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Journey to world top emitter: An analysis of the driving forces of China's recent CO_2 emissions surge

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[1] China's economy has been growing at an accelerated rate from 2002 to 2005 and with it China's carbon emissions. It is easier to understand the growth in China's carbon emissions by considering which consumption activities - households and government, capital investments, and international trade - drive Chinese production and hence emissions. This paper adopts structural decomposition analysis, a macro-economic approach using data from national statistical offices, to investigate the drivers of China's recent CO_2 emissions surge. The speed of efficiency gains in production sectors cannot cope with the growth in emissions due to growth in final consumption and associated production processes. More specifically, Chinese export production is responsible for one-half of the emission increase. Capital formation contributes to one-third of the emission increase. A fast growing component is carbon emissions related to consumption of services by urban households and governmental institutions, which are responsible for most of the remaining emissions.
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1. Introduction

[2] China's recent double-digit economic growth, from 2002 to 2007, was largely driven by rapid growth of export production, placing China as the third largest exporter and fourth largest economy in the world. China's export-orientated production has grown by 26% annually over this period, twice the average export growth rate since 1990, when China opened its trade with the West. By 2005, total export was one-third the size in comparison to China's GDP, increased from 12% in 1987 and 23% in 2002. The dominant exporting sectors include electronics, metals, chemicals and textiles products.

[3] The large-scale boom in manufacturing has lead to an increased consumption of carbon-intensive fuels. China's primary energy consumption nearly doubled from 2002 (1,482 million tones coal equivalence - Mtce) to 2007 (2,656 Mtce), reflecting exponential growth in energy consumption [*Guan et al.*, 2008]. Consequently, in 2007 China emitted 21% of the global CO_2 emissions, up from 14% in 2002 and 8% in 1981. This profligate growth has made China the largest emitter of CO_2 in the world [*Gregg et al.*, 2008], closely followed by the US, which is now responsible for 19% of world CO_2 emissions.

[4] China's energy sources have not changed much over the last decade. Coal has long dominated energy consumption accounting for 70% of total energy supply. Oil and gas are responsible for 23%, with the remaining 7% due to nuclear and renewables. The continued dominance of coal has meant that China's energy and CO_2 intensity have stayed almost constant over the period of 2002–2007 at about 2.4 MJ and 0.23 kg CO_2 per 2002 Yuan of GDP. China is now facing a serious challenge to comply with its first commitment on energy efficiency improvement, set in the 11th Five-Year Plan in 2006. The commitment states that "the country's energy intensity should be reduced by 20% from 2005 to 2010" [*National Development and Reform Commission*, 2006]. Understanding the major causes of China's recent emission increase will help manage the key driving forces and pave the way for China to fulfill its first binding target towards the transition to low-carbon economic development.

[5] A number of studies have analyzed the driving forces of China's emission growth since the economic reform [e.g., *Andresosso-O'Callaghan and Yue*, 2002; *Garbaccio et al.*, 1999; *Hubacek et al.*, 2007; *Lin and Polenske*, 1995; *Wang et al.*, 2005]. Recently, *Guan et al.* [2008] and *Peters et al.* [2007] described a competition between increasing consumption and efficiency gains over recent decades. Increased consumption was mainly driven by urban households and large capital investments until the early 2000s. Furthermore, *Wang and Watson* [2007] and *Weber et al.* [2008] argued that China's export production for developed countries consumption is another important driver in contributing Chinese emissions increase, particularly since 2000.

[6] However, to date, there are no studies examining the recent acceleration in China's emissions trajectory and specifically how the significant economic structural changes may have altered it. In this paper, we focus on illustrating the driving forces for the changes of CO_2 emissions from 2002 to 2005 to further analyze these ongoing structural shifts using the most recent data available. This work is an extension and update of our previous studies [*Peters et al.*, 2007; *Weber et al.*, 2008].

2. Method and Data

2.1. Structural Decomposition Analysis (SDA)

[7] SDA is defined as an "analysis of economic change by means of a set of comparative static changes in key

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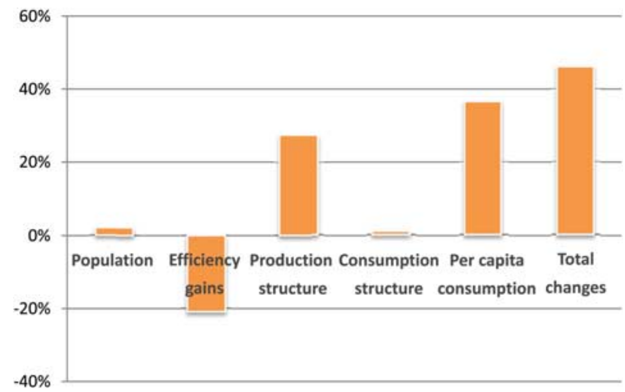

Figure 1. The contribution of driving forces in Chinese production based CO_2 emissions increase from 2002 to 2005.

parameters in an input-output table'' [*Rose and Casler*, 1996, p. 34]. Input-output tables (IOTs) represent the monetary flows of goods and services between economic sectors and between production and consumption, both within and between countries. While any number of decompositions of emissions is possible, we choose a five-factor decomposition. Aggregate CO_2 emissions are decomposed into five driving forces: population (p), emission intensity ($\mathbf{F}$), economic production structure ($\mathbf{L}$), consumption pattern ($\mathbf{y_s}$) and per capita consumption volume (y_v). Bold notation denotes matrices (capitals) and vectors. By considering the change in each variable over time the SDA can be expressed as in equation (1):

$$\begin{aligned}\Delta CO_2 &= CO_{2(t)} - CO_{2(t-1)} \\ &= p_{(t)} \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t)} \cdot \mathbf{y}_{\mathbf{v}(t)} - p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \\ &\quad \cdot \mathbf{y}_{\mathbf{s}(t-1)} \cdot y_{v(t-1)} \\ &= \Delta p \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t)} \cdot y_{v(t)} + p_{(t-1)} \cdot \Delta \mathbf{F} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{\mathbf{s}(t)} \cdot y_{v(t)} \\ &\quad + p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \Delta \mathbf{L} \cdot \mathbf{y}_{\mathbf{s}(t)} \cdot y_{v(t)} + p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \\ &\quad \cdot \Delta \mathbf{y_s} \cdot y_{v(t)} \\ &\quad + p_{(t-1)} \cdot \mathbf{F}_{(t-1)} \cdot \mathbf{L}_{(t-1)} \cdot \mathbf{y}_{\mathbf{s}(t-1)} \cdot \Delta y_v \end{aligned} \quad (1)$$

Each of the four terms in equation (1) represents the contribution to change in CO_2 emissions triggered by one driving force while keeping the rest of variables constant. Further literature and explanations for SDA can be found in our previous studies [*Guan et al.*, 2008; *Peters et al.*, 2007].

2.2. Data Sources

[8] This study requires two sets of data: IOTs and the corresponding energy and CO_2 emissions data. We obtained IOTs for 2002 and 2005 from the National Bureau of Statistics [*National Bureau of Statistics*, 2006, 2008] with identical sectoral classification of 42 sectors. The final demand category in Chinese IOT consists of rural and urban households' consumption, government expenditure, capital formation and exports. We deflate the 2005 tables to 2002 prices based on the double deflation method [*United Nations*, 1999] using price data from the ''Price'' chapter of China Statistics Yearbook 2006 [*National Bureau of Statistics*, 2007b]. The preparation of the I-O tables follows our previous work *Guan et al.* [2008].

[9] The energy data we used in this paper is extracted from official Chinese statistics [*National Bureau of Statistics*, 2007a]. Several authors have pointed towards underreporting, for example, in the case of coal consumption published in Chinese official energy statistics for the period of 1996 to 2004 [*Sinton*, 2001; *Streets et al.*, 2001; *Wu*, 2007]. Despite this issue, we have to rely on the most updated data from the Chinese statistical agencies as it is the most consistent dataset and published annually. Further, China regularly reviewed and revised its energy statistics; there have been several upward revisions of the coal consumption data for the early years of this decade. The energy statistics for year 2002 shows no significant deviations from the original and revised versions.

[10] The complete dataset consists of 18 types of fuel, heat, and electricity consumption in physical units. CO_2 emissions from combustion of fuels and industrial processes were calculated using the IPCC reference approach [*Intergovernmental Panel on Climate Change*, 2006]. The energy and emissions data for both years comprise 38 production sectors and 2 households sectors (urban and rural). The normalization process between energy data and input-output tables follows our previous work [*Guan et al.*, 2008].

2.3. Removing Impact of Imports in Environmental I-O Model

[11] The standard I-O model assumes that imports are produced with Chinese technology. This is clearly inadequate given the differences in production and emissions across countries [*Peters and Hertwich*, 2008; *Weber and Matthews*, 2007]. Therefore, we removed imports from the I-O data to give a better picture of the role of domestic components as the driving forces in China's emissions growth. It is common to derive new requirements matrices ($\mathbf{A}$) and final demand vectors ($\mathbf{y}$) in which only domestic goods are included, $\mathbf{A_d}$ and $\mathbf{y_d}$. The core assumption of this method is to assume that every economic sector and final demand category uses imports in the same proportions since there is no import matrix available for China but only a column of imports. Further explanation to this approach can be found in our previous work [*Weber et al.*, 2008].

3. Results

3.1. Structural Decomposition Analysis

[12] As shown in Figure 1, China's production-related CO_2 emissions have increased by 46% from 3,406 (million metric tones) MMT in 2002 to 4,984 MMT in 2005. Using the latest official Chinese statistics, we find the emissions to be 6,566 MMT in 2007. Since economic input-output data is not available for 2007, we focus our study on the period 2002 to 2005.

[13] Between 2002 and 2005 two main factors drive the growth in emissions: an increase of per capita consumption volume or per capita GDP (y_v) and production structural change ($\mathbf{L}$). Per capita GDP alone would drive 37% of emission increase by keeping other driving forces constant while production structure change would increase the emission by 27% on top of 2002 level. Population growth (p) and changing lifestyles ($\mathbf{y_s}$) are relatively weak factors by causing only about 2% and 1% of emission increase, respectively, from 2002 to 2005. By contrast, efficiency gain ($\mathbf{F}$) which was a strong driver in offsetting emissions

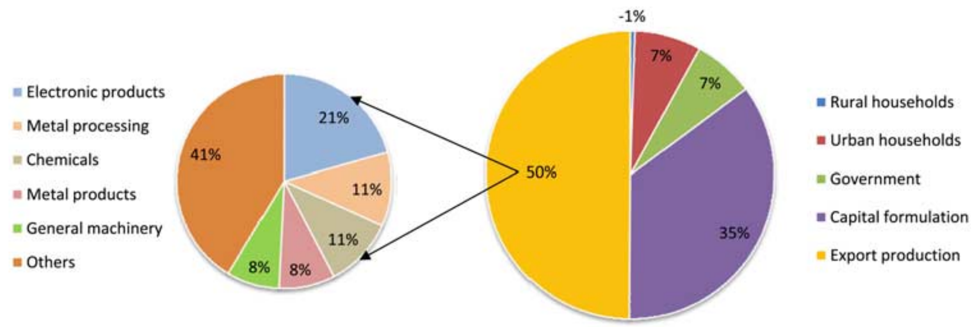

Figure 2. Final demands driving the changes from 2002 to 2005.

over the past two decades [*Guan et al.*, 2008; *Peters et al.*, 2007], has largely lost its capacity to balance overall emissions. In this case, the efficiency gain would only offset 21% of emissions with other factors kept constant. This is mainly due to the fact that electricity generation continues to be coal dominated. As a result, the carbon intensity for most production sectors has remained approximately stable over the past five years. China added 170GW to its existing 350GW since 2002 to reach a total electricity capacity of 520GW by the end of 2005, of which conventional thermal power was 405GW or 78% of the total. In 2006, another 100GW of thermal power was newly installed [*China Electricity Council*, 2007]. While power plant efficiencies are increasing due to intense efforts to install and retrofit with best available coal technology in order to meet the 2010 energy efficiency goal [*Zhao and Gallagher*, 2007], it is clear that these efforts are not keeping pace with growing electricity demand.

[14] Change of production structure (**L**), as one of the two strong drivers in recent years emission increase, was not found in other studies [*Guan et al.*, 2008; *Peters et al.*, 2007]. This is largely due to China's growth in manufacturing, especially for export. The share of primarily industry (agriculture and mining) in GDP has declined from 25% in the early 1980s to 9% in 2002 and further to around 5% in 2005. Meanwhile, service sectors have increased from 22% in 1980 to 38% in 2002 and declined somewhat to 35% in 2005. Construction has remained relatively stable at 15 to 18%. The share of manufacturing had also been relatively constant at approximately 38% of GDP until 2002, but the figure climbed up to 46% by 2005. Furthermore, 8% of production structure changes in manufacturing sectors are contributed to production increases of electronics, machinery, instruments and food products. These increases largely originated from export demand.

[15] The above analysis covers China's CO_2 emissions from the *production* of products and services which represent 90–95% of the total. There are also direct household CO_2 emissions such as the fuel used in private transportation and for heating and cooking. The direct CO_2 emissions increased by 33 MMT, from 181 MMT in 2002 to 214 MMT in 2005. This increase is partly due to the rapid consumption increase of gasoline for private transportation by urban citizens contributing 18% to the overall increase, although coal-sourced heating in rural areas is still dominating the emission increase by contributing 40% to the growth. The ownership of private cars increased significantly from less than 1 car per 100 households in 2002 to 3.4 cars per 100 households in 2005 [*National Bureau of Statistics*, 2007b]. As a result, per capita gasoline consumption has increased over 30% from 29 litres per person in 2002 to 38 litres per person in 2005. Although these numbers are still far smaller than 1,783 litres/person in the US, this can be seen as a potential driver for further emission increases as urban China continues to follow the West's motorization path.

3.2. Exports and Capital Investments Drive Increased Emissions

[16] When allocating the production-related emissions increase of 1,578 MMT CO_2 to different final users, as shown in the right pie chart of Figure 2, we find that half of the emission increase, 796 MMT, was due to the production of exported products and services for consumption in other countries. Another 563 MMT, or 36% of emission increase was due to capital formulation. Only 109 MMT (7%) was due to emissions triggered by production for governmental expenditures, and 111 MMT (7%) was triggered through household consumption (119 MMT increase from urban households offset by 8 MMT emission decrease through a change of rural household consumption patterns). Table 1 further breaks down the emission increase by sector, which

Table 1. Top 15 Final Demand Sectors in Driving the Emission Changes From 2002 to 2005

Final demand sector	Contribution Sectors	% to Overall Emission Increase	CO_2 (unit: MMT)
Capital	Construction	15.41	243.2
Capital	Machinery and equipments	11.53	181.9
Export	Electronic products	10.41	164.2
Export	Metals smelting and pressing	5.60	88.4
Export	Chemicals	5.35	84.3
Capital	Transport equipment	4.83	76.2
Export	Metal products	4.25	67.1
Export	General machinery	3.95	62.3
Export	Electric equipment and machinery	3.64	57.5
Export	Instruments, meters and office machinery	2.91	46.0
Urban	Health services and social welfare	2.86	45.1
Export	Textile goods	2.69	42.4
Capital	Food products and tobacco processing	2.66	42.0
Government	Health services and social welfare	2.65	41.8
Government	General technical services	1.85	29.2
	Subtotal	80.59	1271.6

ranks the 15 most important drivers that together contribute over 80% of the emission increase from 2002 to 2005. The majority of these sectors are related to exports and capital formation.

[17] In terms of economic structure, primary industry (e.g., agriculture and mining) decreased total emissions by 4% from 2002 to 2005. Secondary industry (e.g., manufacturing) was responsible for 1,073 MMT or 68% of emission growth, of which 70% (505 MMT) was due to exports. Services represented the remaining 568 MMT or 36% of total growth; however, the construction sector alone contributes 246 MMT or 16% of total emission growth, while other service sectors together contributed 322 MMT or 21% of the emission increase.

[18] The boom of production for exports is the prime driving force to China's recent emissions surge. As stated above, our result shows that 50% of the emission growth from 2002 to 2005 was triggered by export production and 60% of these commodities are exported to the West [*Weber et al.*, 2008]. In other words, consumers in developed countries are at least partially responsible for one-third of Chinese emission increase from 2002 to 2005. To investigate further, we illustrate the top five export production sectors which increase the CO_2 emissions increase the most, as shown in the left pie chart of Figure 2.

[19] China is trying to avoid direct exports of raw materials or material/energy intensive products through export taxes and subsidy elimination and has instead attempted to produce higher value-added items. For example, TV sets exports have increased more than four times from 21 million sets in 2002 to 86 million sets in 2005, while overall exports of electronic products in terms of monetary value has increased 2.6 times over the same period. The main destination of Chinese export electronics is the West: for example 30% to the US, 18% to the EU, and 13% to Japan. The emissions resulting from the production of electronic products for export have increased from 88 MMT in 2002 to 252 MMT in 2005 due to their energy-intensive supply chains and accounts for 21% of total export driven emission growth.

[20] Metals production (including metal smelting, processing and products) represents the other side of the coin; here China's focus on discouraging export of energy-intensive goods was clearly necessary. During 2002 to 2005, China's exports for metallic products increased 1.6 times, and the resulting emissions increased by 154 MMT (88 MMT for raw metals and 67 MMT for metal products), which is responsible for 19% of total export driven emission growth. More than half of the metallic products were exported to the West.

[21] After the two major driving industries of electronics and metals, chemicals, rubber and plastics exports caused an increase of 84 MMT emissions during 2002 to 2005, which accounts for 11% of total export-driven emissions growth. Machinery production is the remaining large contributor, responsible for 62 MMT (8%) of export emissions increase.

[22] After exports, capital formation is the other important motor in driving the increase of CO_2 emissions in 2002 to 2005. Of the 563 MMT emission increase driven by capital formation, 56% or 315 MMT have occurred in manufacturing sectors, with major shares from producing general machinery (182 MMT) and transport equipment (76 MMT). The remainder of investment-related emissions, 43% or 243 MMT is from construction, driven largely by urbanization, urban renewal and building of infrastructure. For example, the length of highways has been extended by almost 90% from 177 million kilometres in 2002 to 335 million kilometres in 2005 [*National Bureau of Statistics*, 2007c].

3.3. Role of Services

[23] From 2002 to 2005 public services contributed 21% of overall production-related emission growth (321 MMT). 115 MMT (36%) of services-driven emission increase occurred to meet demand by urban household consumption, while 108 MMT (34%) was from governmental expenditures. The remaining 98 MMT (30%) of the increase was to meet service demand by export and capital investment industries. Of the 115 MMT increase related to urban households, health and social welfare services, telecommunication and information technology services, and public transportation were the largest drivers, contributing 45 MMT (39%), 28 MMT (24%) and 24 MMT (21%), respectively.

[24] A similar trend of consumption towards more services can also be found in government expenditure pattern in recent years. Of the 108 MMT emission increase, the Chinese government caused an increase of 42 MMT (39%) through health and social welfare expenditures, 29 MMT (27%) by expenditures on technical support services, and 27 MMT (25%) through education and scientific research. These results reflect the recent strengthening of social services provisions by the Chinese government. Regrettably, energy efficiency and conservation in Chinese service sectors is quite poor, making service sectors in China unusually carbon-intensive. The very recently enacted policy, "Domestic Buildings Energy Saving Statute" [*The Central People's Government*, 2008] is a policy indication to conserve energy and use energy efficient products in domestic and commercial buildings construction.

4. Conclusions

[25] The failure of efficiency gains to offset increased energy consumption and emissions puts China's commitment of improving 20% energy intensity relative to 2005 level by 2010 in doubt. Without significant changes in China's coal-dominated energy consumption pattern, this goal may be out of reach. Efficiency gains have only made a minor impact on China's carbon emissions between 2002 and 2005 and have not been able to keep pace with the rapid growth in demand for Chinese exports, construction activities, and domestic consumption.

[26] The growth in Chinese exports between 2002 and 2005 is the primary cause of China's emissions growth; and developed countries are responsible for over half of the growth in Chinese exported carbon emissions from 2002 to 2005. The export of manufactured products is the major contributor to export growth. Construction activities have also made a significant impact on Chinese emissions driving one-third of the recent growth. Domestic consumption by households and government have also made some contribution to the growth of China's carbon emissions.

[27] This work has four main implications for Chinese climate policy. First, China must pay further attention to

create energy-efficient capital stocks in manufacturing sectors and strengthen international cooperation in acceleration of low-carbon technologies developments and spillovers and to implement mature technologies in large scale. These will reduce future mitigation costs. Second, China needs to revisit its current export structure. To continue its impressive export orientated growth in recent years, China may need to further add value to its exports [*Rodrik*, 2006]. Third, extensive capital formation due to urbanization will continue over the next decades. To improve material use efficiency in construction would avoid emissions from upstream production sectors such as cement, steel, and glass. Fourth, China should pay further attention to improve energy conservation such as lighting and air-conditioning at the consumer level.

[28] Finally, the global financial crisis in 2008 would temper the rapid growth of Chinese export production. As a consequence, Chinese CO_2 emissions are not expected to grow as fast as in previous years, however in the long-run, export-related emissions would continue to significantly contribute to the growth of Chinese emissions if, after the economic crisis, China returned to the same growth trajectory with similar economic structure and technology as today.

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