Drivers of Changing Household Carbon Footprints in China: Combined Structural Decomposition and Structural Path Analysis

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1. Introduction

To encourage economic progress, China's government has been pushing domestic consumption as a substitute for its waning growth in investment and exports. However, China's energy conservation and climate mitigation policies have focused on industries and have largely neglected households. China's households have experienced fairly radical lifestyle changes during the few decades. With rapid income growth, Chinese households 'moved up' the consumption ladder. Newly formed middle class has been emulating energy-addicted Western lifestyle with the purchase of cars, bigger homes, and more labor-saving appliances. Although China has also been promoting greener policies for growth, of which green consumerism is a prime component. Given its energy security concerns, global warming pressures and internal environmental concerns, China undoubtedly should be more cautious and alter its energy and climate policy course to include households. This study

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aims to examine the changing carbon footprint trends of Chinese households, explore related driving forces and identify emission hotspots.

2. Methodology and Data

A multiplicative structural decomposition analysis and a structural path analysis were used to explore the drivers and key supply chain paths of household indirect carbon emission.

3.1 Structural Decomposition Analysis

Household CO_2 emissions (F) is the sum of direct CO2 emissions (F^d) and indirect CO2 emissions (F^d) associated with energy used directly and indirectly by households. Household use energy directly for heating, lighting, transportation, and other purposes, and indirectly though purchased goods (e.g. food, cloth, ect.) and services (e.g. public transport, insurance, ect.)

Structural decomposition analysis (SDA) is commonly used to understand the underlying driving force of changes in energy use and CO2 emission. Using I-O tables, SDA can account both the supply- and demand-side effects(Miller and Blair, 2009).

Households' CO_2 emissions that stem from household spending can be expressed mathematically as:

$$F^i = \mathbf{f}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{h} = \mathbf{f}'\mathbf{L}\mathbf{h} \quad (1)$$

Let n be the number of industries, the other definitions are as follows: F^i is the CO_2 emissions embodied in goods and services that are consumed by households (Scalar); $\mathbf{f}'$ is a vector with f_k as the CO_2 emissions per unit of output for industry k ($1\times n$ vector); $\mathbf{L}$ the Leontief-inverse matrix $\mathbf{L}=(\mathbf{I}-\mathbf{A})^{-1}$, which is a matrix of total input requirements ($n\times n$ matrix); $\mathbf{I}$ the identity matrix ($n\times n$ matrix); $\mathbf{A}$ is a $n\times n$

matrix that shows the intersectoral direct requirements of each sector's production; $\mathbf{h}$ household consumption of production by industry ($n \times 1$ vector).

We further decompose carbon efficiency $\mathbf{f}'$ into two factors: $\boldsymbol{f}' = \boldsymbol{c}' \circ \boldsymbol{e}'$. $\boldsymbol{c}$ is the vector with c_k carbon emission per unit of energy consumption for industry k ($n \times 1$ vector). $\boldsymbol{e}$ is the vector with e_k indicates energy consumption per unit of output for industry k ($n \times 1$ vector).

Since China has experience rapid urbanization during the past two decades, we decompose household spending $\mathbf{h}$ into $\mathbf{h} = \mathbf{H}_\mathrm{p} \cdot \mathbf{p}_\mathrm{s}$ to show the differences of urban and rural household spending. $\mathbf{H}_\mathrm{p}$ denotes per capita sectoral expenditures by urban and rural households ($n \times 2$ matrix) and $\mathbf{p}_\mathrm{s}$ is the two-element vector representing the population of rural and urban households. We further decompose $\mathbf{H}_\mathrm{p}$ and $\mathbf{p}_\mathrm{s}$ into structure and volume components with $\mathbf{H}_\mathbf{P} = \mathbf{H}_\mathrm{s} \cdot \hat{\boldsymbol{y}}$ and $\mathbf{p}_s = p \cdot \mathbf{u}$. $\mathbf{H}_\mathrm{s}$ is household consumption preference by urban and rural households ($n \times 2$ matrix), and $\hat{\boldsymbol{y}}$ is a 2×2 diagonal matrix that shows per capita household expenditure of urban and rural households. p denotes total population (2×1 vector) and $\mathbf{u}$ is the urban and rural shares of total population (2×1 vector).

We decompose household indirect CO_2 emissions into seven partial factors which are related to changes in population levels (Δp), urbanization ($\Delta\mathbf{u}$), carbon emission per unit of energy ($\Delta\mathbf{c}$), energy efficiency ($\Delta\mathbf{e}$), interindustry input mix ($\Delta\mathbf{L}$)

household consumption preference ($\Delta\mathbf{H_s}$), and per capita household consumption level ($\Delta\hat{\boldsymbol{y}}$)[1] :

$$\frac{F_1^i}{F_0^i} = \frac{\mathbf{f}_1'\mathbf{L}_1\mathbf{h}_1}{\mathbf{f}_0'\mathbf{L}_0\mathbf{h}_0} = (2a)\times(2b)\times(2c)\times(2d)\times(2e)\times(2f)\times(2g) \qquad (2)$$

$$= \frac{(\boldsymbol{c}_1'\circ\boldsymbol{e}_1')\mathbf{L}_1\mathbf{h}_1}{(\boldsymbol{c}_0'\circ\boldsymbol{e}_1')\mathbf{L}_1\mathbf{h}_1} \qquad (2a)$$

$$\times\frac{(\boldsymbol{c}_0'\circ\boldsymbol{e}_1')\mathbf{L}_1\mathbf{h}_1}{(\boldsymbol{c}_0'\circ\boldsymbol{e}_0')\mathbf{L}_1\mathbf{h}_1} \qquad (2b)$$

$$\times\frac{\mathbf{f}_0'\mathbf{L}_1\mathbf{h}_1}{\mathbf{f}_0'\mathbf{L}_0\mathbf{h}_1} \qquad (2c)$$

$$\times\frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s1}\hat{\mathbf{y}}_1)(p_{\mathbf{1}}\mathbf{u_1})}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_1)(p_{\mathbf{1}}\mathbf{u_1})} \qquad (2d)$$

$$\times\frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_1)(p_{\mathbf{1}}\mathbf{u_1})}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_{\mathbf{1}}\mathbf{u_1})} \qquad (2e)$$

$$\times\frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_{\mathbf{1}}\mathbf{u_1})}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_{\mathbf{0}}\mathbf{u_1})} \qquad (2f)$$

$$\times\frac{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_{\mathbf{0}}\mathbf{u_1})}{\mathbf{f}_0'\mathbf{L}_0(\mathbf{H}_{s0}\hat{\mathbf{y}}_0)(p_{\mathbf{0}}\mathbf{u_0})} \qquad (2g)$$

Where $\Delta\boldsymbol{c}'$ represents the effect of changes in CO_2 emissions per unit of energy consumption by industry (Equation 2a); $\Delta\boldsymbol{e}'$, the effect of changes in energy requirements per unit of output (Equation 2b); $\Delta\mathbf{L}$, effect of changes in sub-industrial structure (Equation 2c); $\Delta\mathbf{H_s}$, effects of changes in household consumption preferences (Equation 2d); $\Delta\hat{\boldsymbol{y}}$, effect of changes in per capita household consumption level (Equation 2e); Δp, effect of changes in total population(Equation 2f); $\Delta\mathbf{u}$, effect of changes in China's urbanization level (Equation 2g).

[1] Above we only show one of two possible polar decompositions. Like many other studies, we examine both polar decompositions in the end using Fisher indices—the geometric means of the polar decompositions—to analyze results as suggested by Dietzenbacher et al. (2000).

3.2 Structural path analysis

Structural path analysis (SPA) is used to explore important supply chain paths of household carbon footprints. SPA has advantage to trace the embodied energy consumption or carbon emission that are driven by final demand back to the production activities (Li et al., 2020).As a I-O based economic network analysis tool, SPA decompose the Leontief inverse matrix to different transmission layers by Taylor series expansion (Liang et al., 2014; Su et al., 2019; Wood and Lenzen, 2009).

Here, we split household carbon footprint into different layers to extract key paths and critical transmission sectors.

$$F^i = \mathbf{f}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{h} \quad (3)$$

$$= \mathbf{f}'(\mathbf{I}+\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots+\mathbf{A}^n)\mathbf{h}$$

$$= \mathbf{f}'\mathbf{I}\mathbf{h}+\mathbf{f}'\mathbf{A}\mathbf{h}+\mathbf{f}'\mathbf{A}^2\mathbf{h}+\mathbf{f}'\mathbf{A}^3\mathbf{h}\ldots+\mathbf{f}'\mathbf{A}^n\mathbf{h}$$

3.3 Data Sources

This study is based on five types of data: household direct energy use data, sectoral-level energy consumption data, carbon emission factors, and national I-O tables. The energy data were taken from *China Energy Statistical Yearbook* for 1997, 2002, 2007, 2012 and 2017. CO_2 emission factors for the combustion of fuels were from *2006 IPCC Guidelines for National Greenhouse Gas Inventories* ((IPCC), 2006).

China's national input-output tables are used to calculate indirect CO_2 emissions for urban and rural households. Here we use the I-O tables for 1997 (124 sectors), 2002 (122 sectors), 2007(135 sectors), 2012 (139 sectors) and 2017(149 sectors) compiled by National Bureau of Statistics of China. To maintain consistency in this study, we aggregate all I-O tables to 91 industrial sectors and use double deflation method to adjust these tables to the constant 2017 prices. The price indices are taken from *China Price Statistical Yearbooks* and *China Statistical Yearbooks*.

Since China's national I-O tables are competitive tables, this paper readjusted the I-O tables with non-competitive imports assumptions. We distinguished the intermediate and final use of domestic and imported products based on Weber et al. (2008) and Li et al. (2020). With rapid expansion of China's foreign trade, the amount and the proportion of imported products are increasing. It is necessary to reflect the incomplete substitution relationship between the imported and domestic products and estimate the impacts of imported products on domestic economy.

Similar as Peters et al. (2007) and Zhang, Haiyan et al. (2016), the energy and CO_2 emission data are mapped to 91 sectors used in the I-O tables through a coordinate matrix. The demographic data of urban and rural population is from *China Statistical Yearbook*. For easy prestation and discussion, the detailed I-O and SDA analysis results for the 91 sectors are aggregated to 28 sectors. The sector names are listed in Table 1. To balance the explanatory power of calculation results and the complexity of the calculation process, we also aggregated the non-competitive I-O tables to 28 sectors for SPA-based sectoral analysis. This study focused on the first four transmission layers and integrated all other higher transmission layers as "Other layers".

Table 1 The detailed 28 economic sectors

	Sector
1	Agriculture
2	Mining
3	Food processing & Production
4	Beverage & Drink
5	Tobacco
6	Textile Products
7	Sawmills and furniture
8	Paper and Printing
9	Processing of Petroleum, Coking & Nuclear Fuel
10	Manufacture of raw chemical materials & products
11	Nonmetal products

12	Metals smelting and pressing
13	Metal products
14	Manufacture of General Purpose and Special Purpose Machinery
15	Transport equipment
16	Electric equipment and machinery
17	Electronic equipment
18	Instrument, meter & Others
19	Production and Supply of Electricity & Steam
20	Production and Distribution of Gas
21	Production and Distribution of Water
22	Construction
23	Transportation & storage
24	Postal, Information & Software Services
25	Commercial, Catering & Hotel
26	Finance, Insurance & Real Estate
27	Education, Health, Sports & Recreation
28	Other Service

2.5 Limitations and Uncertainties

We assume that the proportion of imported products in each sector's intermediate demand and final demand (excluding exports) is the same as the average import proportion in the corresponding sector when constructing the non-comparable input-output tables, which may lead to a discrepancy between the results and the actual situation (Tian et al., 2018).

The interpretation of uncertainties in the results is a key limiting factors; more efforts are needed to develop a standardize procedure for uncertainty estimation (Mi et al., 2020).

Measuring the emissions embodied in imports with domestic technology assumptions would lead to high uncertainty (Wu, 2019).

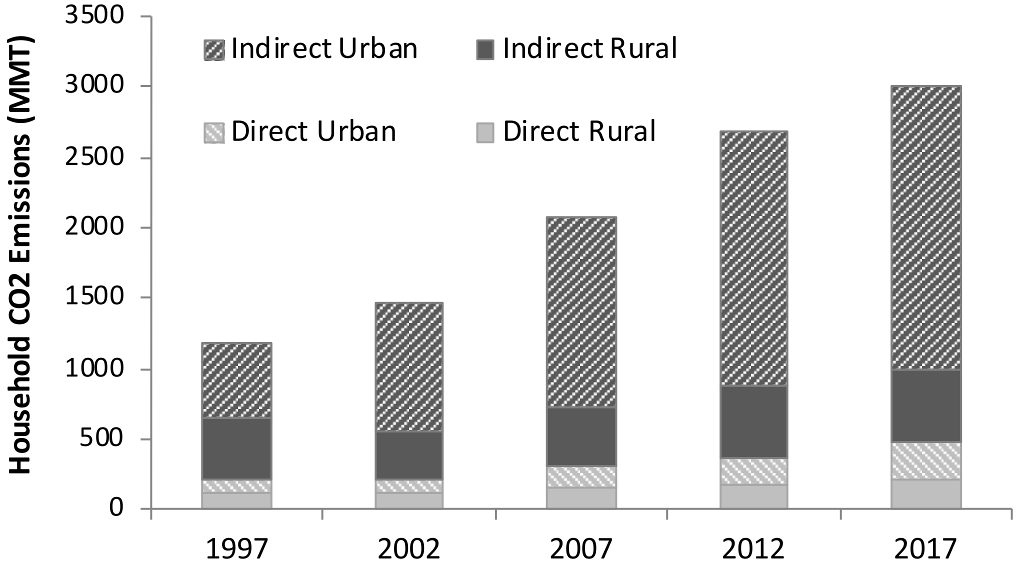
3. Results and Discussions

3.1 Households' CO_2 emission Trends

3.1.1 Residential direct CO_2 emissions

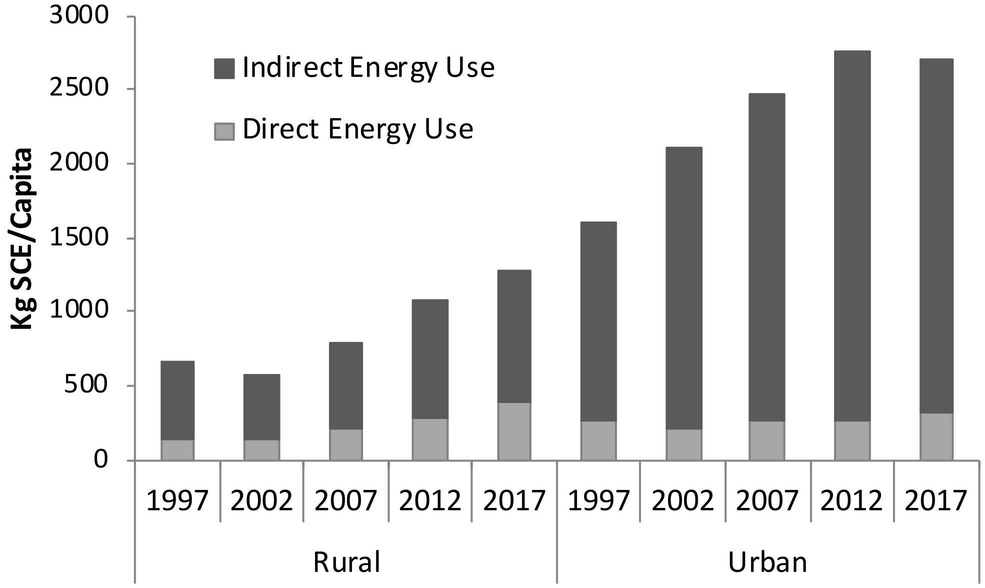
From 1997 to 2017, household direct CO2 emissions rose from 217 million metric tons (MMT) to 488 MMT. The growth rate kept stable still from 1997 to 2002 and then rose gradually at an average annual rate of 5.6% to 488 MMT of CO2 in 2017. Meanwhile household indirect CO_2 increased at an average annual rate of 4.9% from 964 MMT in 1997 to 2509 MMT in 2017 (See Figure 1). In 2017 Chinese households' CO_2 emissions in aggregate was split about 16 : 84 between direct and indirect emissions. Interestingly, from 1997 to 2017, aggregate direct CO2 emissions rose 99% for rural households and 152% for urban households. Meanwhile over the same period, aggregated indirect CO_2 emission increased only 12% for total rural households but 286% for total urban households. These changes were largely caused by the rapid urbanization and residential fuel substitution in China. Indeed, between 1997 and 2017, the share of urban population in China had rose from 31.9% to 60.2%, with its total urban population increased 114%, while its total rural population decreased 34%.

Figure 1. Resident's direct and indirect CO_2 emissions



Household energy consumption per capita has risen in both rural and urban China (See Figure 2). The fuel mix of both urban and rural households changed quite a bit from 1997 to 2017. The rising wealth, improving transportation and expanding electrical grid enabled rural residents to purchase more commercial energy resources such as coal, gas, and electricity (Wang and Feng, 2001). Urban households experienced a parallel transition. Their relatively higher wealth and more central locations enabled them to spend much larger shares of their consumption on commercial energy (Pachauri and Jiang, 2008). Direct use of coal by households fell steadily; residents moved to units with central heating and switched to electricity for cooking and water heating. Coal's share decreased from 61.2% in 1997 to 16.8% by 2017. Within 20 years, per capita CO_2 emission from urban households' direct coal use dropped precipitously from 192 kg to 39 kg, while it more than doubled for rural households from 120 to 267 kg. The decreasing direct use of coal in homes significantly improved indoor air-quality. With increased income, the type of energy resources used directly by households became more diversified: electricity, municipally provided heating, liquefied petroleum gas (LPG), and natural gas became more widely used. Electricity's share rose most rapidly, from 14.1% in 1997 to 29.5% in 2017. From 1997 to 2017, electricity usage per capita rose from 22.1 to 72.3 kg sce for urban residents and from 7.3 to 90.3 kg sce for rural residents.

Figure 2. Per capita resident's direct and indirect CO_2 emission



Compared to their rural counterparts, China's urban residents use greater shares of alternative commercial fuels such as natural gas, heat and LPG. Urban residents nearly fully replaced coal through the use of electricity, gasoline, natural gas, and LPG. In this regard, rural households have more work ahead. Direct coal use per capita by rural households kept rising from 1997 to 2017. In some rural areas that have limited access to electricity, coal continues to replace some non-commercial energy sources, such as firewood, straw, and other biomass as an important energy source for cooking and heating. While the rural-urban gap in direct household energy use shrank, by 2017 a typical urban resident still used 13.4% more direct energy than did a typical rural resident. The direct energy used by urban residents rose rapidly from 2002 to 2017, and the growth showed no sign of relenting (See Figure 2). But rural residents showed an even greater proportional change in their demand for direct energy use, especially for alternative commercial energy beside coal. Hence, rises in per capita residential direct energy use should be expected in both urban and rural areas of China in the future.

Due to fuel substitution in residential direct energy use, per capita direct CO_2 emissions of urban residents decreased from 272 kg in 1997 to 217 kg in 2002, but rose to 320 kg by 2017. For urban households, the contribution of natural gas to all direct CO_2 emission rose from 4% in 1997 to 34% in 2017. Trends in direct CO_2 emission per capita in rural areas were generally similar, but surpass urban levels since 2012. In 2017, per capital direct CO_2 emission for urban households was 22% higher than that for their rural counterparts. The contribution of coal to direct CO2 emissions by rural households decreased but only to 68% by 2017.

Increases in the ownership of private vehicles continue to play an ever-important role in residential direct CO2 emissions. Over the two decades ending in 2017, their contribution rose from 4% to 25% for urban households and rose from 2% to 14% for rural households. As more residents, both urban and rural, use more natural gas as well as motor vehicles, there is little reason to believe that direct CO_2 emissions produced by households will do anything but rise.

Table 2 Per capita household direct CO_2 emissions by fuel types (kg CO_2 SCE)

		Coal	Gasoline	Kerosene	Diesel Oil	LNG	Natural Gas	Total
Rural	1997	120	2	2	2	4	0	130
	2002	131	2	1	2	4	0	141
	2007	185	10	1	6	15	0	217
	2012	220	25	1	14	20	0	280
	2017	267	56	1	20	46	1	392
Urban	1997	192	10	0	5	53	12	272
	2002	115	14	0	10	56	21	217
	2007	91	27	0	21	67	51	258
	2012	51	47	0	30	54	87	269
	2017	30	80	0	12	91	108	320

3.1.2 Residential indirect CO2 emissions

CO_2 emissions embodied in goods and services consumed by a typical rural resident have also experienced major transformations. From 1997 to 2002, per capita indirect CO_2 emissions in rural areas decreased 17.1% to 436 kg in 2002, then it rose at an average annual rate of 4.9% to 888 kg in 2017. From 1997 to 2002, per capita rural household consumption only rose 5.0%, while the average energy requirement per unit of output had decreased by 33.4%. Energy efficiency gains, fuel substitution in production processes, changes in the rural households' consumption preferences and relative stagnant levels of rural household consumption all contributed to the 17.1% drop in per capita indirect CO_2 emissions of rural households from 1997 to 2002.

For urban households, indirect CO_2 emissions rose relatively steadily from 1997 to 2012, at an average annual rate of 3.7% to 2,760 kg. It then decreased slightly to 2,760 kg in 2017. The gap in indirect CO_2 emissions per capita between urban and rural households expanded over the first 15 years of that period—a typical urban resident emitted 798 kg more indirect CO_2 through goods and services than her rural counterparts in 1997 and 1690 kg more by 2012. But the gap closed to 1500 kg by 2017.

Households emitted more CO_2 indirectly than directly over the study period. Indeed, the contribution of indirect CO_2 emissions of urban household rose from 83% in 1997 to 90% in 2002 and then held fairly steady through 2017. Due to rural fuel shortages, the share of indirect CO_2 emitted by rural households decreased steadily from 80% in 1997 to 69% in 2017. As the supplies of rural energy resources became more abundant, the direct CO_2 emitted by rural residents rose more rapidly than did the indirect CO_2 emissions.

Households accounted for 38.6% of all CO_2 emissions in China in 1997 but just 27.8% in 2012. As China's economy turning back to households for economic growth, it rose slightly to 30% in 2017. Thus, it is clear that China must start to focus more on households when identifying CO_2 emission-reduction options. In this vein, diagnosing the driving forces of trends for household indirect CO_2 emission is important as well.

3.2 The Contribution of drivers to household CO_2 emissions

3.2.1 Driving forces of household indirect CO_2 emissions

Table 2 shows the overall average Fisher index as well as for each SDA component. Changes in the level of per capita consumption ($\Delta\hat{\mathbf{y}}$), dominated the growth in CO_2 emissions—effectively causing them to rise at an average annual rate of 7.1% from 1997 to 1992. It remained high and dominant through all four study sub-periods. Energy efficiency improvements ($\Delta\mathbf{E}$) tended to counteract influences of increments in per capita consumption. In fact, emission efficiency improvements more than offset the effects of household consumption per capita from 2002 to 2007. After 2007, energy efficiency gains edged downward to just 0.9% annually to 2012. It then rose slightly to 2.4% during the 2012 to 2017 period. Changes in CO_2 emissions per unit of energy consumption ($\Delta\mathbf{c}$) helped reduce household indirect carbon footprint for most of the past two decades except the 2002-2007 period. This can be contributed to greener energy structure in China during the most of the past two decades.

Table 3 Average annual changing rates of driving forces of household indirect CO_2 emissions

	$\Delta \boldsymbol{C_i}$	$\Delta \boldsymbol{E_i}$	$\Delta\mathbf{L}$	$\Delta\mathbf{H_s}$	$\Delta\hat{\mathbf{y}}$	$\Delta\mathbf{u}$	Δp	Total
1997-2002	-0.7%	-5.0%	0.8%	0.5%	7.1%	1.8%	0.8%	5.2%
2002-2007	0.1%	-9.3%	6.8%	1.9%	4.8%	1.8%	0.6%	6.7%
2007-2012	-0.5%	-0.9%	-2.2%	-1.7%	8.4%	1.5%	0.5%	5.2%
2012-2017	-1.1%	-2.4%	-2.1%	-0.7%	5.9%	1.1%	0.5%	1.3%

Changes in household preferences ($\mathbf{\Delta H}_s$) tended to effect little change in household indirect CO_2 emissions, enabling annualized changes in CO_2 emissions on the order of just -0.7% to 1.9%. Since 2007, changes in household preferences tend to help reduce households' carbon footprints. Annualized changes in CO_2 emissions attributable to interindustry input mix ($\Delta\mathbf{L}$)—akin to technology change—caused emissions to grow 6.8% annually from 2002 to 2007 period; this component's effects switched signs, reducing emissions by an average annual rate of around 2.2% thereafter.

During the study period, demographic factors always tended to cause household indirect CO_2 emissions to grow in China. But their contributions to the change in CO_2 emissions have tended to be comparatively small. Urbanization effects ($\Delta\mathbf{u}$) dominated population growth effects ($\Delta\mathrm{p}$). This domination is likely due to China's enforcement of its one-child policy, the effects of population growth have decreased gradually from 0.8% annually in the 1997–2002 period to 0.5% in the 2007–2017 period.

By focusing on the recent periods, we now further explore the contributions of household consumption preferences, household consumption levels and demographic changes in more detail.

3.2.2 Household consumption preferences

From 1997 to 2017, per capita annual spending rose significantly for both urban and rural households. The share of spending on core necessities—food and clothing—by all households, decreased from around *67*% in 1997 to about 36% in 2017. Meanwhile, the share of household expenditures on health care, transportation and communication services increased from 1997 to 2017. Chinese households clearly pursued a more comfortable style of living that depends on a developed service sector.

The nature of lifestyle changes affected households' indirect CO_2 emissions. Changes in household consumption preferences (**ΔH_S**) caused household indirect CO_2 emissions to rise from 1997 to 2007. Thereafter, households shifted their consumption preferences in a manner that helped to reduce their indirect CO_2 emissions though 2017 (see Table 3). Shifts towards spending on services partly explain these reductions.

A key element, from 1997 to 2017, was households' rising use of production from the *Utilities* sector, which accounted for 72% of the rise in indirect CO_2 emissions per capita in rural areas and 68% for urban areas. Not surprisingly, during this same period per capita electricity consumption rose 226% to 72.3 kg sce for urban households and 1137% to 90.7 kg sce for rural households.

Thus, the rising use of electricity explains much of rapid rise in indirect CO_2 emissions for all households. Outside of the *Utilities* sector, much of increase in indirect household emissions was due to rises in the consumption of services by energy-intensive *Transportation and Wholesale* sector, which accounted for 6.6% and 6.4% of indirect CO_2 emissions for rural and urban households, respectively. This rising indirect CO_2 emissions of the *Transportation and Wholesale Service* sector reflects China's ever-improving market accessibility and the increasing sensitivity of its consumer market to prices and product variety.

In the 2007–2017 period, *Raw chemical materials & products* accounted for 5% of the rise in per capita indirect CO_2 emissions for urban residents and 2% for rural residents. Per capita household indirect CO_2 emissions of products from this sector rose 53 kg for urban residents and 8 kg for rural residents. A large part of this increment was undoubtedly caused by the rising use of privately owned vehicles especially in urban China. *Metal Smelting, Pressing & Metal Products* accounted for 10% of the rise in per capita indirect CO_2

emissions of urban residents and 7% for rural residents. Households' rising consumption of living space and ownership of home appliances explains much of such indirect CO_2 emissions (Zhang, H. et al., 2016).

Fortunately, changes in household consumption preferences ($\Delta \mathbf{H}_s$) helped reduce household indirect CO_2 emissions from 2007 to 2017. For urban households, per capita indirect CO_2 emissions actually decreased 33 kg from the *Food and Tobacco Products* sectors, 15 kg from the *Textile Products* and 28 kg from the *Non-metal Products*. Rural households' indirect CO_2 emissions per capita from the *Food and Tobacco Products* sector increased only 3 kg from 2007 to 2017. From 2007 to 2017, urban households have been gradually shifting their consumption pattern toward low carbon goods and services.

Table 4 Per capita household indirect CO_2 emissions in China from 1997 to 2017

		Urban					Rural				
		97	07	17	97-07	07-17	1997	2007	2017	97-07	07-17
1	Agriculture	37	58	70	22	11	26	27	40	1	13
2	Mining	37	39	29	2	-10	16	10	10	-5	0
3	Food Production	49	75	51	25	-23	22	23	27	1	4
4	Beverage & Drink	13	21	12	8	-9	7	7	6	0	-1
5	Tobacco	5	2	0	-3	-1	2	1	0	-1	0
6	Textile Products	27	29	13	2	-15	8	6	4	-2	-2
7	Sawmills & furniture	4	3	1	0	-2	1	1	0	0	0
8	Paper & Printing	16	21	12	5	-9	5	5	4	0	-1
9	Petro-, Coking & Nuclear Fuel	15	45	53	30	8	7	11	16	4	5
10	Raw chemical materials & products	111	157	164	46	7	55	45	63	-10	18
11	Nonmetal products	62	50	22	-12	-28	19	10	9	-9	-2
12	Metals smelting & pressing	88	162	197	74	35	36	37	63	1	26
13	Metal products	3	3	2	0	-1	1	1	1	-1	0
14	Manufacture of Machinery	8	6	3	-2	-3	3	2	1	-2	-1
15	Transport Equipment	5	6	6	1	-1	3	1	1	-1	0
16	Electric equipment & machinery	3	3	1	0	-2	1	1	0	-1	0
17	Electronic Equipment	1	1	1	0	0	0	0	0	0	0
18	Other Manufacturing	6	2	1	-4	-1	2	0	0	-2	0
19	Utilities_Electricity & Steam	664	1250	1393	587	143	249	318	512	69	193

20	Utilities_Gas	10	4	1	-5	-3	0	1	0	0	-1
21	Utilities_Water	0	0	0	0	0	0	0	0	0	0
22	Construction	1	1	1	0	-1	0	0	0	0	0
23	Transportation & storage	66	102	153	36	50	30	28	59	-2	31
24	Postal, Information & Software Services	31	61	91	30	30	8	14	33	6	19
25	Commercial, Catering & Hotel	24	46	41	22	-5	9	13	14	4	1
26	Finance, Insurance & Real Estate	14	28	36	14	8	7	8	12	1	4
27	Education, Health, Sports & Recreation	11	18	15	7	-3	2	4	5	1	1
28	Other Service	10	18	20	8	2	4	4	6	0	2
Total		1323	2213	2388	890	175	525	578	888	52	311

3.2.3 Household consumption level

With rapid economic growth, households' incomes have increased steadily in both urban and rural China. Average per capita income rose at an average annual rate of 8.3% from 4,989 Yuan in 1992 to 24,565 Yuan in 2012 in urban areas but just 6.5% annually from 2,261 Yuan to 7,917 Yuan in rural areas (constant 2012 prices). Needless to say, large urban and rural disparities in income per capita persist across China. Rapid income growth has enabled significant lifestyle changes that have led households to become increasingly responsible for China's CO_2 emissions.

Chinese households have tended to adopt more energy-intensive and carbon-intensive lifestyles (Golley and Meng, 2012). According to Zhang, H. et al. (2016), Chinese households have increased their living spaces, electric appliance ownership, demands for space heating and cooling, and personal mobility. Each of these elements alone would lead any household anywhere to be responsible for more CO_2 emissions.

Better housing conditions have been responsible for higher indirect household CO_2 emissions through the enhanced use of products of the *Metal Smelting, Pressing & Metal Products* and *Petroleum, Chemical & Non-metal Mineral Products* sectors in the home construction process. Improved personal mobility has tended to increase CO_2 emissions directly via the use of vehicles that burn petrol and indirectly through the supply chain required to produce the vehicles, the construction of transportation infrastructures, and so on. As their incomes rise and residences enlarge, Chinese households have been buying more home appliances. The spreading use of home appliances has lifted households' CO_2 emissions indirectly both at utilities through the use of electricity and through appliance production.

As incomes in China continue to increase, more and more households will climb the consumption ladder. And as long as they have aspirations for an easier life—one with improved housing conditions, personal mobility, indoor climate control, and time-saving devices— Chinese households will consume in a more carbon-intensive manner; just how carbon intensive it will be remains unclear.

3.2.4 Demographic changes

Since 1997 and through 2017, China's population rose 0.6% annually to reach a total of 1.39 billion inhabitants. The number of urban households grew even faster—3.7% annually and now at a count of 433.1 million. The difference in these two changes is explained by a reduced average size of China's households, which declined by nearly a whole person to 3.02 people per household over the 20 years ending in 2012. Still, rapid urbanization appears to be a main motivation for this change over the past two decades; the urban share of China's population, which was 31.9% in 1997, increased to 58.5% by 2017. According to China's New Urbanization Plan (2014–2020), the share of urban population in China is expected to rise to 60% in 2020. This plan foresees 100 million moving to China's cities by 2020.

Over the last few years, China has relaxed its one-child policy to counter the problems created by it, in which the count of China's elderly was poised to become substantially larger than that of the working population that would be available to support it. In November 2013, China adjusted its family planning policy to allow couples to have a second child if one spouse was an only child. In October 2015, China further loosened its fertility policy to allow all couples to have two kids (*China Daily*, 2015). The policy change has brought a "second-child baby boom" to China.

The above prospective demographic changes are likely to manifest in household consumption levels and patterns through several different pathways. First, small households consume more energy and resources per capita. China's shift to smaller households poses serious challenges to energy conservation and CO_2 emissions ; Second, with rapid urbanization, the geographical expansion of large cities and newly formed urban zones dramatically increased the demand for buildings and transportation infrastructure. Meanwhile, due to the huge urban-rural gap per capita in CO_2 household emissions, urbanization should in the foreseeable future continue to significantly enhance the total household CO_2 emissions, both directly and indirectly; Third, the universal second-child policy will not only bolster population growth but also spur new spending on healthcare, clothing, educational goods and services, and related items. In summary, the combined demographic trends of ever-smaller household sizes, increasing urbanization, and a planned baby boom will continue to cause household CO_2 emissions to surge in the long run.

4. Conclusions & Policy Implications

Chinese households' CO_2 emissions have risen 154% from 1,181 MMT in 1997 to 2,997 MMT in 2017. The rural-urban gap in CO_2 emissions between urban and rural households has risen too, so that in 2017, household CO_2 emissions per capita were 1,280 kg for rural households and 2,708 kg for urban households. Households have been increasingly shifted their consumption towards more energy- and carbon-intensive goods, like Primary Iron and Steel Manufacturing. From 1997 to 2007, the main factors increasing such emissions were income levels, consumption preferences, and interindustry input mix. Further increases in demand for living space, electric appliance ownership, heating and cooling, and personal mobility will cause China's residential sector to become more emissions-intensive.

The lifestyle changes mentioned above could amplify CO_2 emissions even further by inducing changes in China’s production structure. Fortunately, changes in interindustry input mix, household consumption preferences, energy efficiency gains and energy structure change have helped reduce household indirect CO_2 emissions from 2007 to 2017. Moreover, urban households have been gradually shifting their consumption pattern toward low carbon goods and services. Generally speaking, emission efficiency gains have largely offset the effects of household consumption rises.

China's household energy consumption is lower than the Western standards, but its potential for growth looms large. As their incomes rise, Chinese households tend to consume more, as was mentioned earlier. China's newly formed urban middle class has been emulating energy-addicted Western lifestyle with the purchase of cars, bigger homes, and evermore labor-saving appliances. At the same time, rapid urbanization is inducing smaller household sizes, narrowing the urban-rural income gap, and providing large sources of domestic demand and services. Since rural households have been producing fewer CO_2 emissions, their potential producing more of emissions per capita is particularly high if they continue a desire to emulate their urban counterparts. With income-induced lifestyle change, increasing urbanization, and the pending "second-child baby boom", household-based CO_2 emissions could well rise for many years to come. In this vein, a focus on household-based CO_2 emissions is paramount in any policy developments or further research on carbon emissions in China.

China is now encouraging private consumption to boost its economy. Given this and the trends promising rises in household-based emissions per capita, it is clear that guiding Chinese residents' lifestyles toward low carbon consumption must be part of a strategy used by China to achieve its 2030 peak carbon emission target. A low-carbon future depends on what we do today. The long-run lock-in effect of infrastructure binds future households' choices through the sets of alternatives that China makes available now, such as greener building, more public transit, and supporting renewable energy technologies (e.g., the generation of electricity through wind, solar, geothermal, and hydro power). Thus, the Chinese government must take an active, central role in promoting green consumption by implementing regulations, like stricter building codes and higher energy efficiency standards as well as coordinate cross-sector policies that may have potential environmental impacts on household decisions. Corporations and enterprises also should adopt low carbon responsibility by managing emissions through their supply chains as well as by facilitating low-carbon consumption through labeling such as via a green-product certification system. In all, China needs to shift to a low carbon economy that will help counter climate change and at the same time as promote economic and social progress.

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