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Measuring progress of China's circular economy

Heming Wang[a,b,*], Heinz Schandl[b,c], Xinzhe Wang[a], Fengmei Ma[b,d], Qiang Yue[a], Guoqiang Wang[a], Yao Wang[a], Yao Wei[a], Zhihe Zhang[a], Ruiying Zheng[e]

[a] State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, Shenyang, China
[b] Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia
[c] Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan
[d] College of Economics and Management, Shenyang Agricultural University, Shenyang, China
[e] Department of Geography and Environment, St Clement's, London School of Economics and Political Science, Houghton Street, London, United Kingdom

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ABSTRACT

As the largest user of primary materials globally China has made a commitment to rebuild its economy to a circular model and to enhance the efficiency of material use, which is spelled out in the Circular Economy Promotion Law. Measuring progress of the new policy requires datasets, metrics and indicators that monitor the performance of the economy regarding the scale of primary materials use, waste flows, and recycling and circularity. We employ material flow analysis, including measures for inputs and outputs, to assess progress of the circular economy in China over time. We find that circularity increased from 2.7% to 5.8% between 1995 and 2015, from an input socioeconomic cycling rate perspective. End of life waste recycling improved from 7.2% to 17% over the same time frame and occurred against the backdrop of a strong physical growth dynamic during this whole period. We present a set of policy indicators and situate them in the context of the Chinese indicator sets for a Green Development Indicator System, the Ecological Civilization Construction Assessment Target System and the Sustainable Development Goals. Moving from an economy based on infrastructure and capital investment production for the world market, to a consumption-based economy, may increase the potential for circular economy in China in the future. The policy indicators can also be used to set targets and create ambition for a swift transition to closed loop urban and industrial systems in China.

1. Introduction

With global primary materials use soaring and China requiring an ever-growing share of the global natural resource base, issues of supply security of primary materials and the associated environmental impacts of rising material demand have received increasing attention from the Chinese policy community. The sheer scale of Chinese primary materials use of 35 billion tons in 2015 (Wang et al., 2019) of a total of 90 billion tons of global materials consumption (Schandl et al., 2020; UNEP, 2019) has raised important issues around how to secure the required demand (Geng et al., 2019) and how to mitigate the environmental impacts of climate change (Chen et al., 2020; Hertwich et al., 2019; UNEP-IRP, 2020; Yue et al., 2015), biodiversity loss (Lenzen et al., 2012), resource depletion (Wang et al., 2020; Zhao et al., 2019) and pollution (Chen et al., 2019; Qi et al., 2019; Sun et al., 2019; Yu et al., 2017) across the supply chain of natural resources.

The options discussed for reducing material use and improving resource efficiency in China include investment in new technologies and changes in consumption behavior of households and governments, as well as improvements in the built environment (Jiang et al., 2019; Ma et al., 2018; Wang et al., 2014; Xu et al., 2008). These objectives are addressed in the subsequent economic and reform plans of the Chinese government (the five-year plans), the Circular Economy Promotion Law (National People's Congress of China, 2008) and the broad intent to transition China to an ecological civilization by enabling social and economic outcomes to occur within planetary boundaries (Steffen et al., 2015). The new policy objectives of economic resilience, resource efficiency and environmental sustainability deal with complex issues and require agreement on how to best approach the objectives and ensure effective and efficient outcomes from public policy initiatives. To this end, the knowledge base for evidence-based policy needs be improved, especially with regard to creating a good understanding of the main characteristics of the physical economy of China, to measure the

* Corresponding author at: State Environmental Protection Key Laboratory of Eco-Industry, Northeastern University, No. 11, Lane 3, Wen Hua Road, He Ping District, Shenyang, Liaoning 110819, China.
E-mail address: wangheming2006@gmail.com (H. Wang).

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current rate of circularity, i.e. the amount of secondary materials that re-enter the economic process, and to set ambitious policy targets for improving circularity in the future.

Such improvements may result from either a better recycling rate for end of life waste or a more fundamental restructuring of the Chinese economy, resulting in a reduction of the overall amount of materials that are processed on a yearly basis. In short, this is what is aspired to by the circular economy (CE), which is based on redesigning major provision systems including housing, mobility, food, energy and water, in addition to improvements in major consumer good sectors for long-lived goods.

The new information required for advancing circular economy policy is provided through comprehensive material flow accounts (Pauliuk, 2018; Schandl and Miatto, 2018) which are complementary to economic accounts but report volumes of materials introduced to an economy (through extraction or imports), the production of goods (for export and domestic markets) and resulting waste and emissions. Various previous studies have established accounts for material use in China (Dai and Wang, 2017; Wang et al., 2012; Xu and Zhang, 2007), but a standard set of material flow accounting indicators with a focus on circularity and comparable to other countries is still needed. The accounting framework used in this study is based on internationally agreed methodological standards (EUROSTAT, 2016) and has been applied for the period 1995–2015. Generating the results benefits from previous studies of economic circularity (Haas et al., 2015; Jacobi et al., 2018; Mayer et al., 2018) but has required substantial and systematic reworking of the research strategy to accommodate the data characteristics and data availability of China. As a result, we report a standard set of material flow accounting indicators with a focus on the output side and measure the circularity of the economy based on a material balance of the Chinese economy. We complement the analysis with resource efficiency indicators and link the metrics used in this study to the data needs of newly established Chinese indicator sets and the Sustainable Development Goals.

2. Methods and data

In this study, we developed a monitoring framework for China's CE at the macro level, based on the Chinese statistical system and previous research that linked EW-MFA with secondary material flows to allow for monitoring CE in national economies (Haas et al., 2015; Jacobi et al., 2018; Mayer et al., 2018). Due to the large number and variety of material and waste flows involved in the framework (up to 155 categories of flows, see SI), the amount of data is very large. For the sake of understanding, we code each material flow, and then introduce them in the CE model (Fig. 1), monitoring indicators (Table 1) and data sources (Table S1 in SI), respectively.

2.1. Basic model and indicators for monitoring China's circular economy

The basic monitoring framework for comprehensive material flow accounts of the Chinese economy is shown in Fig. 1 and enables us to trace 14 main material and waste flow categories (M1–M14) including the extraction of primary materials and imports, the transformation of materials within the production system, and outputs of commodities for export and disposal of emissions and waste. Boxes represent the main stages of material flows across the entire socioeconomic system: 1) the origin of material inputs [M1. Domestic extraction (DE) and M2. Import], 2) the transformation and processing stages [M5. Processed materials (PM), M6. Energetic use (eUse), M7. Material use (mUse), M11. Solid and liquid wastes from energetic use, M12. End of life (EoL) wastes, and Societal in-use stocks], and 3) the destination of outflows [M3. Export, M13. Domestic processed output (DPO) emissions, and M14. DPO wastes]. The flows of material and waste between these boxes are displayed as arrows (see further detail in Table 1).

We employ this framework, which is based on previous studies and guidelines (Eurostat, 2013; Haas et al., 2015; Jacobi et al., 2018; Krausmann et al., 2018; Mayer et al., 2018; Wang et al., 2019), to construct a new dataset for China covering two decades from 1995 to 2015. Many of the indicators displayed in Table 1 have become standard indicators that are calculated from material flow accounts and have been agreed by the research and statistical community (Eurostat, 2013; Fischer-Kowalski et al., 2011; Krausmann et al., 2018). To enable the analysis of circularity, a new category of secondary materials (SM) is introduced, which refers to the recovery of materials through all forms of recycling, reuse and remanufacturing and also includes downcycling and cascading (Mayer et al., 2018). Secondary materials include recycled materials from End of Life (EoL) wastes and industrial solid wastes. By adding DMC and SM we establish the amount of materials that are processed (PM), which is the apparent domestic consumption of materials with secondary flows included. Processed materials (PM) are distinguished between Energetic use (eUse) and Material use (mUse), which has consequences for their further use pathways. Energetic use comprises fossil fuels and biomass for energy production. Not all fossil fuels are used for energy and a small fraction is used as a feedstock material (e.g., plastics and bitumen). The eUse of biomass mainly refers to fuel wood and the biomass used to generate metabolic energy for humans and livestock.

Employing the principle of conservation of mass, net additions to stock (NAS) are calculated by gross additions to in-use stocks (GAS) minus demolition and discard, where GAS equals mUse minus throughput materials. The amount of throughput materials can be ascertained directly from the Chinese statistical system.

On the output side, except for DPO (including DPO emissions and DPO wastes), two additional indicators are introduced: EoL wastes and Interim Outputs (IntOut). The former is equal to the sum of throughput materials, demolition and discard, and solid and liquid wastes from energetic use, and the latter equals EoL waste plus DPO emissions. It is notable that, in contrast to previous studies, we did not consider extractive wastes separately, but included them in DPO wastes, because in China these data are included in industrial solid wastes and they can be reused as SM (e.g., metallurgical slag can be used to produce cement), rather than emitted directly to the environment.

Input socioeconomic cycling rate (ISCr, share of PM) and Output socioeconomic cycling rate (OSCr, share of IntOut) are the main indicators for monitoring the recycling of materials from the perspectives of the input side and output side, respectively. The ISCr is relatively significantly affected by changes in PM, while the OSCr is less affected since waste quantities are not dynamically coupled with EW-MFA input data as a result of effects from stock dynamics (Jacobi et al., 2018).

2.2. Data

The data sources and accounting methods for each basic material and waste flow are summarized in Table S1 in the SI, and more detailed explanations of the 155 categories of flows are provided in the SI using the year 2010 as a representative example (Table S2). To complete the accounting for all material flows, we constructed six sub-accounts focusing on waste flows, which are also shown in the SI: A1 Industrial solid waste reused, A2 Industrial solid waste emitted, A3 Household waste, A4 Construction waste, A5 Food balance, and A6 Human and animal metabolism.

For category A1 Industrial solid waste reused and category A2 Industrial solid waste emitted, we allocated China's industrial solid waste (recycled or emitted) from the original data from the China Environmental Statistics Yearbooks (National Bureau of Statistics: Ministry of Ecology and Environment, 1996–2016) and the proportions of different material categories (biomass, metal ores and metals, non-metallic minerals, fossil fuels, material use, and energetic use) were established using the classification from (Mayer et al., 2018). For category A3 Household waste, we allocated China's household waste data available from the China Statistical Yearbooks

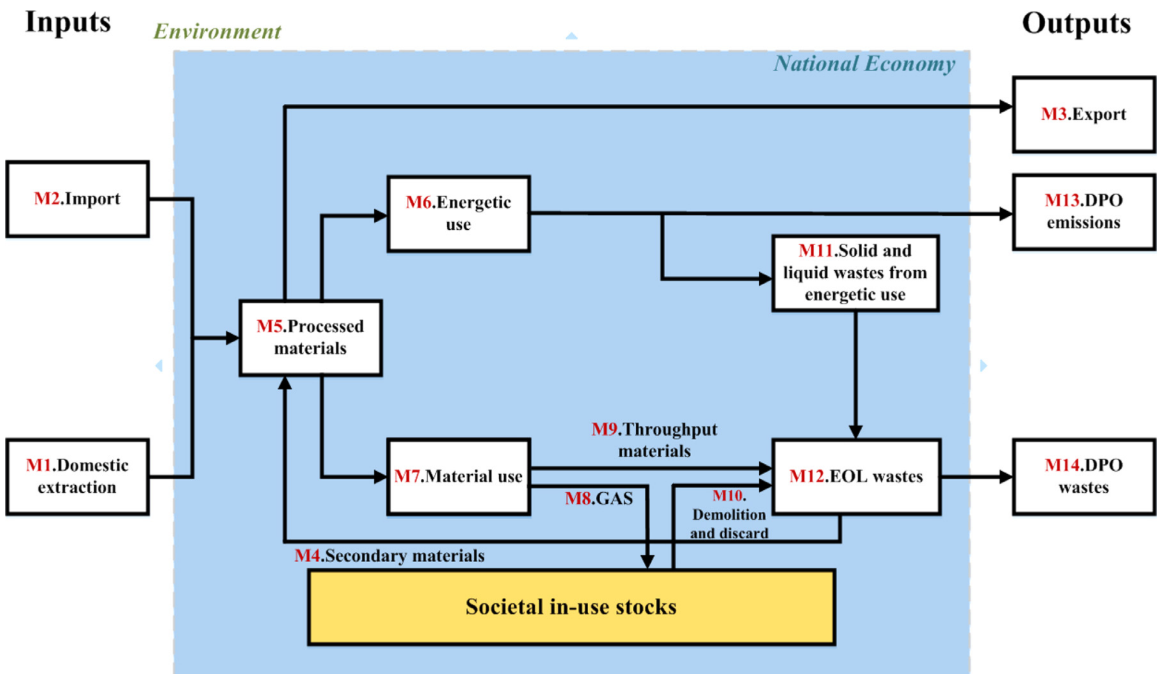

Fig. 1.. Basic monitoring model of China's Circular Economy. Adapted from (Haas et al., 2015; Jacobi et al., 2018; Mayer et al., 2018).

(National Bureau of Statistics of China, 1996–2016) and the proportions of different material categories follow the principles from (Mayer et al., 2018).

For category A4 Construction waste data is very limited. 1.8 billion tons of construction demolition waste are reported in statistical sources for 2016 (Zhang, 2017). We mainly refer to (Zheng et al., 2017), who analysed the generation and flows of construction and demolition waste in China during 2003–2013 and data for all other years is established through linear regression. It is notable that based on (Zhang, 2017), the generation of China's construction waste would be 4.85 billion tons,

Table 1
Basic monitoring indicators of China's Circular Economy. Adapted from (Eurostat, 2013; Haas et al., 2015; Jacobi et al., 2018; Krausmann et al., 2018; Mayer et al., 2018).

Indicators	Definition	Equations	Description
DE	Domestic extraction	DE = M1	Domestic extractive pressure on natural resources.
DMI	Domestic material input	DMI = DE + Import = M1 + M2	Natural resource requirement of production.
DMC	Domestic material consumption	DMC = DE + Import – Export = M1 + M2 – M3	Total quantity of materials directly used within an economic system.
PTB	Physical trade balance	PTB = Import – Export = M2 – M3	The physical trade surplus or physical trade deficit of a country.
PM	Processed materials	PM = DMC + SM = M1 + M2 – M3 + M4	All materials domestically processed in a given year.
eUse	Energetic use	eUse = M6	The part of PM that is used as energy.
mUse	Material use	mUse = M7	The part of PM that is used as material.
GAS	Gross additions to stock	GAS = M8 = M7 – M9	The quantity of material going into the stocks.
NAS	Net additions to stock	NAS = GAS – Demolition and discard = M8 – M10	The net amount of material added to the stocks per year.
DPO	Domestic processed output	DPO = DPOe + DPOw = M13 + M14	DPO comprises releases from the socioeconomic system to the natural environment.
DPOe	DPO emissions	DPOe = M13	The emissions (e.g., CO_2 and SO_2) released from the socioeconomic system to the natural environment.
DPOw	DPO wastes	DPOw = M14	The solid and liquid wastes (e.g., slag and heavy metal pollutants) released from the socioeconomic system to the natural environment.
IntOut	Interim Outputs	IntOut = EoL waste + DPO emissions = M12 + M13	All wastes and emissions after the use phase.
EoL wastes	End of Life (EoL) wastes	EoL waste = Secondary materials + DPO wastes = M4 + M14; EoL waste = Throughput materials + Demolition and discard + Solid and liquid wastes from energetic use = M9 + M10 + M11	End of Life (EoL) wastes comprise all liquid and solid residues, which are equal to Secondary materials plus DPO wastes, and also equal to the sum of Throughput materials, Demolition and discard, and Solid and liquid outputs.
SM	Secondary materials	SM = M4	The amount of materials, which undergo material recovery including downcycling and cascading use of materials.
ISCr	Input socioeconomic cycling rate, share of PM	ISCr = Share of secondary materials in PM = SM / PM = M4 / M5	The share of secondary materials in total materials processed (PM).
OSCr	Output socioeconomic cycling rate, share of IntOut	OSCr = Share of secondary materials in IntOut = SM / PM = M4 / (M12 + M13)	The share of secondary materials in interim outputs (IntOut).

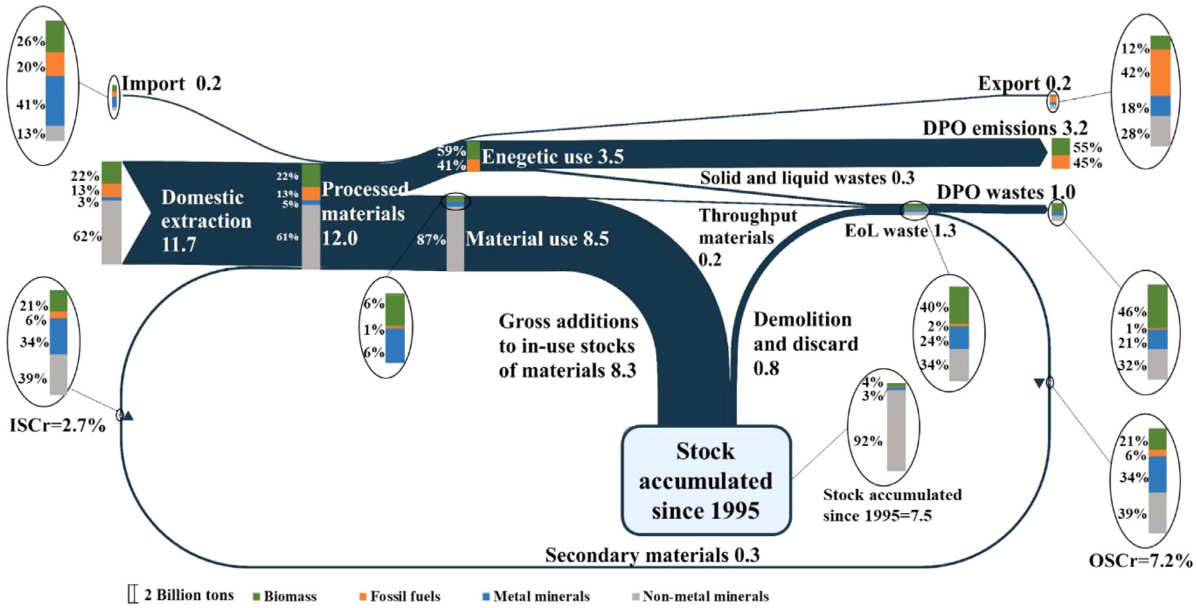

Fig. 2.. The state of China's Circular Economy in 1995 (aggregated flows). Unit: Billion tons.

which is 2.69 times the figure in the official data. To be consistent with the official data, we divided the construction waste generation data from (Zhang, 2017) by this coefficient of 2.69 for the whole dataset. This may underestimate the amount of construction waste generated in China to a certain extent.

The split of category M5 processed materials into energetic and material use was established based on material characteristics and additional information from food balances (FAO, 2019) and energy balances. The solid and liquid wastes of people and livestock were estimated by the daily manure production coefficients shown in A6 in the SI.

3. Results

Applying the CE monitoring framework to China for the period of 1995–2015, we can generate a comprehensive material flow balance (Figs. 2–4), disaggregated flow balances for four material groups (Figs. 5–8), and additional basic monitoring indicators (Table 2). The following paragraphs provide analysis of the full picture of China's material flows and the circularity of four major material groups.

3.1. Material flows of China's economy

During the period 1995 to 2015 the amount of materials processed (PM) in the Chinese economy increased by a factor of 3.1, from 12 billion tons to 37.5 billion tons, an average annual growth rate of 5.9% (Figs. 2–3 and Table 2). In 1995, 97.2% of PM (12.0 billion tons) was extracted domestically (DE), 2.7% of PM (0.3 billion tons) comprised secondary materials (SM) and only 0.1% of PM (14.5 million tons) was net physical imports (or PTB = imports – exports) (Fig. 2). Compared to 1995, the proportion of DE somewhat declined to 94.1% (19 billion tons) in 2005 and 89.9% (33.7 billion tons) in 2015 (Fig. 3) and net

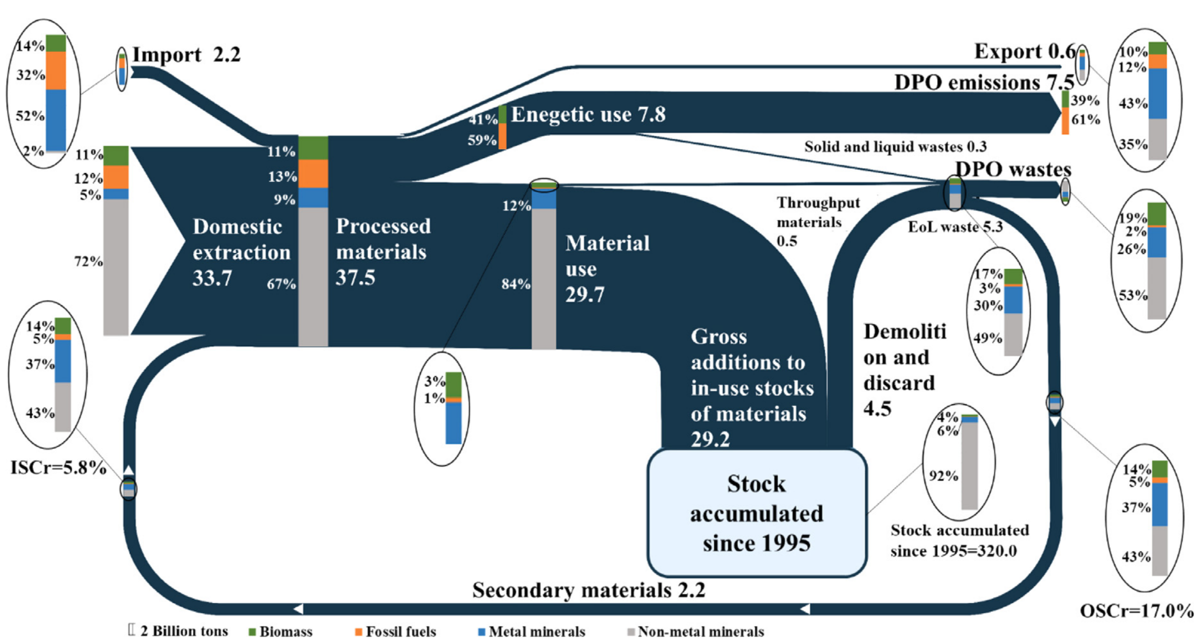

Fig. 3.. The state of China's Circular Economy in 2015 (aggregated flows). Unit: Billion tons.

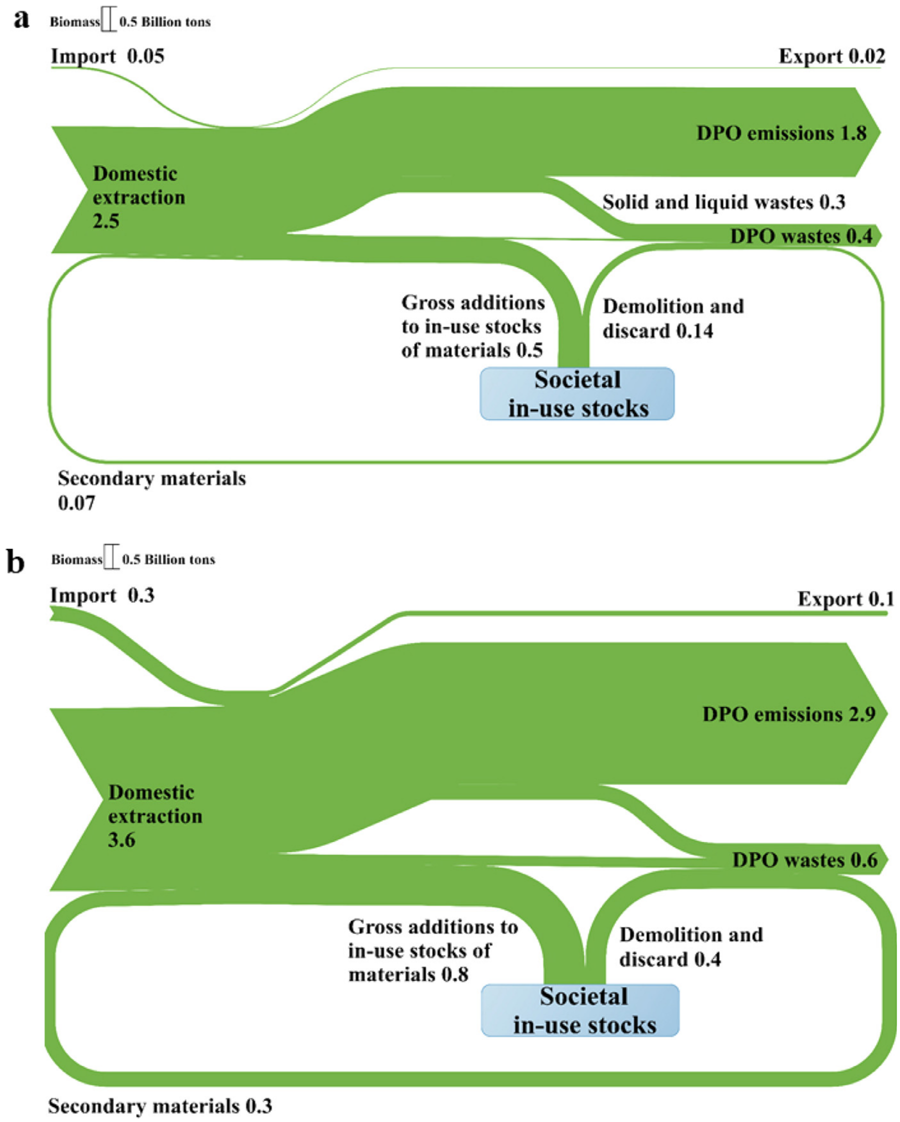

Fig. 4.. Comparison of China's biomass flows between 1995 and 2015. (a) and (b) show the biomass flows for the years 1995 and 2015, respectively. Unit: Billion tons.

imports and secondary materials gained in importance. Overall, during the two decades, China continued to rely heavily on domestic natural resources.

The share of material use of all processed materials grew over time from a share of 70.5% (8.5 billion tons) in 1995 (Fig. 2), to 74.7% (15.1 billion tons) in 2005, and 79.1% (29.7 billion tons) in 2015 (Fig. 3); only 29.5% (8.5 billion tons) in 1995, 25.3% (15.1 billion tons) in 2005, and 20.9% (29.7 billion tons) in 2015 were used for energy generation.

Most of the material use has been required for building up residential, commercial and industrial infrastructure and transport and communication networks and was added to stocks (GAS). In 1995, the GAS was 8.3 billion tons, and with the rapid urbanization process, it increased to 29.2 billion tons in 2015, increasing by a factor of 3.5. During these two decades, the accumulated stock reached as high as 320 billion tons, which provides the physical basis of China's improving infrastructure. Simultaneously, very large amounts of construction demolition waste, industrial solid waste and residential waste were disposed of with only a small amount re-entering the economic process as secondary materials through recycling. For example, in 2015 EoL waste was 5.3 billion tons, out of which only 2.2 billion tons were recycled. The remaining part was landfilled or incinerated and disposed to the environment. With increasing energy and biomass consumption, China's DPO of emissions increased from 3.2 billion tons in 1995 to 7.5 billion tons in 2015, with an annual increasing rate of 4.3%, adding significantly to global GHG emissions and making China one of the largest polluters globally.

While material use, waste flows and emissions accelerated, China's circularity rates also increased significantly. The input socioeconomic cycling rate (ISCr, SM share of PM) increased from 2.7% to 5.8% and the output socioeconomic cycling rate (OSCr, SM share of IntOut) increased from 7.2% to 17.0%. It is obvious that ISCr is much lower than OSCr, because a large share of China's processed materials (PM) were added to stock and the interim outputs (IntOut = EoL waste + DPO emissions) were much lower than PM. Compared to the European Union (EU), whose ISCr was 9.6% in 2014 (Mayer et al., 2018), China's ISCr is significantly lower, mainly because of the lack of a sound recycling system and the large amount of GAS. On the contrary, China's OSCr is relatively higher than that of the EU, whose OSCr was 14.8% in 2014, because most of China's SM is from industrial solid waste and the central government has imposed mandatory targets (utilization efficiency of general industrial solid waste) for local governments and enterprises in recent years, contributing to higher rates of end of life recycling.

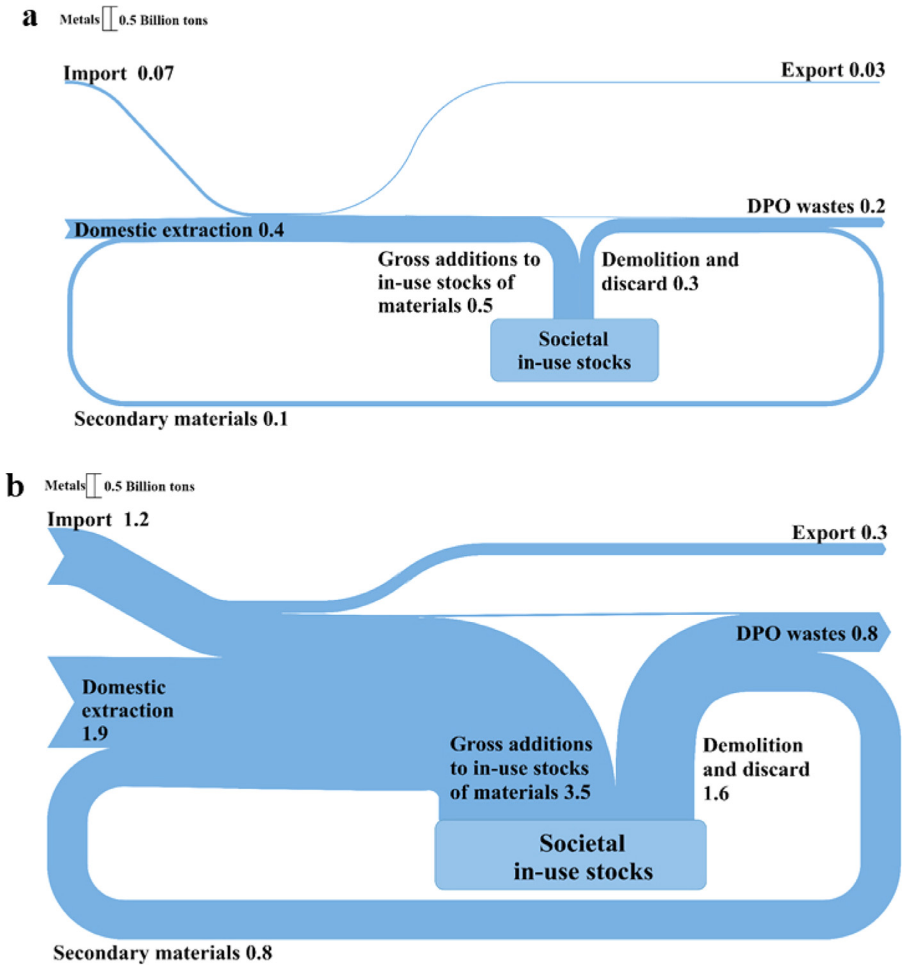

Fig. 5.. Comparison of China's metal ore flows between 1995 and 2015. (a) and (b) show the metal ore flows for the years 1995 and 2015, respectively. Unit: Billion tons.

3.2. Circularity of four major material groups

Figs. 4–7 show the disaggregated flows for the four major material groups – biomass, fossil fuels, metal ore and non-metallic minerals – in China's economy between 1995 and 2015. During the two decades, biomass extraction increased from 2.5 billion tons to 3.6 billion tons, and recycled biomass (mainly from waste paper, waste wood and residues) increased from 68 million tons to 314 million tons, increasing the ISCr of biomass from 2.6% to 7.5% and the OSCr from 3.0% to 8.3% (Fig. 4). The biological cycles have very large potential for full circularity, which is far from being achieved in China.

Metal extraction also increased rapidly from 0.4 billion tons to 1.8 billion tons during 1995–2015(Fig. 5), and in 2015 imported metal ores were as high as 1.2 billion tons. The high economic value and criticality of supply contributed result in a significant amount of secondary materials and higher recovery rates. Specifically, the SM amount (including refining waste) increased from 109 million tons to 806 million tons, resulting in comparatively high ISCr of 19.7% in 1995 and 22.7% in 2015 and OSCr of 35.4% in 1995 and 49.9% in 2015. This also reflects that metal recycling is economically viable and developed markets exist for secondary materials. The main reason for making metal recycling economically attractive is the very high energy costs of primary metal extraction.

Among the four groups, non-metallic minerals dominate material flows by volume, e.g., 67% of PM came from non-metallic minerals in 2015 (Fig. 6). Moreover, due to its low economic value, nearly all of China's PM of non-metallic minerals is sourced from DE, and the recycling rate is not as high as for metals, despite the potential for reuse of construction demolition waste in road base. Nevertheless, the recycled amount and recycling rate of non-metallic minerals has been continuously increasing. Recycled non-metallic minerals grew by a factor of 7.4, from 126 million tons to 938 million tons, their ISCr increased from 1.7% to 3.5% and their OSCr grew from 29.1% to 36.0%. Even though the recycling rate has been increasing significantly, there is still a large amount of waste from non-metallic minerals released to the environment due to the huge amount of consumption.

As only minor shares of fossil fuels went to stocks in the form of plastics and bitumen, the recycled amount and recycling rate of fossil fuels are the lowest among the four material groups (Fig. 7). In 1995, its SM amount was only around 20 million tons and the ISCr and OSCr were 1.3% and 1.4%, respectively. Twenty years later, the SM amount of fossil fuels had increased to 110 million tons, meaning the ISCr and OSCr for both had increased to 2.3%. Increasing circularity in the energy sector will require a shift to renewable energy generation and away from burning fossil fuels. Such a transition would result in some increase in metals and would help combat climate change significantly.

4. Discussion

This study provides a framework for measuring the progress of China's Circular Economy, which is not only directly linked to China's Circular Economy policies, but also linked to the Sustainable Development Goals (SDGs), Chinese indicator sets for the 13th Five Year Plan (2015–2020), the Green Development Indicator System, and

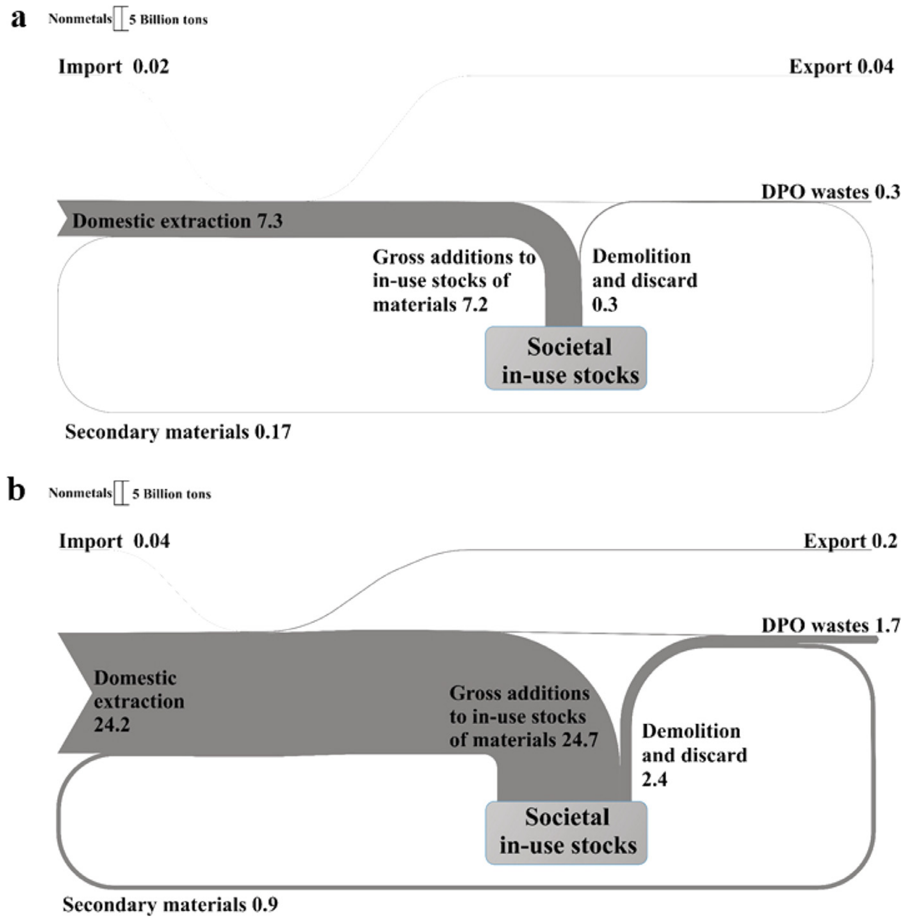

Fig. 6.. Comparison of China's non-metallic mineral flows between 1995 and 2015. (a) and (b) show the non-metallic mineral flows for the years 1995 and 2015, respectively. Unit: Billion tons.

the Ecological Civilization Construction Assessment Target System. Based on the findings above and these linkages, policy implications are provided for the Circular Economy and sustainable development of China.

4.1. Discussion on findings and policy implications

The physical scale of the Chinese economy, i.e. processed materials (PM) per capita, increased by a factor of 2.7 from 9.9 t/cap in 1995 to 27.3 t/cap in 2015. As a consequence of this rapid growth per capita, PM in China is now higher than in the EU-28 (15.7 t/cap) and in Austria (24.5 t/cap), for which similar analysis is available (Jacobi et al., 2018; Mayer et al., 2018). 80% of processed materials were used in biological and technical supply chains and only 20% used in energy provision, which also contributes to a higher level of Gross additions to stock (GAS) for China compared to the European Union and is explained by China's massive infrastructure build up.

During 1995–2015, around 320 billion tons of materials were accumulated as stock of buildings and infrastructure, including residential and commercial buildings, industrial infrastructure, and transport and communication networks. While material use has grown, the growth rate has decelerated, foreshadowing that China's resource consumption may peak in the near future. As a result, it has been suggested that the focus of China's sustainable resource use policy should gradually shift from consumption reduction to sustainable management of stocks (Krausmann et al., 2020; Wiedenhofer et al., 2019), for example, through increasing the lifetime of infrastructure and using recyclable modular buildings (Cao et al., 2019).

At the same time, a large amount of long-lived consumer goods accumulated during the studied period and China will gradually enter the scrap stage and generate huge amounts of secondary materials, such as scrap steel (Xuan and Yue, 2016; Yue et al., 2016), copper (Zhang et al., 2015, 2019), aluminum (Chen and Shi, 2012; Li et al., 2020; Yue et al., 2014), and electronic waste (Zeng et al., 2016). Effectively recycling of end of life waste will depend on improved waste management and recycling infrastructure and will determine the extent to which China can reduce primary (virgin) material demand in the future.

In the past 20 years, China has made great progress in the comprehensive utilization of industrial solid waste, which is the main reason why China's end-resource recycling rate has reached EU level. After entering the scrap stage, another transition in waste management and recycling capability for comprehensive treatment of end of life consumer waste will be required.

In addition to focusing on these two shifts in China's future, a comprehensive indicator system that allows reporting of primary material demand in the economy, greenhouse gas emissions and waste disposal in one coherent analytical framework is also needed for policy development. Focusing on end of life waste recycling, reducing waste to landfill and improving resource efficiency to address waste issues at the source are all worthwhile short-term policy principles that are no-regret strategies. While resource efficiency reduces cost and is economically attractive (Hatfield-Dodds et al., 2017), climate mitigation has a short-term cost. Waste recycling is economically worthwhile for metals, but this is not generalizable for all materials.

In the medium term (Fig. 8), 10 to 20 years, the economy requires structural adjustments to help reduce waste flows through designing new materials, products and processes that service the needs of the

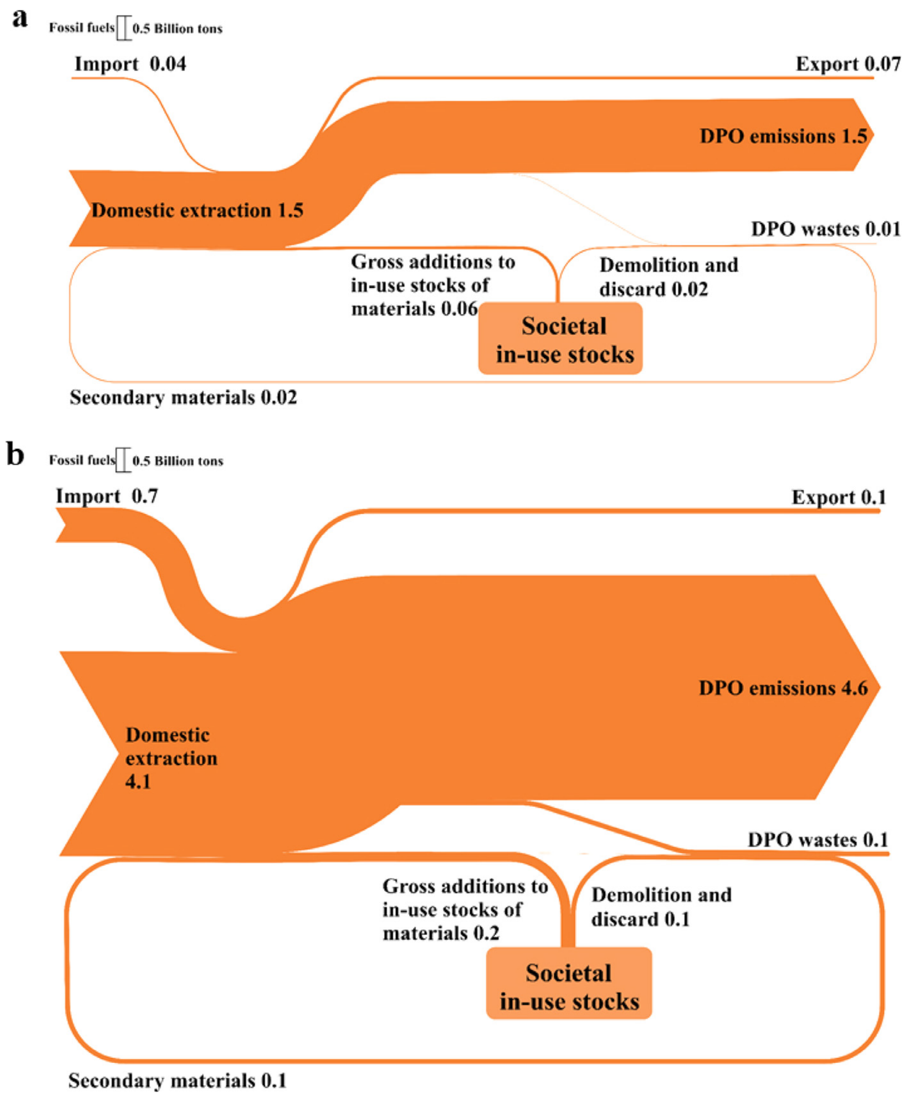

Fig. 7.. Comparison of China's fossil fuel flows between 1995 and 2015. (a) and (b) show the fossil fuel flows for the years 1995 and 2015, respectively. Unit: Billion tons.

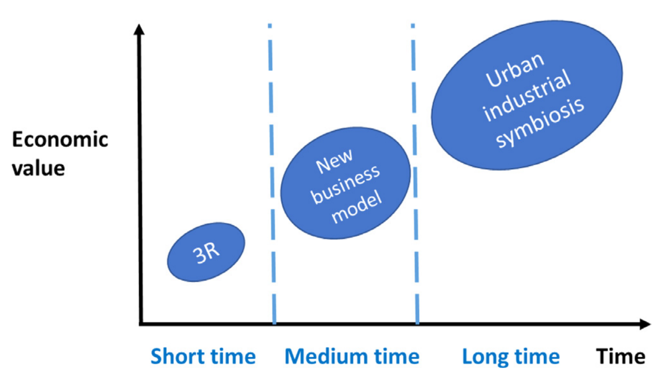

Fig. 8.. Three-phase circular economy policy.

population but require considerably fewer materials and result in significantly less waste and lower emissions. Changes in supply chains that allow for redesign of production and consumption promise much larger economic benefit, compared to short-term changes of reduce, reuse and recycle. They may generate the economic and employment opportunities of the future enabled through the bio, digital and circular economies.

In the long run, urban and industrial systems must be established as closed loop systems in order to allow wellbeing and living standards for large numbers of people and within planetary boundaries. Generalizing high living standards for 9 billion people needs lots of additional natural resources and will add additional pressure on material supply systems and will continue to overshoot planetary boundaries. Closing the loop allows to relieve some of this pressure and avoids the need of tapping into those natural resource reserves that have the largest negative social and environmental impacts (IRP, 2019). Urban industrial symbiosis (also called industrial and urban symbiosis in some literature) (Dong et al., 2016, 2017; Geng et al., 2010; Sun et al., 2017) promises a restructuring of the way in which cities and industries are operated as closed loop systems.

4.2. Linking circular economy indicators to key policies

China has been making progress in the promotion of circular economy (CE) for decades and has published around 280 CE or resource use related laws, policies and regulations (Zhu et al., 2018). To monitor and evaluate the effectiveness of the Circular Economy Promotion Law, new CE metrics and indicators have been proposed for the macro economy and for industrial parks (Geng et al., 2012; McDowall et al., 2017). Most circularity indicators focus on specific materials or waste flows, such as the recycling rate of iron scrap, non-ferrous metals, waste

Table 2
Basic monitoring indicators of China's Circular Economy during 1995–2015.

Indicators	Unit	1995	2000	2005	2010	2015
DE	MT	11,689	13,169	19,048	29,529	33,716
DMI	MT	11,863	13,476	19,782	31,066	35,931
DMC	MT	11,704	13,246	19,406	30,630	35,351
PTB	MT	15	77	357	1,101	1,635
PM	MT	12,027	13,686	20,241	32,304	37,519
eUse	MT	3,543	3,508	5,113	6,982	7,827
mUse	MT	8,484	10,178	15,128	25,322	29,692
GAS	MT	8,305	9,982	14,901	25,034	29,218
NAS	MT	7,529	8,904	13,141	21,751	24,742
DPO	MT	4,175	4,342	6,265	8,878	10,609
DPOe	MT	3,216	3,178	4,742	6,654	7,464
DPOw	MT	959	1,164	1,522	2,224	3,145
IntOut	MT	4,498	4,782	7,100	10,552	12,777
EoL waste	MT	1,282	1,604	2,358	3,898	5,313
SM	MT	323	440	835	1,674	2,168
Biomass	MT	68	83	144	254	314
Metal ores	MT	109	142	284	580	806
Non-metallic minerals	MT	126	190	361	762	938
Fossil fuels	MT	20	24	46	77	110
ISCr	%	2.7	3.2	4.1	5.2	5.8
Biomass	%	2.6	3.0	4.3	7.0	7.5
Metal ores	%	19.7	23.2	24.0	22.0	22.7
Non-metallic minerals	%	1.7	2.1	2.8	3.5	3.8
Fossil fuels	%	1.3	1.9	1.8	1.8	2.3
OSCr	%	7.2	9.2	11.8	15.9	17.0
Biomass	%	3.0	3.3	4.9	7.8	8.3
Metal ores	%	35.4	35.7	47.9	53.6	49.9
Non-metallic minerals	%	29.1	30.8	35.3	39.2	36.0
Fossil fuels	%	1.4	2.0	1.8	1.8	2.3

paper, plastics, rubber, and industrial solid waste, and there is a lack of indicators and clear targets for general whole of economy recycling rates on both the input and output sides. Moreover, because of the lack of a detailed and standardized accounting process, significant barriers to the implementation of the new indicators exist. Therefore, this study can be regarded as an important reference for establishing indicators of circularity for the whole economy.

In order to realize the full potential of CE, it is important to link CE indicators to existing key policy priorities and decision processes. We present a set of CE indicators and situate these in the context of the SDGs, the Chinese indicator sets for the 13th Five Year Plan (2015–2020) (Central Committee of the Communist Party of China, 2016), the Ecological Civilization Construction Assessment Target System (NDRC, 2016a), and the Green Development Indicator System (NDRC, 2016b) (Table 3). At the global level, several indicators provided by this study can be directly or indirectly linked to the SDGs (Schroeder et al., 2019; UNSTATS, 2019). For example, there are three SDGs for which MFA based indicators have been selected to monitor progress by the Inter Agency Expert Group, namely SDG 8.4, SDG 12.2 and SGD 12.5. For SDGs 8.4 and 12.5 the standard indicators of Domestic Material Consumption and Material Footprint are used to calculate resource productivity (SDG 8.4) and per-capita material use (SDG 12.2). Reporting on the output side and for circularity allows to inform SDG 12.5 in triremes of recycling rate and total end-of life waste and waste to landfill.

However, only half of them can be related to the key national policies of China, most of which are focused on the utilization of industrial solid waste, energy consumption, emissions reduction and intensity indicators. This study can contribute to measuring these indicators. For instance, resource productivity is an important indicator in China'sGreen Development Indicator System, but it still lacks a standardized accounting method in China. Regarding general national circularity indicators, Japan and the EU countries have already set this indicator as one of the main monitoring indicators for CE (European Commission, 2018; Moriguchi, 2007), and this research provides a timely and necessary reference both on perspectives of indicator selection and a standardized accounting process.

4.3. Research limitations

There are several limitations to our approach to accounting for China's CE indicators that we would like to acknowledge. The whole CE framework includes the following basic material flows: input flows, output flows, secondary materials and stocks, and the generally problematic data are from the latter three flows. Regarding input flows, we divided the processed materials of biomass and fossil fuels into energetic use and material use materials, but we can only find the proportion for biomass, and wechose to use the proportion of energetic use for fossil fuels from (Mayer et al., 2018). Regarding output flows, even though the Chinese National Statistical Office publishes annual data on industry solid waste and household waste, there is no distinction between the four types of material groups. Therefore, we adopted the proportion coefficients of these four material groups for EU countries from (Mayer et al., 2018). As Chinese economic structure and waste treatment levels are different from EU countries, this coefficient transplant could cause a degree of uncertainty and the final indicators may be sensitive to this. As for SM, although the development of CE in China started earlier, the statistics for SM data are relatively recent and most of them are from unofficial sources. Thus, in this study the SM of several materials (e.g., wastepaper, waste plastic and steel scrap) was derived from different literature. In addition, for a few years between 1995 and 2000 there was no data available for several recycled materials, which we used the linear interpolation method to estimate. Stock data is another important issue (Fishman et al., 2016; Krausmann et al., 2017; Miatto et al., 2017), which relates to the other three main material flows. However, there is little official data on Chinese stocks (Liu et al., 2019) and related construction waste, including recycled and disposal waste. In this study we estimated these data based on the limited official data and a relevant study (Zheng et al., 2017) (see A4 in the SI). Overall, the above limitations call for a comprehensive and fast improvement in the Chinese statistical system for CE.

5. Conclusion

This study has provided a framework for measuring the progress of China's Circular Economy, including a CE model, datasets, metrics and indicators monitoring the performance of the economy regarding the scale of primary materials use, waste flows, and recycling and circularity. Using this framework, the Chinese CE situation during 1995–2015 has been examined.

The results indicate that during the study period, on the input side China's Processed Materials (sum of DMC and Secondary Materials) increased by a factor of 3.1 from 12.0 billion tons to 37.5 billion tons, which is dominated by DE of non-metallic minerals. On the output side, China's Interim Outputs (sum of DPO of emissions and DPO of waste) increased by a factor of 2.8 from 4.5 billion tons to 12.8 billion tons. The difference between Processed Materials and Interim Outputs contributed more than 320 billion tons of Net Additions to Stock. Apart from the input side and output side material flow indicators, China's circularity rates also increased dramatically. The Input Socioeconomic Cycling Rate (ISCr, SM share of PM) increased from 2.7% to 5.8%, whereas the Output Socioeconomic Cycling Rate (OSCr, SM share of IntOut) rose from 7.2% to 17.0%.

Based on the framework of Chinese CE provided, we linked CE indicators to the Sustainable Development Goals (SDGs), Chinese indicator sets for the 13th Five Year Plan (2015–2020), the Green Development Indicator System, and the Ecological Civilization Construction Assessment Target System. We find that this study can supplement these indicators. Last but not least, three-phase (short-time, medium-time and long-time) policy suggestions have been provided for the Circular Economy and sustainable development of China.

Table 3
Relationship between basic CE indicators and existing policy indicators.

Indicator name	Purpose	Policy	SDGs	13th Five Year Plan (2015–2020)	Green Development Indicator System	Assessment Target System of Ecological Civilization
DE	Extractive pressure	Mining and agriculture policy	2.5.1, 14.4.1, 15.1.1, 15.2.1, 15.3.1	—	—	—
Import	Pressure on other countries	Trade policy	2.b.1	—	—	—
Export	Pressure from other countries	Trade policy	2.b.1	—	—	—
PTB	Position of global economies	Trade policy	2.b.1	—	—	—
Import of DMC	Supply security	Trade policy	2.b.1	—	—	—
Export of DMC	Rely on world market	Trade policy	2.b.1	—	—	—
DMC	Consumption pressure	Consumption policy	7.2.1, 8.4.2, 12.1.1, 12.2.2	Share of Non-Fossil Fuels in Primary Energy Consumption.	Total Energy Consumption; Share of Non-Fossil Fuels in Primary Energy Consumption.	Total Energy Consumption; Share of Non-Fossil Fuels in Primary Energy Consumption.
RE = GDP/DMC	Efficiency of resource use	Resource efficiency policy	7.3.1, 8.4.2, 12.2.2	Reduction in Energy Consumption per unit of GDP.	Resource Productivity; Reduction in Energy Consumption per unit of GDP.	Reduction in Energy Consumption per unit of GDP.
DPO	Pressure on domestic ecosystem	Waste or emission management policy	6.3.1–2, 9.4.1, 11.6.1, 12.3.1, 12.4.2	Reduction in Total Emission of COD, Ammonia Nitrogen, Sulfur Dioxide, and NOx; Reduction in CO_2 Emission per unit of GDP.	Disposal Rate of Hazardous Waste; Reduction in Total Emission of COD, Ammonia Nitrogen, Sulfur Dioxide, and NOx; Harmless Treatment Ratio of Household Waste; Centralized Sewage Treatment Ratio; Reduction in CO_2 Emission per unit of GDP.	Reduction in Total Emission of COD, Ammonia Nitrogen, Sulfur Dioxide, and NOx; Reduction in CO_2 Emission per unit of GDP.
ISCr	Cycling condition on input side	CE policy	12.5.1	—	—	—
OSCr	Cycling condition on output side	CE policy	12.5.1	—	Utilization Efficiency of Crop Straw; Utilization Efficiency of General Industrial Solid Waste.	—

Note: explanations of related SDG indicators are shown in the Excel file: A7 SDGs indicators in the SI.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Supplementary materials

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