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The Drivers of Chinese CO_2 Emissions from 1980 to 2030

Abstract

China's energy consumption doubled within the first 25 years of economic reforms initiated at the end of the 1970s, and doubled again in the past 5 years. It has resulted of a threefold CO_2 emissions increase since early of 1980s. China's heavy reliance on coal will make it the largest emitter of CO_2 in the world. By combining structural decomposition and input-output analysis we seek to assess the driving forces of China's CO_2 emissions from 1980 to 2030. In our reference scenario, production-related CO_2 emissions will increase another three times by 2030. Household consumption, capital investment and growth in exports will largely drive the increase in CO_2 emissions. Efficiency gains will be partially offset the projected increases in consumption, but our scenarios show that this will not be sufficient if China's consumption patterns converge to current US levels. Relying on efficiency improvements alone will not stabilize China's future emissions. Our scenarios show that even extremely optimistic assumptions of widespread installation of carbon dioxide capture and storage will only slow the increases in CO_2 emissions.

Keywords: CO_2 emissions, China, Climate Change, Sustainable Consumption, Lifestyles, Input-Output Analysis, Structural Decomposition Analysis, Carbon Capture and Storage.

1 Introduction

Rapid growth in gross domestic production since the 1980s has made China the fourth-largest economy and the third-largest exporter in the world as of mid-2006 (World Trade Organization, 2007). Economic success has brought wealth to its population while at the same time creating the world's largest income inequality between rural and urban dwellers (Li and Yue, 2004). In major cities, many urban Chinese are pursuing western, consumerist lifestyles while 27% of its rural population is still earning less than $1 per day measured in purchasing power parity (PPP) and 70% earning less than $2 per day (National Bureau of Statistics, 2007c).

China's booming economy, especially in manufacturing sectors, has driven rapid growth in energy consumption. Total energy consumption doubled from 603 million tons of coal equivalent (tce)[1] in 1980 to about 1,200 million tce in 2002 and, strikingly, doubled again in the past 4 years (National Bureau of Statistics, 2007b). China's overall energy intensity has significantly improved from 4.3 tce per 10,000 2002 Renminbi (RMB) of gross domestic production (GDP) in 1980 to a low of 1.3 tce per 10,000 RMB in 2002, although China's energy intensity increased to 1.4 tce per 10,000 RMB in 2006. The energy intensity in 2006 is more than 9 times higher than Japan and 3.4 times higher than the USA measured in market exchange rates (MER)[2]. Furthermore, China's energy mix has not changed significantly. In the early 1980s, coal accounted for 71% of total energy consumption. It dropped to its lowest point of 66% in 2002, but by 2006, it had climbed back to 70% (National Bureau of Statistics, 2007b). Some scholars have debated the authenticity of the drop in coal consumption around 2000 (Akimoto et al., 2006; Sinton, 2001).

Using the most recent official Chinese energy data (National Bureau of Statistics, 2007b) we estimate that China's total CO_2 emissions[3] in 2006 were approximately 5,670 million metric tons (MMT) which is slightly lower than the US estimate of 5,955 MMT (EIA, 2007). The

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[1] 1 tce = 29 gigajoules (GJ).

[2] MER refers to GDP valued exclusively at Market Exchange Rates. Energy intensity represents the amount of energy consumed to produce one unit of GDP. However there are two ways to measure GDP, either by using MER or PPP. The energy intensities in this paper are measured as energy consumed per 10,000 2002 RMB of GDP, valued according to the MER. The difference in measuring energy intensity between by MER and PPP for China is substantial. For example, China's energy intensity is more than 3 times than the US level measure by MER, but if measured by PPP, the figures between China and US are quite similar. MER does not give a true indication of wealth and PPP is often used to measure GDP, but is less appropriate when speaking of internationally traded goods. For our purpose, we only intend to give an indication of the variation in emission intensity between countries.

[3] Production-related CO_2 emissions refer to all CO_2 emissions released due to burning fuels and process emissions by smelting metals, cements and some chemicals.

Netherlands Environmental Assessment Agency (2007) reported that China overtook the US as the world's largest CO_2 emitter in 2006 and given China's faster growth rates, we also would expect China to overtake the US sometime in 2007 or 2008 (Gregg et al., 2008). Nevertheless, despite the absolute emissions levels, China's per capita emissions are much lower than those of other developed countries (Hubacek et al., 2007).

In addition to being a major contributor to global climate change, China is one of the countries most likely to be severely affected. Global sea level rose an average of 1.5 millimeters per year over the past 50 years (IPCC, 2007). If emissions of CO_2 and other green house gases (GHGs) continue at the current rate, average sea level would rise 20-60 centimeters by end of the century (IPCC, 2007). Impacts would include salt-water intrusion, which would threaten the water supply of China's coastal mega-cities including Shanghai and Guangzhou and affect tens of millions of people (IPCC, 2007).

Thus, it is crucial for both Chinese and global climate and energy policy to understand the key driving forces of China's growing energy consumption and greenhouse gas emissions. We extend the *Impact = Population × Affluence × Technology (IPAT)* model (Commoner et al., 1971; Ehrlich and Holdren, 1971) by using structural decomposition analysis (Leontief and Ford, 1972; Rose and Casler, 1996) to assess the key drivers of China's CO_2 emissions since its economic reforms, first initiated at the end of 1978, and to develop three illustrative scenarios to describe potential levels of China's CO_2 emissions in 2030.

The *IPAT* equation was developed in the 1970s (Ehrlich and Holdren, 1971) to explain the environmental effects of population, affluence (usually measured in GDP per capita), and technology (usually measured in emissions per unit GDP), and to project future environmental change based on changes in these main driving forces (Commoner, 1972; Dietz and Rosa, 1997; York et al., 2002). One of the key limitations of *IPAT* and its variants is that the model can only assess the direct impacts on the environment caused by these driving forces. Furthermore, it is too aggregated to clearly allocate the sources of emissions to particular industries or consumers (Chertow, 2001). The limitations of the *IPAT* model can be overcome using input-output (IO) analysis (Hertwich, 2005). Input-output analysis is a suitable tool to evaluate both direct and indirect environmental impacts by examining the flow of goods and services among the producing and purchasing sectors of a country or region (Leontief, 1986). By adopting this approach, the *IPAT* variable *affluence* can be represented by a disaggregated final demand which accounts for household consumption in sectoral detail; the variable *technology* is better described by the Leontief inverse matrix which captures the inter-linkages between all economic sectors.

Just as the standard *IPAT* analysis decomposes changes over time into components for population, affluence, and technology, using input-output analysis the main driving forces can be divided into more detailed subcomponents by employing a technique called structural decomposition analysis (SDA) (Hoekstra, 2005). Rose and Casler (1996, p34) define SDA as an "*analysis of economic change by means of a set of comparative static changes in key parameters in an input-output table.*" The first application of SDA to environmental issues can be traced back to the early 1970s (Leontief and Ford, 1972). Most earlier SDA studies focused on energy consumption and its related emissions in developed countries or regions (see Hoekstra and van der Bergh, 2002). SDA studies have been performed for China (Andresosso-O'Callaghan and Yue, 2002; Garbaccio et al., 1999; Lin and Polenske, 1995); the most recent by Peters et al. (2007) concluded that the increase in China's CO_2 emissions from 1992 to 2002 were mainly driven by capital investment and household consumption, which were only partly offset by efficiency gains and technical change in production. They also found that the rapid growth in exports had been tempered by a growth in imports. Until now, there are no studies that assess the drivers of China's CO_2 emissions from its economic reform at the early of 1980s to the present.

The combination of IO-IPAT and SDA strengthens the standard IPAT analysis by identifying which economic sectors and final consumers drive changes. We use IO-IPAT and SDA to decompose the key drivers behind increased Chinese CO_2 emissions from 1981 to 2002. We then forecast Chinese CO_2 emissions in 2030 using three illustrative scenarios: (i) a reference case, (ii) increased demand driven by rapidly westernizing lifestyles, and (iii) greater penetration of low-carbon technology through adoption of carbon dioxide capture and storage (CCS) technologies. We draw several recommendations for China's climate change policy based on past experiences and future trends in population, economic growth, lifestyle changes, and technology improvements.

2 Method and Data

The principal formula for IO-IPAT SDA can be illustrated as $\mathbf{CO_2} = p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y}_\mathbf{s} \cdot y_v$. CO_2 emissions can be decomposed into five driving forces: population (*p*), emission intensity (**F**), economic production structure (**L**), consumption pattern ($\mathbf{y_s}$) and per capita consumption volume (y_v). Bold notation denotes matrices (capitals) and vectors. The change in CO_2 emissions from time *t-1* to time *t* can be decomposed into changes in the component driving forces, but there is no unique solution for the decomposition; the five factors utilized in this paper have *5!=120* first-order decompositions (Dietzenbacher and Los, 1998). One of the 120 possible decompositions is shown in Equation 1.

$$\begin{aligned}\Delta \mathrm{CO}_2 &= \Delta \mathrm{CO}_{2(\mathrm{t})} - \Delta \mathrm{CO}_{2(\mathrm{t}-1)} \\ &= p_{(\mathrm{t})} \cdot \mathbf{F}_{(\mathrm{t})} \cdot \mathbf{L}_{(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{v}(\mathrm{t})} - p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \mathbf{L}_{(\mathrm{t}-1)} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t}-1)} \cdot y_{v(\mathrm{t}-1)} \\ &= \Delta p \cdot \mathbf{F}_{(\mathrm{t})} \cdot \mathbf{L}_{(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot y_{v(\mathrm{t})} + p_{(\mathrm{t}-1)} \cdot \Delta \mathbf{F} \cdot \mathbf{L}_{(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot y_{v(\mathrm{t})} \\ &+ p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \Delta \mathbf{L} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot y_{v(\mathrm{t})} + p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \mathbf{L}_{(\mathrm{t}-1)} \cdot \Delta \mathbf{y}_\mathbf{s} \cdot y_{v(\mathrm{t})} \\ &+ p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \mathbf{L}_{(\mathrm{t}-1)} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t}-1)} \cdot \Delta y_v \end{aligned} \qquad (1)$$

Each of the four terms in Equation (1) represents the contribution to change in CO_2 emissions triggered by one driving force with keeping the rest of variables constant. For example, the first term — $\Delta p \cdot \mathbf{F}_{(\mathrm{t})} \cdot \mathbf{L}_{(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot y_{v(\mathrm{t})}$ represents the change in CO_2 emissions due to changes in population, with all other variables (**F**, **L**, $\mathbf{y_s}$ and y_v) remaining constant. This also serves to highlight a methodological issue with SDA – non-uniqueness. For instance, in the fourth term **F**, **L**, $\mathbf{y_s}$ and y_v can be evaluated at the start or the end-point of the time-period investigated. There are several methods for dealing with this issue. We average all possible first-order decompositions; for a detailed discussion see Hoekstra & van der Bergh (2002).

This study requires two sets of data: time-series input-output tables and the corresponding energy and CO_2 emissions data. We employed China's input-output tables (IOT) from Li and Xue (1998) for 1981, 1983, 1987, 1990, 1992, 1995. They edited the six tables with 18 sectors in 1990 price. We obtained the input-output tables from the Chinese National Bureau of Statistics (NBS) for 1997 with 40 sectors (National Bureau of Statistics, 1999), 2000 with 40 sectors (National Bureau of Statistics, 2002) and 2002 with 42 sectors (National Bureau of Statistics, 2006). These three tables were in current prices. However, there was considerable overlap in the classifications. All the tables are aggregated to a uniform classification with 18 sectors (see production sectors at Table 1) in 1990 price using the double deflation method

(United Nations, 1999). The Chinese input-output tables include several categories of final consumption: rural and urban households, government, total capital formation, exports and imports.

The energy data for 1981-2002 were extracted from the *China Energy Databook* published by Lawrence Berkeley National Laboratory (2004). The complete dataset consists of 18 types of fuel, heat, and electricity consumption in physical units. CO_2 emissions including both the combustion of fuels and industrial processes were calculated using the IPCC reference approach (IPCC, 2006). The energy and emissions data for all years comprise 37 production sectors and 2 households sectors (urban and rural). Energy data were normalized to harmonize the sectors between the input-output tables and the energy/CO_2 data when performing the analysis. We also extracted energy data for 2005 and 2006 from the *China Energy Statistical Yearbook 2006* (National Bureau of Statistics, 2007a) and China's *Statistical Yearbook 2007* (National Bureau of Statistics, 2007b) to track the most recent trends in CO_2 emissions in China and use the data as the reference for projections to 2030.

3 IO-IPAT SDA results from 1981 to 2002

Our IO-IPAT SDA results broadly show a competition between GDP growth and efficiency gains over the past two decades in Figure 1. The increase in GDP per capita, "Δy_v" (light blue line) would have increased production-related CO_2 emissions by 469% from 1981 if population, efficiency, economic structure and consumption patterns had stayed constant at 1981 levels. Similarly, efficiency gains (red line) would have offset total CO_2 emissions by 425% of 1981 levels if the other factors remained constant. The change in population (blue line) would lead to a 72% increase in total CO_2 emissions; the change in household consumption patterns (purple line) would contribute 42% to the increase and change in economic production structure (green line) would contribute 45%. In total, the emission increased 202%, or from 1,346MMT to 3,623MMT, during 1981-2002 period. Since 2002, Chinese emissions have grown another 50% to reach 5,400 in2006

It is possible to further decompose the growth in GDP by the different final users. The bar chart in Figure 2 allocates the total increase in CO_2 emissions to the separate final demand categories. Of the 2,277 MMT (202%) increase in CO_2 emissions from 1981 to 2002: 1,174

MMT (52%) was due to the growth in fixed capital investments; 944 MMT (42%) was due to household consumption – of which 856 MMT (38%) was from urban households and only 88 MMT (4%) from rural households – and 229 MMT (10%) resulted from government consumption. China's CO_2 emissions rose 43% to produce exports for other countries' needs. If it is assumed that all the imports to China are produced with Chinese technology, imports would temper this emission by 46%. However, given China's high use of coal in electricity production and inefficient production systems relative to those nations exporting goods to China, this assumption largely overestimates the *actual* embodied CO_2 in China's imports (Peters and Hertwich, 2008a). Peters and Hertwich (2008a) found that the actual emissions embodied in Chinese imports were almost four times lower than the emissions embodied in Chinese exports.

The left pie chart of Figure 2 illustrates the top consumption items of urban households and the associated increases in CO_2 emissions to produce these items. Of the 877 MMT increase in CO_2 emissions due to urban household consumption, the major components are electricity (26%), agriculture (8%) and services (36%), which can be further split into 18% from public transport, 9% from trade, restaurants and hotels, and 7% from freight transport, post, and telecommunication services.

The vastly improved living standard since the economic reforms has allowed many urban households to 'westernize' their lifestyles. Changing lifestyles have resulted in rapid growth in direct energy consumption[4], from less than 6 million tce in 1981 to 235 million tce in 2005. Electricity demand has significantly increased both directly, through the use of household electrical appliances, and indirectly, through the production of goods. Consumption of household electrical appliances quickly increased in both quantity and category since 1990. For example, ownership of refrigerators and color television sets in urban areas has more than doubled from 40 and 60 sets per 100 urban households in 1990 to 80 and 130 sets in 2005, respectively (Hubacek et al., 2007). Air-conditioners and personal computers have become essential household items for many urban families. A similar situation is observable for telecommunication services; mobile phones are very popular in urban China; the average urban household had 1.37 sets in 2005 (National Bureau of Statistics, 2007b). On the other hand, owning a car is still an unachievable goal for the vast majority of households. But

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[4] Direct energy consumption consists of all residential energy consumption (e.g. lighting, cooking, energy for appliances etc) and fuels for private transportation.

despite this fact, one can already observe a trend of the car replacing traditional ways of commuting (e.g. walking, cycling, or by bus). This future trend will result in a boom of car production and other automotive-related sectors, inevitably leading to a further increase in CO_2 emissions from car use, car production, and building roads.

The right pie chart of Figure 2 illustrates the top five sectors causing increases in CO_2 emissions in fixed capital investment: construction and machinery production contribute 63% and 33%, respectively; the remaining 4% are shared among service sectors. Since the economic reforms, the government has paid special attention to infrastructure construction. Annual fixed capital investments in the construction sector have increased 6 times in 25 years (National Bureau of Statistics, 2007b). As a result, the length of highways extended from 900,000 in 1981 to 1,700,000 kilometers in 2002 (National Bureau of Statistics, 2007b). The number of civil airports similarly increased from 94 in 1990 to 141 by 2002 (National Bureau of Statistics, 2007b).

4 Scenario design and results

Building on the historical analysis and on current projections of the different driving forces affecting Chinese CO2 emissions, we construct several scenarios to illustrate potential levels of Chinese emissions in 2030. We first construct a reference scenario on the future development of China's energy, economic, and social conditions through 2030. We adopt 2002 as the base year for all economic and social factors and 2005 for the energy consumption patterns and volume, since at the time of writing 2002 was the most up-to-date input-output table and 2005 was the most up-to-date energy data available. The reference scenario is built around the reference scenarios of the International Energy Agency (2007)

We further propose two *extreme* scenarios – 'westernizing lifestyles' and 'carbon capture and storage' scenarios, in order to estimate the maximum extent that these two important factors, lifestyle and technology improvements, could influence China's future CO_2 emissions. Scenarios will always be open to debate as they are attempting to model the unknown. A scenario must be closely related to the question being asked. It is unlikely that the two scenarios we consider will be met in reality, but even so, the scenarios do serve as relevant illustrations. Both these scenarios should be seen as what-if thought experiments rather than predictions. The ‘westernizing lifestyles’ scenario reflects how China’s CO_2 emissions could develop in a ‘worst case’ situation where China continues its current trend in adopting western lifestyle, while the ‘carbon capture and storage’ scenario reflects a best-case scenario of the implementation of the technology. The scenarios therefore reflect potential upper and lower bounds of different policy directions.

4.1 Reference scenario:

Economic growth: Due to spectacular growth over a sustained period, China’s GDP growth has averaged 9.5% per year over the past two decades, accelerating to around 11% in 2006 and the first half of 2007. In the reference scenario, we use similar assumptions to those of the International Energy Agency, China’s annual GDP per capita growth rate averages 8.4% per year until 2010, slowing to 5.0% from 2010-2030 (International Energy Agency, 2007, Chapter 7). Rapid growth has cut poverty dramatically since early of 1980s, yet China’s per-capita income is still less than one-quarter of the OECD average today (International Energy Agency, 2007, Chapter 7). Income differences are striking between rural and urban areas and the gap is likely to remain in the coming decades. This scenario assumes that urban per capita income would increase by 5.7% annually from 2002 to 2010, and 4.7% annually from 2010 to 2030. A similar, slightly slower, trend would occur in rural households, where per capita income would increase by 5.2% per year until 2010 and 4.2% from 2010 to 2030 (International Energy Agency, 2007, Chapter 7).

Population dynamics and urbanization: At 1.32 billion people (in 2002), China has the largest population in the world – a fifth of the total. Since the “one-child” policy was put in force in 1979, China has maintained a low fertility-rate with the average woman having 1.7 children in her lifetime. Households in China will thus become older and smaller in the next two decades. The retired population will more than double by 2030 (International Energy Agency, 2007, Chapter 7). In order to delay the aging of their society, the Chinese government in July 2007 announced a new version of its population policy. One of the important decisions is that in “*all Chinese provinces … except for Henan, couples in which both are the only child can themselves give birth to two children*” (Xinhua, 2007, own translation). This revised scenario projected that China’s population would reach 1.5 billion by 2030, compared to 1.45 billion projected by United Nation (2004) under the previous “one-child” policy. The urbanization rate would reach 61% by 2030, increasing from 39% in 2002 (United Nations, 2004).

Changing consumption patterns: For 2002, consumption patterns for urban and rural households were taken from the 2002 input-output table. We adopted sector-specific income elasticities of demand and per-capita income estimations to project people's consumption patterns in 2030 for rural and urban households (Hubacek and Sun, 2001). The income elasticity measures the rate of response of quantity demand due to a raise in a consumer's income. Table 1 shows the employed income elasticities for projecting Chinese household consumption in 2030. Hubacek and Sun (2001; 2005) modified the income elasticities to project Chinese consumption in 2025 based on the estimates and calibrations in Huang and Rozelle (1998) and Huang and Chen (1999), and on their own adjustments to accommodate the sectoral setup in the input-output model. Consumption patterns for both urban and rural residents would change significantly. For example, the share of consumption expenditures for food and other related agricultural products would decrease from 39% and 21% in 2002 to 17% and 6% by 2030 in rural and urban households respectively. In contrast, transports and services took 27% and 33% of total rural and urban households' expenditure; both would increase to 39% and 44% by 2030 respectively. The consumption proportions for manufacturing products in both rural and urban areas would only change slightly. Our projection on consumption expenditures are 15,600 2002 RMB or 19,850 2002 US$ in PPP per urban dweller, and 3,613 2002 RMB or 4,600 2002 US$ in PPP per rural resident.

Technical and structural change: We use the RAS technique to estimate the Leontief technical coefficients matrix (A matrix) for 2030 (Miller and Blair, 1985). RAS is a widely-used method for updating an input-output table over a certain time period. The basic method is outlined in Miller and Blair (1985). We projected China's annual GDP in 2030 as the main constraints in balancing the table, which would be 38 trillion 2002 RMB. The share of agriculture in GDP would drop from 12% to 3% by 2030, and the share of industry would stay at roughly 50% as now, and services would make up the remaining 47% in the target year, increased from the current 38%.

Energy demand and fuel mix: We also adopted the energy demand and fuel mix assumptions of the International Energy Agency's *World Energy Outlook 2007*. Given an average annual GDP growth rate of 5.6% from 2002 to 2030, China's total final energy consumption would increase by 3.1% on average (International Energy Agency, 2007, Chapter 9). Total final consumption of coal would grow by 4.7% per year on average between 2005 and 2015, before easing off between then and 2030, growing at under 1% per annum. Most of the increase in coal use comes from manufacturing sectors. Final gas consumption would increase nearly fourfold. Final oil demand would rise by 3.9% per year, driven mainly by transport; oil would account for 96% of total energy for transport in 2030, similar to today (International Energy Agency, 2007, Chapter 9). Demand for electricity would grow faster than for any other energy form, almost catching up to oil as the leading end-use fuel. Electricity use would increase more than threefold between 2005 and 2030 (International Energy Agency, 2007, Chapter 9), and about 70% of electricity consumption would be generated by coal-fired plants (International Energy Agency, 2007, Chapter 10). Although China has goals to increase shares of renewable energy in both the transport and electricity sectors, current trends show the short term goals are going unmet, and we adopt conservative assumptions for both sectors as in International Energy Agency (2007).

Results:

Our reference scenario suggests that in 2030 China's total CO_2 emissions would reach 11,900 MMT; and its production-related emissions will more than double, from 4,800 MMT in 2005 to 11,000 MMT in 2030. Residential direct emission will increase from 213 MMT to about 900 MMT mainly due to the growth of gasoline consumption for private transportations. As shown in blue in Figure 3, by 2030, production-related CO_2 emissions would increase by 222% relative to the 2002 level. However, per capita consumption would drive an increase of 362% in production-related CO_2 emissions relative to the 2002 level keeping other factors constant, mainly resulting from the increase in urban household consumption. Efficiency improvements alone would offset just over half (193%) of that increase in emissions. The growth of population would lead to a 6% increase. Chinese economic structure would change significantly over the next 30 years as stated above. But the change of consumption structure alone would drive 5% increase of the emissions and the changes in production structure would increase the emissions by 42% above the 2002 level keeping other factors constant. The reason of both production and consumption structures being relatively weak drivers for emissions increase is that the GDP/consumption expenditures move from one low CO_2 sector (e.g. agriculture) to another (e.g. services) while keeping a similar proportion of carbon-intensive manufacturing sectors (e.g. electricity and machinery related products).

If we broaden our timescale to encompass 50 years of Chinese economic development from the reforms of the early 1980s through 2030, China's annual CO_2 emissions would increase over 9-fold. China's CO_2 emissions growth would be much faster than in many developed countries, which is partly due to different development stages. For example, annual CO_2 emissions in the US increased about 3 times, and 6 times for Japan, since the 1950s.

The pattern of final consumers contributing to the increase in CO_2 emissions in 2030 exhibits some notable changes compared with 2002 (Figure 2). Urban households replace capital investment as the largest contributor to increased emissions. In 2030, urban households are responsible for 49% of the 7,551 MMT increase in CO_2 emissions, followed by capital investments at 33%. In the urban household sector, electricity production would still be the largest contributor to the increase of CO_2 emissions, representing 20% of the total, assuming that China would still have a similar energy mix as today. Public transport and services such as banking, insurance, and education together rank as the second largest source for CO_2 emissions triggered by production for urban household consumption (17%). Due to the rapid increase in consumption of processed food by urban households and increasingly by rural households, food processing (with 14%) would overtake traditional agriculture to become the third largest CO_2 emitter triggered by urban household consumption.

In the capital investment sector, machinery production would replace construction as the largest CO_2 emitter, contributing 62% of emissions in this sector by 2030. Construction would still contribute 22% of sectoral emissions. Increasingly, capital investments will take place in rural areas to improve antiquated infrastructure such as rail, road, water, and electricity as well as agricultural machinery.

4.2 Westernizing lifestyles scenario

This scenario is designed with particular focus on the driving forces of lifestyle changes and their contributions to CO_2 emissions. Lifestyle change consists of changes in per capita consumption volume and changes in consumption patterns. In this scenario, we assume Chinese urban household consumption would grow more rapidly so as to achieve the current average US consumption patterns and expenditures of 2002 $25,000 in PPP terms by 2030, which is about 25% higher than in the reference scenario. This increase would require the income of every urban dweller to increase at a 5.9% per year over the 28 years from 2002. We keep the same trends for urban and rural income as our reference scenario. Therefore, the income of rural residents would increase at 5.4% annually from 2002 to 2030 with conversion towards current urban households' consumption pattern. To sustain these changes in lifestyles in both urban and rural households, Chinese GDP per capita would need to grow at an average of 6.4% through 2030, which is higher than the value of 5.6% in the reference scenario. The consumption pattern for 2030 would reflect a transition for China to a relatively more service-based economy. Services would account for 60% (compared to 47% in the reference scenario) overall GDP and the share of agriculture would drop to 2% by 2030 (compared to 3% in our reference scenario). The driving forces of population (p) and the efficiency gains (**F**) are identical to our reference scenario. Due to the differences in final demand between the reference and lifestyle scenarios, we re-balanced the input-output table in 2030 using the RAS technique.

Results:

Under the westernizing lifestyle scenario, China's total emissions would reach 16,600 MMT by 2030, with production-related CO_2 emissions reaching 13,600 MMT. This is 2,500 MMT or 24% more than in the reference scenario. As shown in the red series in Figure 3, keeping other factors constant, the change in per capita consumption would drive a 491% increase in CO_2 emissions, which is 1.4 times higher than in the reference scenario. Efficiency gains could only offset 257% (i.e. about half) of the increase in CO_2 emissions.

Even though attaining US consumption levels would increase emissions, the current US consumption structure (the urban Chinese consumption pattern in 2030 in the westernizing lifestyle scenario) would be "cleaner" than the projected one in our reference scenario since US residents consume relatively more services and less manufacturing products compared with projected consumption by urban population of China in the reference scenario. For example, the average US household spends 5% of their total expenditures on processed food products, 4% on machinery, electrical and electronic goods, and 2% on clothes, but 21% on retailing, restaurants and hotels, and 56% on public transportation and other services (U.S. Bureau of Economic Analysis, 2008). By contrast, the projections for urban household expenditures in our reference scenario show much larger shares for manufactured and processed products including 11% on processed food, 17% on electrical goods, and 9% on clothes, with only 13% and 26% on retailing and public transport/other services, respectively. This phenomenon is also reflected in Figure 3, where the change in CO_2 emissions due to consumption patterns would decrease emissions by 938 MMT or 28% of the total increase in this scenario if other driving forces stay constant, compared to the increase of 158 MMT or

5% relative to 2002's CO_2 emissions predicted by our reference scenario. However, the increase in direct emissions from private transportation sectors would be significant. For example, on average, each US household owned 1.9 cars and consumed 1,143 gallons (3.6 tons) of gasoline in 2001. If we assume that every Chinese urban household by 2030 would drive the same amount as every American, direct gasoline consumption would increase emissions by about 3,000 MMT.

The change in production structure would lead to an 87% increase in CO_2 emissions, compared to a 42% increase under the reference scenario. One of the main reasons for this rise is that increased expenditure on services and transport would require greater energy consumption, including electricity and gasoline. The CO_2 emissions from electricity production would almost double to 9,769 MMT, from 4,791 MMT in the reference case. The demand for public transport would be 2.5 times higher than in our reference scenario, however, that would not drive significant increase in petroleum extraction, refinery and distribution related emissions in China since 80% of China's oil consumption would rely on imports (International Energy Agency, 2007, Chapter 10).

Allocating the increase in CO_2 emissions to the different final consumers, we find urban households are responsible for 48% of the total growth, followed by capital investments (30%), government (23%) and rural households (8%). Producing exports would result in 3,925 MMT in increased emissions for China. The exports of machineries and other metal products would result in 1,459 MMT CO_2, which would be almost one-third of total emissions from producing all exports. If it is assumed that China produces its own imports, then China would avoid 3,109 MMT of CO_2 through imports. About 15% of this is in the extraction, refinery and distribution of oil and gas. The oil and gas would be primarily used in transportation sector; the combustion would result in about 3,000 MMT CO_2 emissions as stated above. In this westernizing lifestyle scenario, the freight and passengers transport is projected to increase 5% of GDP from 2002 to 2030; further the private vehicles ownership for urban Chinese would increase from less than 2 in 2002 to 190 cars per 100 households by 2030 (same as current US level).

4.3 Carbon dioxide capture and storage (CCS) scenario

Technological innovations and improvements are one of the most effective ways of reducing CO_2 emissions. Our historical results suggest that technological improvements would result in a 77% reduction in CO_2 emissions in 1981 level over the past two decades if other driving forces had kept at the same level as in 1981. Such reductions in emissions are highly desirable given ongoing structural changes. For example, by 2030, electricity could occupy more than 40% of China's final energy consumption due to structural change toward services, and coal-fired power plants would likely still dominate electricity as a whole, amounting to 70% ~ 80% of China's electricity supply (International Energy Agency, 2007, Chapter 10). Geological storage of CO_2 emissions from power plants could allow China to continue to use its abundant domestic coal reserves while reducing its CO_2 emissions. Carbon dioxide capture and storage (CCS) technology can offset roughly 85% of carbon dioxide emissions from the power plants, enabling continued use of fossil fuels accompanied by large reductions in CO_2 emissions. Much of the CCS technology is already demonstrated (IPCC, 2005), but still requires full scale implementation. As the leading emitter of CO_2, China will come under increasing pressure to assume more responsibility for its emissions. Some Chinese businesses are already willing to take action. For example, China Huaneng Group, one of the largest energy companies in China is leading a consortium building China's first integrated gasification combined cycle (IGCC) plant in Tianjin with 250 megawatts (MW) capacity by 2009 that will be expanded to 650 MW and fitted with capture and storage (Xu and Gao, 2006; Zhao and Gallagher, 2007). However, broad implementation of CCS faces several problems such as efficiency loss, locating appropriate sequestration sites. The potential cost of CCS equipped power plants is probably the most crucial issue. A survey by Reiner et al. (2007) of more than 100 Chinese key stakeholders found both government and industry respondents to be reluctant to invest heavily in CCS technology without significant outside investment.

The uncertainties of CCS implementation make scenario development difficult. We decided to take a best-case scenario to give an upper limit of the mitigation potential of CCS in China. Our CCS scenario assumes the same economic and social conditions as our reference case. In order to sustain the economic growth, China's total electricity generation would need to increase 8,627 terawatts hours (TWh) by 2030 (International Energy Agency, 2007) from 2,866 TWh in 2006 (National Bureau of Statistics, 2007b). Currently coal-fired plants account for 83% of total electricity generation; and the figure would decrease to about 70% due to the increase in generation from natural gas, nuclear, hydro and other renewable energy sources

(International Energy Agency, 2007). The newly installed coal-fired plants would provide 3,500 TWh of electricity generation, which accounts about 40% of the total generations by all coal-fired plants. This scenario assumes "best available technology" is imposed on coal consumption in the chemical, metal and construction materials production sectors and that all newly built coal-fired electricity generation would be fitted with CCS, eventually representing 40% of coal-fired power plants in 2030. The other driving forces are kept the same as in our reference scenario.

With CCS technology, the projected production-related CO_2 emissions in 2030 would drop by 44% to 6,100 MMT from 11,000 MMT in our reference scenario, which is still 1.8 times higher than 2002 emissions. As shown in the green series of Figure 3, efficiency gains would offset 272% of the increase of total production-related CO_2 emissions while the change in per capita consumption would drive a 308% increase in CO_2 emissions. Other driving forces had small effects: growth in population (5%), change in production structure (35%), and change in consumption patterns (4%).

5 Discussion

To date, China's annual CO_2 emissions have increased more than fourfold since the economic reforms began in 1978. Production-related emissions contributed the most to this increase. Per capita GDP growth was the major factor in driving the increase of Chinese CO_2 emissions while efficiency gains reduced the emissions only partly. However, efficiency gains will be less effective if China continues to develop in a similar manner as it has in recent decades.

Our reference scenario projects a threefold increase in production-related emissions in the next three decades above the 2002 level. Strikingly, our more radical projection on CO_2 emissions under a westernizing lifestyles scenario yields a fivefold emission growth if every urban Chinese would adopt a 2002 American lifestyle by 2030. Although there are concerns that US consumption is not sustainable, in fact US consumption patterns include larger shares of service sectors, which would be more "sustainable" than if Chinese consumption patterns simply followed its current trend, even after structural changes occurred. Efficiency and technology improvements will remain important in offsetting emissions (Peters et al., 2007). Importantly, even with the extremely optimistic scenario of the implementation of CCS on all new coal-fired generation, China's CO_2 emissions will still increase about 80% by 2030 over 2002 level.

China is a non-Annex B country in the Kyoto Protocol and consequently does not have an emission reduction commitment for pre-2012 period. Although China's annual CO_2 emissions will then be the world's largest in absolute terms, it is unlikely that China will take such a commitment in the near future (Adam, 2007; Zhang, 2000). Nevertheless, assuming that at this point China would commit to reduce its 2030 CO_2 emissions to its 2000 level, China's CO_2 emission would need to drop more than 70%, from 11,900 MMT based on our reference scenario to about 3,200 MMT. This reflects the enormity of recent Chinese growth in carbon emissions. To ensure the same economic growth as our reference scenario and simultaneously achieve the emissions reduction target, all Chinese sectors that consume coal would be required to install CCS devices, or more than half of China's energy would need to be supplied by renewable and nuclear energy, both of which seem unrealistic at the current time.

Even with efficiency improvements and rapid penetration of the best available technology assumed in the CCS scenario, it is unlikely that China's CO_2 emissions can be reduced to the 2000 level by 2030. Therefore further attention must be paid to the other driving forces, in particular structure changes in both production and consumption. Household consumption is playing an increasingly important role in the growth of CO_2 emissions and urban households will be responsible for at least half of the emission growth in the future. It is unrealistic and would be considered unfair to limit Chinese households to consume in certain ways. However, policy choices could be useful in shifting the growing Chinese consumption toward more climate-friendly patterns by encouraging public transportation and energy efficiency in the home, imposing a carbon tax on automobiles and so on. Any policies, however, would require sufficient considerations of their implications on income inequality.

Capital investment was the largest sector contributing to CO_2 emissions growth in the past, and as the importance of capital investment decreases with development (Crosthwaite, 2000), its environmental impacts will likely decrease as well. Nevertheless, we estimate capital investments would still account for at least one quarter of total production-related emissions by 2030, particularly as infrastructure is developed in rural and western China. Construction and machinery production have been and will continue to be major CO_2 emitters.

The growth in Chinese exports will continue to be an important question for the growth in Chinese emissions. This raises the question of where goods should be produced from an environmental perspective (Peters and Hertwich, 2008b). Many developed countries would have a comparative advantage in environmental terms to China in producing technology- and carbon-intensive products; and large amounts of emissions would be avoided if certain products were produced elsewhere and imported to China (Liu and Diamond, 2005). This does not imply Chinese exports are bad, rather, that the production systems and electricity system in China is dirtier than in many other competing countries. An increased focus of international trade in climate negotiations may increase pressure on China to improve its environmental profile to avoid isolation (Peters and Hertwich, 2008a; Wang and Watson, 2007; Weber et al., 2008). Furthermore authorities of developed countries should take the lead on new low-carbon technologies developments collaborating with developing countries as well as implement incentives for their firms to accelerate spillovers of advanced energy technologies to developing countries.

6 Reference

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