the basis of the methodology, the activity data and emission factors discussed above, we calculated the CO_2 emissions from the production of alumina, plate glass, soda ash, ammonia and calcium

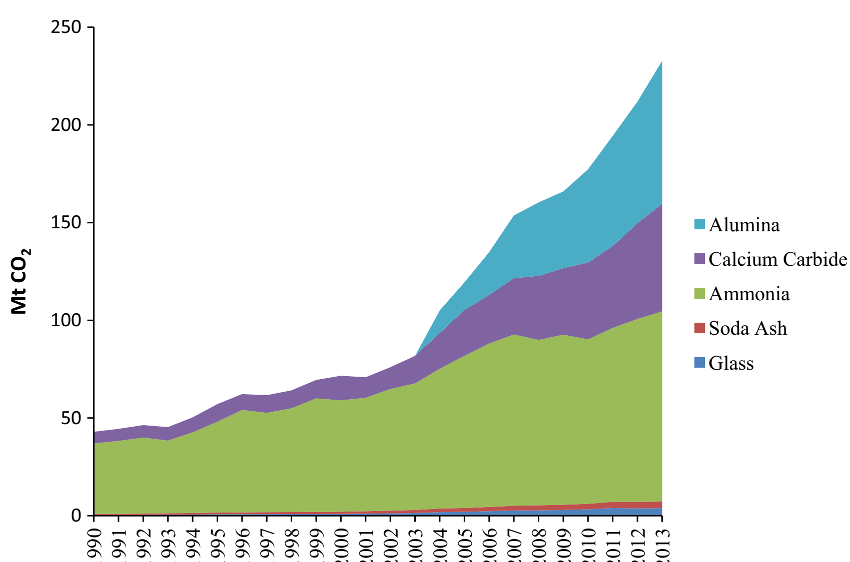

Fig. 1. Industrial process emissions from the production of alumina, plate glass, soda ash, ammonia and calcium carbide in 1990–2013.

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carbide for the period 1990–2013. The CO_2 emissions from these five industrial productions rose rapidly over the studied period: the total CO_2 emissions from the production of alumina, plate glass, soda ash, ammonia and calcium carbide totaled only 43 Mt CO_2 in 1990 but 233 Mt CO_2 in 2013. The cumulative industrial emissions of manufacturing the 5 products is also significant, and during the 1990–2013 period, it measured approximately 2.5 Gt CO_2, exceeding the total annual emissions of India. Annual 233 Mt CO_2 emissions are equivalent to approximately 25% of the total emissions from cement production. However, such emissions are not reported by current international emission datasets or by China's national emission inventories that are reported to the UN.

The emissions from the production of ammonia and alumina constitute the highest proportion of total emissions from the 5 industrial processes. In 2013, emissions from ammonia and alumina contributed 42% and 31% of total industrial process emissions, respectively. Emissions from calcium carbide production constituted the third largest contribution, constituting 24% of total industrial process emissions. The contributions from glass production and soda ash production are relatively small, namely 1.7% and 1.4%, respectively. For the 1990–2013 period, the industrial emissions of all five production processes increased rapidly. In particular, the emissions from alumina production increased substantially from 12 Mt CO_2 in 2004 to 73 Mt CO_2 in 2013, a sixfold increase within ten years. The trend of increasing emissions from ammonia production is relatively smooth compared with that from the production of the other four products. This finding may be due to the long history of Chinese agricultural development, and the associated demand for ammonia as a fertilizer has been relatively stable because of the scale and status of China's agriculture system. Additionally, the emissions from the production of alumina, calcium carbide and ammonia fluctuated around the year 2008, which can be explained as the impact on the production processes of the global economic crisis [25]. After 2008, the emissions from these processes continued their rapid growth trends. China initiated a 4000 billion RMB economic stimulus plan in 2008 to counteract the effects of the global economic crisis and invested most of the capital in infrastructure construction, which stimulated industrial production [26]. For example, the emissions from alumina production doubled during the period 2008–2013. This doubling can be explained by the rapid development of heavy industries after 2008.

The provincial distribution of total emissions from the 5 industrial processes in 2013 is presented in Fig. 2, which shows that the total emissions were concentrated in China's southern and eastern coasts where the industries were more developed. However, the central and southwestern underdeveloped regions show sharp increases in the total process emissions over the previous 23 years. For example, underdeveloped Western regions such as Xinjiang, Qinghai, Tibet and Yunnan experienced significant increases in their emissions during the period 1990–2013. By contrast, the emission increases in developed regions were lower, such as in Beijing, Tianjin and Shanghai. When comparing the per capita emission of cement production with the per capita GDP (Fig. 3), the developed eastern coastal provinces have high per capita GDP, but the central and southwestern regions have higher emissions with relative lower per capita GDP. The emissions per unit of GDP indicates that the central and western underdeveloped regions rely more extensively on heavy industries and have a higher emission per unit production compared with other regions. These results are consistent with the results of previous studies, which indicated the outsourcing of heavy industry and manufacturing from China's developed regions to its underdeveloped regions [27,28]. Such a trend could increase China's total carbon emissions, given the spatial-longer logistical and lower technology efficiencies in the central and western underdeveloped regions.

5. Discussion

These updated results for carbon emissions from the industrial production processing of alumina, plate glass, soda ash, ammonia

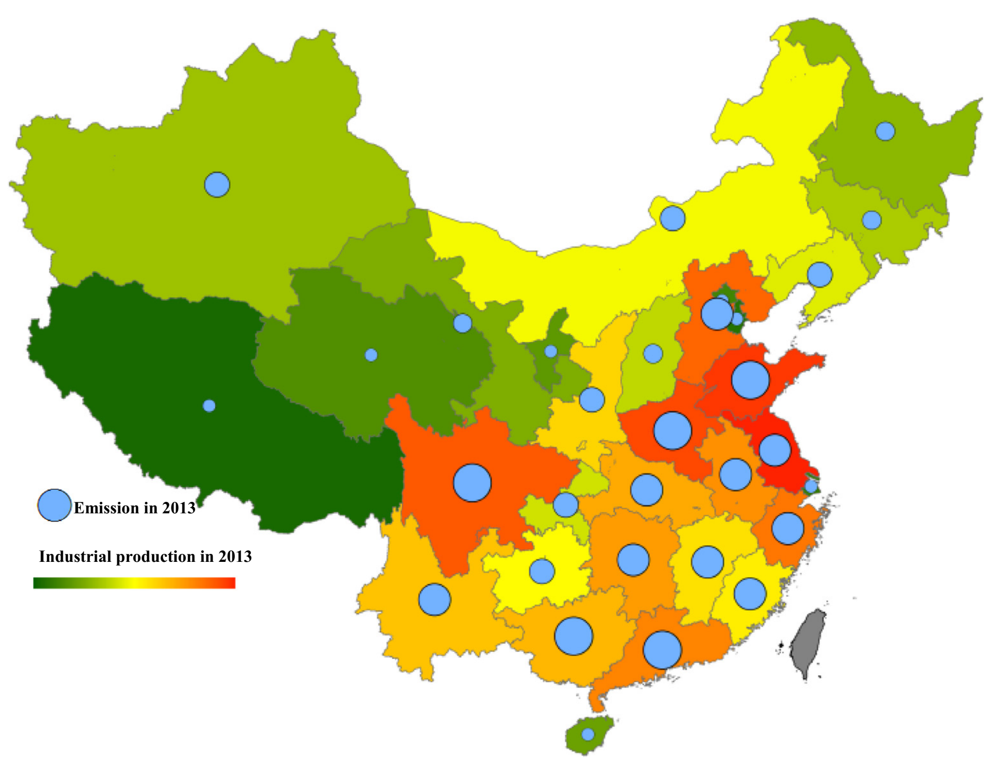

Fig. 2. Spatial pattern of the industrial process emissions from the production of alumina, plate glass, soda ash, ammonia and calcium carbide. Industrial production refers to the production of non-metal products (in tons).

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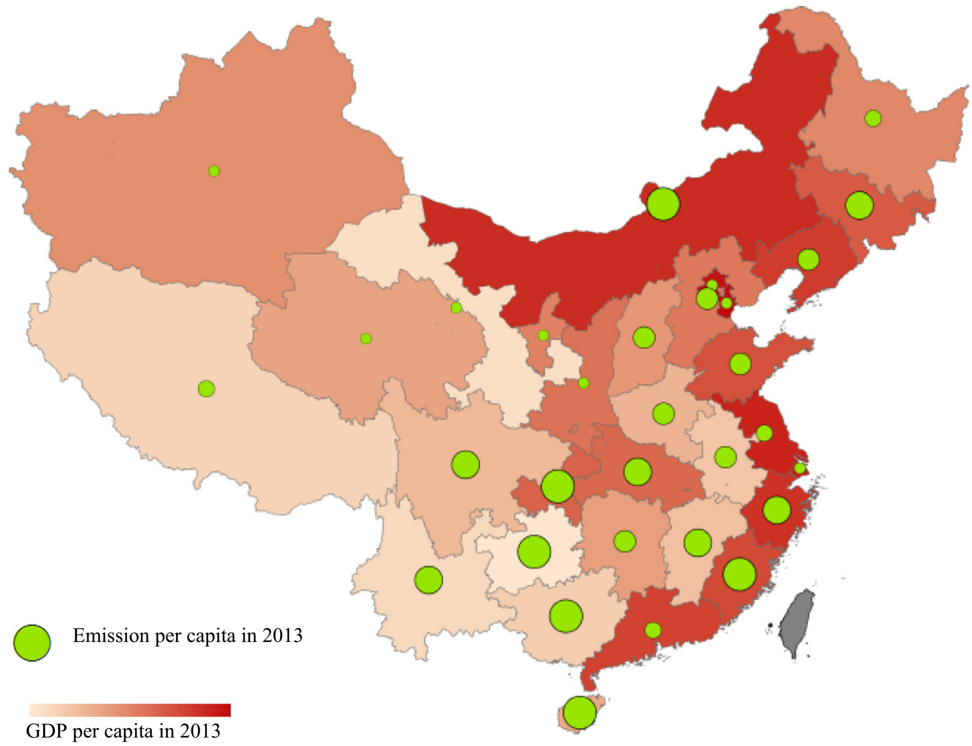

Fig. 3. Spatial pattern of the GDP per capita and the per capita industrial process emissions from the production of alumina, plate glass, soda ash, ammonia and calcium carbide.

and calcium carbide could have profound implications. A robust carbon accounting framework is crucial for performing climate modeling, addressing regional cap-and-trade systems and allocating mitigation responsibilities both domestically and internationally [29]. However, excepting the emissions from cement production, the emissions from other industrial production process have not been widely reported and discussed. We show that the 233 Mt CO_2 emissions from the production of 5 major industrial products were already equivalent to the combined annual emissions of several developed countries. The 233 Mt CO_2 emissions are also significant compared with the emissions from the cement process (Fig. 4). The total emissions from all industrial processes constitute approximately one-third of the emissions from cement production in China. Thus, it is important to include such emissions data within the national greenhouse gas emission inventory.

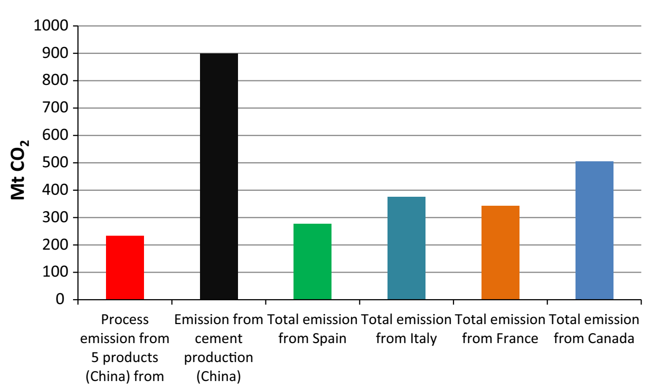

Fig. 4. Carbon emissions from China's industrial process and cement production, and the total carbon emission from several developed countries (data based on EDGAR).

In this study, we used the national average emission factors to complete the calculations. Our method could introduce uncertainties, given that the emission factors for real technology may differ from our estimates. The national average emission factors are suggested by the National Development and Reform Commission (NDRC), which is based on a sample investigation of hundreds of factories. The NDRC suggested emission factors that are close to the IPCC default values for global average estimation. However, precisely estimating the emission factors for the national average remains a significant challenge, given China's tremendous industrial scale and the dynamics of technology development. Additionally, we used the activity data provided by national statistics, which were reported to have discrepancies in the energy statistics [30]. Hence, it is possible that the reported amounts of industrial emissions are also uncertain to some extent. Acknowledging these uncertainties from both the emission factors and the activity data, future studies should strive to undertake a more accurate and in-depth analysis of the quantification of such uncertainties.

Improvements enabling more precise emissions reports can be obtained by incorporating the following methodological revisions: (1) use direct activity data rather than estimated data, such as carbon emissions calculations from factory-level production technology that are based on actual production statistical data, not data from the Statistics Yearbook; (2) develop the "Measurement, Verification and Reporting (MRV)" emission inventory in which activity data, emission factors and total emissions are reported separately, which will provide benefits such as data verification and improved emission inventories; (3) conduct in situ site monitoring and satellite measurements [31,32] as complementary methods; and (4) construct "bottom-up" emission inventories in which the emissions of cities, specific sectors and individual products are also developed.

The results show that the carbon-intensive industries are mainly distributed in the central and eastern regions of China. Hence, it is reasonable to encourage the transfer of international

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technologies and capital inputs for carbon mitigation to those regions. Such action could effectively reduce the industrial process emissions of these regions. Considering the emissions from both industrial processes and fossil fuel combustion can supply incentives for such actions. China should improve the energy efficiency and more broadly, the environmental performance of industrial practices in its poor regions, perhaps by adopting technologies already used on its eastern coast, which exhibits lower carbon emission intensities. Climate policy must address the balance between the sustainable development efforts between the northern and southern and the rich and the poor regions, as well as between production and consumption.

6. Conclusion

In this study, we quantified the industrial process emissions from the production of alumina, plate glass, soda ash, ammonia and calcium carbide. The total emissions from the industrial processing of these five products reached 233 Mt CO_2 in 2013. The cumulative emissions from the production of these five products was approximately 2.5 Gt CO_2 during the period 1990–2013. The scale and rate of increase of China's industrial process emissions are significant in global terms, with the emission from the 5 industrial processes comparable to the combined emissions of some developed countries. However, such emission amounts have not been reported by international carbon emission data sets and national emission inventories. Such emissions must be considered when designing a low carbon policy and development strategy [33,34]. More importantly, given the considerable uncertainty regarding the estimation of China's carbon emissions, more precise estimates and in situ studies based on bottom-up data sources must be prioritized in future research [35].

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Appendix. A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.11.005.

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