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Unraveling the GWP mitigation potential from recycling subway-related excavated soil and rock in China via life cycle assessment

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Data availability statement

Supplemental Data for this manuscript is available in the Supporting Information (SI). Requests for further data are available upon request from first author N Zhang, n.zhang@ioer.de.

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research. We would also like to thank the Ms. Karin Hosking for proofreading and editors and reviewers for their comments to improve this paper.

Highlights:

- This study focuses on the GWP assessment of ESR.
- Cumulative CO₂ mitigation potential by recycling ESR was calculated.
- Over 8 million USD profit could have been reached annually between 2006 and 2018.
- Cumulative CO₂ mitigation potential could have been as high as 1.5 Bt from 2010 to 2018.

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. This present study evaluates global warming potential (GWP, expressed by CO₂ eq.) from different ESR recycling and landfilling scenarios via a life cycle assessment 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 1.1–1.5 Mt (Million tonnes) of CO₂ 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 9 million USD annually. The findings of this study could provide better recycling options for ESR-related stakeholders. It is important to mention is that there still much work to be done before this recycling work can be popularized in China. **Keywords:** Excavated soil and rock (ESR); Recycling; CO₂ 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).

ESR 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 (Sáez et al., 2014; Yeheyis et al., 2013; McNeil and Kang, 2013). 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 C&D waste reduction strategy can also reduce environmental impact.

It is generally believed that landfilling and backfilling of C&D waste and ESR causes more significant negative impacts than recycling, such as land subsidence, vegetation deterioration, landslide risk, and increasing the difficulty of ecological environment recovery (Duan et al., 2019; Vossberg et al., 2014; Arm et al., 2017). Simion et al. (2013) used LCA to compare the environmental impacts of producing concrete aggregates from recycling and natural inert/mining
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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 three treatment scenarios for C&D waste in Spain, and the eco-friendliest 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 also conserving land when compared to disposal in landfills. In addition, recycling some components of C&D waste to energy regeneration and carbon capture and storage (CCS) can help in building climate-friendly societies (Lousselet et al., 2016; Lousselet et al., 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) studied the overall environmental benefits of Waelz slag incorporation into bricks by LCA; their results showed that a great reduction in impact on climate change could be achieved, but in the process of firing, more sulfur dioxide (SO₂) 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 et al. (2020b) indicated that mismanagement of ESR (disposed of mainly through dumping sites) threatens the natural environment and poses high landslide risks in China. This article is protected by copyright. All rights reserved.

Therefore, further detailed research into ESR recycling is urgent and necessary. This study evaluates the CO₂ 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 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 (Paes et al., 2019; Zhang et al., 2020a; Zheng et al., 2017). As these previous studies revealed, much C&D waste is generated in urban areas (e.g. Zhang et al., 2019; Wu et al., 2014), and recycling such waste is effective in reducing the negative impacts from C&D landfilling and increasing CO₂ mitigation by using recycled construction materials. However, ESR recycling, which is a great opportunity to further reduce CO₂ emissions and waste production at the urban scale, hasn't 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, this study aims to compare the environmental impacts of manufacturing ESR-based construction materials versus traditional construction materials and assess the potential economic benefits from recycling ESR. This study applies an LCA model to evaluate the total GWP (measured as carbon dioxide equivalents, CO₂ 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 two different disposal methods in China; recycling of ESR or C&D waste refers to the reprocessing of waste materials into recycled construction materials, while backfilling is a recovery method and is not taken into account here (Galán et al., 2019).

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ESR 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 (RS-NS and RBB-CSB). For the other two replacements (RBFBS-CSB and 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 this study is carried out in mainland China, a rapidly growing and densely populated 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. This study uses CO₂ eq. as a measurement unit to analyze the GWP from ESR landfilling, combined with different recycling plans, from 2000 to 2018.

Data in this 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). The data on composition and flow of ESR are derived from the average calculation of results in Zhang et al. (2020b) (see Eq.1). Further generation and flow data on main components were obtained from interviews with government officials and previous studies (Zhang et al., 2020b; Zheng et al., 2017) (see Eq.2).

Equation 1

$$P_x = \sum_{l=1}^7 P_{xl} / 7 \quad (1)$$

Eq.1 represents an average calculation of one type of ESR material in seven Chinese regions. P_x refers to the average proportion of materials of type x

across China, while P_{xl} is the proportion of materials of type x in region l .

Equation 2

$$Q_{xyt} = G_y \times P_x \times R_{xt} \quad (2)$$

In Eq.2, Q_{xyt} refers to the quantity 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 this study, the treatment method t only represents 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/LCC data inventory, which usually contains CO₂ emission factors and energy and materials consumption.

LCA model

The LCA model is the main methodology in the study. It strictly follows the requirements of the ISO 14044 standard (ISO, 2006), a widely accepted standard that describes the principles and framework for life cycle assessment. The methodology framework for LCA consists of the following four 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. Since the recycling and landfilling processes all use ESR as the raw material, “1 kg (tonne) of ESR” is selected as the functional unit for this research. A reduced-scope LCA is adopted in this study (see Fig.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 CO₂ emissions; the Chinese CO₂ 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 CO₂, methane (CH₄), and fluoride, are expressed in the weight of CO₂ eq. (Deviatkin et al., 2019). Following the IPCC method, an assessment time frame of 100 years is used in this study to assess the GWP (IPCC, 2007).

The following $M_1 \sim M_4$ in Eqs.3–6 refer to the total CO₂ 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.

Equation 3

$$M_1 = E_{LC.NS} - E_{RS} \quad (3)$$

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

Equation 4

$$M_2 = E_{LC.CSB} - E_{RFBFB} \quad (4)$$

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

Equation 5

$$M_3 = E_{LC.CSB} - E_{RBB} \quad (5)$$

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

Equation 6

$$M_4 = E_{LC.SCB} - E_{RBB} \quad (6)$$

where $E_{LC.ACB}$ 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 above, CO₂ eq. is adopted to assess GWP value. Therefore, based on the CO₂ mitigation results, we compare GWP among the different replacement schemes.

Economic analysis model

In the cost-benefit analysis (Eqs.7–9), the recycling company is selected from among multiple stakeholders for this 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. Since the financial data comes 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.

Equation 7

$$NP = R_{total} - EP_{total} \quad (7)$$

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

Equation 8

$$R_{total} = R_R + R_S + S_G \quad (8)$$

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).

Equation 9

$$EP_{total} = EP_A + EP_R + EP_S + EP_E + \sum_{i=1}^n EP_O \quad (9)$$

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 nine 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 the large cities mentioned above, since this type of recycling behavior only occurs 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

ESR recycling network

After a series of field investigations in ESR and C&D waste recycling plants in China, we found that ESR can generally 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. Fig.2 shows a general process of recycling ESR; typically, from ESR to recycled materials, three 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

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convert ESR into building materials, mainly recycled bricks.

As shown in Fig.3, nationwide ESR typically consists of four main components – sand, clay, miscellaneous fill, and stone (see Fig. S2 in Supporting Information (SI)). 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 Fig.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 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 Fig.4, though sand and clay are the two 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 Mt (Million tonnes) (comprising sand 10 Mt and clay 8 Mt), while 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).

CO₂ 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. Fig.5

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provides a more detailed view of CO₂ mitigation from different recycling methods. The results 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).

In Fig.5b, there are four material replacement schemes. Using ESR to screen out recycled sand and replace natural sand only achieves a small CO₂ mitigation efficiency. However, when sand screening is followed by further recycling, significant CO₂ mitigation could be achieved. In addition, per brick CO₂ 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 CO₂ eq. cumulatively between 2010 and 2018.

The results in Fig.5a show that recycling ESR can achieve a “double emission reduction” effect. The CO₂ mitigation from recycling and avoided emissions from landfilling have significant potential in reducing GWP. Landfilling would result in 30 Kg CO₂ eq. per tonne of landfilled ESR, in comparison with GWP reduction of 42 (37–48) Kg CO₂ 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 CO₂ 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 CO₂ eq./ Kg gasoline and 0.49 Kg CO₂ eq./ Kg diesel in China, data from GaBi database); and (2) the new material being replaced has different emission factors (e.g. 0.18 Kg CO₂ eq./ Kg for clay solid brick, 0.03 Kg CO₂ eq./ Kg for natural sand in China, data from GaBi database).

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, Fig.6 shows the estimation of economic benefits and costs if recycling plants take

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ESR to produce recycled baking-free bricks.

As shown in Fig.6, recycling ESR could have produced ever-increasing net proceeds between 2006 and 2017, reaching a sizable amount of 22.8 million USD 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 USD). 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. Since 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 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, landslide and collapse risk (Duan et al., 2019). Also, the results of this study illustrate that recycling ESR could reduce GWP and meet the targets in China's 13th Five-Year Plan – CO₂ 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 CO₂ 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 this article, but further taking construction companies, government, and other stakeholders into consideration can make up for this one-sided result and better

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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

This study applied the life cycle costing and environmental assessment method to assess the relative economic feasibility and CO₂ emissions intensity of different recycling plans for two 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 article is protected by copyright. All rights reserved.

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 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 et al., 2020b). 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 USD to the national economy. On 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 37–48 Kg CO₂ 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 CO₂ 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.

Table 1. The recycle and replace scenarios

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Table 2. The data inventory for LCA

Note: * μf means the fineness modulus, it is an index that characterizes the degree and type of natural sand particle size. The fineness modulus of ordinary construction sand is 3.0~1.6.

Table 3. Explanations of different terms for construction materials (according to Chinese national standards: GB/T5101-2017, GB/T 21144-2007, and GB/T 14684-2011)

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

Table 5. Data for variables used in Eqs.7–9 for economic analysis in 2017

Note: * Kt is the abbreviation for kiloton; soil in Table 5 means the clay component in ESR. ** The labor cost is a mixture of labor and overhead costs.

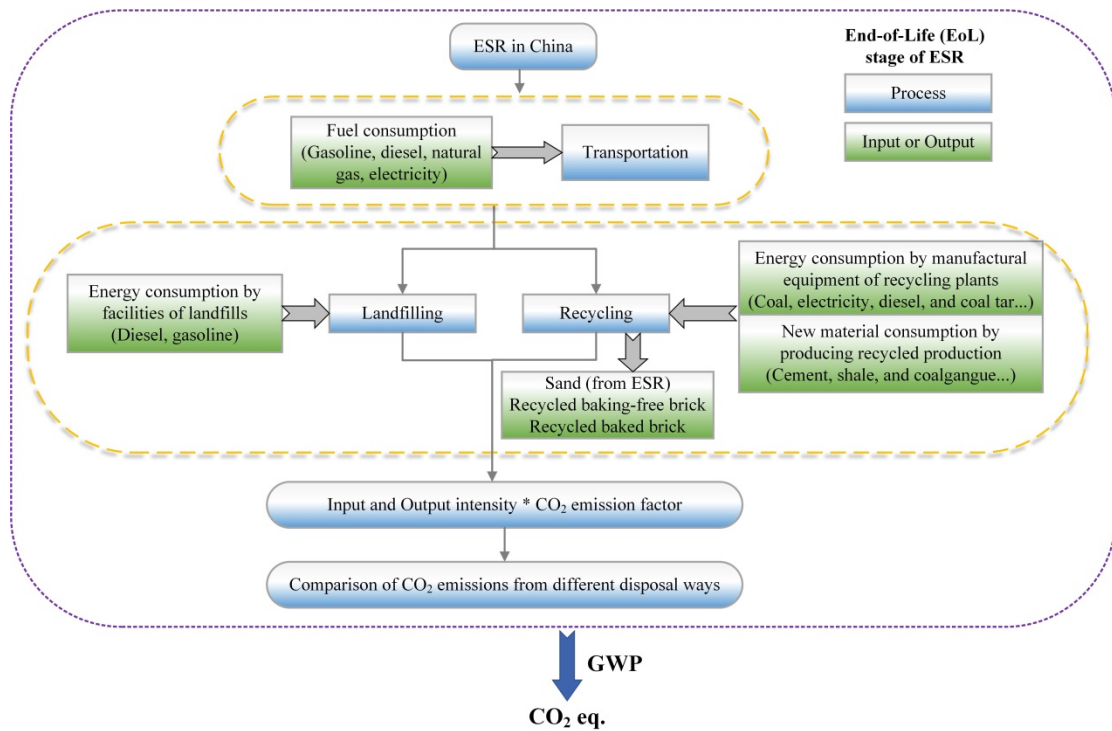


Figure 1. The system boundary and study scope for LCA

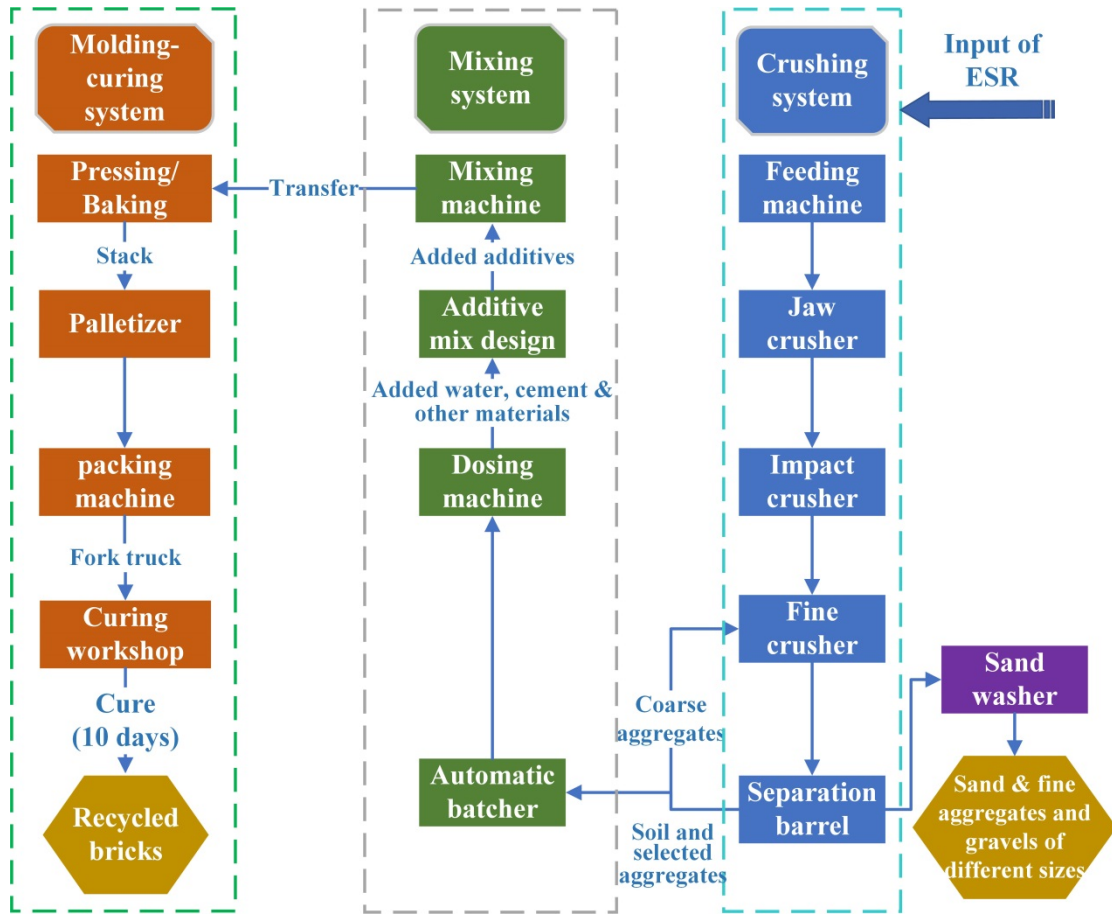


Figure 2. Schematic flowchart of recycling ESR

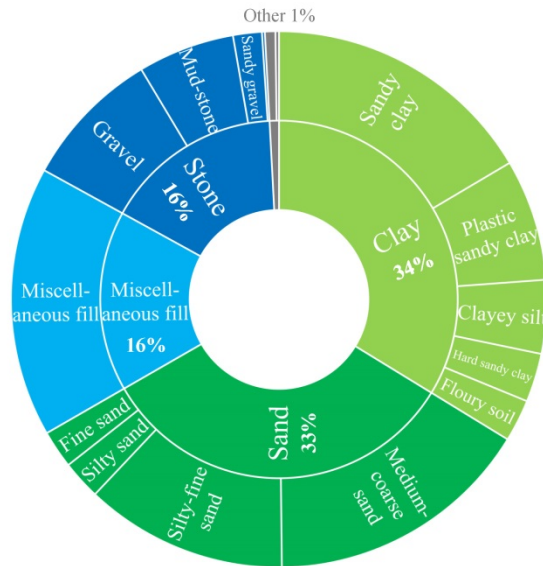


Figure 3. Primary and secondary components of ESR in China (national average value based on regional data from Zhang et al. (2020b))

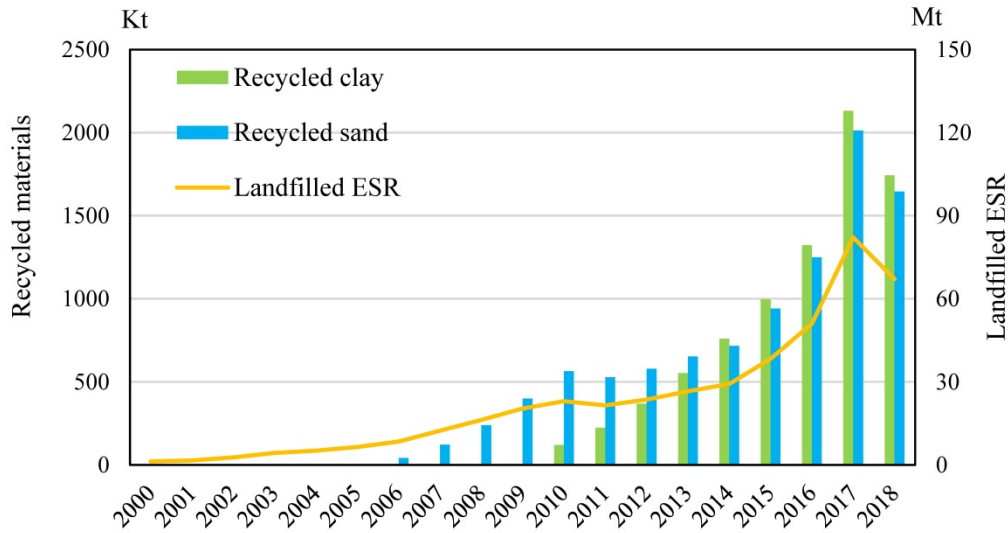


Figure 4. The present situation of ESR recycling in China

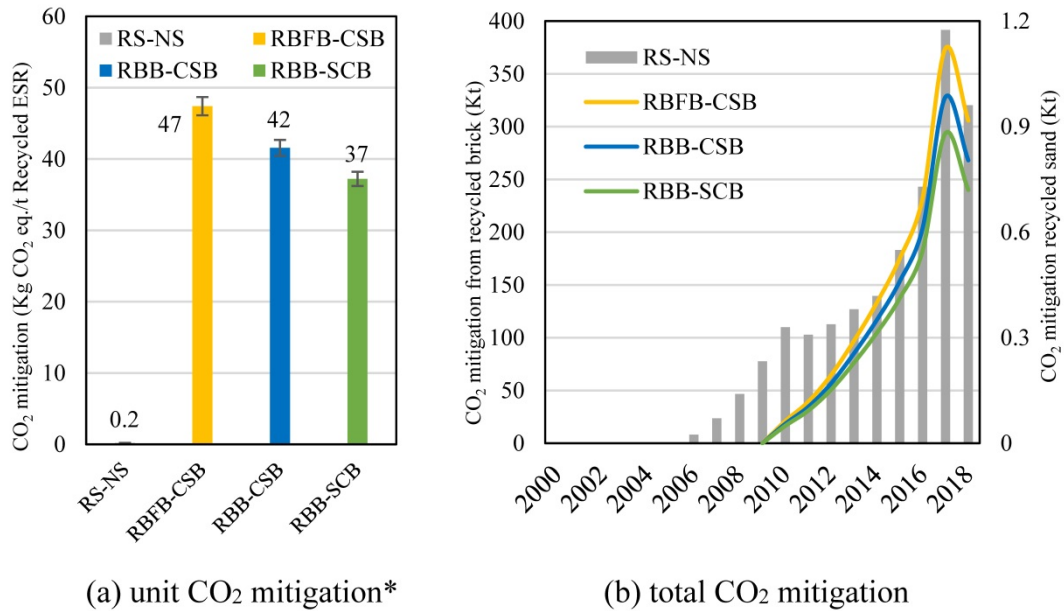


Figure 5. The CO₂ mitigation of different ESR recycling plans

Note: * CO₂ 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 CO₂ emissions caused by landfilling (30 Kg CO₂ eq. / landfilling ESR). The legends in Fig.5 refer to the material replacement schemes; their full definitions are shown in Table 1.

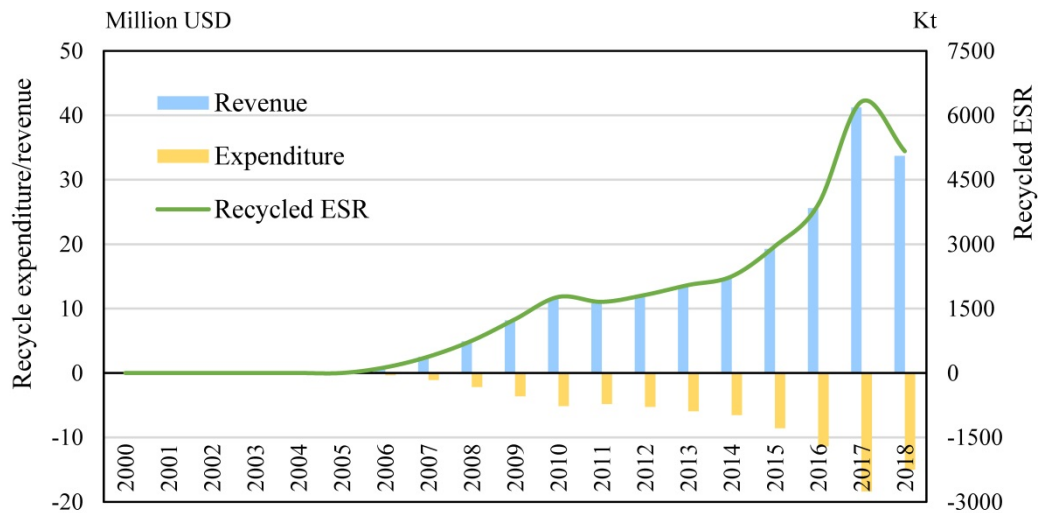


Figure 6. The economic analysis of ESR recycling (taking producing recycled sand and baking-free bricks as an example)

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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	RFBF-CSB
Baking	Recycled baked brick	Traditional clay solid brick	RBB-CSB
		Solid concrete brick	RBB-SCB

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
Coal	0.28 kg CO ₂ eq./kg	GaBi database
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
Natural sand ($\mu_f=3.0\sim 1.6$)*	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	

*Note: * μ_f means the fineness modulus, it is an index that characterizes the degree and type of natural sand particle size. The fineness modulus of ordinary construction sand is 3.0~1.6.*

Table 3. Explanations of different terms for construction materials (according to Chinese national standards: GB/T5101-2017, GB/T 21144-2007, and GB/T 14684-2011)

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, recycled concrete aggregates (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.

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

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

Table 5. Data for variables used in Eqs.7–9 for economic analysis in 2017

Technical data (Unit)	Equipment information			Total
Equipment	Impact crusher	Screening machine	Forming machine	-
Oil cost (USD/Kt soil*)	148	44	106	298
Dedusting cost (USD/Kt soil)	6	-	4	10
Consumable cost (USD/Kt soil)	86	19	59	164
Maintenance cost (USD/Kt soil)	12	9	10	31
Labor cost** (USD/ Kt soil)	12	-	-	12
Other cost (USD/ Kt soil)	15	15	15	45
Amortized equipment (USD/Kt soil)	112	48	59	219
Plant rent (USD/ Kt soil)	According to the lease price of plant in suburb, 2.17 USD/m ² · month			1160
Total cost (USD/Kt soil)	778	521	640	1939

*Note: * Kt is the abbreviation for kiloton; soil in Table 5 means the clay component in ESR. ** The labor cost is a mixture of labor and overhead costs.*