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Policy Analysis

Greenhouse Gas Emissions and Decarbonization Potential of Global Fired Clay Brick Production

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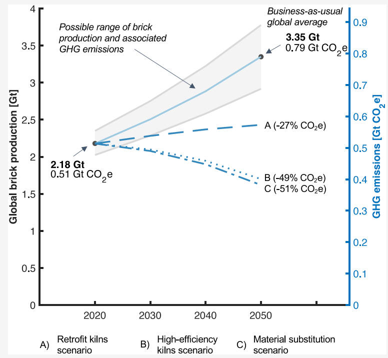
ABSTRACT: Fired clay bricks (FCBs) are a dominant building material globally due to their low cost and simplicity of production, especially in low- and middle-income countries. With a projected rising housing demand, commensurate growth in brick demand is anticipated, the production of which could result in significant greenhouse gas (GHG) emissions. Robust models are needed to estimate brick demand and emissions to systematically address decarbonization pathways. Few sources report production values; hence, we present two novel proxy models: (i) a consumption prediction model, relying on country-specific clay extraction data, dynamic building stock modeling, and average material intensity use allowing for projections to 2050; and (ii) a GHG emissions model, using literature-based data and production technology-specific inputs. Based on these models, the current global FCB consumption is estimated as 2.18 Gt annually, resulting in approximately 500 million tCO_2e (1% of current global GHG emissions). If unaddressed, this fraction could increase to 3.5−5% in 2050 considering a moderate SSP 2-4.5 climate change mitigation scenario. Consequently, we explored three potential decarbonization pathways: (i) improving energy efficiency; (ii) shifting production to best practices; and (iii) replacing half of FCB demand with hollow concrete blocks, resulting in 27%, 49%, and 51% reduction in GHG emissions, respectively.



KEYWORDS: *Fired clay brick, Brick production, Low-carbon construction, Material demand mapping, Decarbonization potential*

1. INTRODUCTION

Within the next three decades, the global population is projected to grow by almost 2 billion people, with the majority of growth in just eight countries, all in Asia and Africa.[1] The estimated global demand in building floor area is expected to double between 2015 and 2050,[2−4] and hence, there is an anticipated surge in demand for building materials. Among these, fired clay bricks (FCBs) are one of the most affordable and commonly used, with approximately 87% produced in Asia.[5,6] In 2016, the global consumption of brick was estimated to be 1.9−4.1 Gt/year (∼40% uncertainty), representing about 9% of total material demand.[7] Others have estimated the lower and upper limit to global production of FCB at approximately 2−3 Gt/year.[8,9] China, India, Pakistan, Bangladesh, and Vietnam are the largest brick-producers,[9] with nearly two-thirds of global production occurring in China.[10,11] Despite the global effort to shift to low-carbon substitutes, change has been limited for this material. For example, in India, the demand for bricks is projected to increase by 3- to 4-fold in the next two decades, reaching an annual demand of 750−1000 billion bricks.[12] The sector employs nearly 15 million people[13] and is currently responsible for a 90% share of the country's construction block market, with limited changes projected despite the availability of alternative materials.[14]

In the regions expecting the highest growth in demand for FCBs, less efficient material production practices that result in higher energy use and greenhouse gas (GHG) emissions are widely prevalent. In South Asia, FCB production technologies have been slow to change over the past century, resulting in pollution.[11] It has been estimated that in India, Africa, and several countries in South Asia, material-related GHG emissions will more than double between 2020 and 2060, with FCBs contributing 18% of these emissions (second only to concrete and steel, contributing 60% combined).[15] The energy demand to produce 1 kg of FCB ranges from 0.5 to 5 MJ,[11,16−20] and the associated GHG emissions are highly dependent on the kiln technology efficiency and the fuel used for thermal energy.[14,21,22] Coal is the most commonly used fuel, contributing to high GHG emissions intensity per produced brick.[22,23] This use of coal makes the brick sector the second largest coal-consuming industry in India[11] and the third largest in Pakistan;[24] but less GHG-intensive fuels such as wood, wastes, oil, and natural gas are also used to some extent.[5,6,22] In addition to GHG emissions, current brick production leads to emissions of SO_2, CO, particulate matter

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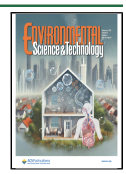

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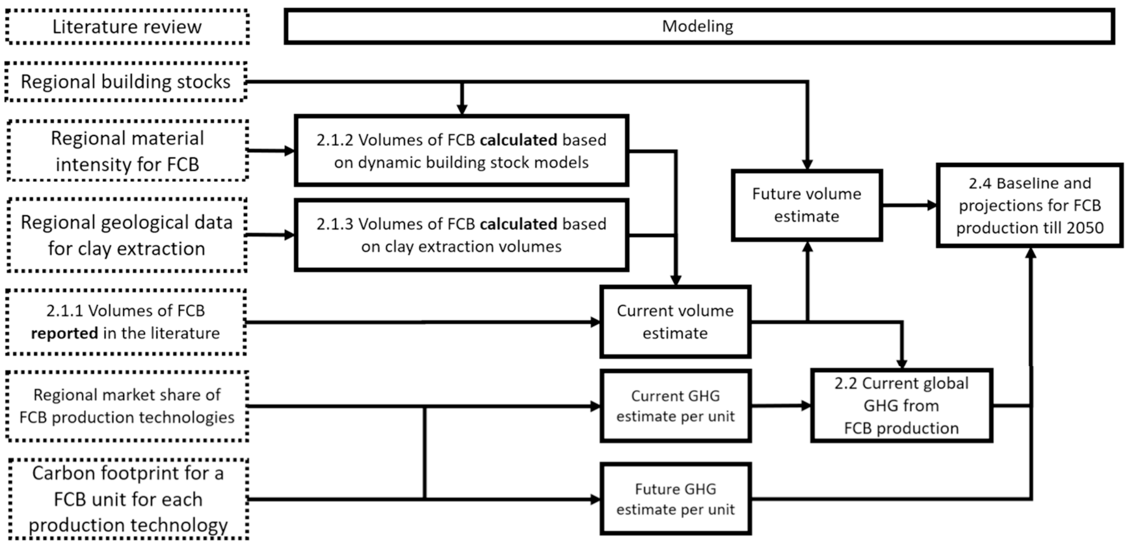

Figure 1. A schematic flowchart of the data sources and the different models prepared for this paper. Note: the numbers shown in the flowchart correspond to the Methods sections in the manuscript.

(PM), NO_X, as well as black carbon.[5,6,14,25] In some areas, 90% of all PM emissions can be attributed to this one industry.[13] Accurate data on the carbon footprint of FCB production technologies are scarce, but the literature reports a range from 0.07 to 0.34 kg CO_2e/kg for brick for the most common production techniques,[14,17,18,26−33] and it has been suggested that brick production in the five main brick-producing countries in Asia (China, India, Pakistan, Vietnam, and Bangladesh) may be responsible for 1.24% of global anthropogenic CO_2 emissions based on coal consumption for producing brick.[9] Yet, robust models to assess such impacts are still needed.

To produce FCB, there are six predominant technologies with varying energy efficiency: (i) the Clamp kiln; (ii) the Fixed Chimney kiln; (iii) the Zigzag kiln; (iv) the Hoffman kiln; (v) the Tunnel kiln; and (vi) the Vertical Shaft Brick kiln (VSBK). The Clamp kiln is a nonpermanent structure composed of green bricks stacked in a pyramid shape (with a rectangular base) interspersed with combustible material, which is a setup associated with high heat loss and therefore high energy demand.[9,11,21] The Fixed Chimney kiln and the Zigzag kiln are the most common technologies used in South Asia.[11] The Fixed Chimney kiln has been shown to be inefficient compared to newer technologies,[34] but the Zigzag kiln is considered a more advanced technology, as it uses suction fans to move and draw the fire between bricks stacked in a zigzag pattern.[35,36] For the Tunnel kiln, preheated green bricks are loaded on carts and moved through the kiln[18] with high firing process control.[11,18] The VSBK is considered the most energy-efficient kiln, due to its insulated shaft walls and efficient heat transfer.[11,27]

The main decarbonization pathways for FCB production include using production methods with higher energy efficiency, using alternative raw materials and fuels, or using other low-carbon bricks (i.e., resource efficient bricks such as hollow or lightweight bricks or stabilized earth bricks that do not require firing).[9,37,38] Based on the known differences in the efficiency of different kiln types, increasing energy efficiency is a logical decarbonization lever, but it requires substantial capital investments,[11,18] which can hinder implementation. Retrofitting kilns may be a more cost-effective measure than kiln replacement, and depending on conditions and retrofit method, retrofits can improve energy efficiency by up to 20% and reduce PM emissions by 50%.[13] Further, use of cleaner fuels and alternative raw materials, such as fly ash, coal dust, and coal slurry, has been reported as a means to lower GHG emissions.[13,14,32,37] Low-carbon bricks may also substitute for FCB to reduce emissions. For example, compressed earth blocks (CEBs) have been proposed as alternative low-carbon bricks;[39,40] however, the need to incorporate stabilizing materials in the earth mix, mainly cement or lime, to achieve the minimum required performance can increase the environmental impact of CEBs significantly.[41,42] Concrete blocks have lower GHG emissions than FCBs,[43−45] and the emissions from producing these concrete blocks can be reduced further by using cement with low clinker content, such as limestone calcined clay cement (LC3).[46]

Despite the awareness of large material consumption and emissions from FCB production, the values of the material stocks, and hence the demand projections for bricks, are not well reported and data are considered either unreliable or incomplete.[47] Miatto et al.[48] performed a material flow analysis of bricks used in Italy, and Tibrewal et al.[49] estimated the brick production and associated regional energy consumption in India, but similar analyses are missing among the other main brick-producing countries and at a global scale. Further, to the best of the authors' knowledge, none of the global decarbonization roadmaps have indicated specific baseline CO_2 values or future targets for FCB production. A recent article explored the social and environmental injustice associated with global FCB trade, but not the production.[50] With initial estimates suggesting that the coal consumption in the production of FCBs alone could be contributing to over 1% of the global anthropogenic GHG emissions, mitigating GHG emissions from the FCB industry becomes crucial to reach net-zero CO_2 emissions by 2050.[9] The aim of this study is to use systematic models to quantify the global volume of FCBs produced and the total GHG emissions associated with the production of FCBs. We use these models to establish a current baseline and project the demand for and GHG emissions from bricks to 2050 with and without different decarbonization strategies.

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Table 1. Global Brick Production (kg/year) Estimates from the Literature and Both Proxy Models Developed (FA = Floor Area, Inc. = Increase, and MI = Material Intensity)

	global literature values	model 1: building stock data				model 2: clay extraction		
region/country	FCB (Gt/year)	FA inc. (Bm^2/year)[a]	FCB MI (kg/m^2)	ref	FCB (Gt/year)	clay extracted (Mt/year)	FCB (Gt/year)	
India	0.399	1.2	952	Ramesh et al. (2013)	1.114	0.723	0.325	
Africa and Middle East	0.008	0.41	90	Asadollahfardi et al. (2015)	0.037	0.109	0.049	
Latin America and Oceania	0	1.06	296	Evangelista et al. (2018)	0.314	0.131	0.059	
China	1.46	0.51	374	Huang et al. (2013)	0.191	3.789	1.705	
remaining Asia	0.151	0.58	493	Heeren and Hellweg (2019)	0.286	0.229	0.103	
North America	0	0.34	160	Arehart et al. (2022)	0.054	0.029	0.013	
Europe	0.003	0.41	392	Sprecher et al. (2022)	0.161	0.203	0.091	average:
	2.02				2.16		2.35	2.18 Gt

[a]Based on the average of the modeled values by refs 2, 58, and 59.

2. MATERIALS AND METHODS

Here, we establish an estimated baseline for the global production for FCBs and the associated GHG emissions as well as project demands and emissions to 2050 as a first step in understanding the role of decarbonization strategies. The methodology is portrayed schematically in Figure 1.

2.1. Estimating the Total Brick Demand in 2020. First, we assess the global current production through three different approaches: (1) by collecting the country-specific mass of FCB production from secondary sources, which we note does not alone give a robust means to estimate global production; (2) by multiplying the average material intensity of FCBs used in a building by the global built-up floor area from building stock models; and (3) by deriving a proxy for the global production of brick based on a percentage of extracted clay per world region. We consider brick production to correspond with brick consumption in a region, as it is a low-cost commodity, limiting transportation. This assumption is supported by data reported by the United Nations (UN) (Comtrade) database, which indicates that less than 1% of bricks produced in the five largest brick-producing countries are exported.[51] Similarly, this modeling is based on the assumption that there is minimal difference between the FCB demand and production, and consequently, the consideration of waste is not integrated into the analysis.

2.1.1. Brick Demand Based on Secondary Sources. The most direct method of determining the global mass of FCB produced was to determine if values have been reported in secondary sources, such as papers and reports. Using ScienceDirect to retrieve literature with the following search terms "fired" AND "clay" AND "bricks" OR "production" OR "volume", 20 references were found, of which only 9 papers reported the mass of brick production in one or more regions (see Supplementary Data 1). Due to limited data availability, the collected data for brick production show temporal variability, meaning not all data points reflect 2020 production values. However, this was based on a study by Svedrup et al.,[52] which found only minor changes in cement supply between 2017 and 2020; it is assumed herein that the brick production data from the time-horizon considered are representative. Here, we use a summation of the regional values of mass of produced brick reported by refs 6, 10, 14, 25, and 53−57 to estimate the global brick demand. The data found were generated mainly from countries with the highest production. While we found some estimates for the number of bricks produced (1500 billion bricks globally),[10] there were no robust data on the mass of produced bricks globally. To better understand the potential future demands of this resource, the following two models were developed to triangulate estimated global FCB production.

2.1.2. Material Intensity and Building Stock Modeling Approach. By adapting dynamic building stock models for estimating the global floor area, we can derive a proxy for quantifying brick consumption globally. There are several existing stock models that present estimates of the floor areas built in different regions of the world in 2020. The Global Alliance for Buildings and Construction presented in their 2016 Global Status Report[2] that the expected building floor area globally in 2020 would be 258.2 billion square meters (Bm^2), while Güneralp et al.[58] and Deetman et al.[59] estimated it at 225.5 and 242.8 Bm^2, respectively (see Supplementary Data 2). Each of the three models divided the global floor area in different numbers of regions, so in this work, we aggregate the floor area values into the 7 following countries and regions that were common or could be determined across all studies to quantify a global average model: (1) India; (2) Africa and Middle East; (3) Latin America and Oceania; (4) China; (5) remaining Asia; (6) North America; and (7) Europe. Next, we calculated material intensities for FCB, i.e., the amount of brick used per m^2 floor area, as an average regional intensity based on data collected from the literature (based on inputs from refs 60−66 and presented in Table 1). The majority of the presented material intensity data are for residential buildings, but some intensities are presented as not specific to a certain building typology. In this model, the material intensities are assumed to be for a generalized unit, based on an average of typical housing units and general use units, and FCB production globally is estimated as

$$P_{FCB} = \sum_i FA_i \times MI_i \tag{1}$$

where P_{FCB} is the global production of FCB, FA is the floor area for each region, MI is the region-specific material intensity of brick used per m^2 floor area, and i represents each region assessed (Table 1 presents the values used for FA_i and MI_i).

2.1.3. Brick Demand Based on Clay Extraction Data. Again, noting the paucity of data and the degree of assumptions necessary for the prior methods, we employ a

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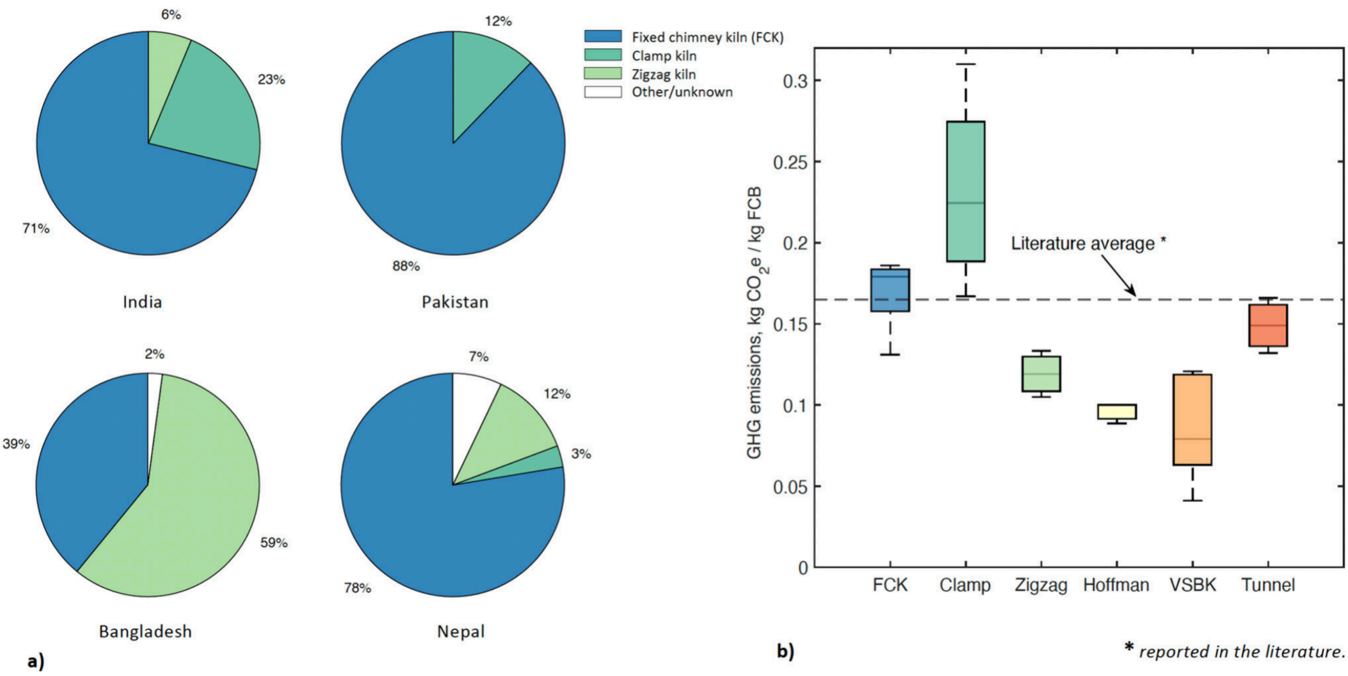

Figure 2. Technology share of FCB production. (a) Market share of FCB production technology in each of the modeled brick-producing countries.[11,17,74] (b) GHG intensity for each production technology. FCK = Fixed Chimney kiln, VSBK = Vertical Shaft Brick kiln.[10,13,14,26−29,75] The reported literature average, shown as a dashed line in (b), is based on ref 76 and the assumption that 75% of total cradle-to-gate emissions are from the production process. See Supplementary Data 3.

third method. This method adapts a value reported by the United States Geological Survey, which states that 45% of extracted clay is used in the production of FCB.[67] This method of estimating the FCB production based on clay extraction was also employed by Miatto et al.[8] Here, we collect data on the global extraction of clay from Materialflows.net (2019),[68] which reports resource extraction based on the Global Material Flows Database developed by the UN International Resource Panel. We then assume that for each Gt of extracted clay in a specific region of the world, 0.45 Gt of FCB is produced, and use that ratio as a multiplicative factor with outputs from ref 68. The estimates of global FCB production from the methodologies in sections 2.1.1− 2.1.3 are presented in Table 1 in the Results and Discussion section, along with the arithmetic mean of the three modeling outputs that is used in the modeling herein.

2.2. Global GHG Emissions from Brick Production. Next, we estimate the FCB contributions to anthropogenic GHG emissions. A cradle-to-gate system boundary (i.e., from the extraction and transportation of raw materials as well as the production process of the FCB) was the most reported scope for brick production in the literature.[69] The emissions factor for brick production is calculated according to eq 2 as GHG emissions per 1 kg of FCB:

$$\text{GHG}_{\text{FCB-region}} = \frac{E_{\text{kiln-avg}}}{P} \tag{2}$$

where P is a dimensionless factor representing the share of production process in the total emissions for cradle-to-gate production of FCB, which the literature suggests ranges between 70 and 80%[70−72] (75% used in calculations herein) depending on transportation distance and clay moisture content. The energy intensity, $E_{\text{kiln-avg}}$, is the region-specific emissions intensity of the FCB kilns production process, which is calculated using eq 3:

$$E_{\text{kiln-avg}} = \sum E_{\text{kiln}} \times M_{\text{i}} \tag{3}$$

where E_{kiln} is the specific emission intensity of a kiln type, namely: Fixed Chimney kiln, Clamp kiln, Zigzag kiln, VSBK, and Tunnel kiln. M_i is the market share of each kiln type in the regional market in four of the highest FCB-producing countries (India, Pakistan, Bangladesh, and Nepal). The values are based on a compilation of inputs from refs 10, 13, 14, 17, and 26−29, and the calculations are presented in the Supplementary Data. A unified emissions factor was then determined by multiplying each region-specific emissions factor ($\text{GHG}_{\text{FCB-region}}$) by the region's global market share of FCB. The authors point out that China and Vietnam have notable contributions to the global FCB production market, but because data on the FCB kiln technology market shares are scarce in these countries, they were excluded from the weighted average of technology-specific emissions factors for the main discussion. Technology market shares for the high FCB-producing countries considered in this model are presented in Figure 2a, and Figure 2b shows the ranges of GHG emissions per kilogram of brick for each kiln technology obtained from the literature. The estimation of a global GHG emissions factor, used as the baseline hereafter, is determined as the average value of GHG emissions per kilogram of brick and production technology.

To address parameter uncertainty and the potential effects of some modeling assumptions, a sensitivity analysis is performed. In this analysis, we assess the influence of including brick production in China, based on the limited information about technology market shares and emissions factor data available. For this analysis, we model 90%, 5%, and 5% of China's FCBs to be produced using Hoffman kiln, Tunnel kiln, and VSBK, respectively. The emissions factor for the Hoffman kiln is

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obtained from Chen et al.[73] We also assess the sensitivity of brick production and technology market share between the largest brick-producing countries, India, Pakistan, Bangladesh, and Nepal, and how these shares influence the global emissions factor (Supplementary Data 3).

2.3. Business-as-Usual Projections for the 2050 FCB Demand: Mass and GHG Emissions. We pair the outputs of the models in sections 2.1 and 2.2 to estimate the increase in demand for FCB in the period 2020−2050 as well as the resulting GHG emissions if no decarbonization efforts take place (i.e., the "business-as-usual" scenario). As the baseline for global brick production in 2020, we use the arithmetic mean of the three values estimated based on reported literature data, brick intensity per floor area, and clay extraction data. Because we cannot perform projections of secondary source values or mining statistics, our projections of the demand between 2020 and 2050 are based on building stock dynamics, and we extract future floor area values from Dean et al.,[2] Güneralp et al.,[58] and Deetman et al.[59] As was done in eq 1, we scaled the floor area by FCB material intensity. Due to a lack of data on how FCB material intensity may change per unit floor area, we consider the material intensity to remain unchanged and growth in demand to be solely a function of increased floor area. GHG emissions were then determined by assuming a constant emissions factor for FCB, calculated based on regional market shares of FCB technology and each region's share of global FCB production. Each region-specific market share of production technology is presented in Figure 2a, and the average emissions factor for each production technology is presented in Figure 2b. As a baseline business-as-usual scenario, we model the technology and energy resources, and hence the GHG emissions, as remaining the same between 2020 and 2050.

2.4. Decarbonization Scenarios until 2050 for FCB Production. Noting that there are several decarbonization pathways that are possible for brick production, here we consider three key routes to mitigate emissions from this industry. The first, "Retro", is a low-tech, low-capital investment scenario in which existing kilns are retrofitted with energy-efficient interventions, as is commonly investigated for industrial manufacture in the literature.[77,78] This scenario considers three means of kiln retrofit, namely, (a) adapting the Zigzag technology in Fixed Chimney kilns (a retrofit option which requires low investment, as it can be integrated with already used production processes),[9,30] (b) replacing 50% of Clamp kilns with Zigzag kilns, and (c) improving the energy efficiency of Tunnel kilns. Each of these measures would result in higher energy efficiency (i.e., use of flue gases to preheat bricks and improved insulation), thus lowering GHG emissions. We model Retro intervention (1) by replacing the average emissions factor for Fixed Chimney kilns (responsible for nearly 72% of the total market share in the countries considered herein) with the emissions factor of the best-practice Zigzag technology. Likewise, (2) we assume that 50% of Clamp kilns can be replaced by best-practice Zigzag kilns. In this assessment, "best practice" is assumed to result in an emissions factor in the lower 25th percentile (i.e., the energy efficiency is improved to the extent that the emissions factor is lower than 75% of the Zigzag kilns), as opposed to the average emissions factor (see Figure 2b). Similarly, we model Retro intervention (3) by replacing the average emissions factor Tunnel kiln technologies with the lower 25th percentile emissions factor.

The second scenario, "Tech", is based on a high capital investment assumption that all FCB produced with Fixed Chimney and Clamp kiln technologies would shift to VSBKs and Hybrid Hoffman kilns (50/50 share of the Fixed Chimney and Clamp kiln market share). This shift could reflect a best-practice alternative, as these are reported to be the most efficient kilns being used at this large scale. To model this shift, we replace the emissions factor for the market share of Fixed Chimney and Clamp kilns (72% and 19% of FCB production, respectively) with the emissions factor for the "best-practice" (i.e., lower 25th percentile emissions) VSBK and Hybrid Hoffman. This scenario also considers the same improvement in energy efficiency for the Tunnel kilns as in the Retro scenario.

The third scenario, "Sub", assumes that 50% of the demand for FCB could be met by substitution with other materials such as low-carbon hollow concrete blocks (HCBs), assuming the same material performance, with the remaining 50% of FCB production following the Retro scenario. To assess reductions in emissions from material replacement, we decoupled material demand projections from the energy-related emissions from FCB production. The standard size for an FCB is 240 × 115 × 55 mm, while that of an HCB is 390 × 190 × 190 mm; so, we define a comparable unit of a m^3 of wall for which ∼1800 kg of FCB or ∼1100 kg of HCB would be required.[44] Although the bulk density of lightweight concrete typically used in blocks is 1800 kg/m^3, the gross density of the block is as low as 1100 kg/m^3 due to the void:solids ratio typical of the material. A typical mix for a concrete block contains 200 kg of cement, 130 kg of water, and 1850 kg of aggregates mostly less than 2 mm.[79] Given that the average GHG emissions per kilogram for limestone calcined clay cement (LC3) is 0.5 kg CO_2e (assuming it is 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum) and that for water and aggregates is 0.0001 and 0.01 kg CO_2e, respectively,[80] the GHG per m^3 of a wall would be approximately 73 kg CO_2e as opposed to the 220 kg CO_2e baseline for FCB. Therefore, we model the 50% replacement of materials as leading to a 67% reduction in the emissions factor for 50% of brick demand. In this scenario, the remaining quantity of nonreplaced brick is also modeled by implementing the Retro methods. We note that many other common strategies for decarbonizing industrial materials production, such as switching to less GHG emissions intense fuels, are outside the scope of this work but may be necessary to reach net-zero emissions from FCB production. The decarbonization scenarios presented herein are assumed to be implemented linearly between 2020 and 2050, with full implementation by 2050, and the resulting emissions factors in 2050 for each scenario are presented in Figure 6.

3. RESULTS AND DISCUSSION

3.1. Global Demand for FCB in 2020. The estimates for the global production of FCB using the three methods described in section 2.1 are presented in Table 1. The first approach, in which we sum the country-specific mass of bricks reported by secondary sources, resulted in an estimate of 2.02 Gt of FCB demand per year. Using dynamic building stock models and materials intensity data to calculate the global FCB production yielded an almost identical value (2.16 Gt of FCB/year). However, it is important to highlight that while the sums are similar, regional values do not consistently correspond between the literature and the building stock-based models. This inconsistency arises due to the higher values expected in

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the floor area increase in India and Latin America compared to China, which reduces the estimate for China from 1.5 Gt/year (around 70% of the total) to only 0.19 Gt/year (around 10% of the total). Additionally, there is inherent data uncertainty due to the variance in the building stock inputs (around 30%). Although this uncertainty makes the model less accurate for current volume estimates, the ability to use building stock dynamics to predict the production volumes in the future, depending on the floor area increase, is advantageous. Estimating FCB production based on clay extraction data from the UN database[68] again resulted in a similar value, 2.35 Gt of FCB/year (15% greater than the values summed from the literature). This method of estimating brick production resulted in proportional global market shares of FCB production as those reported in the literature, suggesting that this may be a reasonable proxy for global FCB production estimates going forward. Further, these findings show that regardless of the model used, a few key politically and culturally diverse countries in what has sometimes been referred to as "the Global South" are the dominant producers of FCB (95%). To present unified results, hereafter we present findings based on the average value of the three brick production estimation methods presented in Table 1, namely, 2.18 Gt of FCB in 2020.

3.2. Global Emissions from FCB Production in 2020. Quantifying GHG emissions from FCB production using region-specific differences in kiln technology results in average GHG emissions factors of 0.18−0.24 kg CO_2e/kg FCB, accounting for the different ratios of the kiln technologies in use, as shown in detail in the Supplementary Data. The calculated weighted average GHG intensity based on the global production market share is 0.24 kg CO_2e/kg FCB, where the upper limit average value is a result of India and Pakistan having both the highest FCB production and emissions factors. The calculated value matches the cradle-to-gate average value for GHG emissions per unit mass of FCB production reported by the University of Bath's Inventory of Carbon and Energy (ICE),[76] namely, 0.22 kg CO_2e/kg FCB (0.165 kg CO_2e/kg from the production process, assuming 75% of the total is process emissions). However, a recent UN Environment Programme report cites 0.24 and 0.34 kg CO_2e/kg FCB as the minimum values for natural gas and oil-fired kilns, respectively.[81] Further, references such as Huang et al.,[64] Ncube et al.,[25] and Eil et al.[11] reported the following region-specific values: 0.25, 0.86, and 0.52 kg CO_2e/kg FCB for China, Africa, and India, respectively. To reflect these factors, we model the emissions by multiplying the specific energy demand per unit mass (MJ/kg) of each technology (which is shown in Table 2, compiling data from the literature) by the average GHG intensity for energy use (0.101, 0.072, and 0.056 kg CO_2e/MJ for coal, oil, and natural gas, respectively).[82] The global average value for energy use per unit mass of FCB production was back calculated using the same method, resulting in an estimate of 2.22 MJ/kg FCB. Using this output, the carbon intensity was determined as 0.22, 0.16, and 0.12 kg CO_2e/kg FCB for coal, oil, and natural gas, respectively. The reason behind the lower estimate in the energy-sourced emissions modeled could be attributed to the scarcity and high variability in the secondary data for energy intensity of FCB production.

A sensitivity analysis is also performed to examine the robustness of results with different modeling inputs. In this sensitivity analysis, China's approximately 67% share of global FCB production is included in the weighted global emissions factor, with 90% of the Chinese market share being Hoffman kilns. Based on the work by Chen et al.,[73] the Hoffman kiln emissions factor is estimated as 0.58 kg CO_2e/kg FCB just based on fugitive emissions. Including China's market share of global brick production, the estimated global emissions factor is 0.53 kg CO_2e/kg FCB as opposed to the 0.24 kg CO_2e/kg FCB that was estimated when China is excluded. However, other sources have reported a notably lower emissions factor for the Hoffman kilns (however, not China-specific), 0.09−0.10 kg CO_2e/kg FCB, which in turn results in a global emissions factor of 0.13 kg CO_2e/kg FCB. When comparing with the values calculated based on energy consumption, the emissions factor ranges from 0.10 to 0.18 kg CO_2e/kg FCB depending on the fuel source (coal, oil, or natural gas). This notable difference highlights the need for reliable data from Chinese FCB production. Consequently, the effect of FCB production in China on emissions per kilogram of FCB is excluded from the primary results discussion herein; although, we do still consider the estimated mass of bricks produced in China when emissions are scaled to global levels. Further, in this sensitivity analysis, we assess the influence of using the lowest and highest reported values for the FCK, Clamp, Zigzag, VSBK, and Tunnel kilns. Varying these parameters results in an estimated range of 0.18−0.27 kg CO_2e/kg FCB globally, excluding China.

Using an annual global FCB production volume estimate of 2.18 Gt from averaging across methods, the associated GHG emissions would be equal to 0.51 Gt CO_2e/year (0.40−60 Gt CO_2e/year, using the lowest and highest estimated emissions factors), based on the weighted average emissions factor calculated in section 3.2. Given that the global anthropogenic GHG emissions in 2020 were approximately 50 Gt CO_2e,[83] the share of those GHG emissions from FCB production can be estimated as ∼1%. As shown in Figure 3, the degree of production in each region leads to commensurate GHG emissions. Depending on local resources and needs, the influence of social and economic sustainability indicators on decarbonization strategies may vary. Compared to the mounting efforts to decarbonize industries such as cement and steel by 2050, the limited attention to decarbonizing the FCB production industry highlights a key area where more effort is needed. The annual mass of cement and steel produced are 4.1 and 1.3 Gt, respectively,[84,85] resulting in approximately 1.6 Gt and 2.6 Gt of CO_2 emissions each.[86,87] The production of FCB contributes to CO_2 emissions on a

Table 2. Energy Intensity of FCB Production Technologies: The Energy Intensity (MJ) per Kilogram of FCB for Each Studied Production Technology Used to Calculate the Average GHG per Kilogram of Brick for Each Technology[11,14,18]

	EE intensity of fired clay bricks (MJ/kg)					
ref	Fixed Chimney kiln	Clamp kiln	Zigzag	Hybrid Hoffman	VSBK	Tunnel
Rajarathnam 2014	1.25	1.48	0.95	-	0.85	-
Eil 2020	-	-	1.30	1.20	-	-
Maithel and Heierli 2008	1.50	4.50	-	-	1	2.50
average:	1.4	3.0	1.1	1.2	0.9	2.5

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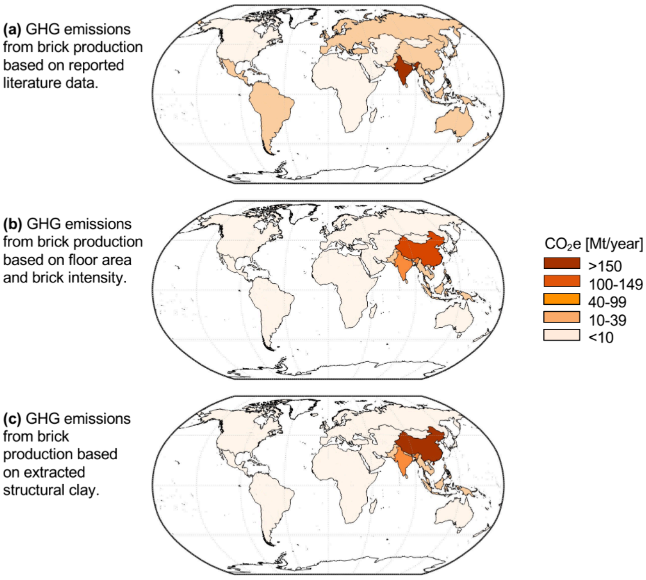

Figure 3. Greenhouse gas (GHG) emissions from global brick production in 2020 estimated based on (a) brick production reported in the literature, (b) floor area increase (Bm^2/year) and brick intensity (kg brick/m^2), and (c) brick production based on fraction of extracted structural clay.

comparable scale to these other major material industries (Figure 4).

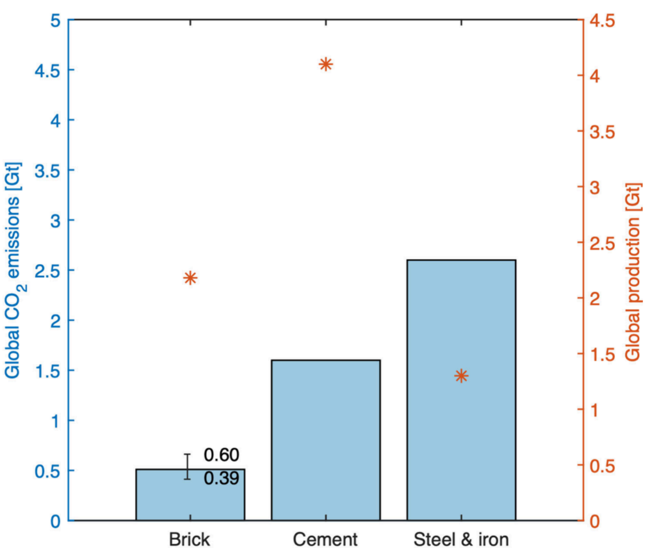

Figure 4. Estimated global production and GHG emissions from FCB, cement, and steel. The left axis shows the global GHG emissions associated with the production of brick, cement, and steel, reflected as bars. The right axis shows the global production of these materials, shown as "*".

3.3. Projections and Decarbonization Strategies for FCB Production until 2050. From a combination of the material intensity and building stock model developed in section 2, the amount of FCB produced is projected to increase by over 50% by 2050, reaching between 2.92 and 3.78 Gt annually (see Figure 5). Without improvements to production methods (i.e., the business-as-usual production), the resulting GHG emissions would be ∼0.68−0.89 Gt CO_2e. Considering the targeted reduction in global GHG emissions to 20 Gt CO_2e in 2050 following a moderate decarbonization scenario of SSP 2-4.5,[88] the global share of GHG emissions from FCB production could increase to 4.5% if no action (i.e., a business-as-usual scenario) is taken. As such, FCB production should be a key target to consider in decarbonization strategies.

Each of the improvement strategies considered in this work yields reductions in emissions. The Retro scenario, in which Fixed Chimney kilns are retrofitted to be Zigzag kilns and the energy efficiency of Tunnel kilns is improved to reflect the best practice (i.e., 25% percentile), results in a 27% reduction in the global emissions factor. Because Tunnel kilns represent <1% of all kilns, the reduction is almost entirely a result of a transition from Fixed Chimney kilns to the Zigzag technology. In the Tech scenario, in addition to having more efficient Tunnel kilns, it is considered that all FCB produced with the Fixed Chimney and Clamp kiln technologies would be replaced by best-practice VSBKs and Hoffman (each increase from <1% to approximately 45% of total FCB production). This scenario results in a 49% reduction in GHG emissions, as illustrated in Figure 6. However, this Tech scenario, requires significant capital investment (as discussed below), compared to the Retro scenario. Such investment could lead to a more centralized high-cost mode of production of FCB, limiting access to FCB in rural parts of developing economies.

The Sub scenario, where 50% of the global market demand for bricks was assumed to be met by hollow concrete blocks instead of FCB, results in slightly greater reductions in GHG emissions of 51%. However, there are several potential challenges to the realization of this scenario, starting with the high capital cost (CAPEX) of concrete block factories. It is reported that a concrete block factory requires a CAPEX of $150k for a capacity of 6 million bricks/year, which is double that of a typical FCB Zigzag kiln ($75k),[85,86] yet only half that of the more modern VSBK and Hoffman FCB kilns ($300k).[85,86] Also, the selling market price for concrete blocks is currently slightly higher compared to FCBs, but this could be subject to change given fossil fuel price increase and potential carbon taxes.[89] The switch would also require a cultural change due to the difference in size and masonry technique between FCB and concrete blocks, which could affect construction practice. Further, the shift from FCB production to more centralized hollow concrete block production facilities could lead to longer transportation distances for blocks.

3.4. Discussion. With a substantial portion of future construction expected to take place in low- and middle-income countries, pathways to support necessary infrastructure buildup with limited environmental impacts are crucial. The three GHG mitigation scenarios outlined in this study aim to address current challenges and barriers to adopting sustainable practices in brick production. The Retro scenario offers the most practical and cost-effective solution for reducing emissions. The findings in this work shows that by upgrading from Fixed Chimney kilns to Zigzag kilns, which mainly involves reconfiguring the brick stacking pattern to optimize heat flow, significant emission reductions can be achieved with limited investment.[35] This option is particularly viable for small-scale kilns, which are predominantly used in rural areas and common in India as well as low- and middle-income countries.[90,91] Data collection efforts supported by the UN Development Programme have identified and localized highly polluting kilns across India, which has led to targeted financial

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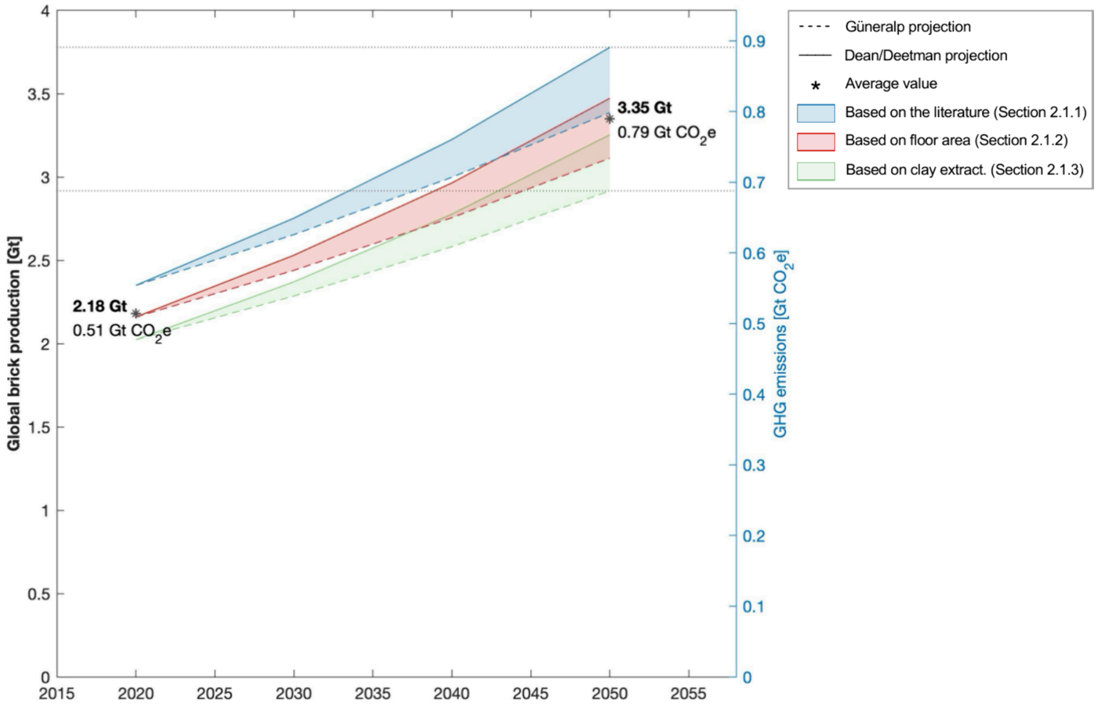

Figure 5. Scenarios for increase in global brick production between 2020 and 2050, showing global brick production demand and CO_2e from brick production in 2020 based on the brick estimation models from sections 2.1.1−2.1.3 and the estimated projected increase in global brick demand using projected floor area increases by refs 58, 59, and 2. Note: the Dean and Deetman models project the same floor area increase between 2020 and 2050 (17% per 10 years). Input data are presented in Supplementary Data 4.

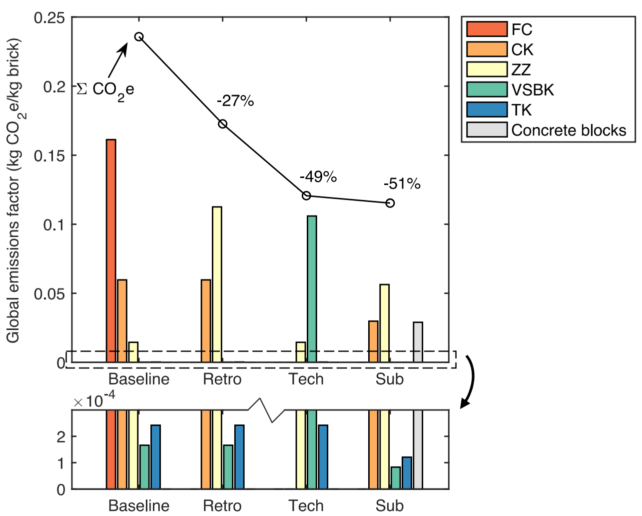

Figure 6. Global CO_2e emissions factor of FCB in 2050. Contribution per technology market share to the global emissions factor for four scenarios. The baseline scenario is compared to three scenarios for alternative technology market shares. Retro: 100% of Fixed Chimney kilns can be retrofitted to use the Zigzag technology; Tech: 100% of Clamp kilns and 100% of Fixed Chimney kilns can be replaced by highly efficient VSBK and Hoffman kilns and Tunnel kilns can be improved; and Sub: 50% of FCBs can be substituted by hollow concrete blocks, in addition to reductions achieved by the Retro scenario. Circles represent the total CO_2e emissions from global FCB production for each scenario in 2050. Input data are presented in Supplementary Data 5. FC = Fixed Chimney kiln, CK = Clamp kiln, ZZ = Zigzag kiln, HK = Hoffman kiln, VSBK = Vertical Shaft Brick kiln.

aid aimed at supporting sustainable transitions.[90] However, regulatory enforcement for energy-efficient practices remains a challenge, especially in rural areas, where small-scale operations dominate. Cultural and workforce barriers can further complicate the implementation. The brick industry in countries such as India employs over 12 million unskilled workers, many of whom rely on small-scale brick production.[91] Thus, any technological shift must carefully balance environmental goals with the need to protect these livelihoods through training and financial assistance to avoid disrupting local economies.

The Tech scenarios considered herein involve higher capital investment to replace traditional kilns like Fixed Chimney and Clamp kilns with more advanced options, such as VSBK and Hybrid Hoffman kilns. This scenario will likely rely heavily on government subsidies and policy interventions to offset costs. Nepal, for instance, has taken steps to modernize its brick industry by banning highly polluting kilns like the Bull's Trench kiln and promoting Zigzag and VSBK technologies.[92] Despite the successful adoption of Zigzag kilns, the transition to VSBK has been slow, primarily due to financial barriers. Similar changes have taken place in Bangladesh, where brick production is moving away from the highly polluting Bull's Trench kilns toward VSBK and Hybrid Hoffman kilns.[91] Larger operations in India are currently mostly using the Fixed Chimney kiln and to some extent the VSBKs.[91] Hence, a technology transition could be made without impeding the local rural brick production. Ultimately, more research is required to assess the regional feasibility of decarbonization strategies, as each country faces unique challenges when adopting energy-efficient technologies. Such effort was taken to assess the feasibility of brick production modernization in Nepal.[92] With increased availability and accuracy of region-specific data, policymakers can design financial incentives and regulatory frameworks that support effective and just transitions to lower emitting alternatives.

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Substituting part of the market with concrete blocks (such as was presented in the Sub scenario), while theoretically possible, could require several shifts in production and consumption. Use of cement-based materials for block production would demand investment in new infrastructure and the development of appropriate raw material supply chains. This shift would also necessitate substantial government support (e.g., through code development, procurement policies, and incentives), workforce training (in both production and construction), and financial backing to ensure a smooth transition. Additionally, it could shift architectural or design styles, which may have both engineering and cultural implications. Such an implementation is likely possible in urban areas with more established value chains. Thus, assuming a 50% implementation was performed in this analysis to reflect potential challenges related to scaling this production technology, particularly in rural areas.

Excluding China from global emissions assessments poses a significant risk of skewing results, as China accounts for a significant amount of global FCB production. China predominantly uses modern, more energy-efficient Hoffman kilns,[9] but data on Chinese brick production remain limited, restricting its inclusion in this analysis. Environmental policy in China mainly targets concrete, steel, and timber, which make up most of the construction materials market.[93] Further research is needed to accurately assess the impact of Chinese kilns on global emissions and fully understand the potential benefits of more advanced kiln technologies. Herein, we also highlight the need for more robust data for regional brick production quantities, kiln energy efficiencies, and estimates for the future demand for bricks as construction material, including how market shares may shift between regions and between production technologies, as well as shifts to other construction materials.

This study presents key methodologies to estimate the global quantities of production of FCBs and the associated GHG emissions. FCBs are a popular material in several key countries, where most of the projected construction is expected to happen until 2050. The methodology presented here combines literature-based data and a proxy to the nationally reported clay extraction volumes which estimated 2.02−2.35 Gt of FCB production currently, and projections indicate that this demand will increase to between 2.92 and 3.78 Gt by 2050. Despite the uncertainties in the data used in the model, these projections indicate that FCB production would continue to contribute significantly to GHG emissions if the current carbon-intensive production methods continue to be used. The annual GHG emissions from this class of materials could rise from 0.51 Gt CO_2e currently to 0.89 Gt CO_2e. This rise in emissions is a concern, particularly as minimal attention is given to FCB in most industrial decarbonization roadmaps.

Three scenarios were developed to estimate the savings in GHGs of different decarbonization strategies based on the estimated production in 2050. The first shows that retrofitting Fixed Chimney kilns into the more energy-efficient Zigzag kilns would yield a 27% reduction in GHG emissions. The second assumes a high-investment global shift from conventional production techniques to modern VSBKs, leading to a potential reduction of 49%. Finally, a combination of the first scenario and a 50% global market shift to concrete hollow blocks shows the potential to reduce the carbon footprint of FCB production by 51%. In the future, a systematic analysis of potential decarbonization pathways, such as those performed for the cement- and steel-producing industries, should be extended to brick production.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c08994.

Calculations and collected data used in the modeling (XLSX)

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Notes

The authors declare no competing financial interest.

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