Policy Analysis

China's Growing CO_2 Emissions—A Race between Increasing Consumption and Efficiency Gains

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China's rapidly growing economy and energy consumption are creating serious environmental problems on both local and global scales. Understanding the key drivers behind China's growing energy consumption and the associated CO_2 emissions is critical for the development of global climate policies and provides insight into how other emerging economies may develop a low emissions future. Using recently released Chinese economic input—output data and structural decomposition analysis we analyze how changes in China's technology, economic structure, urbanization, and lifestyles affect CO_2 emissions. We find that infrastructure construction and urban household consumption, both in turn driven by urbanization and lifestyle changes, have outpaced efficiency improvements in the growth of CO_2 emissions. Net trade had a small effect on total emissions due to equal, but significant, growth in emissions from the production of exports and emissions avoided by imports. Technology and efficiency improvements have only partially offset consumption growth, but there remains considerable untapped potential to reduce emissions by improving both production and consumption systems. As China continues to rapidly develop there is an opportunity to further implement and extend policies, such as the Circular Economy, that will help China avoid the high emissions path taken by today's developed countries.

Introduction

China's rapid economic growth is bringing wealth and prosperity, but the Chinese environment (*1*, *2*) and society (*3*, *4*) are struggling to keep pace. Recently, China has undergone profound transformations from a centrally planned toward a market-oriented economy and a shift from a rural agriculturally based to an urban industrially based society (*5*). China has become one of the fastest growing economies in the world with an average annual GDP growth rate of 9.7% (*6*). The economic success has resulted in considerable improvements in people's quality of life (*4*) with large sections of the population experiencing a transition out of poverty and toward consumerist lifestyles (*6*). However, the economic achievements have required significant natural resources inputs. Between 1990 and 2004 China's total energy consumption has grown 5.0% annually from 18 EJ (10^{18} J) to 58 EJ (*7*), and CO_2 emissions grew by 4.8% per year from 1446 million metric tons (MMT) to 4707 MMT (*8*).

In a global context, China is the second-largest contributor to CO_2 emissions, emitting 17% of global CO_2 in 2004, up from 8% in 1980 (*8*). China is predicted to become the world's largest emitter by as early as 2009 (*9*). Understanding the key drivers behind China's growing energy consumption and associated emissions is critical for both Chinese and global policy. It is likely that other developing countries such as Vietnam and India will develop similarly to China, and the lessons learned by analyzing China's changing energy consumption may provide guidance toward a low emission development path for other countries. Equally important, CO_2 emissions occurring in China have a global impact, and China's engagement in global climate change mitigation is essential. Given China's population and expanding economy, increases in China's CO_2 emissions are likely to offset potentially high cost mitigation efforts elsewhere (*10*, *11*). In fact, global CO_2 emissions have increased (*12*) despite global effects through the United Nations Framework Convention for Climate Change (UNFCCC) and its Kyoto Protocol (*13*).

We utilize structural decomposition analysis (SDA) (*14*) to analyze the causes of China's recent growth in energy consumption and associated emissions. Some SDA studies on China have been performed previously but have used different methods and addressed different issues. An earlier study by Lin and Polenske (*15*) analyzed the changes in Chinese energy consumption between 1981 and 1987. They found that consumption growth outweighed efficiency improvements and that structural changes were relatively small. Increased expenditure on capital products was the main factor increasing emissions, followed by households, with the emissions avoided by imports growing faster than the emissions embodied in exports. Garbaccio, Ho, and Jorgenson (*16*) analyzed the changes in the energy-output ratio from 1987 and 1992, and Andresosso-O'Callaghan and Yue (*17*) analyzed the changes in economic output from 1987 to 1997. Both studies found efficiency improvements were most important with structural changes being of minor importance. There have been several index decompositions studies (*18*—*21*), but these studies cannot provide the sectoral detail that is found in SDA (*22*).

This study analyzes China's CO_2 emissions from 1992 to 2002 with results for energy consumption and SO_2 and NO_x emissions in the Supporting Information. Following other SDA studies we focus on the emissions caused by the production of consumable goods and services, and we do not analyze direct fuel use by households. The direct CO_2 emissions in households cover 5—10% of China's total emissions and are often studied separately due to specific data requirements, particularly with regards to biomass (*23*, *24*). The following section details the methods and data utilized in the analysis, followed in turn by the decomposition results and a discussion of the implications for China, other developing countries, and global climate policy.

Methods and Data

In general, a country's energy demand and associated emissions change over time for a variety of reasons—growth

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in economic output, changes in trade structure, infrastructure investment, efficiency improvements, and changes in the production and consumption systems. A key method for understanding the relative contribution of each of these effects is structural decomposition analysis (*14*). SDA is based on environmental input−output analysis (*25*) which has become an established method in life cycle assessment and energy analysis (*26*, *27*). IOA determines the economy-wide environmental repercussions stemming from economic activity and can be expressed mathematically as

$$\mathbf{f} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{1}$$

where $\mathbf{y}$ is a vector of the final demand purchases from each economic sector, $\mathbf{A}$ is a matrix showing the monetary relationship between different sectors in the economy (the technology), $\mathbf{I}$ is the identity matrix, $\mathbf{F}$ is a matrix with the rows representing the emission intensities of each pollutant in each sector, and $\mathbf{f}$ is a vector with each element representing the resulting emissions. We further decompose $\mathbf{y}$ into structural and volume components $\mathbf{y} = \mathbf{y_s}y_v$ and consider the production structure through the Leontief inverse, $\mathbf{L} = (\mathbf{I}\text{-}\mathbf{A})^{-1}$. By considering the change in each variable over time the SDA of (1) can be expressed as

$$\Delta\mathbf{f} = \Delta\mathbf{F}\mathbf{L}\mathbf{y_s}y_v + \mathbf{F}\Delta\mathbf{L}\mathbf{y_s}y_v + \mathbf{F}\mathbf{L}\Delta\mathbf{y_s}y_v + \mathbf{F}\mathbf{L}\mathbf{y_s}\Delta y_v \tag{2}$$

where the first term represents the contribution to change in emissions, Δf, due to aggregated changes in the emission intensities (efficiency), $\mathbf{F}$; the second term represents changes in the production structure, $\mathbf{L}$; the third term represents changes in the consumption structure, $\mathbf{y_s}$; and the fourth term represents changes in the consumption volume (GDP), y_v. When performing the SDA it is possible to compare terms relative to the start or end of each time-period, and this leads to a uniqueness problem. To account for this issue we take the average of all the first-order decompositions (*28*−*30*). These issues are detailed in the Supporting Information.

China has a long history of IOA, and the necessary data are compiled every 5 years (*31*). In this study we use the 1992, 1997, and the recently released 2002 data compiled by the Chinese National Statistical Bureau. The IO tables are in the industry-by-industry format with the assumption of homogeneous sector output (i.e., no joint products). The data are converted from some 120 sectors (depending on the year) into a consistent industry classification with 95 economic sectors and then converted to 1997 constant prices using the double deflation method. The Chinese IO data include several categories of final demand—rural and urban households, government, capital formation, changes in inventories, exports, and imports. The preparation of the IO tables is described in the Supporting Information.

The energy and environmental data were taken from previous research (*32*) and built on two main sources: China's Energy Statistical Yearbooks and compiled national data from the Lawrence Berkley National Laboratory (*7*). The emissions from both combustion of fuels and industrial processes were calculated using the IPCC reference approach (*33*). The 1992 energy and emissions data have 36 industry sectors, and the 1997 and 2002 energy and emissions data have 44 industry sectors. We constructed a concordance matrix to map the energy and emissions data to the 95 economic sectors. More details are contained in the Supporting Information.

Results

In the 10 years from 1992 to 2002, China's production-related CO_2 emissions increased by 59% from 2163 MMT CO_2 to 3440 MMT CO_2. Our structural decomposition analysis for 1992, 1997, and 2002 shows that increased GDP (consumption volume) drives the increase, with efficiency improvements offsetting some of the increases, Figure 1. If China's technology and economic structure had remained constant, GDP growth would have caused China's CO_2 emissions to increase by 2786 MMT (129%) between 1992 and 2002, and improved energy efficiency (energy consumption per unit output) would have caused a 1246 MMT (−62%) decrease. Structural changes in production led to a 229 MMT (−11%) decrease, and structural changes in consumption led to a 65 MMT (3%) increase. These findings are consistent with changes in the 1980s for China (*15*) and more broadly with studies on a wide range of developed countries (*14*). We find similar results for energy consumption and SO_2 and NO_x emissions (see Supporting Information). Figure 1 also shows that there is a more notable improvement in efficiency from 1997 to 2002 compared to 1992 to 1997. Below, we investigate whether this apparent improvement is caused by the under-reporting of Chinese coal consumption from 1996 to 2003.

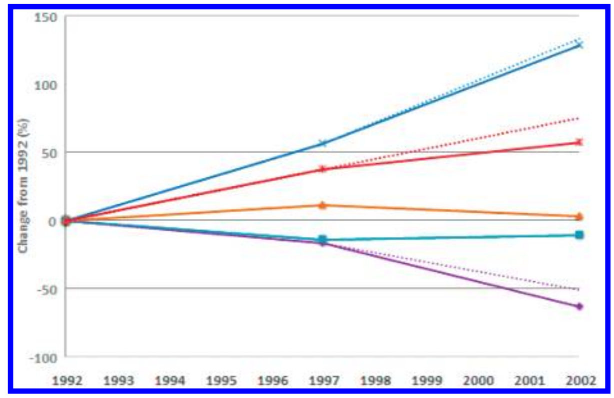

FIGURE 1. The solid red line shows the percentage change in CO_2 emissions from 1992 to 2002 (red, 59%). The solid colored lines represent the contribution to change from GDP growth (dark blue, 129%), efficiency improvements (purple, −62%), production structure (light blue, −11%), and consumption structure (orange, 3%). The dashed line shows the percentage change in CO_2 emissions from 1992 to 2002 (red, 76%) using the modified coal consumption data, with the contribution to change from GDP growth (dark blue, 134%), efficiency improvements (purple, −50%), production structure (light blue, −10%), and consumption structure (orange, 2%).

We only analyze the CO_2 emissions from the production of products and services which represent 90−95% of China's CO_2 emissions. There are also direct household CO_2 emissions such as the fuel used in private transportation and for heating and cooking. We estimated the direct CO_2 emissions as 246 MMT for 1992, 227 MMT for 1997, and 181 MMT for 2002. The decline in direct household CO_2 emissions is due to reductions in household coal and biomass consumption, especially in rural China (*23*, *24*, *34*).

Figure 2 shows an allocation of the total emission increases to the separate final demand categories. Of the 1276 MMT (59%) increase in CO_2 emissions from 1992 to 2002, 712 MMT (56%) was due to capital investment, 482 MMT (38%) was due to households with a 557 MMT (45%) increase in urban households and a 88 MMT (−7%) decrease in rural households, 100 MMT (8%) was due to government expenditure, and 17 MMT (−2%) was due to net trade. We now consider each of these final demand categories separately.

In 2002, capital investment was responsible for 52% of China's total CO_2 emissions, increasing from 45% in 1992. Of the 712 MMT increase in CO_2 emissions from capital investment, 78% was due to construction activities. The increased CO_2 emissions from construction resulted from a 155% increase in demand for construction activities, tempered by a 55% improvement in efficiency and a 22% improvement in production structure, mostly due to reduction in inputs of cement, electricity, steel, and other nonmetallic mineral products (e.g., bricks, tiles, glass, and

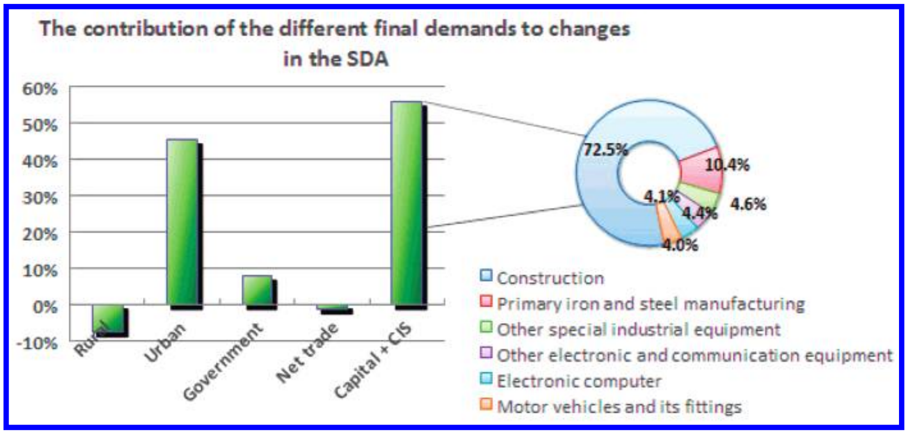

FIGURE 2. The final demand categories causing the increase in China's CO_2 emissions. Gross capital formation is responsible for half of the increase, and this is dominated by construction and related activities. Urbanization and increased wealth of households has caused the next biggest increase in emissions.

other lightweight building materials) into the construction sector.

After construction, the energy consumption required in the production of products and services for household consumption contributed to a 482 MMT (38%) increase in CO_2 emissions from 1992 to 2002. Of particular importance is the disparity between urban and rural households. While households represent about 40−45% of expenditure and emissions, the distribution across rural and urban varies considerably (*6*, *35*). In 1992 rural households represented over half of household expenditure and emissions and in 1997 the split was roughly equal, but by 2002 urban households spent and emitted about three times more than rural households. In total, urban households caused China's CO_2 emissions to increase 557 MMT (45%), while rural households caused a decrease of 88 MMT (−7%). This large shift and increase in emissions reflect an increase in the urban population of 180 million and a decrease in the rural population of 68 million (*36*). This trend is set to continue, with the urbanization rate of 38.6% in 2003 predicted to increase to 60.5% by 2030 (*37*). Urban households tend to have much higher income and consumption levels and thus higher energy consumption (*35*, *36*).

Of the 482 MMT increase in CO_2 emissions due to household consumption, the largest increase was from electricity consumption (33%), followed by strong growth in many service sectors such as education, real estate, and dining, see Table 1. This mirrors trends in developed countries (*38*). The large increase in electricity consumption reflects increasing rates of rural electrification since 1990 and increasing consumption of computers, refrigerators, TVs, and air conditioners (*34*, *36*). Together, service sectors are responsible for 51% of the growth in household emissions, more than the growth in electricity-related emissions. The growth in some service sectors, such as education and health, is due to both deregulation of these services and increased income (*6*).

The shift to services represents an economy-wide trend, driven largely by changes in household consumption, government expenditure, and export of services. While the monetary shift to services was considerable, with services representing 28% of the economy in 1992 and 41% in 2002, the shift in CO_2 emissions was much smaller, 23% of 1992 emissions to 26% in 2002. This is because services generally have lower emissions intensities (*39*). Of the 1276 MMT increase in CO_2 emissions from 1992 to 2002, 64% of the increase occurred in manufacturing sectors, while 35% occurred in the service sectors. However, 44% of the increase was in construction and 14% in electricity production (mainly for households), leaving the remainder of the manufacturing sectors contributing to only 6% of the total increase in CO_2 emissions. Put in this context, the aggregated increases in services are quite significant. Despite the large growth in services, the overall effect of changes in consumption structure, as seen above, was fairly small since emission reductions from increased services were offset by shifts toward products with high-CO_2 intensity, notably construction and electricity.

Surprisingly, net trade, measured as exports minus imports, contributed very little to changes in China's overall environmental impacts, though this may vary on a regional basis (*40*). There is a rough balance between CO_2 emissions from the production of exports and emissions avoided by imports. Despite this balance, there has been strong absolute growth in both exports and imports. In 1997 the CO_2 emissions embodied in exports was 25% of China's total CO_2 emissions, but 24% of the total CO_2 emissions were avoided by imports. These figures grew to 32% for exports and 34% for imports for 2002. Unfortunately only data on net exports are available in 1992. Interestingly, China was a net exporter of pollution in 1997 and a net importer in 1992 and 2002, while economically China has been a net exporter in those same years. For a brief analysis of the sectoral breakdown of trade see the Supporting Information.

Under-Reporting of Coal Consumption. Despite increases in Chinese CO_2 emissions, official energy statistics show a significant decrease in coal consumption from 1996 to 2000 (*36*). According to official statistics, from 1996 to 2000 China's coal consumption declined substantially, Figure 3, and then rapidly increased from 2000 to 2004 back to the historic trends. During this time period non-coal-based energy increased in line with historical trends. Some have argued that the decrease was realistic and resulted from successful Chinese policies aimed at structural change and efficiency improvements (*18*, *21*, *41*, *42*). However, recent satellite data suggest that there was significant under-reporting of coal consumption and that the official statistics should not be used for emission inventories (*43*). Poor statistics may be due to a number of highly dispersed users—such as smaller often rural enterprises and households—using coal from small and inefficient coal mines. Further, the policy to close these small mines has probably been less successful than thought as many continue production illegally (*44*, *45*). Two of the data points in our analysis are affected by the unusual coal consumption, but only 2002 differs substantially from the historic trend, Figure 3. To account for the potential under-reporting for 2002 we perform a scenario which scaled up the coal consumption in 2002 to reflect the historic trend (more details in the Supporting Information).

TABLE 1. Top Sectors Responsible for the Increase in CO_2 Emissions in Production Sectors Triggered by Household Consumption from 1992 to 2002[a]

	1992−1997	1992−2002
electricity and steam production and supply	23.30%	32.90%
educational services	3.60%	11.30%
real estate	5.10%	9.90%
cement and cement asbestos products	2.20%	8.30%
eating and drinking places	2.90%	8.00%
residential and other services	0.30%	7.30%
post and telecommunications	3.90%	4.40%
wearing apparel	7.60%	4.20%
wines, spirits, and liquors	4.00%	−2.30%
tobacco products	−0.50%	−2.40%
highway freight and passengers transport	−6.50%	−2.40%
crop cultivation	5.90%	−2.80%
other general industrial machinery	−7.60%	−3.80%
cotton textiles	−8.60%	−4.00%

[a] The figures are expressed as a percentage of the increase in household emissions (all sectors add to 100%).

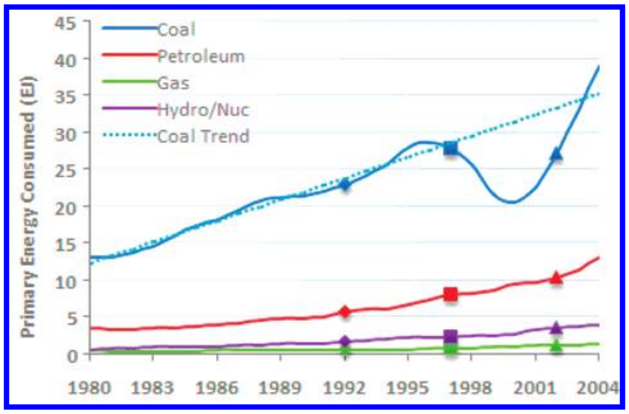

FIGURE 3. Historic energy consumption in China showing the dip in coal consumption from 1996 to 2003 which may be due to under-reporting of coal consumption. The dashed line shows the linear trend in coal consumption from 1980 to 1996. The data points for 1992, 1997, and 2002 are shown by the diamond, square, and triangle.

With the modified coal data, Chinese CO_2 emissions grew 1646 MMT (76%) from 1992 to 2002 instead of 1276 (MMT) 59% in the unmodified data, Figure 1. The contribution of GDP growth to increased emissions was 134%, up from 129% in the unmodified data; efficiency improvements reduced emissions 50%, a considerable decrease from 62% in the unmodified data; and structural changes were unaffected. Despite these changes, the general form of Figure 1 remains unchanged suggesting that even though coal consumption was under-reported, there were still significant improvements in energy efficiency between 1997 and 2002 (*41*). Further analysis shows that there are significant efficiency improvements in the other fuel-types, in particular liquid based fuels (calculations not shown).

Uncertainties

Uncertainty arises in IOA through many avenues (*25*), but of greatest concern when performing SDA is the construction of constant price data and uniqueness issues. While the double deflation method is a widely accepted method of constructing constant price data, there are other methods with various advantages and disadvantages (*46*). Key issues and assumptions for our methodology are discussed further in the Supporting Information. Similar methodological issues arise in SDA, with the uniqueness issues discussed earlier.

In addition to the methodological uncertainty in IOA and SDA, data uncertainty may also be significant but is often difficult to quantify. Because we utilize both underlying energy and economic data from Chinese national statistics, uncertainties in either of these data sources will affect the results. The main concern with the energy data is the under-reporting of coal consumption (discussed above). On the economic side, several authors have questioned the reported economic growth and resulting GDP by Chinese authorities (*47*, *48*). The GDP error in isolation would make the Chinese economy look more energy and pollution intensive since the same amount of reported energy consumption would be used to produce less output.

Finally, the trade results require careful interpretation. Due to data limitations, we could only calculate the emissions through avoided production in China by imports and not the actual emissions embodied in imports. The difference between these quantities, as discussed in the Supporting Information, is due to differences in production structures between China and its trading partners. Compared to most countries China has a relatively pollution-intensive economy (*49*, *50*), and it is likely that the emissions embodied in China's imports will be lower than the emissions avoided by producing the imports elsewhere. Peters and Hertwich considering regional differences in production technologies and energy mixes for 87 countries found that for 2001 the CO_2 emissions embodied in China's exports was 26% of domestic emissions, while the CO_2 emissions embodied in China's imports was 9% (*51*). Consequently, China is actually a net exporter of CO_2 emissions to other countries.

Discussion

Capital investments such as in infrastructure are an important motor for economic growth in many developing countries (*52*, *53*), but the downside is increased pollution through the production of cement, steel, glass, etc. Since the importance of construction decreases as a country develops (*52*), it is likely that the environmental impacts associated with the construction sector will decrease as well. There is recent evidence for this observation in the global iron cycle (*54*). On the other hand, infrastructure may lead to increased use-phase emissions. For instance, the emissions from personal car transportation are likely to increase rapidly as infrastructure is put in place (*55*). One potential strategy to avoid this and similar scenarios is to leapfrog to low emission technologies (*56*). Examples include avoiding the need for fixed telephone infrastructure by leapfrogging straight to mobile technologies (*57*) and moving to natural gas for transportation skipping limited efficiency improvements in gasoline or other liquid fuels. Given that infrastructure is in place for decades or centuries and that China is now heavily expanding its infrastructure, it is an opportune time for China to invest in infrastructure that meets both its development goals and a low emissions future.

Increases in CO_2 emissions related to household consumption are driven by a combination of urbanization and increased expenditure of urban households. Despite a positive structural shift toward consumption of less energy-intensive services, increased consumption of energy-intensive products such as electricity and appliances at the household level and construction activities at the national level mostly offset efficiency gains. It is likely that the environmental pressures from increased household consumption, urbanization, and population will continue with China's development goals (*2*, *6*, *35*).

International trade has been an important driver for China's economic growth (*53*). The increased economic activity for the production of exports may have a significant regional impact for local pollutants (*40*), but for global pollutants such as CO_2 the impacts may balance. While our analysis determined the emissions avoided by imports and found a rough trade balance for emissions, other studies using more realistic assumptions that include regional differences in economic structure and energy mix show that China is a net exporter of CO_2 emissions (*50*, *51*). This raises the question of where goods should be produced from an environmental perspective (*11*). While Chinese production has several advantages for the global economy, it currently causes greater environmental impacts compared to if the goods were produced in many other regions (*1*). This situation can be remedied by technological and energy mix improvements within China.

What can other countries learn from China's experiences? In the near future, it is likely that China will pursue continued economic growth in an attempt to reduce poverty and improve quality of life (*4*). In the context of this study, this leaves efficiency improvements or structural changes in production and consumption as the only methods to reduce energy consumption and emissions. As in most countries, China has improved energy efficiency, and this has effectively reduced China's CO_2 emissions by 50−60%. There is considerable potential for further efficiency gains through continued energy conservation, fuel switching, renewable energy, carbon capture and sequestration, and so on (*58*, *59*). However, recent research suggests that if China and India strive to have similar income levels as Japan, technological improvements alone are unlikely to stabilize emissions (*6*). While efficiency and technology improvements will remain important, strong policies are required to capture the still-untapped potential to reduce emissions through structural changes in production and consumption.

In the observed time period, China's CO_2 emissions were 10−15% lower due to changes in production structure, mainly through reduced inputs of concrete, nonmetallic products, iron and steel, and electricity into the construction sector. The Chinese government has already placed strong support for structural improvements in production systems through the political goal of the 'Circular Economy' (*60, 61*). While the Circular Economy is not concretely defined, the central idea is to close material loops, reduce inputs, and reuse or recycle products and waste to achieve a higher quality of life through increased resource efficiency. In practice, this encompasses the creation of optimized resource flow networks among companies, ecoindustrial parks, and regional infrastructure (*62*). Not only is continued implementation of the Circular Economy needed but also is its extension across scales—such as regional, provincial, national levels. Extending the Circular Economy paradigm to include household consumption will help China meet greater structural improvements.

Parallel to policies targeting the performance of production systems and addressing regional imbalances are policies addressing the behavior of consumers. Recent research is reinforcing the importance of considering well-being as a measure of progress instead of relying mainly on economic measures such as GDP (*63*, *64*). Evidence suggests that reducing material consumption and/or shifting toward less material-intensive consumption may achieve both environmental and social objectives (*65*). Addressing consumption behavior need not mean consuming less but consuming more of what makes us happy, such as time with family and friends, recreation, and so on. As the wealth of the Chinese population increases it is important for policies to encourage consumers to find a balance between material and nonmaterial consumption.

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Supporting Information Available

Detailed discussion of model development, sectoral descriptions, and more figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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