China's bulk material loops can be closed but deep decarbonization requires demand reduction

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Abstract

China, as the largest global producer of bulk materials, confronts formidable challenges in mitigating greenhouse gas (GHG) emissions arising from their production. We explore the emission savings resulting from three circular economy strategies: improved scrap recovery, more intensive use, and lifetime extension. We show that by 2060, China can source the majority of its demand for bulk materials through recycling, partially attributable to a declining population. Province-level results show that while economic development initially drives up material demand, it also enables closed loops when demand approaches saturation levels. Between now and 2060, improved scrap recovery cumulatively reduces GHG emissions by 10%, while more intensive use, resulting in reduced material demand, reduces emissions by 21%. Lifetime extension offers a modest benefit, leading to only a 3% reduction in emissions. Despite the large potential for recycling, our findings highlight the equal importance of demand reduction in meeting global climate targets.

Main text

Materials are indisputably the backbone of our modern civilization[1]. Bulk materials, such as cement, steel, aluminum, copper, glass, and various chemicals, are consumed in large volumes and provide essential services, which are critical for fulfilling basic human needs: shelter, workplace, mobility, and communication. While bulk materials are indispensable for modern society, their production carries a high environmental price. Recent studies calculate that the production of bulk materials accounts for almost 60% of the energy consumption and around 70% of the direct CO_2 emissions from the global industrial sector[2]. Unless measures are urgently taken to change the way materials are produced or consumed, it is expected that soaring needs for housing and infrastructure development will drive up global demand for bulk materials, placing ambitious climate targets at risk[3,4]. Here, we analyze the technical potential and greenhouse gas (GHG) emission savings of several critical measures designed to shift China toward where societal demand for bulk materials is drastically reduced without compromising the level of human well-being[5].

The 2015 Paris Agreement has called for international efforts to limit the increase in the global average temperature to well below 2 °C above pre-industrial levels, and pursue further efforts to limit the increase to 1.5 °C[6]. The 1.5 °C vision entails a transition toward industrial and energy systems with net-zero emissions by mid-century[7-9]. In light of the magnitude of annual CO_2 emissions arising from bulk materials production (8.4 Gt per year in 2020[2]), scientific and policy communities have sought opportunities to decarbonize the production of bulk materials[10]. Yet, decoupling emissions from bulk materials production is challenging for three reasons. First, bulk materials production requires high-temperature heat, which is economically challenging to provide without combusting fossil fuels. Second, a significant fraction of CO_2 emissions from bulk materials production results from process chemical reactions. Avoiding these process emissions entails deployment of carbon capture, utilization, and storage (CCUS) or switching to alternative processes, with both options currently not ready to be deployed at scale[4,11,12]. Last, facilities for producing bulk materials are designed to operate over long periods, in many cases for decades, posing infrastructural lock-ins that delay or prevent the transition to low-carbon alternatives[13].

Production-centric emissions reduction strategies may fall short of addressing emissions from the production of these “hard-to-decarbonize” materials, highlighting the need for broadening the portfolio of decarbonization levers to include measures that reduce societal demand for and promote recycling of bulk materials. Several examples from the literature point to the importance of circular economy strategies (sometimes referred to as material efficiency strategies[14-17]). In a recent International Energy Agency (IEA) report, circular economy strategies for buildings and vehicles contribute approximately 30% of the combined CO_2

reduction for three bulk materials: steel, cement, and aluminum[18]. Other studies have revealed the potential of circular economy strategies in decarbonizing concrete[11,19], steel[20], residential buildings[14,21], commercial buildings[21], and passenger vehicles[14]. Despite the welcome inclusion of circular economy strategies in climate mitigation roadmaps and policy formulation, our understanding of the efficacy of circular economy strategies is still limited to a few specific sectors or materials[22]. The extent to which circular economy strategies will contribute to bulk materials decarbonization remains an open question, calling for examining the opportunities carried in circular economy strategies for a panoply of bulk materials.

China is an ideal testbed for exploring how a circular materials system might help achieve deep emission cuts for bulk materials. The recent decades have witnessed a rapid growth in China's appetite for bulk materials, with China now producing around 60% of the global cement[23], primary aluminium[24], and crude steel[25], as well as around 30% of global plastics[26]. In 2020, China's bulk materials production accounted for more than 60% of the energy consumption and about 75% of the direct CO_2 emissions from China's industrial sector[27]. Previous studies show that regional differences in bulk materials use exist between China's western and eastern areas[28,29]. For example, the use of steel by society, over time, results in the buildup of steel stocks, where steel is embedded in products like vehicles and buildings for long periods. In the less-developed western provinces of China, steel stocks have grown to around 3 to 4 tonnes per capita, comparable to steel stocks in Argentina and Bulgaria. In the more-developed eastern provinces of China, steel stocks have reached around 8 to 9 tonnes per capita, comparable to steel stocks in many developed economies such as Norway and Ireland. A provincial-level analysis of bulk materials production, use, and stocks in China can provide insight into the associated GHG emissions and mitigation options for countries across the globe.

Against this background, we develop an integrated modeling framework—IMAGINE Materials (short for Integrated modeling of the Material-enerGy-emIssion NExus associated with bulk materials), which is populated by the Provincial Material Stocks and Flows Database (PMSFD) for China[30]. A schematic of the modeling framework is provided in Figure 1. The amassed database keeps track of the production, use, stocks, and disposal of 13 bulk materials (cement, steel, aluminum, copper, rubber, plastic, glass, lime, asphalt, sand, gravel, brick, and wood) and 103 product types, grouped into five end-use segments (building, infrastructure, transport equipment, machinery, and household appliances) for domestic consumption during 1978-2018. The data collectively account for 80% of all bulk materials produced in China (see Methods). With these comprehensive datasets, we investigate patterns of bulk materials production, use, stocks, and disposal across China's provinces. We then explore the viability of creating a closed-loop system for bulk materials and its potential contribution toward achieving net-zero emissions for bulk materials in China from 2019 to 2060. To model the GHG savings by circular economy strategies, we pair our database with life cycle assessment (LCA) results and assess the GHG emissions associated with bulk materials production in three distinct future scenarios.

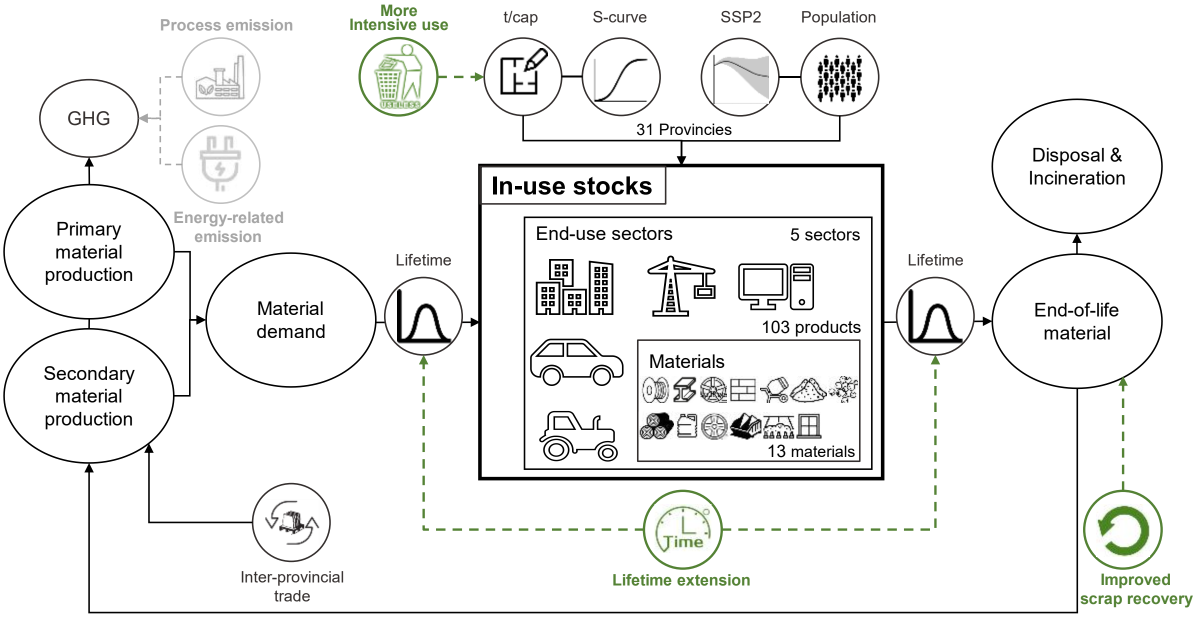

Figure 1 | IMAGINE Materials: integrated modeling of the material-energy-emission nexus associated with bulk materials.

Results

Scenarios and narratives

Using the IMAGINE Materials modeling framework, we design three scenarios to compare the GHG emissions arising from bulk materials production: (1) a *Frozen Progress* (FP) scenario in which all model parameters remain constant from 2019 to 2060; (2) a *Recent Ambitions* (RA) scenario, which is consistent with the IEA ETP 2017 Reference Technology scenario[31]; and (3) a *Circular Economy* (CE) scenario in which circular economy strategies are expected to play a significant role in decarbonizing bulk materials production from 2019 to 2060.

The FP scenario reflects a future where no technological improvements in the bulk materials system take place, and the historical trends for material stocks continue through 2060. The RA scenario depicts the expected joint efforts (e.g., improving energy efficiency and switching from fossil fuels to renewable energy) taken by governments and industry, reflecting the recent ambitions of stakeholders involved in decarbonizing bulk materials production. The CE scenario considers three strategies[32]: (1) *improved scrap recovery*, (2) *more intensive use*, and (3) *lifetime extension*. We choose to model the preceding three CE strategies because evaluating the potential of other CE strategies (e.g., remanufacturing, material substitution, and lightweighting) requires more fine-grained data and models, which are currently unavailable. As opposed to the FP and RA scenarios, the CE scenario envisions a less material-demanding future, where discarded materials are circulated back into the economy while the total societal throughput of materials is minimized. Whenever possible, deployment levels of CE strategies are derived from roadmaps and scenario analyses in the literature, which estimate achievable deployment levels of each strategy (Table 1).

Table 1 | Summary of scenarios and key assumptions.

Scenario	CE strategies	Population	GHG emission intensities	Recycling rates	Per-capita material stocks	Lifetimes
Frozen Progress (FP)	No CE strategies are considered.	Future demographic characteristics broadly follow their historical patterns.	GHG emission intensities remain unchanged from 2019 to 2060.	Recycling rates remain unchanged from 2019 to 2060.	Future trends of per-capita material stocks broadly follow their historical patterns.	Lifetimes remain unchanged from 2019 to 2060.
Recent Ambitions (RA)			Moderate improvements take place in bulk materials production, emulating the IEA ETP 2017 Reference Technology scenario[31].			
Circular Economy (CE)	Improved scrap recovery			End-of-life (EoL) material recycling rate will gradually increase and reach the theoretical maximum by 2060.		
	More intensive use				Material stocks per person in 2060 will be reduced by 0-25%.	
	Lifetime extension					Product lifetime will be gradually prolonged by 30-55% from 2019 to 2060.

Note: The recycling rate represents the proportion of recycled EoL materials, measured as a percentage of the total EoL materials available.

Surging end-of-life materials make closing material cycles possible

Our simulations show that the gradual saturation of material stocks leads to peaks and subsequent declines in material demand (Figure 2). Notably, in the FP scenario where no interventions are taken, the national availability of secondary materials matches, and then overtakes, the total demand for materials around 2050. As material stocks in China start saturating, national material demand falls to a low point of around 7.3 Gt per year in 2036, remains steady from 2037 to 2046, and is expected to decline further due to the combined effect of a shrinking population and saturated per-capita material stocks. By 2060, national material demand is expected to be as low as 6.5 Gt per year. At the same time, the supply of secondary materials rises over time, since increasing amounts of materials become available at the product EoL. As a result, the gap between material demand and secondary supply quickly shrinks between 2019 and 2060. Despite the potential for closing the material cycles through secondary supply, it is still thermodynamically challenging to reach high recycling rates for several materials, such as brick, glass, rubber, and plastics (see Table S7).

The time when a closed-loop bulk materials system becomes viable varies by region and material. In the FP scenario, the more-developed eastern provinces will attain a closed-loop material system a few decades earlier, whereas for the less-developed western provinces, matching material demand with regional secondary supply is possible only after 2040. This difference can be explained by regional inequality in asset accumulation and infrastructure development. The supply of secondary materials is unevenly distributed across provinces due to different stock patterns. From 2019 to 2040, several higher-income provinces, including Beijing, Tianjin, Jiangsu, Shanghai, Zhejiang, and Fujian, are projected to double their availability of EoL materials, creating more opportunities for the recycling and remanufacturing of secondary materials. These provinces will be in the position to fully close their steel, copper, and aluminum cycles from 2040 to 2060 (see Figure S14), providing adequate collection and new alloy separation technologies and infrastructure are in place. By contrast, the supply of secondary materials in less-developed provinces, most of which are located in Northwest China or Southwest China, is insufficient to match material demand prior to 2060. The provinces in inland China will face severe shortages of secondary materials required for closing the material cycles. This is caused by both the rapid rise in material demand, driven by population growth in lower-income provinces, and the reduced availability of secondary materials due to smaller in-use material stocks. As fertility rates—key parameters governing population growth—often fall alongside economic development and urbanization, population declines are expected to arrive later in lower-income provinces. However, the gap between secondary materials and material demand in lower-income provinces may be bridged by transporting the surplus EoL materials from wealthier provinces.

In the CE scenario, we envision a less material-demanding future, where three CE strategies bend the curves of material demand and secondary supply (Figure 2). Our simulations show that the decline in the national demand for materials parallels the decline in the national supply of secondary materials, yet the gap between them closes by 2040, approximately 9 years sooner than in the FP scenario. The exact timing of when material demand is matched with secondary supply varies by region, with several provinces—including Shandong, Shanxi, Shaanxi, Hubei, Fujian, and Sichuan—seeing an even earlier breakeven point.

In the FP and RA scenarios, non-metallic materials, including gravel, sand, cement, and brick, account for the lion's share of the societal throughput of materials, but only a small fraction of the demand for these materials is sourced from secondary supply and inter-provincial trade (Figure 3a). In the CE scenario, more intensive use and lifetime extension combined reduce material demand by 3.4 Gt in 2060, bringing down the national demand to 3.2 Gt (Figure 3b). In the same year, 4.2 Gt of EoL materials is available, of which more than 80% (2.4 Gt) is reprocessed and circulated back into the economy; the remainder of EoL materials (1.7 Gt) is sent to landfills or incinerators. Given the high recycling rates in the CE scenario, only 0.6 Gt of material demand is sourced from primary production in 2060 and 93.7 Mt from inter-provincial trade. In the FP and RA scenarios, inter-provincial trade of EoL materials is projected to reach 2.3 Mt by 2060, with Beijing, Heilongjiang, Jilin, Liaoning, Shanghai, and Zhejiang emerging as the primary exporters (Figure 3c). In the CE scenario, while these provinces maintain their significant role as exporters of EoL materials, Guangdong, Jiangsu, Shandong, and Sichuan assume a dominant position in trading EoL materials (Figure 3d).

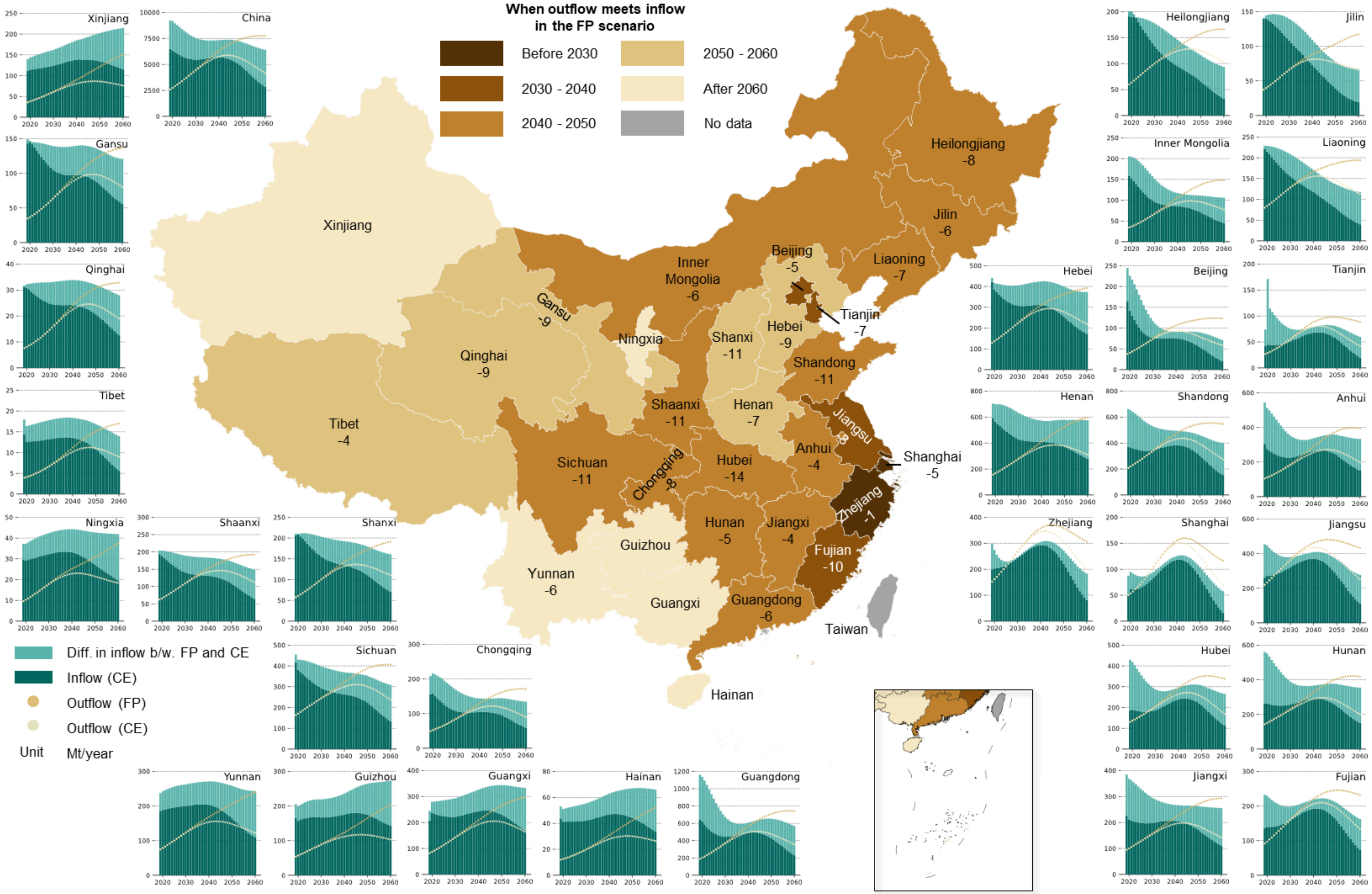
When outflow meets inflow in the FP scenario
Before 2030
2030 - 2040
2040 - 2050
2050 - 2060
After 2060
No data
Diff. in inflow b/w. FP and CE
Inflow (CE)
Outflow (FP)
Outflow (CE)
Unit Mt/year
Xinjiang
Tibet -4
Qinghai -9
Gansu -9
Ningxia
Inner Mongolia -6
Heilongjiang -8
Jilin -6
Liaoning -7
Beijing -5
Tianjin -7
Hebei -9
Shanxi -11
Shandong -11
Shaanxi -11
Henan -7
Jiangsu -8
Anhui -4
Shanghai -5
Sichuan -11
Chongqing -8
Hubei -14
Zhejiang -1
Hunan -5
Jiangxi -4
Fujian -10
Guizhou
Yunnan -6
Guangxi
Guangdong -6
Taiwan
Hainan
China
2020 2030 2040 2050 2060

Figure 2 | Material demand (inflow) and end-of-life material availability (outflow) between 2019 and 2060 across China. The number under each province name represents the time difference between the time when outflow meets inflow in the FP scenario and the time when this becomes possible in the CE scenario. FP stands for Frozen Progress. CE stands for Circular Economy.

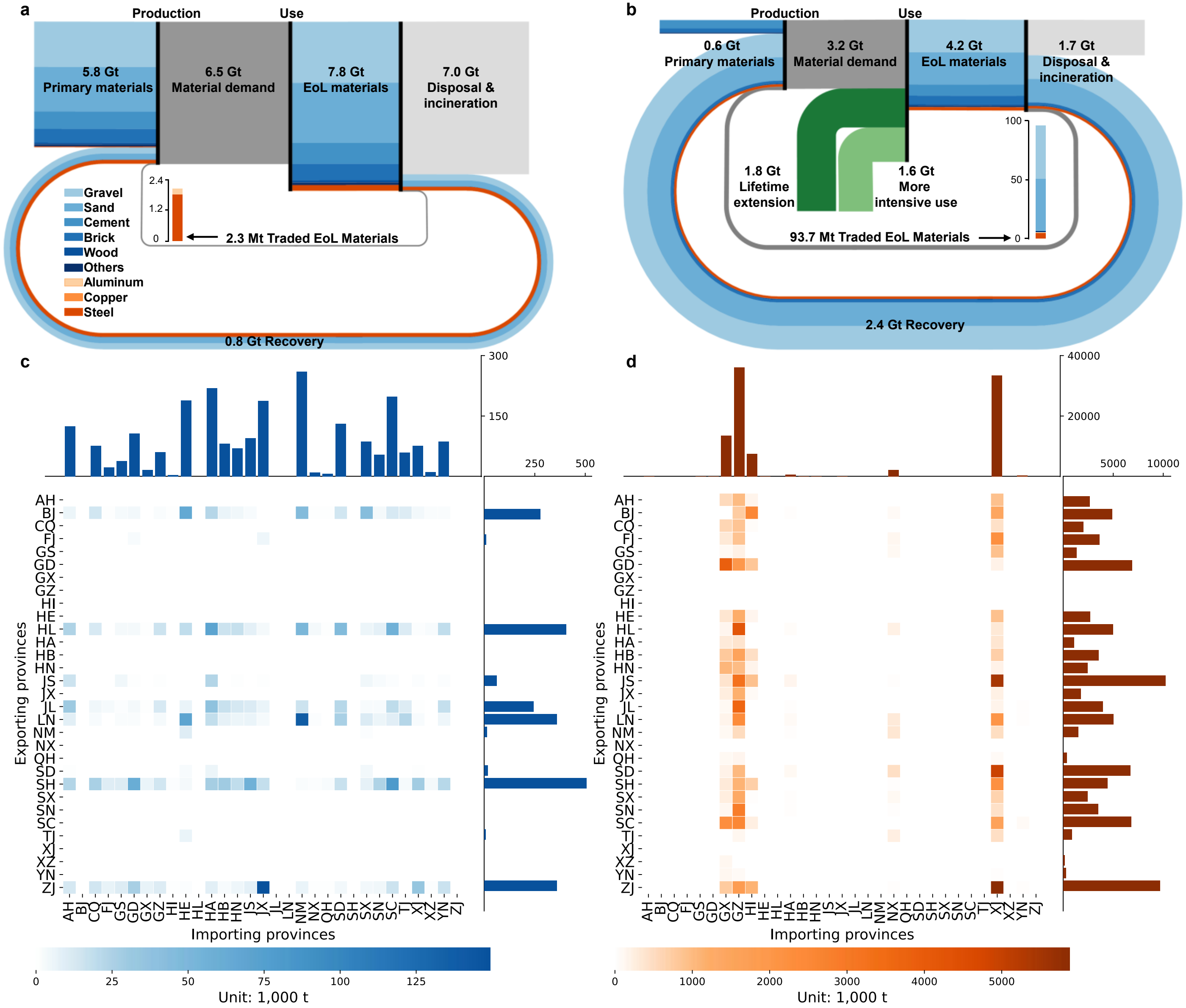
a
Production
Use
5.8 Gt
Primary materials
6.5 Gt
Material demand
7.8 Gt
EoL materials
7.0 Gt
Disposal &
incineration
2.4
1.2
0
2.3 Mt Traded EoL Materials
Gravel
Sand
Cement
Brick
Wood
Others
Aluminum
Copper
Steel
0.8 Gt Recovery
b
Production
Use
0.6 Gt
Primary materials
3.2 Gt
Material demand
4.2 Gt
EoL materials
1.7 Gt
Disposal &
incineration
1.8 Gt
Lifetime
extension
1.6 Gt
More
intensive use
100
50
0
93.7 Mt Traded EoL Materials
2.4 Gt Recovery
c
300
150
250
500
Exporting provinces
AH BJ CQ FJ GS GD GX GZ HI HE HL HA HB HN JS JX JL LN NM NX QH SD SH SX SN SC TJ XJ XZ YN ZJ
Importing provinces
0
25
50
75
100
125
Unit: 1,000 t
d
40000
20000
5000
10000
Exporting provinces
AH BJ CQ FJ GS GD GX GZ HI HE HL HA HB HN JS JX JL LN NM NX QH SD SH SX SN SC TJ XJ XZ YN ZJ
Importing provinces
0
1000
2000
3000
4000
5000
Unit: 1,000 t

Figure 3 | Material demand, end-of-life material availability, material savings, and inter-provincial end-of-life material trade in 2060. (a) Material flows in the FP and RA scenarios. (b) Material flows and savings in the CE scenario. (c) Inter-provincial trade of end-of-life materials in the FP and RA scenarios. (d) Inter-provincial trade of end-of-life materials in the CE scenario. Others include asphalt, glass, plastic, lime, and rubber. Two-letter codes for provinces: AH-Anhui; BJ-Beijing; CQ-Chongqing; FJ-Fujian; GS-Gansu; GD-Guangdong; GX-Guangxi; GZ-Guizhou; HI-Hainan; HE-Hebei; HL-Heilongjiang; HA-Henan; HB-Hubei; HN-Hunan; JS-Jiangsu; JX-Jiangxi; JL-Jilin; LN-Liaoning; NM-Inner Mongolia; NX-Ningxia; QH-Qinghai; SD-Shandong; SH-Shanghai; SX-Shanxi; SN-Shaanxi; SC-Sichuan; TJ-Tianjin; XJ-Xinjiang; XZ-Tibet; YN-Yunnan; ZJ-Zhejiang.

Circular economy strategies can bring substantial GHG savings

Figures 4a and 4b show that, on top of the progress envisaged in the RA scenario, CE strategies can deliver substantial GHG savings, amounting to a cumulative total of 25.4 Gt CO_2e over the period 2019 to 2060 (34% of the cumulative GHG emissions in the FP scenario). In the FP scenario, GHG emissions peak at about 2.3 Gt per year around 2022 and thereafter, steadily decrease to 1.4 Gt CO_2e per year by 2060 due to declines in material demand. In the RA scenario, improvements in materials production cumulatively save 9.8 Gt CO_2e.

Among the three CE strategies, improved scrap recovery saves 322.1 Mt CO_2e per year by 2060 and results in cumulative savings of 7.6 Gt CO_2e emissions from 2019 to 2060, by replacing primary supply with secondary supply. Improvements in scrap collection and secondary material processing can realize the potential of available EoL materials, yet the contribution of this strategy has limits: about 23% of the annual emissions in the FP scenario in 2060 and about 10% of the cumulative emissions in the FP scenario from 2019 to 2060. This is because recycling rates are already relatively high for materials like copper, steel, and aluminum. To achieve net-zero emissions for bulk materials in China, it is apparent that recycling alone will not suffice. While material recycling eliminates the GHG emissions from bulk materials production, these are partially offset by GHG emissions created in secondary material processing (Figure 4c). For example, collection, sorting, and separation of EoL materials consume appreciable amounts of energy, as these waste-handling activities require energy-consuming vehicles and machinery.

More intensive use results in an additional 13% saving in GHG emissions in 2060 or a 21% saving in cumulative GHG emissions from 2019 to 2060 compared to the FP scenario. These emission savings result from activities such as designing reasonably-sized buildings, designing lightweight cars, space-sharing, and ride-sharing. Lifetime extension emerges as a significant option for saving GHG after 2050, resulting in a 15% reduction in annual GHG emissions in

2060 or a 3% reduction in cumulative GHG emissions from 2019 to 2060 compared to the FP scenario. Interestingly, unlike improved scrap recovery, more intensive use and lifetime extension reduce GHG emissions by reducing overall demand and slowing down the turnover of material stocks.

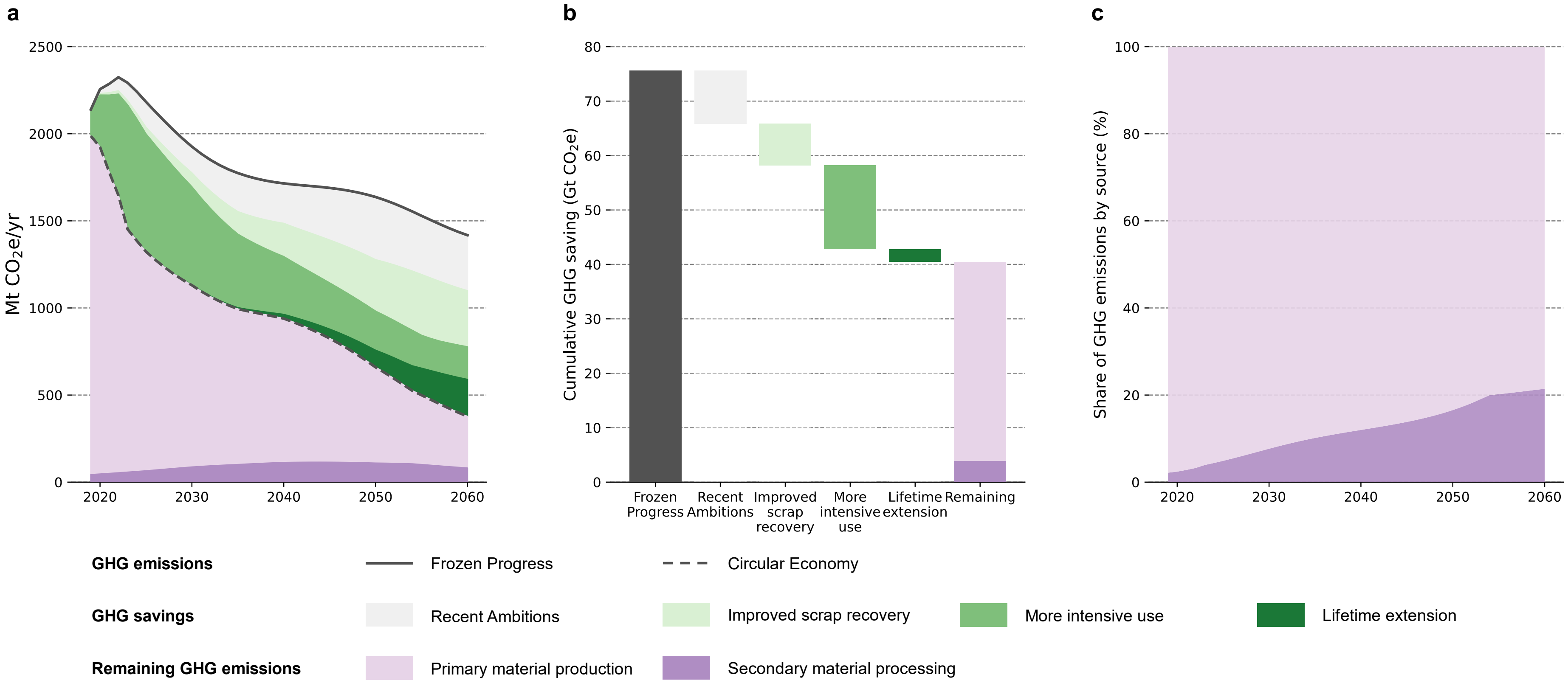

Figure 4 | GHG savings by three CE strategies and remaining GHG emissions. (a) Annual GHG savings by three CE strategies and remaining GHG emissions from 2019 to 2060. (b) Cumulative GHG savings by three strategies and remaining GHG emissions from 2019 and 2060. (c) Breakdown of remaining GHG emissions by source between 2019 and 2060. Solid lines represent the GHG emissions in the FP scenario. The dashed line represents the GHG emissions in the CE scenario, where three CE strategies are synergistically considered. Areas represent the annual GHG savings by recent ambitions or three CE strategies. Stacked bars represent the cumulative GHG savings by recent ambitions or three CE strategies from 2019 to 2060.

Recycling does not always deliver substantial emission cuts for all materials

Although recycling is found to be the most practiced CE strategy, it does not always deliver substantial GHG emission reduction, for all materials. Our results reveal that material recycling has the greatest GHG mitigation potential for metals, while more intensive use and lifetime extension may be more promising strategies for most non-metallic materials, including cement, plastics, and glass (Figure 5). This results from differing ratios of emission intensities for primary versus secondary production across the various materials. The emission intensity of recycling processes for metals is typically much lower than for primary production. By contrast, for non-metal materials, the emission intensities for recycling processes are much closer to primary production levels, sometimes even exceeding the primary production level, for example, in the case of cement.

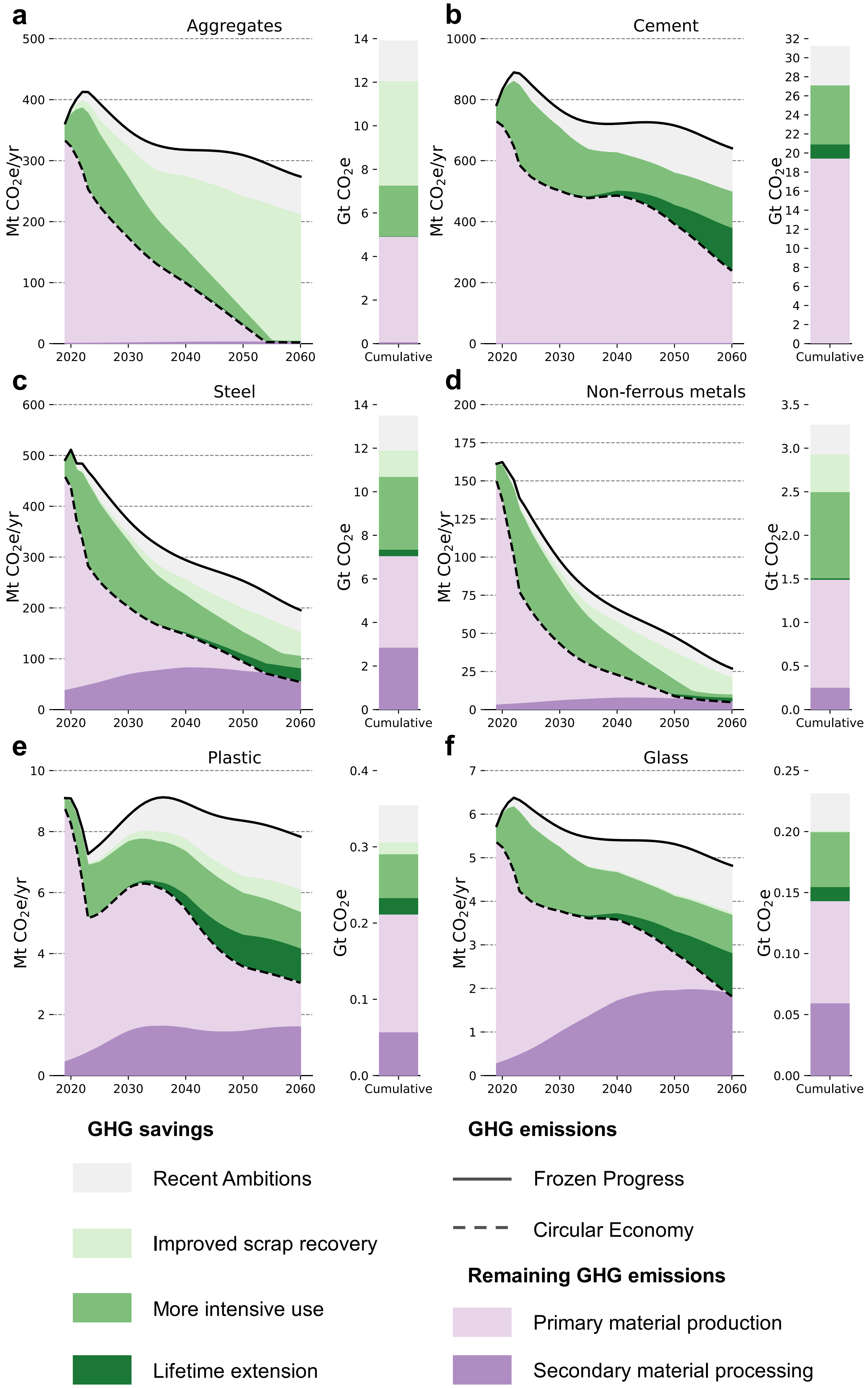
a
Aggregates
Mt CO$_2$e/yr
500
400
300
200
100
0
2020
2030
2040
2050
2060
Gt CO$_2$e
14
12
10
8
6
4
2
0
Cumulative
b
Cement
1000
800
600
400
200
0
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
c
Steel
600
500
400
300
200
100
0
14
12
10
8
6
4
2
0
d
Non-ferrous metals
200
175
150
125
100
75
50
25
0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
e
Plastic
10
8
6
4
2
0
0.4
0.3
0.2
0.1
0.0
f
Glass
7
6
5
4
3
2
1
0
0.25
0.20
0.15
0.10
0.05
0.00
GHG savings
Recent Ambitions
Improved scrap recovery
More intensive use
Lifetime extension
GHG emissions
Frozen Progress
Circular Economy
Remaining GHG emissions
Primary material production
Secondary material processing

Figure 5 | GHG savings by three CE strategies and remaining GHG emissions across materials. Solid lines represent the GHG emissions from 2019 to 2060 in the FP scenario. Dashed lines represent the GHG emissions from 2019 to 2060 in the CE scenario. Areas represent the annual GHG savings by recent ambitions or three CE strategies from 2019 to 2060. Stacked bars represent the cumulative GHG savings by recent ambitions or three CE strategies from 2019 to 2060. More elaborate discussions and detailed results pertaining to other materials are provided in Section S3.4.

Discussion

Stocks dynamics create critical boundary conditions for decarbonizing bulk materials

Our analysis shows that patterns of material stocks set fundamental boundary conditions for future material demand and EoL material availability, which in turn determine GHG emissions. Moving forward, mitigation analyses must consider the timing of ebbs and flows in material demand, in-use material stocks, and secondary supply each region is expected to experience, so as to prepare adequate policy, infrastructure, and technology responses. In line with previous studies[33,34], our analysis reveals that if material stocks in each province conform to an S-shaped pattern, GHG emissions associated with bulk materials are expected to peak around 2025 and decline thereafter, coinciding with the projections by IEA[27] and Boston Consulting Group[35].

Promoting CE strategies should consider timing and regional differences

The exact timing for promoting CE strategies may differ across regions in China. For example, East China could be a first mover and act as a role model for other regions by shifting primary production to secondary supply, as East China will see a rising supply of EoL materials starting after 2030 (Figure 2). Nevertheless, the recycling sector in China is still dominated by small- and medium-sized companies which lack technological progress and environmental awareness, resulting in low-quality, less-competitive recycled products[27]. Given this precious window of opportunity, local governments in East China must address urgent issues that currently hinder effective material recycling, such as infrastructural lock-ins, material dilution, and quality losses. Less-developed regions have an opportunity to learn from the early adopters in more-developed regions, as the former prepares to adopt the latter's CE practices.

Climate benefit of material recycling may be constrained by limited quantity and quality of recovered materials

While our results show that material recycling brings substantial GHG savings, pursuing this strategy alone will not deliver net-zero emission targets. Material recycling, for some materials, does not deliver significant GHG reductions due to thermodynamical constraints[36,37]. Material recycling requires additional energy or material input and emissions involved in the collection, sorting, separation, and reprocessing of EoL materials to close material loops, which undermines the emission savings resulting from avoiding primary production. The presence of material linkages and scrap contamination poses significant challenges to the efficient recovery of materials and limits the potential for emission reduction. These factors hinder the recycling process by introducing complexities and uncertainties that affect the quality and quantity of recovered materials. For some materials, recycling delivers only limited benefits to GHG emission reduction[15,17,38]. For example, glass recycling can be impractical or expensive when waste glass is broken, contaminated, or blended with different colors[17,39]. For this reason, developing high-quality streams of EoL materials through better sorting, separation, or cleaning is insufficient to eliminate GHG emissions for all bulk materials.

Demand reduction is essential to decarbonizing bulk materials

Compared with material cycling, CE strategies that minimize the societal throughput of materials by reducing material demand have received less attention to date, but have great potential for reducing GHG emissions, particularly for materials without a viable recycling loop[32]. For example, while cement is often the most expensive ingredient found in concrete, restoring the properties of EoL hydrated cement would require energy inputs comparable to manufacturing new cement, making it extremely challenging to recycle[17]. For materials that are difficult to recycle, reducing the societal throughput of materials through more intensive use and lifetime extension appears to be promising emission reduction strategies. While more intensive use and lifetime extension could reduce the need for material stocks, the transition toward a less material-demanding world will require fundamental societal and behavioral changes, improved design, cultural transition, and better planning[15,40]. China’s policymakers have high hopes for increasing recycling rates, such as increased utilization of construction waste and electronic waste[41]. Moving forward, we urge China’s policymakers to consider not merely increasing recycling rates but also putting in place far-sighted efforts in more intensive use and lifetime extension.

Concluding remarks

Existing mitigation analyses have often overlooked the significance of CE strategies, instead prioritizing production-side technologies such as CCUS and electrolytic hydrogen[22]. Our CE scenario demonstrates that CE strategies can deliver significant cuts in GHG emissions. Closing the material loops for bulk materials results in significant emission reductions in these "hard-to-decarbonize" sectors and minizes reliance on expensive and unproven production-side technologies. Pursuing CE strategies opens up new opportunities for achieving net-zero emissions, providing an important alternative should production-side technologies not materialize in a timely manner.

Materials and Methods

Modeling framework

We develop an integrated modeling framework IMAGINE Materials (short for Integrated modeling of the Material-enerGy-emIssion NExus associated with bulk materials), which consistently quantifies GHG emissions associated with each bulk material. The IMAGINE Materials model is populated by the Provincial Material Stocks and Flows Database (PMSFD) for China, covering 13 materials (including cement, steel, aluminum, copper, rubber, plastic, glass, lime, asphalt, sand, gravel, brick, and wood) and 31 provinces[30]. The PMSFD includes 103 products, which are grouped into five end-use sectors (building, infrastructure, transport equipment, machinery, and household appliance). We pair the material layer with the GHG emission layer to simulate material demand, EoL material availability, and associated GHG emissions from 2019 to 2060.

Complementary to previous studies that adopt a sector- or material-specific perspective[4,11,12,14,16,20,21], the IMAGINE Materials modeling framework offers a comprehensive assessment of emission reductions stemming from three distinct circular economy strategies at the province level. While the IMAGINE modeling framework aggregates sector-specific nuances, it can shed important light on the efficacy of circular economy strategies across materials and the optimal timing for promoting CE strategies in different regions. This modeling framework serves as a template that allows analysts to explore the combined effect of CE strategies in decarbonizing bulk materials across diverse contexts, should relevant data become available.

Material stocks evolutionary mode identification

The historical material stocks are derived from the PMSFD database, which includes material stocks estimated by the bottom-up accounting approach for 13 materials in 31 provinces in mainland China from 1978 to 2018. We use the level, speed, and acceleration of material stocks, which were recommended by Fishman et al.[42] and Cao et al.[43], to project the evolution patterns of material stocks. The level represents the per-capita material stocks at year *t*; the speed represents the change or differential in per-capita material stocks between two consecutive years; the acceleration represents the change in speed between two consecutive years. The Autoregressive Integrated Moving Average (ARIMA) approach is used to analyze the growth patterns of speed and acceleration. Based on the per-capita stocks and the order of difference at which the time series is stationary, we identify four evolutionary modes, each of which represents a progression stage of an S-shaped curve. Each of the 31 provinces is classified as one of four evolutionary modes (see details in the Supplementary Information).

Future stocks and flows projection

We simulate future material demand and EoL material availability using a stock-driven approach where future material stocks are determined by future population and per-capita material stocks. Population projections for each province in China from 2019 to 2060 are derived from a previous study[44]. Per-capita material stocks are projected as a simplification to follow an S-shaped curve but with differentiated patterns across provinces. The level of per-capita material stocks is deemed an explicit physical representation of service provision to society. As observed in several previous studies[28,43,45,46], the historical patterns of per-capita material stocks show similarities across countries: the growth of per-capita material stocks increases rapidly at first, then slows down, and eventually levels off. As such, we assume that per-capita material stocks (all materials combined) will eventually saturate at defined levels (200 tonnes per capita in the FP and RA scenarios and 150 tonnes per capita or the present-day level in the CE scenario). A modified Gompertz function is used to simulate the development of per-capita material stocks[47]. Considering the observed historical patterns of material stocks, we assume that per-capita material stocks follow an S-shaped curve that moves all provinces toward a national convergence of per-capita material stocks (see details in the Supplementary Information). A certain fraction of EoL materials is recycled to replace virgin materials. A normal lifetime distribution with mean and standard deviation establishes a relationship between material demand and EoL material availability[48].

Circular economy strategies and related GHG emission mitigation potential

We create three scenarios to reflect plausible futures of China's bulk materials system: (1) a Frozen Progress (FP) scenario in which no technological improvements in the bulk materials system will take place, and future trends of material stocks broadly follow their historical patterns; (2) a Recent Ambitions (RA) scenario in which the recent ambitions of stakeholders involved in decarbonizing bulk materials production are considered; and (3) a Circular Economy (CE) scenario in which we consider three circular economy strategies (i.e., improved scrap recovery, more intensive use, and lifetime extension). More intensive use aims to reduce the total societal need for material-intensive products, resulting in reduced material demand. A recent study exploring a "low energy demand scenario" found that a decent living standard can be provided with 30 m^2 per capita of floor space, which is far below the current per-capita housing floor area in several high-income provinces in China[8]. Lifetime extension, which aims to extend the service life of products, requires not only technological measures (e.g., more adaptable and durable designs) but also policy actions (e.g., better zoning policies and better access to quality repair) because the physical durability of products does not always determine their real lifetime. In choosing values for the deployment level of each strategy, we only consider technical feasibility, with no consideration given to investment or deployment costs. Notably, we assume that advanced collection technologies and infrastructure and alloy separation technologies will be deployed to overcome compositional and quality barriers, ensuring that materials sourced from secondary supply (referred to as secondary materials hereafter) can replace virgin materials without a loss of quality. Many previous scenario analyses provide target values by 2050. Therefore, when no deployment values are available for 2060, we extrapolate 2050 values to 2060 based on the previous 5-year growth rate. More details about the methods, data, and assumptions are provided in the Supplementary Information.

LCA results are used to calculate GHG emissions of the primary production (cradle-to-gate) and secondary production (including EoL collection and processing) of each material type. We compile a life cycle inventory (LCI) database by leveraging LCIs available from existing literature and the Gabi database. Details are provided in the Supplementary Information.

Limitations and uncertainty

While the potential of CE strategies is analyzed with comprehensive datasets, there are opportunities to enhance our analysis by integrating sector- and material-specific insights from previous studies. Additionally, the process-based LCI database used by our analysis may underestimate the emission factors of some recycling or production processes due to the difficulty of including small quantifiable processes in the model. Addressing these limitations and incorporating these factors into the current study would be a crucial step for future research.

Another area for improvement lies in considering the decarbonization efforts in secondary material processing to provide a holistic view of decarbonizing bulk materials. Furthermore, it is important to emphasize that our results do not represent future predictions, but rather present potential scenarios or pathways for the implementation of CE strategies aimed at reducing GHG emissions associated with bulk materials production. In order to assess the uncertainties arising from material linkages and scrap contamination, we have conducted additional analyses, which are detailed in Figures S16-S18 of the Supporting Information. These analyses contribute to a more comprehensive understanding of the potential uncertainties associated with our findings.

Data availability

Data used for populating the model is available from the following link: https://figshare.com/s/ba4720334f15519cf9dd.

Code availability

Codes used for simulating material flows and stocks and GHG emissions are available via the following link: https://figshare.com/s/ba4720334f15519cf9dd.

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Author contributions

W.Q.C., L.L.S., and Z.C. conceived and designed the research. W.Q.C. and Z.C. supervised the project. L.L.S. performed the simulations. L.L.S. and Z.C. produced the figures. S.v.E. and E.M. contributed to the scenario design. L.L.S. and Z.C. prepared the first draft. All authors reviewed and edited the manuscript.

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