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How Much Will China Weigh? Perspectives from Consumption Structure and Technology Development

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Current patterns and future possibilities of China's material metabolism are evaluated from perspectives of consumption structure change and technology development using the approach of input−output modeling to integrate ecological and economic systems. A physical input monetary output (PIMO) model is created and is applied to the Chinese economy with 43 sectors and 25 material categories. A set of scenarios, five exploring aspects of consumption structure change and three doing the same for technology development, is analyzed to quantitatively predict China's future possible material metabolism patterns in 2010. The results provide a foundation for quantitative studies of resource consumption and waste generation in China, which given its increasing pivotal role in manufacturing is also helpful for research on the material metabolism of the entire world.

Introduction

Understanding current and potential patterns of material stocks and flows is essential to preserving the life-support system of the planet for the future while meeting fundamental current needs (*1*, *2*). Studies on the implications for sustainability of material needs and use patterns have accordingly been implemented since the mid 1990s under the banner of material flow analysis (MFA) (*3*). Case studies on economy-wide material metabolism have been implemented for most industrialized countries (*4–6*) and some transitional economies (*7*, *8*), especially China (*9*, *10*). Such studies become more complicated, but more important, as the material base of our current economy, nonrenewable resources, cycled in increasingly complex ways, and the limited capacity of the environment to recover from various types of pollution become an even more important consideration.

The pattern of resources consumption and waste generation, also called material metabolism or industrial metabolism (*11*), is mainly determined by the structure, technology mix, and lifestyle implications of an economic system (*12*). Thus, research on future material metabolism patterns requires studies on understanding consumption structure and technology development. Economic input−output analysis (IOA) models (*13*), originally developed as economic modeling tools, have subsequently been widely adapted for evaluating and assessing the environmental impacts of economic activities. As early as 1969, Ayres and Kneese (*14*) and Kneese et al. (*15*) built a basic framework to model material flows using an IOA model. At the same time, Leontief (*16*) introduced a pollution sector into his national input−output model. Subsequently, a number of input−output studies on energy analysis were published in the 1970s and 1980s (*17*, *18*). Entering the 1990s, the IOA model began to be applied in a wider range of fields with two concentrations. One concentration is the improvement of the national accounting system to relate environmental burdens with economic development based on economic input−output matrix. For example, Statistics Netherlands developed the national accounting matrix including environmental accounts (NAMEA) (*19*, *20*) which has then been widely adapted by many countries. The other concentration is the application of IOA in the area of hybrid life cycle assessment (LCA) to model and evaluate the accumulative impacts, direct and indirect, of products or services along their life-cycle supply chains (*21*). We now prepare an extension of the methodology into a specific area, the study of the impacts on material metabolism of the development of a national economic system, with China as our case study.

China is an important case study because of its booming economy, its global importance as an emerging economic powerhouse, and its severe resource and environmental concerns. According to the National Bureau of Statistics of China (NBSC), the Gross Domestic Product (GDP) grew by 11.4% in 2007 (*22*), continuing the double digit economic growth that China has enjoyed since the 1980s. However, this growth necessarily consumes enormous amounts of resources, with resulting waste generation and environmental impacts (*23*, *24*). Although scholars had already studied China's water resources by input−output modeling as early as the 1980s (*25*), the application of IOA techniques in China was mainly concentrated on quantitatively calculating economic loss due to environmental degradation (*26*) and compiling a national accounting system with consideration of natural resources and the environment (*27*).

The goal of this paper is to use a physical input monetary output (PIMO) model to represent the consumption structure change and technology development of the Chinese economic system, therefore gaining a deeper understanding of the implications of economic and technology development on China's material metabolism. A set of scenarios supports this assessment.

Methodology

The Physical Input Monetary Output (PIMO) Model. The PIMO model is not a new construction but a follow-up of the input−output method developed by Ayres and Kneese (*14*) and Kneese et al. (*15*). The PIMO model studies national economic systems specifically from the perspective of material balance. Its core assumption (and a necessary simplification at this point) is that there is a linear relationship between material metabolism and economic growth. Assume that the economic system contains n categories of sectors, whose activities can be represented by conventional economic IOA models. The ecological system provides m categories of resources for the economic system to maintain its functions; it, in turn, generates k categories of wastes, emitted to the ecological system. Considering the wastes received from the economic system as negative input from the ecological system, the conceptual model can be regarded

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as a one-way system which has physical input and economic output which is commonly expressed by monetary input–output tables (MIOT), the computational structure of which can be referred to Miller and Blair (*28*).

Let $\mathbf{r}_{ij}$ indicate the physical amount of resource to sector j from resource category i, and $\mathbf{w}_{(m+i)j}$ indicate the physical amount of waste output from sector j to waste category i. The material efficiency, $\mathbf{e}_{ij}$, can be expressed as

$$\mathbf{e}_{ij} = \begin{cases} \dfrac{\mathbf{r}_{ij}}{X_j}, \; i = 1, 2, \cdots, m \\ \dfrac{\mathbf{w}_{ij}}{X_j}, \; i = 1, 2, \cdots, k \end{cases} \tag{1}$$

where X_j indicates the economic output of sector j.

Let $\mathbf{E} = (\mathbf{e}_{ij})_{(m+k) \times n}$ indicate the matrix of material efficiency, and $\mathbf{M}$, a $(m + k) \times 1$ vector, indicate the physical amounts of materials, including m categories of resources and k categories of wastes. Thus, the vector $\mathbf{M}$ can be expressed as

$$\mathbf{EX} = \mathbf{M} \tag{2}$$

where $\mathbf{X}$ is a $n \times 1$ vector of total outputs by all sectors.

The economic accumulative interaction between sectors also affects the material inputs. Therefore, the accumulative effects on the material inputs, both positive and negative, can be expressed by

$$\mathbf{F} = \mathbf{EB} \tag{3}$$

where $\mathbf{B}$ is the accumulative coefficient matrix, $\mathbf{F}$ is a $(m + k) \times n$ matrix indicating the accumulative material inputs required by unit economic output of each sector. Therefore, accumulative material inputs can be quantified by

$$\mathbf{T} = \mathbf{F}\hat{\mathbf{X}} \tag{4}$$

where $\mathbf{T}$ is a $(m + k) \times n$ matrix whose entities are accumulative requirement of each material by each sector, and hat (^) diagonalizes a vector.

Substituting eq 3 and input–output economics equation $\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}$ into eq 2, one can get

$$\mathbf{E}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{M} \tag{5}$$

where $\mathbf{A}$ is a $n \times n$ technology matrix, whose element, $\mathbf{a}_{ij}$, represents the input from sector i to sector j required to produce a unit of economic output for sector j, with endogenized imports, $\mathbf{Y}$ is a $n \times 1$ vector of final demands by all sectors, and $\mathbf{I}$ is a $n \times n$ identity matrix. Using eq 5, one can estimate the total amount of material inputs $\mathbf{M}$, both positive and negative, implied by different scenarios of economic structure, indicated by the final demand vector $\mathbf{Y}$, and technology mix, indicated by the material efficiency matrix $\mathbf{E}$.

Scenario Analysis. First, scenarios are generated by developing representations of consumption structure change and technology development, expressed by hypothetical final demand vector $\mathbf{Y}$ and material efficiency matrix $\mathbf{E}$, respectively. Second, technology matrix $\mathbf{A}$ is used to calculate the physical material amounts, indicated by the vector $\mathbf{M}$, using eq 5. Then, the result of $\mathbf{M}$ is evaluated against fundamental constraints, such as general physical laws or physical limitations. If the constraints are violated, the original scenario is modified accordingly. This verification–adjustment–compiling process is repeated until all constraints are satisfied. The resulting scenarios are then fed into the analysis.

Data and Scenarios. In this paper, China's 1997 MIOT developed by the National Bureau of Statistics of China is used to compile the PIMO table. To meet the format of material flow data, the original input–output table, containing 124 sectors, is aggregated to a 43-sector format (*29*). Data on material input from 1997 and 2005 are obtained from various statistical publications provided by the Chinese government (*30–32*). The data set has ten categories of resources, five categories of wastes, and ten subcategories of specific wastewater pollutants.

To generate scenarios, the 43 sectors are first grouped into five categories in terms of different economic development policies implemented by the central government of China. The primary difference between the categories reflects the extent to which the central government supports or encourages each sector's development. For example, government policy does not encourage further development in sectors with surplus production capacities, such as *Ferrous Metals Mining and Dressing, Smelting and Pressing of Ferrous Metals*, or *Textile Industry* (*33*).

Scenarios are then chosen to reflect different mixes of consumption structure change and technology development. Consumption structure change is expressed by different growth rates of final demand in different sectors. There are five scenarios in total, from *S1* to *S5*. All scenarios produce an overall economic growth rate of 7.5% annually from 2005 to 2010, as called for by the central government of China (*34*), even though this is thought by some to be an underestimate. In scenario *S1*, final demand of all sectors in 2010 is kept in the same proportion as in 2005. Thus all sectors have the same annual growth rate of 7.5%. In scenario *S2*, final demands of sectors in category 3 grow at an annual rate of 8%, while other sectors have the same growth rate as in scenario *S1*. In scenario *S3*, the final demand of sectors in category 4 grows at the rate of 10%. In scenario *S4*, the final demand of sectors in category 1 is the same as in 2005. Finally, sectors in category 2 grow their final demands by 3% annually in scenario *S5*. In *S2* through *S4*, the final demand of sectors in category 5 grows so as to keep the overall economic growth rate at 7.5%.

The scenarios regarding technology development are defined by varying the productivity of economic sectors which is expressed by the physical amounts of resource consumption and waste generation required to produce a unit of economic output. For those sectors whose upstream suppliers are other sectors but not the ecological system, their productivity is modified in the way of changing coefficients in the $\mathbf{A}$ matrix. The series of *Sector Cleaner Production Standard* implemented by the State Environmental Protection Administration of China (SEPA) are used to quantify these scenarios (*35*). There are three scenarios regarding technology development. The first scenario, *T1*, assumes that the amount of material required per unit of economic output is the same as in 2005 (static technology). The scenario *T2* assumes that technologies in all sectors reach the "domestic cleaner production advanced level" according to the standards, while scenario *T3* assumes all technologies achieve the "global cleaner production advanced level".

Generally speaking, the scenarios, from *S1* to *S5*, and from *T1* to *T3*, correspond to more "reasonable" consumption structures and technology levels according to the mass media. We now turn to an analysis of whether "reasonable" consumption structures and technology levels are also environmentally preferable. The details about the PIMO model, the framework of scenario analysis, sector classification, and scenarios regarding both consumption structure change and technology development can be found in the Supporting Information.

Results

We interrogate the PIMO model using the scenarios to study future material metabolism patterns in China. 2005 is used as the baseline and the scenarios are positioned five years out in 2010. The results of this analysis are sorted in categories of resources (fossil fuels, metal and nonmetal minerals, and

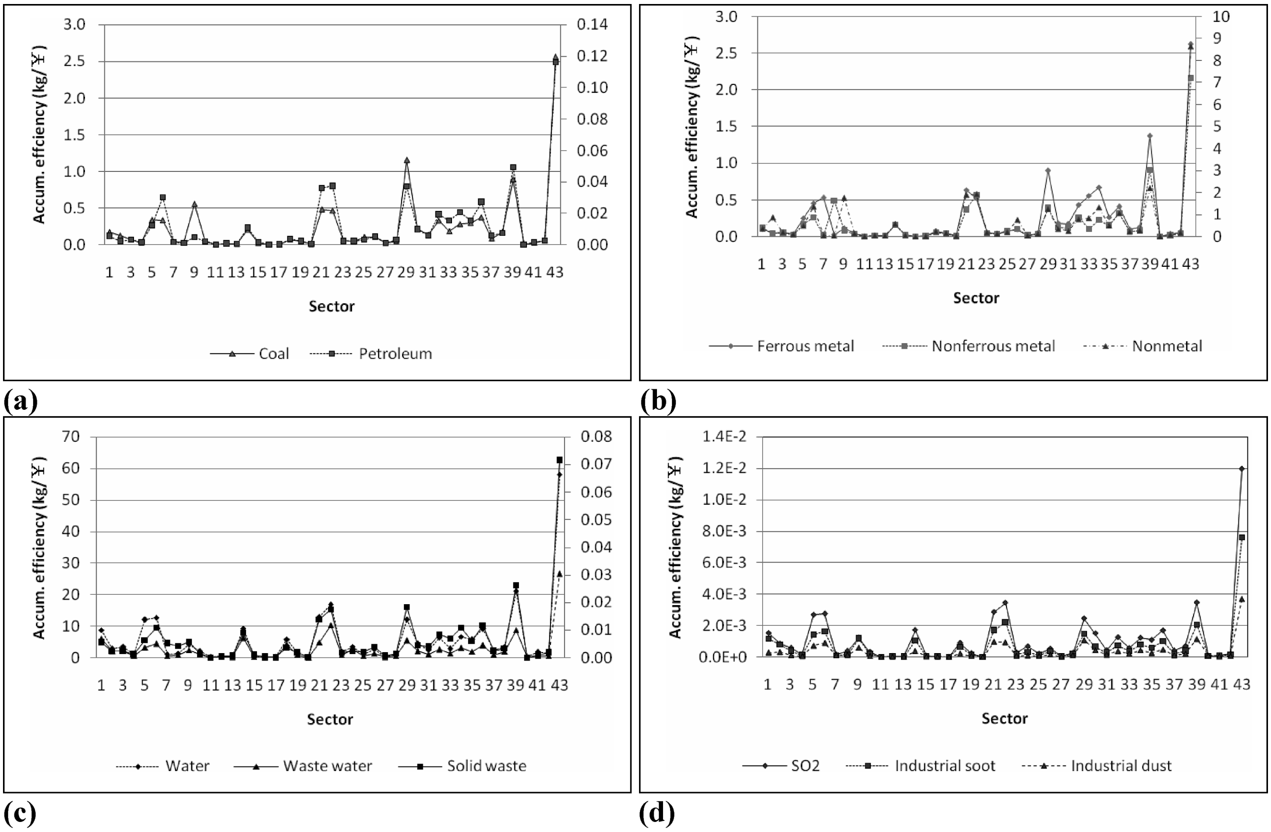

FIGURE 1. Comparisons of accumulative material efficiency in China, 2005, for (a) coal, indexed on the left axis, and petroleum, indexed on the right axis; (b) ferrous and nonferrous metal minerals, indexed on the left axis, and nonmetal minerals, indexed on the right axis; (c) water and wastewater, indexed on the left axis, and solid waste, indexed on the right axis; (d) SO_2, industrial soot, and industrial dust. All values are in kg per ¥.

water), and wastes (air emissions, solid waste, wastewater, and water pollutants). The following section presents our results, details of which are available in the Supporting Information.

Fossil Fuels. The direct amounts of coal and petroleum consumed in 2005 are 3.14 and 0.36 billion tons, respectively. In terms of accumulative consumption per unit economic output for both coal and petroleum, the most efficient sector is *Timber Processing, Bamboo, Cane, Palm Fiber and Straw Products*, and the least efficient is *Tertiary Industry* which require 0.003 and 2.56 kg of coal or 0.001 and 1.16 kg of petroleum, respectively, to produce one Chinese yuan (¥) of economic output. Figure 1a compares the efficiencies of coal and petroleum consumption. Given that most sectors rely on public energy distribution systems, the metabolisms of coal and petroleum have similar efficiency distribution among most sectors, except the sector of *Ferrous Metals Mining and Dressing* consumes more petroleum and the sector of *Nonmetal and Other Minerals Mining and Dressing* requiries more coal.

Results of the scenarios for ten years show that the consumption structures represented by scenarios *S3* and *S4* consume the lowest amount of coal. Therefore, sectors covered in category 5 are dominantly driving coal consumption, although they do not directly consume as much coal as others. Moreover, the government's policy to stimulate the development of sectors in the category 4 will significantly decrease the requirement of coal.

Amounts of petroleum consumed in scenarios *S2*–*S5* are almost the same, and higher than those for scenario *S1*. Sectors in category 3 are the main driving forces for petroleum consumption, because the 5% growth rate in those sectors will generate around 12% increase in petroleum requirements. Given the fact that those sectors are encouraged to develop by the Chinese government, it can be predicted that China will need more petroleum in the next several years. However, technology development can significantly contribute to counteracting the increasing requirement of petroleum as well as coal.

Metal and Nonmetal Minerals. In 2005, China's economic system consumed 0.45, 0.48, and 9.76 billion tons of ferrous metal minerals, nonferrous metal minerals, and nonmetal minerals, respectively. From Figure 1b, it is apparent that accumulative efficiencies of different types of minerals are similar. The sectors of *Timber Processing, Bamboo, Cane, Palm Fiber and Straw Products* and *Tertiary Industry* are the most and least efficiency in terms of accumulative material consumption required to produce a unit of economic output.

Scenario results show that scenarios *S4* and *S5* represent the most efficient consumption structures in terms of ferrous metal. Because the consumption structure difference between *S4* and *S5* does not change the efficiency of ferrous metal consumption remarkably, sectors in category 1, ferrous metals related sectors, are the driving force of ferrous metal consumption. Therefore, keeping those sectors' production capacity constant and developing other sectors accordingly will significantly increase the efficiency of ferrous metal consumption. For nonmetal minerals, scenarios *S3* and *S4* represent the most efficient consumption structures, which implies that the development of sectors in category 4 will be effective in increasing the consumption efficiency. Differently, the change of consumption structure in those scenarios does not have a remarkable effect on increasing but decreasing the efficiency of nonmetal consumption. Sectors in the category 3 have the most significant effect on the consumption of nonmetal minerals, especially the *Construction* sector.

On the other hand, the development of technology can dramatically increase the efficiency of minerals consumption.

Therefore, to improve the consumption efficiency of metals, consumption structure change implemented by the government and technology development both are effective approaches. For nonmetal minerals, however, only the technology development can increase the consumption efficiency.

Water. In 2005, China's economy consumed 229.91 billion tons of water. The *Production and Supply of Electric Power, Steam and Hot Water* and the *Tertiary Industry* sectors are the major direct water consumers. The *Tertiary Industry* sector accounts for the most accumulative water consumption. The pattern of accumulative water consumption among sectors is very similar to that for other raw materials, as shown in Figure 1c.

Scenario analysis shows that the change of consumption structure does not increase but decreases the water consumption efficiency. The growth of *Tertiary Industry* and *Production and Supply of Electric Power, Steam and Hot Water* in those scenarios is the main reason. Therefore, the improvement of water consumption efficiency mainly relies on technology development.

Air Emissions. We address three types of air emissions: sulfur dioxide (SO_2), industrial soot, and industrial dust. The 2005 baselines for those air emissions are 305.78, 31.65, and 16.10 million tons, respectively. The *Production and Supply of Electric Power, Steam and Hot Water* sector emits the most SO_2 and industrial soot: 46% and 36% of total emissions, respectively. The *Tertiary Industry* sector takes second place in terms of SO_2 and industrial soot emission, with 21% and 23% of total emissions. The emission of industrial dust, however, presents a different pattern. The *Concrete Manufacturing, Other Nonmetal Mineral Products*, and *Smelting and Pressing of Ferrous Metals* sectors emit the most industrial dust, 73% of total, among all sectors. The accumulative air emissions required to produce a unit of economic output are compared in Figure 1d. The *Tertiary Industry* sector is least efficient for all three categories.

The scenarios result in that, for SO_2 and industrial soot, scenario *S2* results in the lowest emission levels, which means that sectors in category 4 predominantly drive the emissions of SO_2 and industrial soot. The emission of industrial dust, however, appears lowest in scenarios *S3* and *S4*, which means that it is mainly driven by sectors in category 5. Overall, compared to consumption structure change, technology development is much more effective in reducing air emissions. In particular, technology development to the level of scenario *T2* will reduce about 28%, 29%, and 35% of SO_2, industrial soot, and industrial dust, respectively. Scenario *T3* will increase those reduction percentages to around 55%, 54%, and 61%, respectively.

Solid Waste. The 2005 baseline of solid waste in China is 305.78 million tons. The *Tertiary Industry* sector generates the most solid waste among all sectors, both in direct and accumulative terms, as illustrated in Figure 1c. Scenarios *S3* and *S4* generate the lowest solid waste; we can therefore conclude that sectors in category 5 primarily drive generation of solid waste. As in other cases, technology development plays a critical role in reducing solid waste. Scenarios *T2* and *T3* can, respectively, reduce the generation of solid waste by about 10% and 20%.

Wastewater. The 2005 baseline for wastewater in China is 79.43 billion tons, 56% of which is generated by the *Tertiary Industry* sector. Figure 1c shows the accumulative efficiency for wastewater generation in China, 2005. While *Tertiary Industry* is the least efficient sector, *Cultural, Education and Sports Goods* sector is the most efficient. While scenario *S2* results in the lowest amount of wastewater generated, consumption structure change does not affect the amount wastewater generated by the entire economy as much as technology development does. Scenarios *T2* and *T3* can reduce the generation of wastewater by about 31% and 57%, respectively.

Water Pollutants. There are ten categories of water pollutants: mercury, cadmium, hexavalent chrome, lead, arsenic, volatile hydroxylbenzene, cyanide, chemical oxygen demand (COD), petroleum, and ammonia nitrogen. The total amounts of mercury, cadmium, and hexavalent chrome are below 200 tons. According to Jiang et al. (*36*), approximately 45% of the mercury pollution in China comes from nonferrous metal smelting and 38% from coal combustion. In our research, from Figure 2a, the sectors of *Smelting and Pressing of Nonferrous Metals*, which includes the electroplating industry, and *Raw Chemical Materials and Chemical Products* generate the most mercury pollution in wastewater. Mercury pollution generated from coal combustion is integrated in industrial soot and dust as air emissions in this research. The sector of *Smelting and Pressing of Nonferrous Metals* also produces the most cadmium pollution. The *Metal Products* sector is the main source of hexavalent chrome pollution.

The volumes of lead, arsenic, volatile hydroxylbenzene, and cyanide pollutants range from 500 to 5000 tons. The *Nonferrous Metals Mining and Dressing* and *Smelting and Pressing of Nonferrous Metals* sectors dominate lead pollution, as showed in Figure 2b. Those two sectors, together with the sector of *Raw Chemical Materials and Chemical Products*, are also the main sources of arsenic pollution. Volatile hydroxylbenzene pollution is dominated by the *Papermaking and Paper Products* and *Petroleum Processing and Coking* sectors, while the *Raw Chemical Materials and Chemical Products* and *Smelting and Pressing of Ferrous Metals* sectors generate most of the cyanide pollution.

Volumes of COD, ammonia nitrogen, and petroleum are much higher than other water pollutants. Figure 2c shows the distribution of those three types of pollutants among sectors. The *Tertiary Industry* sector generates the most COD and ammonia nitrogen among all sectors. The *Smelting and Pressing of Ferrous Metals, Raw Chemical Materials and Chemical Products, Petroleum and Natural Gas Extraction*, and *Petroleum Processing and Coking* sectors dominate petroleum pollution.

Figure 2d represents the 2005 accumulative efficiency for water pollutants in China. While busy, the figures show that the patterns for all pollutants are very similar. Several key sectors, such as *Tertiary Industry, Production and Supply of Electric Power, Steam and Hot Water, Smelting and Pressing of Nonferrous Metals, Raw Chemical Materials and Chemical Products*, and *Textile Industry*, generate higher levels of water pollution per unit of economic output. As discussed before for accumulative efficiency of raw material consumption, the accumulative impacts on material metabolism is the reflection of the entire economic system. That is why the distribution patterns of accumulative effects among sectors are similar for almost all kinds of material metabolism.

Scenario results are presented in Table 1. Scenario *S2* reduces the most amounts of mercury, cadmium, hexavalent chrome, and arsenic. Moreover, scenarios *S3*–*S5* will generate more pollutants than the baseline scenario, *S1*. Therefore, sectors in category 4, manufacturing sectors, are the main cause of those four water pollutants. For lead, cyanide, petroleum, and ammonia nitrogen, scenario *S2* also reduces the most amounts of pollutants. Scenarios *S3*–*S5* reduce the generation of those water pollutants in the baseline scenario, although the amounts are higher than those in scenario *S2*. Hence, sectors in category 5 dominate the generation of those four types of water pollutants. Volatile hydroxylbenzene and COD reach the least pollution amounts in scenarios *S4* and *S5*. Therefore, developing manufacturing sectors and controlling *Tertiary Industry* which generates domestic waste-

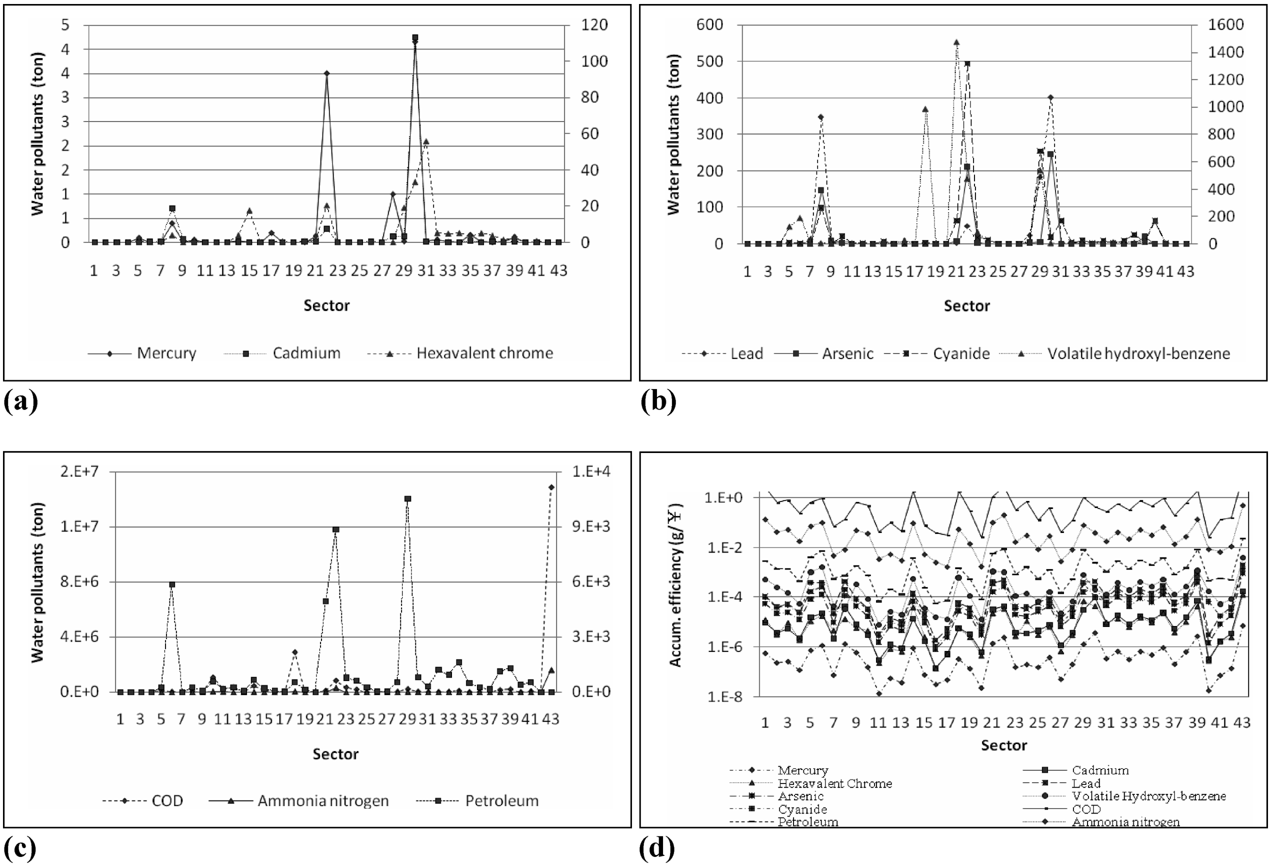

FIGURE 2. Comparisons of water pollutants generated by sectors in China, 2005, for (a) direct generation of mercury, indexed on the left axis, and cadmium and hexavalent chrome, indexed on the right axis; (b) direct generation of lead, arsenic, and cyanide, indexed on the left axis, and volatile hydroxylbenzene, indexed on the right axis; (c) direct generation of COD and ammonia nitrogen, indexed on the left axis, and petroleum, indexed on the right axis; (d) accumulative efficiency for all ten water pollutants. Values are in tons for (a), (b), and (c), and in g per ¥ for (d).

water will significantly reduce the generation of those two kinds of pollutants, especially for COD.

Unsurprisingly, technology development reduces the amounts of water pollutants. Scenario *T1* can reduce cadmium by about 5%, mercury, hexavalent chrome, lead, arsenic, and COD by about 25%, petroleum and ammonia nitrogen by about 30%, and volatile hydroxylbenzene and cyanide by about 40%. Scenario *T2* can increase those percentages of reduction to 15%, 60%, 50%, and 70%.

Policy Analysis. Policies and strategies have been initiated to solve environmental problems in China including cleaner production (e.g., (*37*)) and clean development mechanism (CDM) (e.g., (*38*)). The promotion of cleaner production in major industries encourages lower generation of pollutants. Furthermore, CDM helps China's industries improve technology and then reduce resource consumption and waste generation, although it is hard to meet its goals (*39*). Both policies imply the technology development through *T1* to *T3* in terms of our scenarios. Recently, the National People's Congress is working on constituting the law of circular economy which has been adopted as a development strategy by the central government (*40*). The law preferentially encourages reduction of resource consumption and waste generation in all stages of economic and social activities (*41*). Recycle and reuse are also emphasized as fundamental approaches to achieve circular economy. As a result of this law, technology development is not the only aspect influenced, but also China's economic and consumption patterns. It is unclear yet what impact the law will have. However, it is possible to quantitatively explore the feasibility of specific established policies by scenario analysis using the PIMO model.

For example, the State Council (*34*) established the eleventh five-year (2005−2010) plan for national economic and social development. According to the plan, energy consumption per unit of economic output should be reduced by 20% in 2010. The scenario results of coal equivalent consumed per unit of GDP indicate that all *S3* and *S4* scenarios, and the scenario *S5* with *T3* technology could reach this goal. Similarly with quantity results, consumption structures expressed by *S3* and *S4* are the most efficient in terms of energy consumption. Technology development is also instrumental to increase of energy efficiency. Therefore, to achieve the goal on energy efficiency, it is helpful to encourage the growth of manufacturing sectors and control the growth of ferrous metal related sectors. Based on this improvement in consumption structure, technology development is also necessary by reaching the "domestic cleaner production advanced level" according to SEPA (*35*).

The State Council established a goal of reducing the amount of water required per unit GDP in secondary industry by 30% by 2010 (*34*). According to the scenario results for water consumption, technology development is significant to meet this goal by reaching at least the level represented by scenario *T2*. As a comparison, scenario *T3* can increase water consumption efficiency by almost 50%. Unlike fossil fuels, Scenario *S2* results in greatest water consumption efficiency. Therefore, implementation of current policy will lead to decreasing the efficiency. As a result, the significance of technology development must be emphasized in order to meet the goal of water consumption efficiency.

For air emission, all three types of pollutants could be reduced or at least held to a slight increase in scenario *T2*. However, *T2* does not meet the SO_2 reduction goal of 10%

TABLE 1. 2010 Scenario Results for Water Pollutants[a]

pollutant	scenario	S1	S2	S3	S4	S5
mercury	T1	1.44	1.29	1.55	1.55	1.55
cadmium		1.44	1.28	1.52	1.52	1.53
hexavalent chrome		1.44	1.28	1.51	1.51	1.51
lead		1.44	1.28	1.31	1.30	1.34
arsenic		1.44	1.28	1.47	1.47	1.50
volatile hydroxyl-benzene		1.44	1.35	1.30	1.29	1.29
cyanide		1.44	1.28	1.37	1.36	1.37
COD		1.44	1.28	1.20	1.20	1.20
petroleum		1.44	1.33	1.37	1.36	1.37
ammonia nitrogen		1.44	1.28	1.41	1.41	1.40
mercury	T2	1.02	1.01	1.21	1.21	1.21
cadmium		1.22	1.19	1.43	1.43	1.44
hexavalent chrome		1.03	1.00	1.18	1.18	1.18
lead		0.97	0.95	0.96	0.96	0.99
arsenic		0.95	0.93	1.07	1.07	1.09
volatile hydroxyl-benzene		0.82	0.84	0.79	0.79	0.79
cyanide		0.84	0.83	0.86	0.85	0.86
COD		0.96	0.94	0.88	0.88	0.88
petroleum		0.88	0.89	0.94	0.94	0.94
ammonia nitrogen		0.95	0.94	1.00	1.00	1.00
mercury	T3	0.53	0.53	0.62	0.62	0.62
cadmium		1.09	1.07	1.31	1.31	1.32
hexavalent chrome		0.60	0.59	0.68	0.68	0.68
lead		0.47	0.45	0.46	0.46	0.47
arsenic		0.44	0.43	0.48	0.48	0.49
volatile hydroxyl-benzene		0.40	0.41	0.39	0.39	0.39
cyanide		0.44	0.43	0.44	0.44	0.45
COD		0.57	0.55	0.54	0.54	0.54
petroleum		0.57	0.57	0.60	0.60	0.60
ammonia nitrogen		0.70	0.69	0.73	0.72	0.73

[a] Entities are ratios to the amounts in 2005: 23.03 and 2.30 million tons for chemical oxygen demand (COD) and ammonia nitrogen, and 9.97, 151.35, 190.75, 1048.08, 653.28, 4211.51, 1190.08, and 44916.64 tons for mercury, cadmium, hexavalent chrome, lead, arsenic, volatile hydroxylbenzene, cyanide, and petroleum, respectively.

by 2010 established by the State Council (*34*). Therefore, no matter what consumption structure will be, technology development must exceed the level represented by *T2* and approach the *T3* level to reach the established SO_2 reduction goal.

Discussion

This is not the first attempt to predict an economic system's pattern of resource consumption and waste generation. However, we believe that the methods and the results presented in this paper represent an important advance in that they enable us to systematically and quantitatively describe and forecast the material metabolism pattern of an economic system from the perspectives of consumption structure change and technology development. The application of the PIMO model generates a quantitative picture of China's material metabolism in 2010, which is not only important for China itself, but also for the entire world economy in this era of globalization.

Those sources of uncertainty are endemic to the PIMO methodology: ((1) the time lag of input−output data; (2) the assumption of linear relationships between material metabolism and economic change; and (3) the assumption of homogeneous products in each sector. Input−output data for most countries are usually available only with a three- or four-year time lag at best. Furthermore, detailed input−output data are only compiled once every several years. Nonetheless, although the uncertainties brought by time-lag require attention in all input−output related studies, input−output data are still the most widely available and cheapest data source for national economies in terms of consumption structure and technologies. Second, the assumption of a linear relationship between material metabolism and economic change is common to all current input−output methods. However, we know that the interaction between ecological and economic systems at many different scales is far more complex than this, so an important challenge for the future is developing more complete data sets and suitable methodologies to enable more valid modeling of that complexity. Last, but not least, input−output methods assume homogeneous products in the same sector. This assumption can be improved by developing more data for subsectors, which must be done without increasing the time lag too much. This task is doubly hard with the PIMO model because it utilizes not only economic data, but material metabolism data.

The empirical application of PIMO model in this paper studies both the current pattern and future possibilities of material metabolism in China. Fifteen categories of resources and wastes, together with 10 subcategories of main water pollutants, are quantitatively measured for a 43-sector economic system of China in 2005. The direct resource consumption and waste generation distribute differently among sectors for different categories of materials, while the accumulative impacts of economic activities are similar for most of the material categories. Using 2005 as the baseline, five scenarios in terms of consumption structure change and three scenarios in terms of technology development are used to explore future material metabolism paths. The results of our analysis indicate that the most "reasonable" structure according to the mass media in China may not, in fact, be the best for the environment in terms of resource consumption and waste generation. The results also provide quantitative information about how much resources and wastes can be reduced depending on levels of technology. In a word, the study of this paper preliminarily answers the question how much China will weigh from perspectives of consumption structure change and technology development.

In the real world, the economic system is far more complex than what we have modeled. Consumption structure change and technology development are only two key components of its evolution and complexity. Therefore, future areas of research include disaggregation of the current 43 sectors, especially for the *Tertiary Industry* category which contains significant final consumption activities. Additional scenarios would help to illustrate potential future material metabolism patterns more accurately. Finally, time series analysis is also required to study the historical evolution of material metabolism patterns caused by economic development.

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Supporting Information Available

Details about the conceptual and computational framework of the Physical Input Monetary Output (PIMO) model, classification of sectors in China's economic system, classification of resources and wastes, scenarios, and quantitative results of scenario analysis in tabular form. This information is available free of charge via the Internet at http://pubs.acs.org.

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