Integrated Environmental Assessment and Management — Volume 17, Number 3—pp. 639–650
Received: 12 June 2020 | Returned for Revision: 10 July 2020 | Accepted: 23 November 2020

Life Cycle & Sustainability

Unraveling the Global Warming Mitigation Potential from Recycling Subway-Related Excavated Soil and Rock in China Via Life Cycle Assessment

Ning Zhang,† Hui Zhang,‡ Georg Schiller,† Haibo Feng,§ Xiaofeng Gao,|| Enming Li,# and Xiujie Li††*

†Leibniz Institute of Ecological Urban and Regional Development (IOER), Dresden, Germany
‡School of Chemistry and Environmental Engineering, Wuhan Institute of Technology, Wuhan, China
§Department of Mechanical and Construction Engineering, Northumbria University, Newcastle, United Kingdom
||Department of Urban Engineering, The University of Tokyo, Tokyo, Japan
#School of Resources and Safety Engineering, Central South University, Changsha, China
††Green Lighting System Lab, School of Environment and Energy, Peking University Shenzhen Graduate School, Shenzhen, China

ABSTRACT

Many cities across China are investing in subway projects, resulting in much subway construction activity, which has experienced a surge over the past decade. The construction activities inevitably cause a dramatic quantity of subway-related excavated soil and rock (ESR). How to manage it with minimal environmental impact on our urban ecosystem remains an open question. The present study evaluates global warming potential (GWP, expressed by CO_2 eq) from different ESR recycling and landfilling scenarios via a life cycle assessment (LCA) model based on primary field investigation combined with the LCA software database. The study results illustrate that recycling ESR can significantly reduce greenhouse gas emissions. In comparison with traditional construction materials, the scenarios found that a cumulative amount of 1.1 to 1.5 million tonnes (Mt) of CO_2 eq emissions could have been mitigated by using ESR generated between 2010 and 2018 to produce baking-free bricks and recycled baked brick. Using cost–benefit analysis, potential economic benefits from recycled sand and baking-free bricks are found to reach US$9 million annually. The findings of this study could provide better recycling options for ESR-related stakeholders. It is important to mention that there still is much work to be done before this recycling work can be popularized in China. *Integr Environ Assess Manag* 2021;17:639–650. © 2020 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

Keywords: Excavated soil and rock (ESR) Recycling CO_2 mitigation Life cycle assessment Cost–benefit analysis

INTRODUCTION

Urban expansion has become the "new normal" in China's present development model (Wei et al. 2017). Consequently, traffic congestion has become a common problem in megacities (Kong et al. 2016); many people pouring into cities increases requirements on traffic facilities (Han et al. 2018). Subway construction projects have become the focus of the Chinese government's urban public transportation planning in recent years (Zhang et al. 2017). Demand for better urban mass transit is causing a surge in the construction of subways and unparalleled generation of subway-related excavated soil and rock (ESR) (Sun et al. 2016).

Excavated soil and rock is a major contributor to construction and demolition (C&D) waste in cities (Eras et al. 2013). There are many previous studies related to C&D waste across the world, including generation estimation, environmental impact assessment, and technological innovation in recycling (McNeil and Kang 2013; Yeheyis et al. 2013; Sáez et al. 2014). Concerning the management optimization of C&D waste, multiple approaches have been used in waste management of construction projects (Lu et al. 2017). Jalaei et al. (2019) used life cycle assessment (LCA) and Building Information Modeling (BIM) tools to establish an optimized platform for lifespan quantitative management of C&D waste. Similarly, the application of material flow analysis (MFA) to urban construction material management at the end-of-life (EoL) stage has also proved to be useful in environmental management (Huang et al. 2013). The research of Esa et al. (2017) shows that making full use of the concept of circular economy to establish a

This article contains online-only Supplemental Data.

* Address correspondence to G.Schiller@ioer.de

DOI: 10.1002/ieam.4376

C&D waste reduction strategy can also reduce environmental impact.

It is generally believed that landfilling and backfilling of C&D waste and ESR cause more significant negative impacts than recycling, such as land subsidence, vegetation deterioration, landslide risk, and increase in the difficulty of ecological environment recovery (Vossberg et al. 2014; Arm et al. 2017; Duan et al. 2019). Simion et al. (2013) used LCA to compare the environmental impacts of producing concrete aggregates from recycling and natural inert or mining processing; their results revealed that the main environmental impacts are generated by natural inert processing. Ortiz et al. (2010) also used LCA to compare the global warming potential (GWP) of 3 treatment scenarios for C&D waste in Spain, and the ecofriendliest treatment was recycling, followed by incineration and landfilling. A system dynamics model was developed by Marzouk and Azab (2014), and its findings showed that recycling C&D waste leads to significant reductions in energy consumption and GWP, meanwhile it also conserves land when compared to disposal in landfills. In addition, recycling some components of C&D waste to energy regeneration and C capture and storage (CCS) can help in building climate-friendly societies (Lausselet et al. 2016, 2017). However, if the environmental impact is expanded from climate change to human toxicity and terrestrial acidification categories, there is yet another view. Muñoz et al. (2018) used LCA to study the overall environmental benefits of Waelz slag incorporation into bricks; their results showed that a great reduction in impact on climate change could be achieved, but in the process of firing, more sulfur dioxide (SO_2) and hydrogen fluoride (HF) emissions would be generated. The results were equivocal on environmental impact.

In terms of economic benefits, Tam (2008) did a case-based economic analysis of concrete debris recycling, and the results show that recycling concrete waste as aggregates for new concrete production can be cost effective. Coelho and Brito (2013) analyzed the economic viability of C&D waste recycling plants in Portugal, finding they have high potential for profit, even considering the large initial investment required.

In short, recycling C&D waste is feasible from both economic and environmental perspectives. However, there is a lot of focus on C&D waste, and ESR is generally ignored by researchers. Improper disposal of ESR can also create negative environmental impacts, such as air pollution, water contamination, and damage to vegetation (Duan et al. 2019). A recent study by Zhang, Duan, Sun et al. (2020) indicated that mismanagement of ESR (disposed of mainly through dumping sites) threatens the natural environment and poses high landslide risks in China. Therefore, further detailed research into ESR recycling is urgent and necessary. The present study evaluates the CO_2 mitigation potential of recycling ESR by using an LCA model based on a series of field investigation data (i.e., from recycling plants and landfills); it also analyzes the economic benefits of recycling ESR based on the life cycle costing (LCC) method. The present study provides stakeholders with a recycling management strategy for ESR.

RESEARCH METHODS

Research objective

In recent studies, many researchers have proved that recycling C&D waste is an effective and economically feasible way of mitigating greenhouse gas (GHG) emissions (Zheng et al. 2017; Paes et al. 2019; Zhang, Duan, Miller et al. 2020). As these previous studies revealed, much C&D waste is generated in urban areas (e.g., Wu et al. 2014; Zhang et al. 2019), and recycling such waste is effective in reducing the negative impacts from C&D landfilling and increasing CO_2 mitigation by using recycled construction materials. However, ESR recycling, which is a great opportunity to further reduce CO_2 emissions and waste production at the urban scale, has not been paid enough attention.

To minimize the negative environmental impacts brought by ESR landfilling and clarify the positive environmental and economic results from ESR recycling, the present study aims to compare the environmental impacts of manufacturing ESR-based construction materials versus traditional construction materials and to assess the potential economic benefits from recycling ESR. The present study applies an LCA model to evaluate the total GWP (measured as carbon dioxide equivalents [CO_2 eq]) of different ways to recycle ESR. Meanwhile, an LCC model is developed to assess the potential economic benefits of ESR recycling, as an example. It is worth mentioning that recycling and backfilling are 2 different disposal methods in China; recycling of ESR or C&D waste refers to the reprocessing of waste materials into recycled construction materials, whereas backfilling is a recovery method and is not taken into account here (Galán et al. 2019).

Excavated soil and rock is recycled in various marginal ways to replace traditional construction materials. As shown in Table 1, recycling methods include pressing, baking, and screening, and recycled products consist of recycled baking-free brick, recycled sand, and recycled baked brick.

The same types of natural and recycled materials with similar properties can be replaced for multiple structures (recycled sand–natural sand [RS-NS] and recycled baked brick–clay solid brick [RBB-CSB]). For the other 2 replacements (recycled baking-free brick–clay solid brick [RBFB-CSB] and recycled baked brick–solid concrete brick [RBB-SCB]), due to differences in properties between the materials, there are limitations in the scope of their application. The replacement materials are mainly suitable for low-rise buildings and pavements owing to the heavier weight of recycled baking-free brick. Recycled baked brick and solid concrete brick have a similar range of utilization for masonry walls, leading to feasible replacement.

Study area and data sources

The assessment in the present study was carried out in mainland China, a rapidly growing and densely populated

Table 1. The recycle and replace scenarios

Recycling method	Recycled product	Material to be replaced	Abbreviation of material replacement scheme
Screening	Recycled sand (from ESR)	Natural sand (from river sediment)	RS-NS
Pressing	Recycled baking-free brick	Traditional clay solid brick	RBFB-CSB
Baking	Recycled baked brick	Traditional clay solid brick	RBB-CSB
		Solid concrete brick	RBB-SCB

ESR = excavated soil and rock.

country with 177 urban railway lines as of December 2019 (Jin and Chen 2019). Population growth, plus the great demand for urban mass transit, generates much ESR in China. The present study uses CO_2 eq as a measurement unit to analyze the GWP from ESR landfilling, combined with different recycling plans, from 2000 to 2018.

Data in the present study are gathered from previous literature, stakeholder interviews (e.g., ESR and C&D waste recycling plants, managers of landfill sites), and commercial databases (including eBalance and GaBi software) (IKE 2012; Sphera 2018). The data on composition and flow of ESR are derived from the average calculation of results in Zhang, Duan, Sun et al. (2020) (see Eqn. 1). Further generation and flow data on main components were obtained from interviews with government officials and previous studies (Zheng et al. 2017; Zhang, Duan, Sun et al. 2020) (see Eqn. 2).

$$P_x = \sum_{l=1}^{7} P_{xl}/7. \tag{1}$$

Equation 1 represents an average calculation of 1 type of ESR material in 7 Chinese regions. P_x refers to the average proportion of materials of type x across China, whereas P_{xl} is the proportion of materials of type x in region l.

$$Q_{xyt} = G_y \times P_x \times R_{xt}. \tag{2}$$

In Equation 2, Q_{xyt} refers to the quality of composition x flowing to treatment method t in year y, G_y is the total generation of ESR in year y, and R_{xt} means the rate of composition x flowing to t. In the present study, the treatment method t represents only landfilling and recycling.

The interviews focused on flow data, energy and material consumption at recycling and landfilling stages, revenue from ESR trade, and expenditure on equipment acquisition and site leasing. In brief, the interviews gave a better understanding of how the recycling system works. These data are utilized to structure the LCA and LCC data inventory, which usually contains CO_2 emission factors and energy and materials consumption.

Life cycle assessment model

The LCA model is the main methodology in the present study. It strictly follows the requirements of the International Organization for Standardization 14044 standard (ISO 2006), a widely accepted standard that describes the principles and framework for LCA. The methodology framework for LCA consists of the following 4 components, each of which plays a crucial role in the assessment (Guinée 2001).

1) Goal and scope definition. The intended objective of the LCA is to evaluate the GWP of the EoL stage for the ESR sector. Because the recycling and landfilling processes all use ESR as the raw material, “1 kg (tonne) of ESR” is selected as the functional unit for the present research. A reduced-scope LCA is adopted in the present study (see Figure 1). It focuses on establishing and comparing the energy consumption and GWP implications for ESR landfilling and its recycling in different ways, with only the EoL stage considered.
2) Inventory analysis. Local data are used wherever possible to ensure that the life cycle inventory (LCI) is representative of the current situation in China. Therefore, the primary data, such as the intensity of energy and materials consumption, are gathered from field investigation. Secondary data are available for calculating CO_2 emissions; the Chinese CO_2 emission factors of various processes are collected from the literature, GaBi (LCA software developed by Thinkstep), and eBalance (Chinese LCA software developed by IKE) (Bailey et al. 2020). The detailed data inventory of emission factors is shown in Table 2.
3) Impact assessment. The results of GWP value, such as the impact of CO_2, methane (CH_4), and fluoride, are expressed in the weight of CO_2 eq (Deviatkin et al. 2019). Following the Intergovernmental Panel on Climate Change method, an assessment time frame of 100 y is used in the present study to assess the GWP (IPCC 2007). The following M_1 to M_4 in Equations 3 to 6 refer to the total CO_2 mitigation potential from different material replacement schemes. Table 3 shows the definitions of the construction material terms.

   M_1 means using recycled sand from ESR to replace natural sand from river sediment.

   $$M_1 = E_{LC.NS} - E_{RS}, \tag{3}$$

   where $E_{LC.NS}$ refers to the total emissions of producing natural sand from river sediment (including mining,

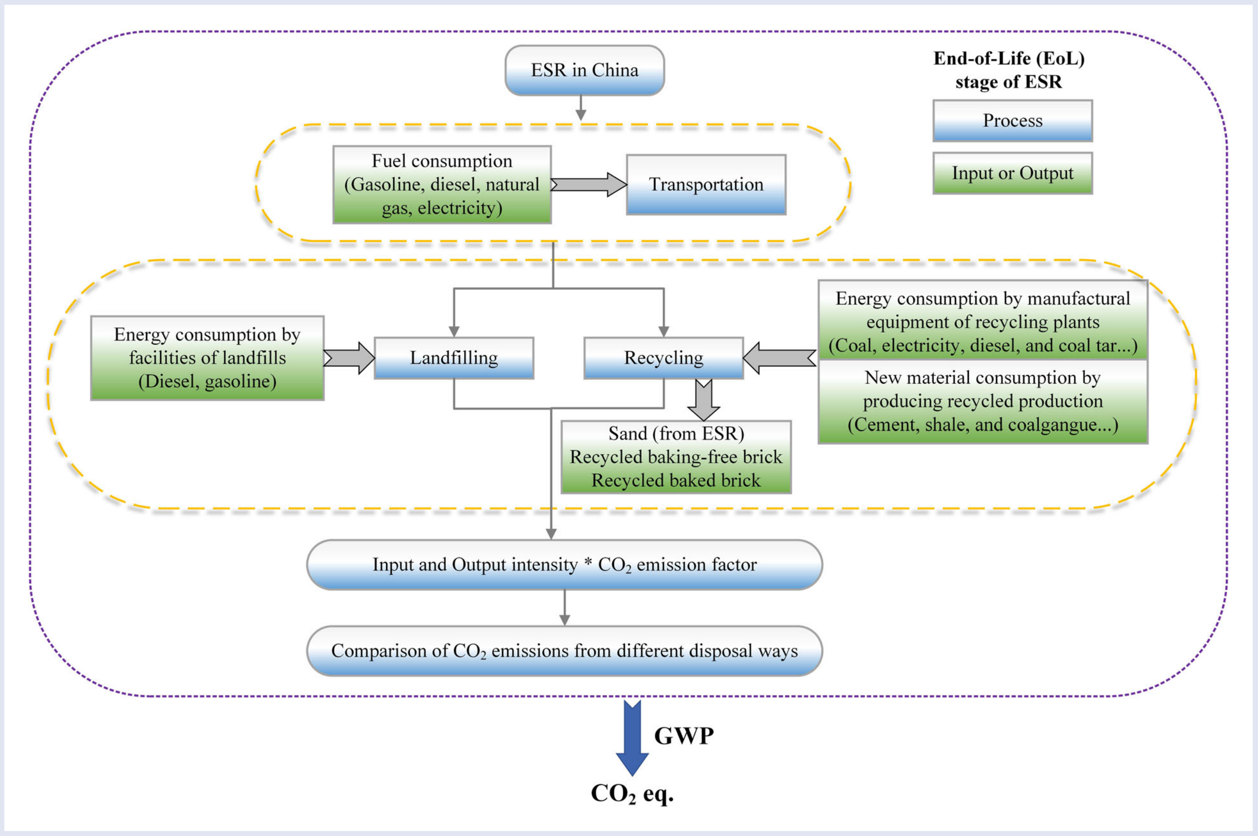

Figure 1. The system boundary and study scope for LCA. ESR = excavated soil and rock; GWP = global warming potential; LCA = life cycle assessment.

transportation, and manufacturing stages), and E_{RS} refers to the emissions of screening recycled sand from ESR (including transportation and screening stages).

M_2 is using recycled baking-free brick to replace traditional clay solid brick.

$$M_2 = E_{LC.CSB} - E_{RBFB}, \tag{4}$$

where $E_{LC.CSB}$ refers to the total emissions of traditional clay solid brick production (including mining, transportation, and manufacturing stages), and E_{RBFB} means

Table 2. The data inventory for LCA

Emission factor	Value	Data source
National grid	0.77 kg CO_2 eq/kWh	eBalance and GaBi databases[b]
Coal	0.28 kg CO_2 eq/kg	GaBi database[c]
Diesel	0.49 kg CO_2 eq/kg	
Gasoline	0.56 kg CO_2 eq/kg	
Transportation (truck with load capacity for 7.5–16 tonnes)	0.22 kg CO_2 eq/t·km	
Natural gas	0.78 kg CO_2 eq/kg	
Coal tar	3.03 kg CO_2 eq/kg	eBalance database[d]
Natural sand (μf = 3.0~1.6)[a]	2.80 kg CO_2 eq/t	
Traditional clay solid brick	0.18 kg CO_2 eq/kg	
Solid concrete brick	334.80 kg CO_2 eq/m^3	

LCA = life cycle assessment; μf = fineness modulus.

[a] μf, the fineness modulus, is an index that characterizes the degree and type of natural sand particle size. The fineness modulus of ordinary construction sand is 3.0 to 1.6.

[b] IKE 2012; Sphera 2018.

[c] Sphera 2018.

[d] IKE 2012.

Table 3. Explanations of different terms for construction materials (according to Chinese national standards: GB/T 5101-2017, GB/T 21144-2007, and GB/T 14684-2011)[a]

Term of construction materials	Abbreviation	Explanation
Traditional clay solid brick	CSB	Produced by mixing clay, water, shale, coal gangue, and other additives. Hardening method is kiln firing.
Recycled baking-free brick	RFB	Produced by mixing recycled clay (from ESR), water, cement, RCAs (from C&D waste), and other additives. Hardening method is machine pressing.
Recycled baked brick	RBB	Produced by mixing recycled clay (from ESR), water, shale, coal gangue, and other additives. Hardening method is kiln firing.
Solid concrete brick	SCB	Produced by mixing cement, water, concrete aggregates, fly ash, and other additives. Hardening methods are forming and curing.
Natural sand	NS	Produced by river dredging.
Recycled sand	RS	Produced by screening from ESR.

C&D = construction and demolition; ESR = excavated soil and rock; RCA = recycled concrete aggregate.
[a] SAC 2007, 2011, 2017.

the emissions from pressing recycled baking-free brick (including transportation and manufacturing stages).

M_3 refers to using recycled baked brick to replace traditional clay solid brick, and M_4 means using recycled baked brick to replace solid concrete brick.

$$M_3 = E_{LC.CSB} - E_{RBB}, \tag{5}$$

where E_{RBB} is the emissions from producing recycled baked brick (including transportation and manufacturing stages).

$$M_4 = E_{LC.SCB} - E_{RBB}, \tag{6}$$

where $E_{LC.SCB}$ refers to the total emissions of traditional solid concrete brick production (including mining, transportation, and manufacturing stages).

4) Interpretation. The aim of the interpretation is to systematically summarize the information from the assessment results. As mentioned in the *Study area and data sources* section, CO_2 eq is adopted to assess GWP value. Therefore, based on the CO_2 mitigation results, we compare GWP among the different replacement schemes.

Economic analysis model

In the cost–benefit analysis (Eqns. 7–9), the recycling company is selected from among multiple stakeholders for the present analysis, and the revenue from ESR trade and expenditure in structuring recycling plants are considered, using data derived from field investigation of ESR recycling plants in 2017. Because the financial data come from a specific recycling plant that makes recycled pressed bricks, the economic analysis takes this project (using recycled baking-free bricks to replace traditional clay solid bricks) as an example.

$$NP = R_{total} - EP_{total}. \tag{7}$$

The net proceeds (NP) of the ESR recycling project are shown in Equation 7. It can be expressed as the difference in value between total revenues (R_{total}) and total expenditures (EP_{total}) of ESR recycling.

$$R_{total} = R_R + R_S + S_G. \tag{8}$$

The total revenues comprise the income from trading recycled products (R_R) on the construction materials market, the handling fees charged by the recycling plants to deal with the ESR (R_S), and the government's financial subsidies for ESR disposal in recycling plants (S_G).

$$EP_{total} = EP_A + EP_R + EP_S + EP_E + \sum_{i=1}^{n} EP_O. \tag{9}$$

Similarly, the total expenditures are divided into the amortized cost of equipment (EP_A), renting plants (EP_R), mechanical consumables (EP_S), energy consumption for recycling (e.g., electricity, diesel, gasoline, and natural gas) (EP_E), and other costs (EP_O). Other costs can be divided into labor, maintenance of equipment, et cetera, where i refers to the categories of these other costs.

Based on field investigation in recycling plants across China (in 9 C&D waste and ESR recycling plants located in Shenzhen, Huizhou, Beijing, Zhengzhou, and Wuhan; these cities are distributed in various regions of China), economic and energy data about ESR recycling lines are gathered. Recycling techniques vary according to the cities' different development levels. The collected data come from these large cities because this type of recycling behavior occurs only in large cities with policy and financial support. The figures for the recycled baking-free brick producing stage are shown in Tables 4 and 5 and were mostly provided by the manufacturers.

RESULTS AND CURRENT STATUS ANALYSIS

Excavated soil and rock recycling network

After a series of field investigations in ESR and C&D waste recycling plants in China, we found that ESR can generally

Table 4. Equipment information for ESR recycling toward baking-free bricks

Technical data (unit) Equipment	Equipment information		
	Impact crusher	Screening machine	Forming machine
Number of machines	1	1	1
Operating power (kW)	328	97	242
Fuel consumption (L/h)	51.96	15.36	37.27

ESR = excavated soil and rock.

be recycled into different building materials based on its composition. Unlike C&D waste, ESR or its components generally include sand, gravel of various sizes, and soil (Priyadharshini et al. 2017); these are mainly inert materials (Duan et al. 2016) and easier to recycle. Figure 2 shows a general process of recycling ESR; typically, from ESR to recycled materials, 3 processes need to be done. Sand and gravel in the ESR are the first step, going through the crushing and screening system to produce recycled sand. The mixing system and molding maintenance system are further steps to convert ESR into building materials, mainly recycled bricks.

As shown in Figure 3, nationwide ESR typically consists of 4 main components: sand, clay, miscellaneous fill, and stone (see Figure S2 in Supplemental Data). The sand and clay are the main targets of recycling. Usually, sand of different sizes can be screened out in the first step of the sand washing process, which can be carried out on the construction site. The remaining clay is pressed into mud cakes and sent to recycling plants for further recycling.

Comparison of different recycling methods

The amount of recycled materials. Results from the primary analysis for material flows of ESR are depicted in Figure 4. In general, because the recycled and landfilled quantity is proportional to the total generation of ESR, the change trends for recycling and landfilling are almost the same as with generation. Although the recycling rate is increasing, the landfill rate for ESR in China has exceeded 90% in recent years. As shown in Figure 4, although sand and clay are the 2 main recycled materials (accounting for approximately 60% of total recycled ESR), the amount of recycled ESR is considerably lower than that landfilled under the present situation. From 2000 to 2018, accumulated recycled materials were only 18 million tonnes (Mt) (comprising sand 10 Mt and clay 8 Mt), whereas approximately 442 Mt of accumulated ESR was still transferred to landfills. Recently, scholars have found that natural sand is a scarce resource that is hard to get, and it is currently necessary to find replacement materials and reuse sand (UNEP 2014; Bendixen et al. 2019). In addition, according to a field survey in China, obtaining natural sand is much more difficult than using recycled sand because current environment protection policies only allow a small amount of natural sand to be mined (NDRC 2020).

CO_2 mitigation potential. As might be expected, the GWP caused from per kg (tonne) ESR recycling is less than that from landfilling. One of the reasons is that only a small amount of ESR is recycled. The other reason is the reduction in transportation impacts. Figure 5 provides a more detailed view of CO_2 mitigation from different recycling methods. The results

Table 5. Data for variables used in Equations 7 to 9 for economic analysis in 2017

Technical data (unit) Equipment	Equipment information			Total
	Impact crusher	Screening machine	Forming machine	—
Oil cost (US$/kt soil[a])	148	44	106	298
Dedusting cost (US$/kt soil)	6	—	4	10
Consumable cost (US$/kt soil)	86	19	59	164
Maintenance cost (US$/kt soil)	12	9	10	31
Labor cost[b] (US$/kt soil)	12	—	—	12
Other cost (US$/kt soil)	15	15	15	45
Amortized equipment (US$/kt soil)	112	48	59	219
Plant rent (US$/kt soil)	According to the lease price of plant in suburb, US$2.17/m^2·mo			1160
Total cost (US$/kt soil)	778	521	640	1939

ESR = excavated soil and rock; kt = kiloton.

[a] Soil means the clay component in ESR.

[b] The labor cost is a mixture of labor and overhead costs.

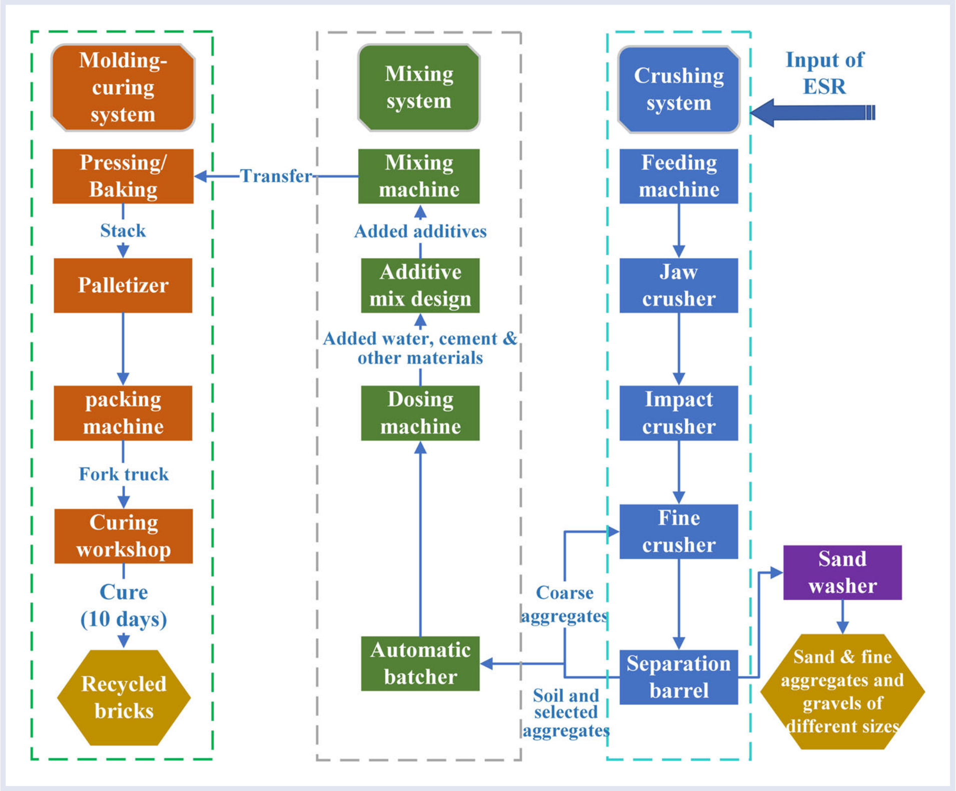

Figure 2. Schematic flowchart of recycling ESR. ESR = excavated soil and rock.

were obtained by carrying out Monte Carlo simulations. Error bars indicate 95% confidence limits with 20 000 times calculations generated by Monte Carlo simulations (assuming the parameters present normal distributions).

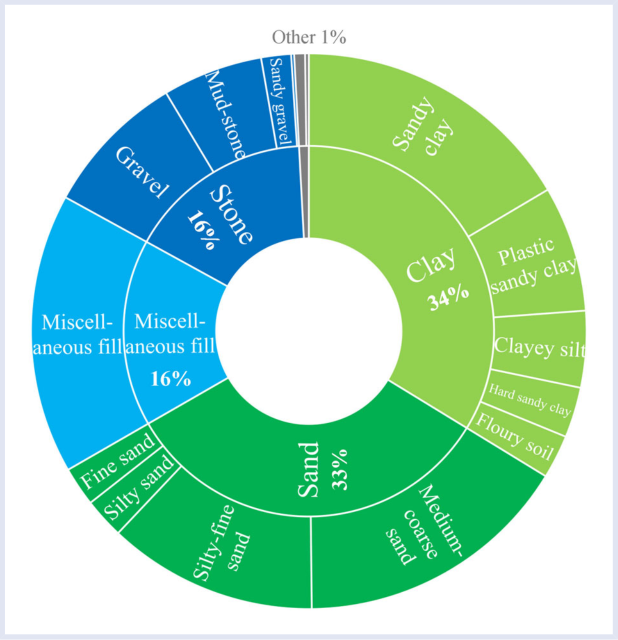

Figure 3. Primary and secondary components of ESR in China (national average value based on regional data from Zhang, Duan, Sun et al. 2020). ESR = excavated soil and rock.

In Figure 5B, there are 4 material replacement schemes. Using ESR to screen out recycled sand and replace natural sand achieves only a small CO_2 mitigation efficiency. However, when sand screening is followed by further recycling, significant CO_2 mitigation could be achieved. In addition, per brick CO_2 emissions from baking are much higher than from pressing, therefore, recycled baking-free bricks replacing traditional clay solid bricks contributes the most mitigation, approximately 1.5 Mt CO_2 eq cumulatively between 2010 and 2018.

The results in Figure 5A show that recycling ESR can achieve a "double emission reduction" effect. The CO_2 mitigation from recycling and avoided emissions from landfilling have significant potential in reducing GWP. Landfilling would result in 30 kg CO_2 eq per tonne of landfilled ESR, in comparison with GWP reduction of 42 (37–48) kg CO_2 eq per tonne of recycled ESR (producing recycled sand and different types of recycled brick). Different types of recycled materials and their replacement schemes have CO_2 mitigation gaps. These differences can be explained mainly by 1) different recycling methods with different mechanical equipment, resulting in differences in energy consumption (e.g., machines that use gasoline have lower emissions than those that use diesel, 0.56 kg CO_2 eq/kg gasoline and 0.49 kg CO_2 eq/kg diesel in China, data from GaBi database) (Sphera 2018); and 2) the new material being replaced has different emission factors (e.g., 0.18 kg CO_2 eq/kg for clay solid brick, 0.03 kg CO_2 eq/kg for natural sand in China, data from GaBi database) (Sphera 2018).

DOI: 10.1002/ieam.4376

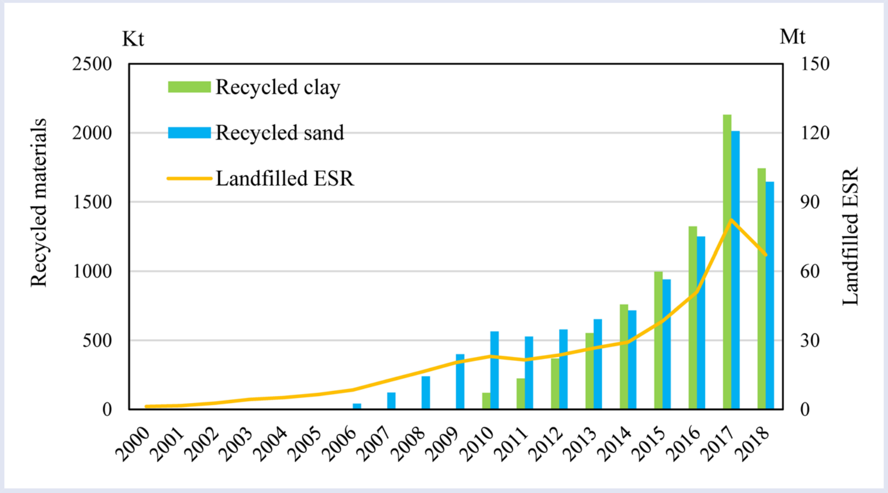

Figure 4. The present situation of ESR recycling in China. ESR = excavated soil and rock.

Economic benefits analysis. With the increasing trend of recycling ESR and C&D waste in China, the market for recycled building materials has substantial potential economic value (Zhao et al. 2010). Based on generation and recycling amounts of ESR in China, Figure 6 shows the estimation of economic benefits and costs if recycling plants take ESR to produce recycled baking-free bricks.

As shown in Figure 6, recycling ESR could have produced ever-increasing net proceeds between 2006 and 2017, reaching a sizable amount of US$22.8 million in 2017 and accounting for 8% of operating revenue of construction companies in China in the same year (NBSC 2018). In 2018, net proceeds follow the downtrend of recycling volume ($18.7 million). High government subsidies and an increasingly favorable environment for trading recycled building products results in consistent revenue for ESR recycling plants. In terms of the cost of recycling ESR, plant rent and the costs of purchasing equipment are the main expenses. Because much ESR is generated in urban areas, from the perspective of convenient transportation, most recycling plants are in the suburbs around cities, and the leasing price of factories is relatively high. However, due to the high

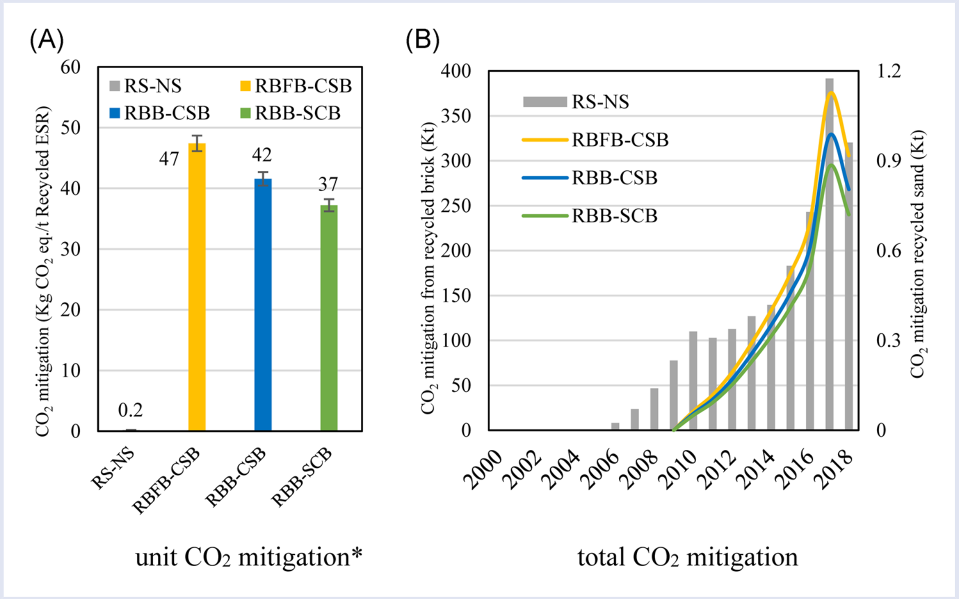

Figure 5. The CO_2 mitigation of different ESR recycling plans. CO_2 mitigation occurs in the process of recycling. As a reminder, due to the landfilling that can be avoided by recycling, there might be potential avoided CO_2 emissions caused by landfilling (30 kg CO_2 eq/landfilling ESR). The legends refer to the material replacement schemes; their full definitions are shown in Table 1. ESR = excavated soil and rock; RBB-SCB = recycled baked brick–solid concrete brick; RBFB-CSB = recycled baking-free brick–clay solid brick; RBB-SCB = recycled baked brick–solid concrete brick; RS-NS = recycled sand–natural sand.

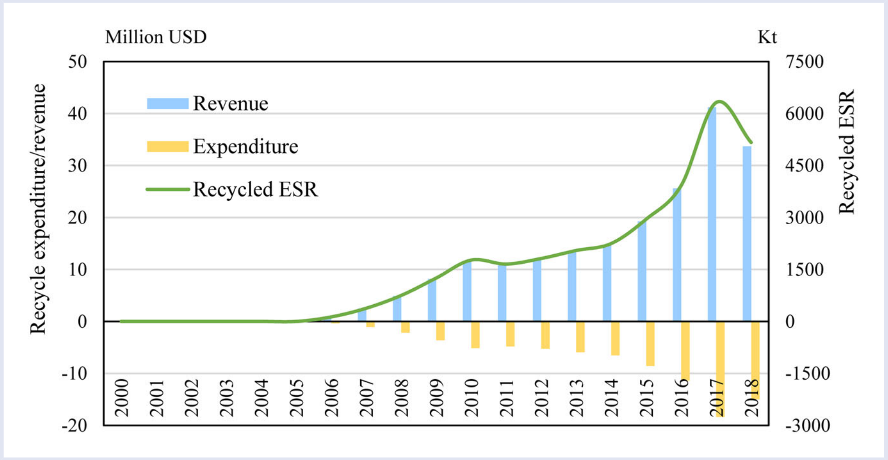

Figure 6. The economic analysis of ESR recycling (taking producing recycled sand and baking-free bricks as an example). ESR = excavated soil and rock.

degree of automation of mechanical equipment, the traditional phenomenon of high labor costs is not significant in the ESR and C&D waste recycling industry (Shan et al. 2011).

DISCUSSION AND OUTLOOK

Landfilling of ESR is a widespread phenomenon across China, which carries a range of negative environmental consequences (Leite et al. 2011). Recycling ESR can significantly reduce the impact of landfilling on urban land occupation, geological damage, and landslide and collapse risk (Duan et al. 2019). Also, the results of the present study illustrate that recycling ESR could reduce GWP and meet the targets in China's 13th Five-Year Plan: CO_2 emissions to be 18% below the 2015 level by 2020 (SCC 2016). Based on estimation, the cumulative mitigation between 2010 and 2018 would be equivalent to Kenya's CO_2 emissions by the coal combustion sector in 2018 (IEA 2019). More importantly, the analysis of GWP based on different ESR recycling plans provides multiple alternative pathways for stakeholders to dispose of ESR.

Economic analysis from the perspective of recycling companies is included in the present article, but further taking construction companies, government, and other stakeholders into consideration can make up for this 1-sided result and better justify economic investment and benefits across the whole recycling chain. Furthermore, it is worth noting that the composition of ESR is not complicated, but the current recycling rate and recycling type are both at low levels in China; expanding the scope of recycling and increasing the recycling rate may remove impediments to potential economic and environmental benefits. Compared with the increasingly mature recycling technology, it is important to improve the waste management level in China. Theoretical studies have shown that policy making for landfill restrictions, recycling incentives, and tax breaks can greatly influence the management of C&D waste and ESR (Ajayi and Oyedele 2017). Generally, government control through legislation can increase sustainability in the building materials sector (Kylili and Fokaides 2017). These results illustrate that governments across the world need to be a driving force for sustainable development in the construction sector.

In the near future, ESR management will no longer be so limited, and secondary resources, ranging from clay and sand to stone, should be considered comprehensively. In terms of economy, economic decision making based on multiple criteria analysis could also be a follow-up direction for this research. At present, much research has been conducted into technological innovation (Lu and Tam 2013; Ajayi et al. 2017) while ignoring the importance of management. As Magnusson et al. (2015) argued, ESR usually lacks sustainable management, and there is a need to evaluate the potential for increased use of ESR. Carrying out such research can provide more evidence to better understand and effectively implement C&D waste management and ESR recycling.

CONCLUSION

The present study applied the LCC and environmental assessment method to assess the relative economic feasibility and CO_2 emissions intensity of different recycling plans for 2 main ESR material flows (sand and clay) in China. Overall results show that for large emerging countries, enormous GWP is caused by the landfilling of construction-generated ESR, and proper use of recycling is an economic and environmentally friendly management strategy. This regionalized case research in China also offers a methodological basis for the transfer of research to other regions.

Regarding the composition of ESR, sand and clay are the typical recycled materials in China. The present study findings show that accumulated recycling of ESR could have reached 20 Mt from 2006 to 2018 (ESR recycling began to be promoted in 2006) (Zhang, Duan, Sun et al. 2020). Recycled sand (6.7 Mt) and clay (5.5 Mt) account for 60% of the total recycled ESR nationwide, and the remaining recycled materials include some localized materials, such as coal and mucky soil.

Taking the example of producing recycled baking-free bricks, recycling ESR can also contribute at least about \$110 million to the national economy. Given present trends, this figure may further increase in future years. This finding, in particular, would be beneficial to stimulate the interest of recyclers.

In terms of environmental analysis, in the general process, screening sand is the first step. Clay recycling shows significant GWP mitigation; the GWP avoidance could reach 37 to 48 kg CO_2 eq per tonne of recycled ESR, and comprehensive recycling of ESR per tonne can reduce the value of GWP by 140% when compared to landfilling per tonne. The results of the economic and environment analysis show that using recycled baking-free bricks to replace solid clay bricks is profitable and can lead to maximal CO_2 mitigation.

At the EoL stage of ESR, recycling should be supported by stakeholders. For construction companies, transporting ESR to recycling plants in suburbs closer to city areas can save dramatic transportation and labor costs. For recyclers and recycling plants, trade in recycled building materials (e.g., recycled sand and recycled baking-free bricks) can earn considerable profits. For local authorities, making policies encouraging that ESR be recycled is an essential point at present. It is also necessary to provide suburban land to build recycling plants at a lower price. Finally, large-scale recycled building materials markets for local ESR recyclers and material buyers must be established and managed. By doing so, the sustainable and healthy management of ESR can be achieved in the near future.

Acknowledgment—The authors declare no conflicts of interest. There is no funding for this research. We would also like to thank Karin Hosking for proofreading and editors and reviewers for their comments to improve this paper. Open access funding enabled and organized by Projekt DEAL.

Data Availability Statement—Supplemental Data for this manuscript are available. Requests for further data are available upon request from author Ning Zhang (n.zhang@ioer.de).

SUPPLEMENTAL DATA

Figure S1. China's urban built-up area and urbanization rate growth trend.

Figure S2. Composition of subway-related ESR in China in 2018.

Figure S3. Forecasting subway-related ESR generation in China.

Table S.1. The length of subway lines in China from 2012 to 2017 (South China) (km)

Table S.2. The length of subway lines in China from 2012 to 2017 (East China) (km)

Table S.3. The length of subway lines in China from 2012 to 2017 (Middle China) (km)

Table S.4. The length of subway lines in China from 2012 to 2017 (Southwest China) km)

Table S.5. The length of subway lines in China from 2012 to 2017 (North China) (km)

Table S.6. The length of subway lines in China from 2012 to 2017 (Northwest China) (km)

Table S.7. The length of subway lines in China from 2012 to 2017 (Northeast China) (km)

Table S.8. The subway-related ESR generation in China 1965–2018 (thousand m^3)

Table S.9. Distribution of subway-related ESR across China (North China) (thousand m^3)

Table S.10. Distribution of subway-related ESR across China (East China) (thousand m^3)

Table S.11. Distribution of subway-related ESR across China (South China) (thousand m^3)

Table S.12. Distribution of subway-related ESR across China (Middle China) (thousand m^3)

Table S.13. Distribution of subway-related ESR across China (Northwest China) (thousand m^3)

Table S.14. Distribution of subway-related ESR across China (Southwest China) (thousand m^3)

Table S.15. Distribution of subway-related ESR across China (Northeast China) (thousand m^3)

Table S.16. Composition of subway-related ESR in China (South China)

Table S.17. Composition of subway-related ESR in China (North China)

Table S.18. Composition of subway-related ESR in China (Northeast China)

Table S.19. Composition of subway-related ESR in China (Northwest China)

Table S.20. Composition of subway-related ESR in China (Southwest China)

Table S.21. Composition of subway-related ESR in China (Central China)

Table S.22. Composition of subway-related ESR in China (East China)

Table S.23. The landfilled ESR and recycled sand and clay in China 2000–2018 (thousand tonnes)

ORCID

Ning Zhang http://orcid.org/0000-0002-1563-1417

REFERENCES

Ajayi SO, Oyedele LO. 2017. Policy imperatives for diverting construction waste from landfill: Experts' recommendations for UK policy expansion. *J Cleaner Prod* 147:57–65.

Ajayi SO, Oyedele LO, Bilal M, Akinade OO, Alaka HA, Owolabi HA. 2017. Critical management practices influencing on-site waste minimization in construction projects. *Waste Manage* 59:330–339.

Arm M, Wik O, Engelsen CJ, Erlandsson M, Hjelmar O, Wahlström M. 2017. How does the European recovery target for construction & demolition waste affect resource management? *Waste Biomass Valori* 8: 1491–1504.

Bailey G, Joyce PJ, Schrijvers D, Schulze R, Sylvestre AM, Sprecher B, Van, Acker K. 2020. Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite. *Resour Conserv Recycl* 155:104675.

Bendixen M, Best J, Hackney C, Iversen LL. 2019. Time is running out for sand. *Nature* 571:29–31.

Coelho A, Brito DJ. 2013. Economic viability analysis of a construction and demolition waste recycling plant in Portugal–Part I: Location, materials, technology and economic analysis. *J Cleaner Prod* 39:338–352.

Deviatkin I, Lyu L, Chen S, Havukainen J, Wang F, Horttanainen M, Mänttäri M. 2019. Technical implications and global warming potential of recovering nitrogen released during continuous thermal drying of sewage sludge. *Waste Manage* 90:132–140.

Duan H, Miller TR, Liu G, Tam VWY. 2019. Construction debris becomes growing concerns of growing cities. *Waste Manage* 83:1–5.

Duan H, Yu D, Zuo J, Yang B, Zhang Y, Niu Y. 2016. Characterization of brominated flame retardants in construction and demolition waste components: HBCD and PBDEs. *Sci Total Environ* 572:77–85.

Eras JJC, Gutiérrez AS, Capote DH, Hens L, Vandecasteele C. 2013. Improving the environmental performance of an earthwork project using cleaner production strategies. *J Cleaner Prod* 47:368–376.

Esa MR, Halog A, Rigamonti L. 2017. Developing strategies for managing construction and demolition wastes in Malaysia based on the concept of circular economy. *J Mater Cycles Waste Manage* 19:1144–1154.

Galán B, Viguri JR, Cifrian E, Dosal E, Andres A. 2019. Influence of input streams on the construction and demolition waste (CDW) recycling performance of basic and advanced treatment plants. *J Cleaner Prod* 236:117523.

Guinée J. 2001. Handbook on life cycle assessment—Operational guide to the ISO standards. *Int J Life Cycle Assess* 6:255.

Han F, Xie R, Lai M. 2018. Traffic density, congestion externalities, and urbanization in China. *Spat Econ Anal* 13:400–421.

Huang T, Shi F, Tanikawa H, Fei J, Han J. 2013. Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. *Resour Conserv Recycl* 72:91–101.

[IEA] International Energy Agency. 2019. CO_2 Emissions from fuel combustion 2019. Paris (FR). 514 p.

[IKE] IKE Environmental Technology Co., Ltd. 2012. Chinese Life Cycle Database (CLCD). Chengdu (CN).

[IPCC] Intergovernmental Panel on Climate Change. 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. IPCC Fourth Assessment Report. Cambridge (UK): Cambridge Univ Pr. 106 p.

[ISO] International Standards Organization. 2006. ISO 14044 Environmental management—Life cycle assessment—Requirements and guidelines. Geneva (CH). 46 p.

Jalaei F, Zoghi M, Khoshand A. 2019. Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM). *Int J Constr Manage* 1–18. https://doi.org/10.1080/15623599.2019.1583850

Jin F, Chen Z. 2019. Evolution of transportation in China since reform and opening up: Patterns and principles. *J Geogr Sci* 29:1731–1757.

Kong X, Xu Z, Shen G, Wang J, Yang Q, Zhang B. 2016. Urban traffic congestion estimation and prediction based on floating car trajectory data. *Future Gener Comput Syst* 61:97–107.

Kylili A, Fokaides PA. 2017. Policy trends for the sustainability assessment of construction materials: A review. *Sustain Cities Soc* 35:280–288.

Lausselet C, Cherubini F, del Alamo Serrano G, Becidan M, Strømman AH. 2016. Life-cycle assessment of a waste-to-energy plant in central Norway: Current situation and effects of changes in waste fraction composition. *Waste Manage* 58:191–201.

Lausselet C, Cherubini F, Oreggioni GD, del Alamo Serrano G, Becidan M, Hu X, Strømman AH. 2017. Norwegian waste-to-energy: Climate change, circular economy and carbon capture and storage. *Resour Conserv Recycl* 126:50–61.

Leite F, Motta R, Vasconcelos LK, Bernucci L. 2011. Laboratory evaluation of recycled construction and demolition waste for pavements. *Constr Build Mater* 25:2972–2979.

Lu W, Tam VW. 2013. Construction waste management policies and their effectiveness in Hong Kong: A longitudinal review. *Renewable Sustainable Energy Rev* 23:214–223.

Lu W, Webster C, Chen K, Zhang X, Chen X. 2017. Computational building information modelling for construction waste management: Moving from rhetoric to reality. *Renewable Sustainable Energy Rev* 68:587–595.

Magnusson S, Lundberg K, Svedberg B, Knutsson S. 2015. Sustainable management of excavated soil and rock in urban areas—A literature review. *J Cleaner Prod* 93:18–25.

Marzouk M, Azab S. 2014. Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. *Resour Conserv Recycl* 82:41–49.

McNeil K, Kang THK. 2013. Recycled concrete aggregates: A review. *Int J Concr Struct Mater* 7:61–69.

Muñoz I, Cifrian E, Andrés A, San Miguel G, Ruiz D, Viguri JR. 2018. Analysis of environmental benefits associated with the incorporation of Waelz slag into fired bricks using LCA. *Constr Build Mater* 168:178–186.

[NBSC] National Bureau of Statistics of China. 2018. China statistical yearbook (2018). Beijing (CN): China Statistics Pr. 943 p.

[NDRC] National Development and Reform Commission (China). 2020. Guiding opinions on promoting the healthy and orderly development of the sand and gravel industry. Beijing (CN). 8 p.

Ortiz O, Pasqualino JC, Castells F. 2010. Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. *Waste Manage* 30:646–654.

Paes MX, Medeiros GA, Mancini SD, Bortoleto AP, Oliveira JAP, Kulay LA. 2019. Municipal solid waste management: Integrated analysis of environmental and economic indicators based on life cycle assessment. *J Cleaner Prod* 119848.

Priyadharshini P, Ramamurthy K, Robinson RG. 2017. Excavated soil waste as fine aggregate in fly ash based geopolymer mortar. *Appl Clay Sci* 146:81–91.

[SAC] Standardization Administration of the People's Republic of China. 2007. GB/T 21144–2007 National Standard of solid concrete brick. Beijing (CN). 16 p.

[SAC] Standardization Administration of the People's Republic of China. 2011. GB/T 14684–2011 National Standard of sand for construction. Beijing (CN). 32 p.

[SAC] Standardization Administration of the People's Republic of China. 2017. GB/T 5101–2017 National Standard of fired common bricks. Beijing (CN). 14 p.

Sáez PV, Merino MR, Porras-Amores C, González ASA. 2014. Assessing the accumulation of construction waste generation during residential building construction works. *Resour Conserv Recycl* 93:67–74.

[SCC] State Council of China. 2016. Notice of the State Council on issuing the work plan for greenhouse gas emission control during the 13th five-year plan period. Beijing (CN). 9 p.

Shan Y, Goodrum PM, Zhai D, Haas C, Caldas CH. 2011. The impact of management practices on mechanical construction productivity. *Constr Manage Econ* 29:305–316.

Simion IM, Fortuna ME, Bonoli A, Gavrilescu M. 2013. Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA. *J Environ Eng Landsc Manag* 21:273–287.

[Sphera] Sphera Solutions GmbH. 2018. GaBi Software-System and Databases for Life Cycle Engineering. Stuttgart (DE).

Sun B, He Z, Zhang T, Wang R. 2016. Urban spatial structure and commute duration: An empirical study of China. *Int J Sustain Transp* 10:638–644.

Tam VW. 2008. Economic comparison of concrete recycling: A case study approach. *Resour Conserv Recycl* 52:821–828.

[UNEP] United Nations Environment Programme Globe Environmental Alert Service (GEAS). 2014. Sand, rarer than one thinks. Nairobi (KE). 15 p.

Vossberg C, Mason-Jones K, Cohen B. 2014. An energetic life cycle assessment of C&D waste and container glass recycling in Cape Town, South Africa. *Resour Conserv Recycl* 88:39–49.

Wei YD, Li H, Yue W. 2017. Urban land expansion and regional inequality in transitional China. *Landscape Urban Plann* 163:17–31.

Wu Z, Ann TW, Shen L, Liu G. 2014. Quantifying construction and demolition waste: An analytical review. *Waste Manage* 34:1683–1692.

Yeheyis M, Hewage K, Alam MS, Eskicioglu C, Sadiq R. 2013. An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. *Clean Technol Environ Policy* 15:81–91.

Zhang N, Duan H, Miller TR, Tam VW, Liu G, Zuo J. 2020. Mitigation of carbon dioxide by accelerated sequestration in concrete debris. *Renewable Sustainable Energy Rev* 117:109495.

Zhang N, Duan H, Sun P, Li J, Zuo J, Mao R, Liu G, Niu Y. 2020. Characterizing the generation and environmental impacts of subway-related excavated soil and rock in China. *J Cleaner Prod* 119242.

Zhang N, Zheng L, Duan H, Yin F, Li J, Niu Y. 2019. Differences of methods to quantify construction and demolition waste for less-developed but fast-growing countries: China as a case study. *Environ Sci Pollut Res* 26:25513–25525.

Zhang Y, Zheng S, Sun C, Wang R. 2017. Does subway proximity discourage automobility? Evidence from Beijing. *Transp Res Part D: Transp Environ* 52:506–517.

Zhao W, Leeftink RB, Rotter VS. 2010. Evaluation of the economic feasibility for the recycling of construction and demolition waste in China—The case of Chongqing. *Resour Conserv Recycl* 54: 377–389.

Zheng L, Wu H, Zhang H, Duan H, Wang J, Jiang W, Song Q. 2017. Characterizing the generation and flows of construction and demolition waste in China. *Constr Build Mater* 136:405–413.