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Reconciliation of energy use disparities in brick production in India

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Energy conservation in brick production is crucial to achieving net-zero carbon emissions from the building sector, especially in countries with major expansions in the built environment. However, widely disparate energy consumption estimates impede benchmarking its importance relative to the steel and cement industries. Here we modelled Indian brick production and its regional energy consumption by combining a nationwide questionnaire survey on feedstock, process variables and practices with remote sensing data on kiln enumeration. We found a large underreporting in current official estimates of energy consumption, with actual energy consumption comparable to that in the steel and cement industries in the country. With a total estimated production of 233 ± 15 billion bricks per year, the brick industry consumes 990 ± 125 PJ yr^{-1} of energy, 35 ± 6 Mt yr^{-1} coal and 25 ± 6 Mt yr^{-1} biomass. The main drivers of energy consumption for brick production are the kiln technology, the production capacity and the fuel mix used. The results suggest that improving operating practices would be a first step in making brick production more energy efficient.

Reducing the embodied energy of buildings (that is, the energy consumed in the production of building materials such as steel, cement, aluminium and bricks) is critical to achieving net-zero emissions from the building sector[1,2], especially in developing countries such as India, where construction activity is expected to double by mid-century[3]. While energy conservation targets have been proposed for India's formal industries[4] (steel, cement and aluminium), there are no mandates to regulate energy consumption in the brick industry. According to India's latest Biennial Update Report (BUR)[5] submitted to the United Nations Framework Convention on Climate Change (UNFCCC), the brick industry accounts for a meagre share of the sector's energy consumption. However, substantial discrepancies exist in the estimated fuel consumption of the brick industry, with the BUR figures differing by a factor of 10–100 from those reported in official statistics[6] and expert studies[7–16] (Supplementary Table 1). This leads to uncertainties in the relative importance of the brick industry compared to other construction-related industries.

Several factors lead to such disagreements in energy consumption. First, incomplete recording by official sources. In practice, official statistics[6] rely on coal receipts to estimate industrial coal use. However,

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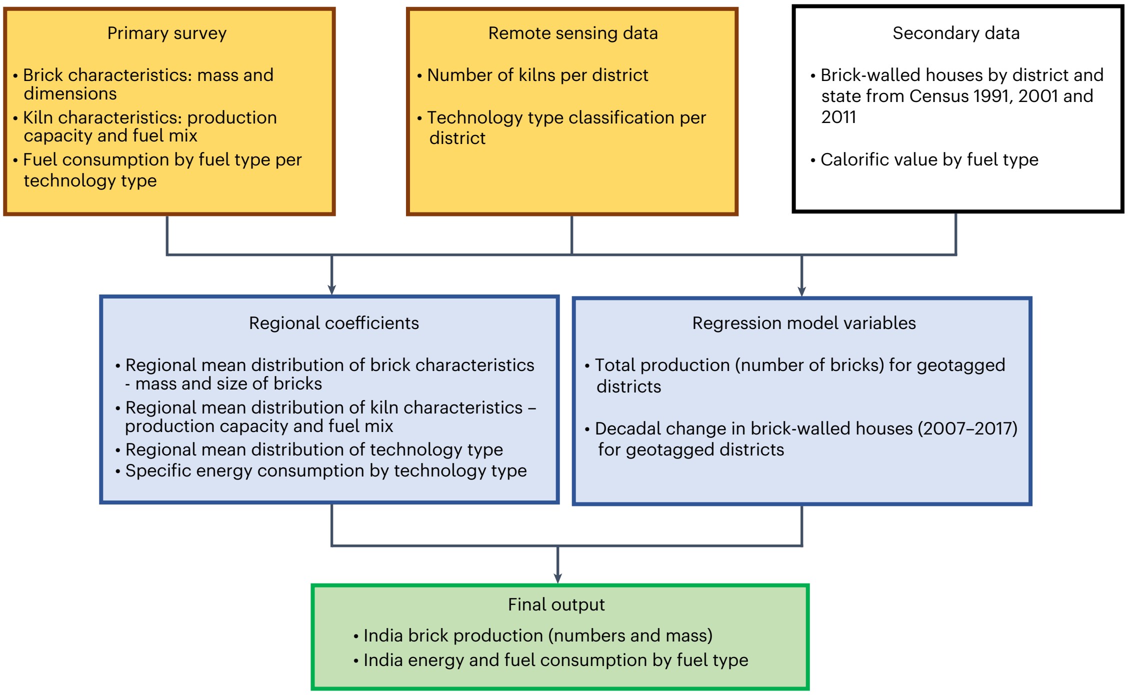

Fig. 1 | Schematic of the research design. Multiple data sources, combining primary survey remote sensing and secondary datasets, to estimate fuel consumption for fired-clay brick production in India.

unlike formal industries such as steel and cement, the brick industry in India is highly unorganized, with no complete record of the actual coal supply and consumption. In addition, the industry also relies on biomass fuels, which are sourced locally and are not captured in official records. Second, there is no official production data to correlate with reported coal consumption. Third, expert studies[7–16] lack methodological detail. Estimates are typically based on rough bottom-up calculations of activity and distribution of kiln technologies at the national level without considering regional differences in operating practices. Finally, despite consultation among brick manufacturers and independent groups of industry experts, an extreme paucity of datasets has impeded robust energy benchmarking for this industry. Therefore, this study aims to resolve the disparities in energy consumption in brick production through a transparent framework that includes sufficient information on raw materials, process variables, practices and kiln counts, with attention to regional diversity. As a result, this study contributes to improving future life-cycle assessments of Indian brick production by generating a new dataset of regional inputs for evaluating the embodied energy of fired-clay bricks.

Framework design

The analysis presented here is based on input from field surveys, remote sensing data and secondary data. Digitally recorded in-person surveys of over 500 kilns—a mix of Bull's trench kilns (BTKs), clamps and zigzag kilns—spread across 25 districts in 9 states (Supplementary Table 2) were analysed to determine the regional mean distribution of kilns by production capacity, type of fuel mix, brick characteristics (that is, mass and dimensions) and energy performance. The survey responses reveal notable differences in kiln characteristics across six broad regions of India: North, Indo-Gangetic Plain (IGP), North-East, East, Peninsula and West (Supplementary Tables 3–6). Three data sources were used to determine kiln density (number of kilns per district): manual scanning of high-resolution satellite imagery of major brick-producing districts in India (Supplementary Fig 2), Right to Information (RTI) petitions registered with state pollution control boards and information available on government websites. These were used to compile a list of over 150 districts and the number of kilns in each (hereafter 'enumerated districts'). The richness of the data is reflected in the complementary interactions between the different data sources (Fig. 1). The remotely enumerated districts and the decadal changes in brick-walled houses derived from the census data were used to develop a model for estimating brick production at the state level. Regional mean coefficients (corresponding to each state, Supplementary Table 3) from field surveys were used to disaggregate production by key operational characteristics for each state. Finally, they were combined with the corresponding energy performance metric to obtain total and subnational energy consumption by kiln technology and fuel mix.

This study presents a framework integrating field surveys and remote sensing to estimate brick production and energy consumption. Field surveys allow a better understanding of the diversity in regional practices, while remote sensing allows better enumeration of kilns and associated total activity. This work adopted a national scale of field surveys and remote sensing beyond the typical cluster-level approach[11,13]. The wide distribution of survey sites in this study, going beyond existing information[11], is useful for investigating regional variations in production capacity, fuel mix, and brick mass and dimensions. It offers new insights into additional factors influencing the energy performance of a kiln. Furthermore, the application of remote sensing to the Indian brick sector in existing studies[17,18] typically focuses on a single technology (that is, BTKs) or region (that is, IGP) and is limited to addressing labour issues and air pollution hotspots. However, this work uses remote sensing to enumerate brick kilns and estimate production at the subnational level, providing new information on sectoral activity by state and technology. Together, these allow benchmarking of overall production and energy use in the Indian brick industry, as well as analysis of subnational practices to inform the decoupling of brick production and energy use.

Overall, this framework attempts to leverage the strengths of field surveys and remote sensing in tandem while recognizing their independent limitations. Recent advances in remote sensing

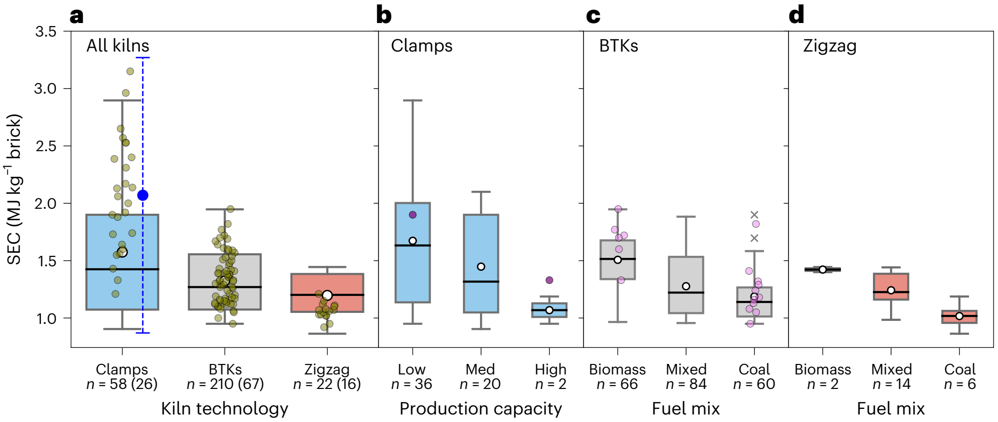

Fig. 2 | Energy performance of dominant kiln technologies in India. a–d, The range of SEC (MJ kg^{-1} brick) for dominant kiln technologies in India: clamps (blue), BTKs (grey) and zigzag (pink) for all kilns surveyed (**a**), clamps distributed by their production capacity (low, med, high) (**b**), BTKs (**c**) and zigzag (**d**) kilns distributed by fuel mix. Boxplots represent the energy consumption from the use of external fuels: box, 25th (Q1) and 75th (Q3) quartiles; whiskers, minimum (Q1 − 1.5(Q3−Q1)) and maximum (Q3 + 1.5(Q3−Q1)); white dot, sample mean; black line, median; 'x', outliers. The clamps surveyed in this study also used internal fuels (see Supplementary Information). The total mean SEC for clamps after accounting for internal fuels is represented by the blue dot and the range is represented by the dashed blue line. Estimates from previously reported studies are shown as scattered dots (in olive). See Supplementary Table 24 for the complete list of studies. '*n*' represents the total number of kilns included in the range from this study (without brackets) and from previous studies (with brackets). Purple dots in **b** denote values from ref. 23 and pink dots in **c** denote values from ref. 14.

techniques have enabled experts to estimate the amount and location of activity over a large region, bypassing the impractical logistical demands of field-based surveys. However, remote sensing cannot capture underlying operational practices, which require carefully designed field surveys that capture regional differences in kiln production capacity, operating hours and fuels used, among other variables. While the framework is illustrated for the Indian brick sector, it could be adapted to similar data-deprived informal sectors across developing countries.

Results

Energy performance of brick kilns

The energy performance of kilns is expressed as the energy consumed (megajoules, MJ) per unit mass of total fired bricks (kilograms, kg), referred to as specific energy consumption (SEC, MJ kg^{-1} brick). This study uses reported information on production numbers, weight of bricks and fuel quantities collected during field surveys to estimate the range of SEC (see Methods). Compared to existing reports (Supplementary Table 24), this study includes a larger number of datasets and greater regional coverage.

Energy performance is primarily a function of kiln technology. In India (as in other Southeast Asian countries), traditional technologies such as BTKs and clamps are dominant[8,19,20], with conservative shares of advanced versions such as zigzag and vertical-shaft brick kilns (VSBKs). Details of the operation of different kiln technologies have been published previously[21]. Briefly, BTKs are a type of continuous kiln in which the bricks are warmed, fired and cooled simultaneously in different parts of an oval circuit around a chimney by the air flowing through the stacked bricks. In contrast, clamps are a type of intermittent kiln in which bricks and fuels are stacked in layers and then fired. The bricks are allowed to cool, emptied and restacked after each fire. Zigzag kilns are an advanced version of BTKs in which the air flows in a zigzag path to improve heat transfer from the hot air to the bricks. Focusing on the three dominant technologies in India, analysis of the survey data showed that the SEC varies by a factor of two across kiln technologies, with clamps having the highest SEC, followed by BTKs and zigzag kilns (Fig. 2a and Supplementary Table 8). BTKs and clamps can reduce their fuel consumption by 10% and 40%, respectively, by shifting to zigzag technology. This reinforces the current governmental push towards zigzag kilns[22]. The SEC range from this study agrees well with those previously reported (Fig. 2a and Supplementary Table 24).

The variability in the SEC can be attributed to several factors, including the diversity of operating practices and feedstocks. The influence of fuel mix and production capacity is discussed here. The evaluation of kiln technologies by fuel mix (Fig. 2c,d) showed that the energy performance of 100% biomass kilns among BTKs and zigzags is almost 1.3 times worse than those using 100% coal. One reason could be the higher moisture content of biomass fuels, which requires part of the combustion energy to drive out the moisture. In addition, for BTKs and zigzags, the improper feeding arrangement of loose biomass fuels (such as mustard stalks) leads to the burning of fuel before feeding, resulting in wasted energy. This is consistent with a previous study[14] that reported higher SEC for biomass-fired kilns. Furthermore, sensitivity analysis (Supplementary Discussion Section 8) confirms that the variation in SEC holds across the range of calorific values of fuel types (Supplementary Fig. 4a). However, this pattern is not evident for clamps. For both BTKs and zigzags, the production capacity of the kiln does not affect the SEC. However, for clamps, the mean SEC decreases substantially, by up to 30%, as the production capacity increases (Fig. 2b). This is consistent with a previous measurement[23] that reported a lower SEC for large clamps. This suggests that the current practice of expressing SEC by kiln technology alone gives an inaccurate picture of energy consumption. Thus, both the adoption of advanced technology and subsequent operational practices are critical to ensuring energy reductions.

Given that both kiln technology and operating characteristics influence energy performance, accurate estimates of the magnitude of energy consumption require estimates of brick production at a 'subnational level', disaggregated by 'operating characteristics and technology'.

Brick production

There are no official statistics on the brick activity at either the national or regional level. Therefore, a model is developed to generate data on state-level production of fired-clay bricks parsed by kiln technology. The demand for brick production is largely driven by the residential housing sector, as almost 50% of all houses in India use fired-clay bricks[24]. Given the large volume of construction underway in response

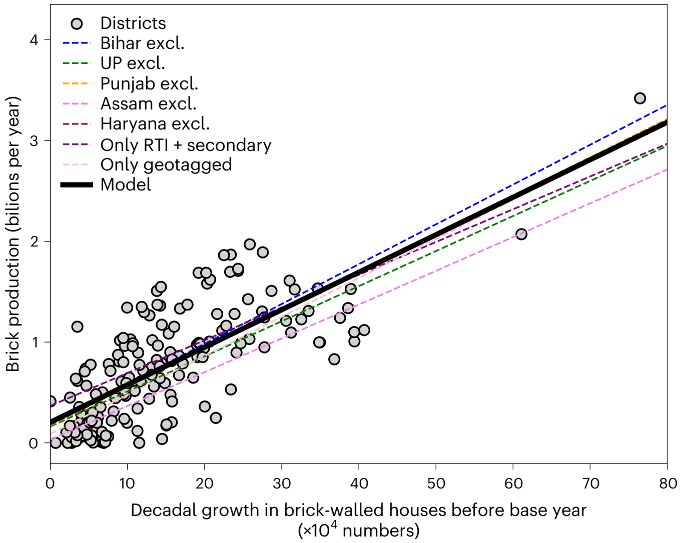

Fig. 3 | Regression model. Regression fit used to develop the brick-production model (black line), with decadal change in brick-walled houses as independent variable and brick production data as dependent variable for districts (grey dots). Additional fits excluding certain datapoints to check the stability of the model are also shown.

to the national housing programme[25,26], production of fired-clay bricks is expected to increase in line with demand. In the absence of adequate data on actual brick production, changes in the number of brick-walled houses serve as a good proxy for estimating expected brick production.

$$\mathrm{Prod} = 0.0037 \times \mathrm{Dec}_{\mathrm{BWH}} + 205.23 \qquad (1)$$

Districtwise production from the enumerated districts is regressed with a decadal change in brick-walled houses from the Census of India[24] to generalize brick production ('Prod') for any year as a function of the decadal change in the number of brick-walled houses before that year ('$\mathrm{Dec}_{\mathrm{BWH}}$') (equation 1). While various combinations of other available secondary data (such as built-up area and land use/cover) were explored, brick-walled houses proved to be the best fit (Fig. 3). Details of the regression inputs, statistics, robustness and validation of the model are provided in the Supplementary Discussion Sections. From the statewise changes in brick-walled houses between 2007 and 2017, the model estimated total brick production in 2017 to be 233 ± 15 billion bricks (Fig. 4a and Supplementary Table 22).

Regionality in brick activity

The following section discusses the regional diversity in brick production, kiln technology and certain operational practices that are essential for accurate energy consumption estimates.

Most of the production (~45%) is concentrated in the IGP region, followed by the peninsula (30%). States in the west and east are responsible for 10% and 8% of the production, respectively, while the contributions from the North and North-East are meagre (~5%) (Fig. 4a). This implies that the operational practices in the IGP and the Peninsula have the largest influence on national energy consumption. Further disaggregation of state-level production by kiln technology using the mean fractional share from the enumerated districts (see Methods) showed that BTKs (75–95%) dominate brick production in all regions except in the Peninsula (~13%), where clamps are the most popular technology (~73%) along with a sparse presence of down draught kilns (DDKs) and Hoffman kilns (Fig. 4a). The penetration of zigzag is notable only in the IGP and North regions (20–25%), with Bihar (~40%) and West Bengal (~30%) accounting for the largest shares. Overall, BTKs contribute 60% to the national production, followed by clamps (24%), zigzag (12%) and DDKs plus Hoffman kilns (4%) (Fig. 4a). Given that almost 90% of the kilns still rely on traditional technologies, the timely implementation of the latest national brick emission standards[22] (that is, a complete shift to advanced technologies such as zigzag and vertical-shaft brick kilns) seems quite ambitious.

Brick kilns are generally found in clusters in rural and peri-urban areas. Kilns within a cluster tend to have similar operating practices. However, there are differences at the regional level due to differences in technical expertise and socio-economic conditions. Descriptions of different categories of operational characteristics are presented in the Methods and Supplementary Discussion Section 4. Medium-capacity kilns dominate all regions and technology types. Low-capacity BTKs are present in the North and North-East regions, while high-capacity BTKs are found in the West and Peninsula regions (Fig. 4b and Supplementary Table 17). Low-capacity zigzag kilns are rare, but high-capacity zigzag kilns are spread across the North and the West. In terms of fuel mix (Fig. 4c, and Supplementary Tables 18 and 19), kilns using only coal are the most common type and are found in almost all regions. Kilns using 100% biomass are confined to the West and Peninsula regions. A large proportion of kilns use a mix of coal and biomass fuels. Of these, the coal-dominated kilns (with >50% share for coal) are found in the North, IGP and East regions, while the biomass-dominated kilns (with >50% share for biomass) are found mainly in the Peninsula region, with a few in the IGP and in the North. The choice of fuel mix also varies considerably from year to year, depending on fuel prices and availability. Characteristics such as the mass and dimensions of the bricks, which are also crucial in expressing the energy performance of a kiln, also show regional variations (Supplementary Tables 20 and 21).

Energy and fuel consumption by the brick industry

In contrast to existing estimates, this study combined relevant input parameters at the subnational level to estimate the energy and fuel consumption (see Methods). The total energy consumption for producing fired-clay bricks in India is estimated to be 990 ± 125 PJ yr^{-1} (Fig. 5). Energy consumption by state is given in Supplementary Table 23. BTKs (55%) have the highest energy consumption, followed by clamps (~35%) and zigzag kilns (10%). In terms of fuel mix (Fig. 5), coal is the most-used energy source (~68%), with a national consumption (as an external fuel) of 35 ± 6 Mt yr^{-1}. Biomass-based external fuels account for 24% of the total energy consumed. The use of crop residues is dominant in the North and IGP regions, while firewood is predominant in the Peninsula, West and East regions. Biomass as an internal fuel is estimated to contribute the remaining ~8%, with bagasse and rice husk as the dominant fuel sources. The total biomass consumption is estimated to be 25 ± 6 Mt yr^{-1}. Rubber tyres and oil are also used as fuel in a small number of kilns. Uncertainty is reported as ±1σ (standard deviation) and was obtained through a Monte-Carlo simulation of 10,000 iterations for a range of values of various input parameters (Supplementary Discussion Section 8 and Fig. 4b)

A comparison of production and energy consumption by state (state-specific SEC) shows that states with higher production have a lower energy ranking (Fig. 5). This highlights the potential for decoupling energy use from brick production through the identification of best practices, in addition to better technology. Statewise SECs vary by a factor of two: Peninsular states have the highest SEC (>1.6 MJ kg^{-1} brick), while states in the East and West regions report moderate SEC (1.3–1.6 MJ kg^{-1} brick). States in the North and IGP have the lowest SEC (<1.3 MJ kg^{-1} brick). Kiln technology and the choice of fuel mix strongly influence the overall performance of a state. The high SEC in the Peninsular states can be explained by the dominance of clamps. Although regions in the East and West have a higher proportion of fuel-efficient BTKs, the energy savings are offset by the presence of biomass-based kilns, resulting in moderate levels of SEC. Finally, the presence of zigzag kilns and coal-dominant fuels results in low levels of SEC in the North and IGP states.

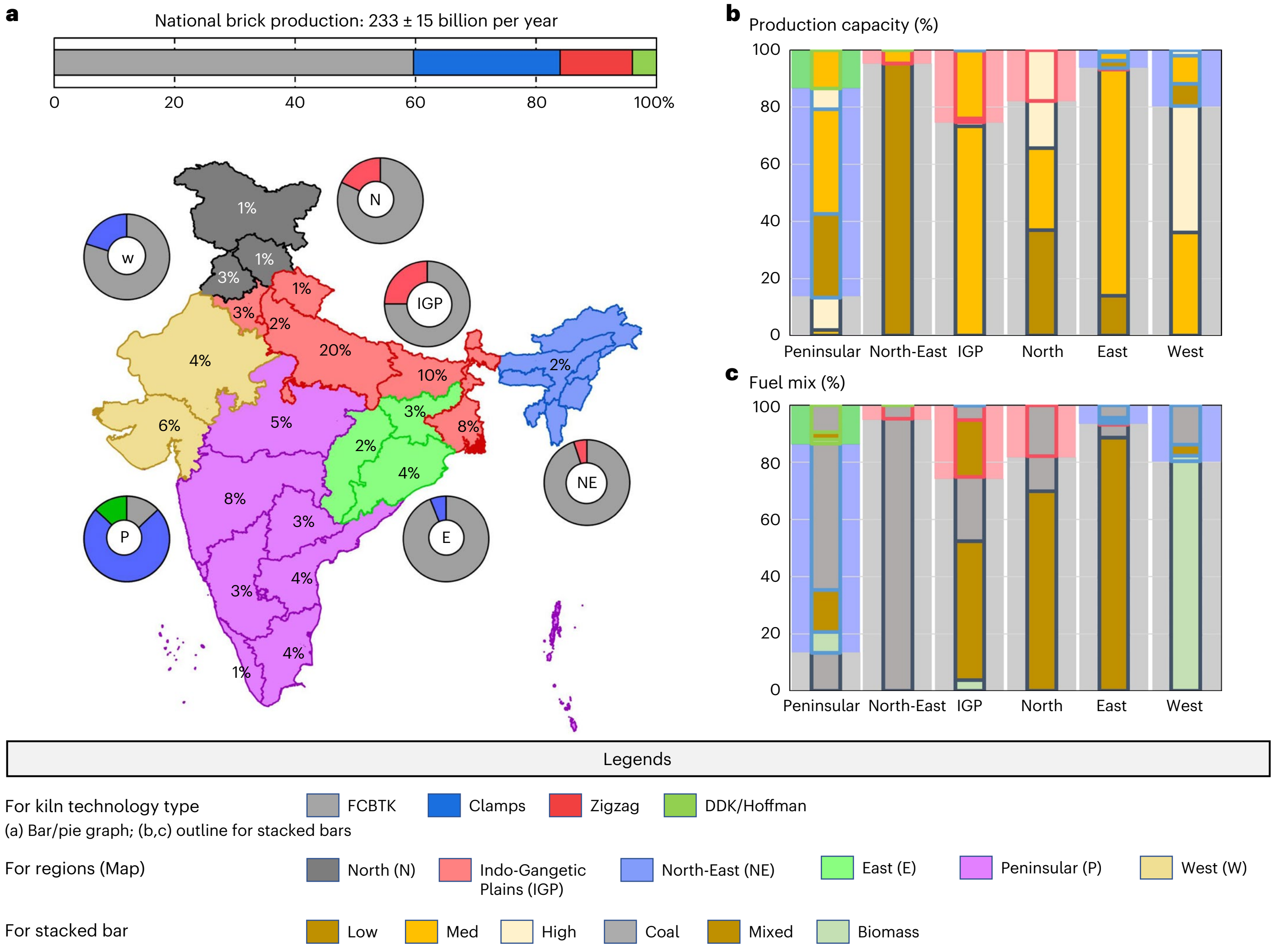

Fig. 4 | Regionality in brick activity. a, Contribution of technology type and state to national production, along with regionwise share of different kiln technologies. The horizontal colour bar represents the contribution from different brick-making technologies (BTKs, clamps, zigzag-fired kilns, DDK and Hoffman kilns). The spatial map shows the regional classification of the country and the statewise contribution to total national production. The pie charts around the map show the share of kiln technologies within individual regions. **b**, The share of kilns by production capacity (low, medium and high capacity). **c**, The share of kilns by fuel mix (100% coal, mixed and 100% biomass), arranged by kiln technology shaded in the background.

The subnational analysis presented here improves the accuracy of total energy consumption by considering regional differences in key operating practices. While coal consumption is in good agreement, biomass consumption estimates from this study are almost double those previously reported (Supplementary Table 1). Previous expert estimates used a single SEC value per kiln technology, which did not account for the higher SEC of biomass-fired kilns, resulting in a lower biomass consumption estimate. In addition, this analysis provides useful insights into the links between industrial activity and energy use at a regional level. Both of these are not readily apparent from a country-level analysis[11,13,15,27].

Discussion

Some limitations of this work are discussed below. The survey did not include physical measurements because of the behaviour bias of the manufacturers who feared government scrutiny or penalties related to emissions or resource extraction. However, response biases were minimized through consistency checks, use of local language interviewers for better communication and ensuring respondent anonymity. Further, the surveys revealed that the use of internal fuels is a growing practice. Also known as filler additives, these help to raise the kiln temperature, thereby reducing the use of external fuels and increasing the strength of the fired bricks. The most common types of internal fuel indicated in the surveys are agricultural waste and fly ash. Other examples of additives include waste from ores and industries[28–31]. However, the exact quantities were not recorded in the surveys. Therefore, the accounting of internal fuels is based on typical ranges reported in the literature (Supplementary Discusssion Section 5). Although internal fuels account for less than 10% of energy consumption, it is worth considering internal fuel use in future models to further improve the accuracy of energy consumption estimates.

Despite the limitations, this analysis provides key insights to improve the current understanding and enhance future sustainability assessments for this sector. First, this study confirms that energy consumption is underreported in official estimates from this sector and urges policymakers to introduce energy-saving measures. According to the framework presented here, the estimated coal consumption of the brick industry is about two orders of magnitude higher than that reported in the third BUR[5]. In addition, biomass fuels account for a substantial share of the unreported energy supply. With the revised estimate, the energy consumption of the brick sector (990 PJ yr^{-1}) is comparable to that of other formal construction sectors such as cement

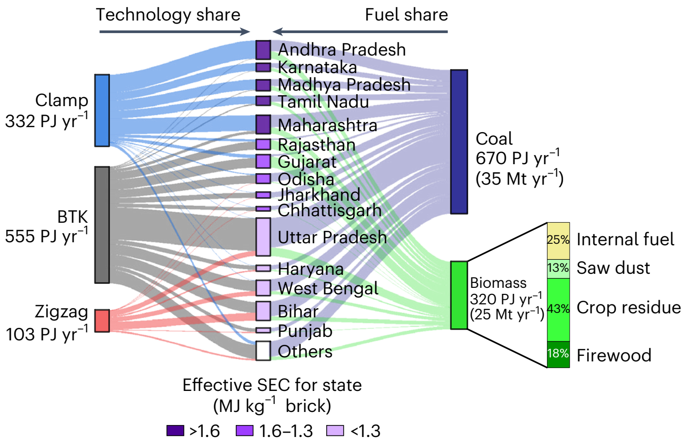

Fig. 5 | Energy and fuel consumption of the brick industry (2017). Total energy consumption for brick production in India for 2017, distributed by kiln technology and fuel type. Total amount of fuel consumed is indicated in brackets. States are arranged by effective specific energy consumption (ratio of total energy (MJ) to total production (kg) for each state). Influence of key drivers of the effective SEC, that is, share of kiln technology and fuel mix to total production in the state is also shown.

(~550 PJ yr^{-1}) and steel (~1,400 PJ yr^{-1})[5]. Moreover, given that the use of traditional, inefficient technologies can contribute to emissions of CO_2 and short-lived climate forcers such as black carbon[20,32,33], it is important not only to update the energy consumption and emissions levels of the brick sector in the communications to the UNFCCC but also to include the sector in the Indian climate agenda[33].

Second, the study makes a formal estimate of the uncertainty in the energy and fuel consumption of brick production and limits it to within 15%. This includes uncertainty in brick production from the regression model, regional distribution of kiln technology and SEC per kiln technology from surveys (Methods and Supplementary Discussion Section 8). For a given technology, the survey covered not only several kilns within a single region but also from several regions. This ensured that the variability in SEC per kiln technology accounted for variability in operational practices due to labour behaviour from kiln to kiln (for example, water removal from the ceramic paste after brick moulding, fuel feeding rate and so on) and geographical factors that vary from region to region (for example, clay type, humidity, wind speed and so on). In addition, the SEC accounted for variability in calorific values based on fuel type (Supplementary Table 7a,b). While methodological improvements involving further disaggregation of SECs by additional behavioural and geographical factors can be attempted in future studies to improve sustainability assessments, uncertainty can be reduced by improving the collection of official data on brick production and fuel consumption. This calls for a sectoral reform that ensures the registration of all brick kilns in operation through formalization under unified administrative oversight. This will also enable monitoring and tracking of the performance of this industry in the future.

Third, this work provides the largest field survey and remote sensing datasets on the Indian brick sector available so far. The survey dataset can be used to develop and disseminate standard operating protocols for sectorwide best practices. It can provide a strong foundation for any future initiative in the sector, particularly for the South Asian region[19]. Furthermore, expanding the scope of kiln enumeration requires a shift from manual geotagging to automated geotagging[18], for which the current set of geotagged data can be used to train image-processing algorithms. These results could provide regional-level inputs for (1) multicriteria decision tools[34] for better selection of sustainable alternatives, (2) life-cycle assessments[35] and embodied energy analysis[36,37] in the building sector, and (3) analysis of energy savings from waste recycling[28–31] and other innovative practices[38,39].

Finally, this study provides evidence for interim energy-saving strategies to decouple energy use and production. Current policies to reform the brick sector primarily endorse (1) a shift towards zigzag and vertical-shaft brick kilns, (2) the use of mixed feedstock with clay as well as new resources such as fly ash from coal-fired power plants and (3) the use of non-fired fly-ash bricks. The results of this study suggest that targeting improved operational practices rather than such large technological shifts, which may be hampered by the unavailability of capital or new resources, is more likely to yield positive results in the short term while setting the stage for large shifts in the future. In particular, shifts from biomass to coal-based fuels in the case of BTK and zigzag kilns, and from low-capacity to high-capacity clamps, through incentives to producer consortia can reduce up to a third of total energy consumption. These constitute vital steps toward improving the sustainability of the building sector.

Methods

Data collection

A pan-India field survey was planned wherein research scholars from various institutes visited brick kilns to collect information through a questionnaire-based survey. The objectives of the survey were primarily driven by the needs of the sectoral methodology to estimate the most representative fuel consumption for fired-brick production, which included gathering information on (1) the typical production capacity per state per kiln type, (2) the weight and dimensions of bricks and (3) fuel mixes used across different states. A systematic approach was adopted to finalize the districts for survey (Supplementary Table 2). In each district, around 20–25 kilns were visited randomly to capture a representative sample. A questionnaire was designed specifically to collect the necessary information for the methodology after consultation with experts from this sector (Supplementary Fig. 1). While the paper-based questionnaire was kept as a back-up, the preferred mode of survey was an android application. The application was designed and developed specifically for the field survey. The questionnaire was pre-loaded in the application for the interviewers to collect the response. The use of the application enabled real-time collection of data in digitized form within a centralized repository, which could then be readily used for subsequent analysis.

Besides the survey data, an effort was made to utilize satellite images to manually scan the area and locate brick kilns (geotagging) and identify their technology types. The aim was to enumerate the kilns within a district. The number of districts where there is ‘high probability’ of finding kilns was obtained on the basis of preliminary information from stakeholders, entrepreneurs, available literature and field surveys. The districts were then selected randomly and no district was preferred on the basis of any specific kiln parameter. Our aim was to cover as many states as possible to capture a nationally representative sample. The Google Earth Pro software was used for mapping because it is open source and has a user-friendly interface to map and organize the marked locations. In the exercise, the district area was scanned grid by grid and each kiln was manually tagged on the basis of certain visual cues. The characteristic shape of BTK is oval and that of zigzag is rectangular. Consultation with industrial experts and brick owners from surveys suggests that this is around 95% valid as a zigzag kiln requires zigzag-line firing, which can be achieved better with a rectangle shape. Both kiln types have a chimney at the centre. DDKs and Hoffman kilns look like a closed shed with a chimney at the centre or at one end of the structure. It was difficult to differentiate between them, hence they were grouped together. Clamps have rectangular shape with visible excavation marks and brick stacks for sun drying. See Supplementary Fig. 2 for the top view of kilns from the satellite images.

The central data collection system facilitated through the android application enabled easy compilation and processing of survey data. Since the survey responses relied mostly on verbal communication, it was prone to erroneous data entries. Thus, a meticulous quality check was carried out for each survey entry. Only responses that were found to have unrealistic values were discarded. This still yielded 210 BTK, 58 clamp and 22 zigzag samples. These are not only larger than all previous studies combined but also include greater regional coverage. For geotagging, several independent scans were repeated at random districts by multiple research scholars to validate for human error. Kiln operating conditions were also checked; common signs of a neglected kiln were dense vegetation cover over a kiln area, lack of soil preparatory activity around a kiln and absence of any major clusters around a kiln. Further, to prevent confusion with other industries, effort was made to scan the surrounding areas for signs of eroded soils, stacks of green bricks, muddy patches and lack of vegetation (also used in recent image-processing studies[18]).

Besides the data collected primarily as part of the project, additional sets of available secondary data were compiled as input to the framework. These comprise the list of districts with number of kilns from RTI petitions, governmental websites[40,41], a published report[42], and the number of brick-walled houses for 1991, 2001 and 2011 from Census of India[24].

Estimating regional coefficients

Regional coefficients are defined as the fraction of kilns in a region having a specific operational characteristic as previously elaborated. These were estimated to analyse the differences in operational characteristics across the country. The whole country was divided into six broad regions that are expected to have common characteristics within them: North, IGP, North-East, East, Peninsula and West, as the key characteristics influential to energy performance (production capacity, mass per brick and fuel mix) varied substantially across these regions (Supplementary Tables 4–6). The list of states grouped into these regions is presented in Supplementary Table 3. For each technology type, the survey responses were parsed by region. For each region, kilns were grouped by one characteristic at a time to estimate the regional distribution for that characteristic. The characteristics included: (1) production capacity, (2) fuel-mix type, (3) volume or size and (4) weight. The production-capacity category included low, medium and high. Based on official standards for BTKs/Zigzag, low-capacity kilns are those with production up to 15,000 bricks per day (~4.5 lakhs per month; 1 lakh = 0.1 million), medium-capacity kilns produce in the range of 15,000–30,000 bricks per day (~4.5–9 lakhs per month) and high-capacity kilns have production greater than 30,000 bricks per day (>9 lakhs per month). For clamps, there is no such standard. However, from expert consultation during surveys, clamps could be categorized as low-capacity kilns with up to 50,000 bricks per stack, medium-capacity kilns with production of 0.5–1 lakh bricks per stack and high-capacity kilns with production greater than 1 lakh per stack. Volumes included 23 × 10 × 7.5 cm (0.0017 m^3), 23 × 15 × 7.5 cm (0.0025 m^3), 25 × 13 × 7.5 cm (0.0023 m^3) and 18 × 7.5 × 7.5 cm (0.0010 m^3). Mass included 2, 3.5, 3 and 4 kg. Fuel mix included 100% coal, 100% biomass and mixed fuel (that is, mix of both coal and biomass, either coal-dominated (>50% coal) or biomass-dominated (>50% biomass)). A summary of the characteristics encountered is discussed in Supplementary Discussion Section 4. A mean picture of fractional shares to total production from the surveyed kilns for each of these characteristics was estimated for each region. For characteristics (1) and (4), the fractional shares were estimated as the production-weighted average of these groupings for each kiln technology–region combination from the survey, while for characteristics (2) and (3), the fractional shares were estimated as the production-weighted average by region. The summary of coefficients is presented in Supplementary Tables 17–21.

Estimating SEC

The energy performance of a kiln was expressed as the total energy consumed (MJ) per unit mass of brick (kg) produced, referred to as SEC (MJ kg^{-1} brick). Total SEC is the sum of input energy from 'external fuels' that are fed externally to the stacks of unfired bricks (external SEC) and 'internal fuels' that are mixed along with the soil during clay preparation (internal SEC). External SEC for each of the three technology types was calculated from the reported fuel quantities that are fed externally into the kilns and brick production from the survey responses (Supplementary Discussion Section 5). The mass of each fuel type was converted into energy units using mean calorific values (Supplementary Table 7). Brick kilns typically source their coal from the nearest coalfield, with northern and central India coal calorific content ranging between 4,000–5,000 kcal kg^{-1} (Supplementary Table 7a) and coal availability weighted mean calorific content being 4,362 kcal kg^{-1} (Supplementary Table 7a), leading to an assumption of coal calorific content of 4,500 kcal kg^{-1} (~19 MJ kg^{-1}) in this estimate. Calorific values of biomass fuels were based on measurements of samples collected during the surveys (Supplementary Table 7b). Calorific values of biomass fuels depend on the type of firewood and crop residue. Thus, we assumed the mean of calorific values from samples of popular biomass types used in kilns across regions. Internal fuels were found only in the Peninsular region, and were thus only accounted for in clamps (Supplementary Discussion Section 5). Estimates from this study were compared with those of previous studies (Supplementary Table 24)

Estimating brick production

Following the assumption that housing construction is the major driver of production, a univariate linear regression analysis was carried out, with district production as the dependent variable and the districtwise decadal change in brick-walled houses from 2007 and 2017 as the independent variable based on Census data.

- Dependent variable. The geotagging exercise enumerated kilns in 96 districts including all districts in Punjab and Assam, among others. The RTI petitions and publicly available information on state governmental websites and few independent studies provided the numbers for an additional 121 districts including all districts of Uttar Pradesh and Bihar, and nearly all for Haryana, among others (Supplementary Table 11). Using the mean production capacity per kiln from surveys, the total brick production in these districts was estimated. For districts that had data from overlapping sources, a comparison was made between the kilns enumerated by geotagging and those collected through RTI petitions and government websites (Supplementary Table 10). Overall, the RTI or officially reported values were on the lower side because RTI and government data account for only registered kilns, which constitute a fraction of the total operating kilns. Other issues with official reporting is probable inclusion of closed kilns, thereby reporting higher numbers of kiln than the geotagged estimate. Thus, for districts that had overlapping sources, geotagged data were preferred.
- Independent variable. Information on districtwise brick-walled houses is available for three years: 1991, 2001 and 2011 from the Census of India. Thus, to estimate the number of brick-walled houses for 2007 and 2017, an exponential curve was fitted across the data for these 3 yr for each district.

Regression statistics are presented in Supplementary Table 12. Other variables such as districtwise built-up area and land-use type from the Bhuvan satellite product were also tested but yielded very poor regression fit. Therefore, the model was based only on one independent variable. A series of steps were followed to make the model more robust (Supplementary Discussion Section 7). First, the standardized residuals were checked to remove outliers through an iterative process. Datapoints yielding standardized residuals greater than 2.5

were removed in each iteration. The iteration was stopped until removing the outliers did not make further notable impact on the regression statistics. Second, the residual plot was checked for random pattern (Supplementary Fig. 3). Finally, a regression was calculated for a series of different cases that excluded all districts from Bihar, Uttar Pradesh, Haryana, Assam or Punjab, or included only geotagged data, public portal data or RTI data (Supplementary Table 13). Moreover, the effectiveness of the model was validated by comparing the model output to a historical estimate (Supplementary Table 14).

The technology-distributed districtwise production from the geotagging was used to estimate the mean technology share for state and region. For each of the 19 states, there were at least 3 districts geotagged. Thus, for each state, a mean production was estimated under each technology type by averaging data for the districts. Using this, a mean fractional share per technology type was estimated as the ratio of mean production for a technology type to the total statewise mean production. Similarly, averaging the districts within a region was done to estimate the fractional share of technology type for the region. Finally, the statewise fractional share was used for states that were geotagged and the regional fractional share was used for states that were not geotagged (Supplementary Table 16). This fractional share was multiplied by the corresponding state-level production to obtain the production by technology type.

Estimating energy use

In our approach for calculating energy and fuel consumption, we began by estimating the state-level brick production ‘B_s’ (millions per yr) using the regression model. For each state, the production, B_s was apportioned into various kiln technologies ‘k’ using the kiln share ‘$t_{k,s}$’ (%) based on geotagging datasets. Further, for each kiln technology, the production was apportioned into specific characteristics ‘$c_{k,s}$’ (%) that influence their energy performance. For BTK and zigzag, production was split into three categories of fuel mix and for clamps, three categories of production capacity. The amount of brick produced was converted to mass of the bricks produced using the representative weight ‘w_s’ (kg) of one fired-clay brick in that state. Subsequently for each kiln technology–factor combination, the corresponding specific energy consumption ‘$\mathrm{SEC}_{c,k}$’ (MJ kg^{-1}) was used to estimate total energy. Energy use was converted to fuel consumption using the regional coefficient for fuel characteristics such as the fractional share of fuel mix ‘$\mathrm{FF}_{f,s}$’ (%) for fuel type ‘f’ in each state and calorific value ‘CV_f’ (MJ kg^{-1}).

$$F_{f,s} = \sum_{k,c} \frac{B_s \times t_{k,s} \times c_{k,s} \times w_s \times \mathrm{SEC}_{k,c} \times \mathrm{FF}_{f,s}}{\mathrm{CV}_f} \tag{2}$$

The production from DDK/Hoffman kilns was very low and it was difficult to separate DDK from Hoffman on the basis of satellite images. Thus, the production from these technologies was added to those for clamps for energy and fuel quantification. For BTKs and zigzag, the SEC varied by choice of fuel mix, while for clamps it varied by production capacity. Thus, the total production was distributed across the fuel-mix and production-capacity categories using regional coefficients from survey responses.

Uncertainty analysis

Uncertainties in SEC, brick production, energy and fuel consumption are reported as ±1σ (standard deviation). Uncertainties in brick production for each state were estimated on the basis of the uncertainties in coefficients from the regression model. The standard deviations for each state were added linearly to calculate the uncertainty for the national brick production, as the state-level values were obtained from common input and were not independent. For SEC, the uncertainty was estimated from survey responses as the mean and standard deviation of all samples per kiln technology. Further, a Monte-Carlo simulation of 10,000 iterations was performed to evaluate the influence of caloric values of different fuels on the SEC values and to compute the uncertainty in total energy and fuel consumption (Supplementary Discussion Section 8).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All input data used in this study are presented in Supplementary Information. Any additional data can be made available upon request to the corresponding author. Source data are provided with this paper.

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Author contributions

K.T., C.V. and H.P. conceptualized the study and formulated the methodology. V.J. and S.M. reviewed the methodology. K.T. curated the data, performed the analysis and wrote the original draft. C.V., H.P., V.J. and S.M. reviewed and edited the draft. K.T., C.V., H.P., V.J., S.M., A. Damle, A.G., P.L., S. Rabha, B.K.S., S. Roy, G.H., S. Rathi, A.G., S.A., T.K.M., M.A.H., A.Q., A. Dhandapani, J.I., S.D., R.S.R., Y.L., G.P., S.K.K., M.S.N., S. Mukherjee, A.C., T.A.N., A.J., J.S., B.S. contributed to field data collection, read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Software and code

Policy information about availability of computer code

Data collection	a) Field surveys:- Custom made android application to collect survey responses. b) Geotagging kilns:- Google Earth Pro for scanning satellite images over desired study areas.
Data analysis	Microsoft excel v2016

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Study description	The analysis presented here is based on inputs from field surveys, remote sensing data and secondary data. We analysed digitally recorded in-person surveys from over 500 brick kilns across India. to determine the regional variations in kiln operations. To arrive at the density of kilns (number per district), we used three data sources: manual scanning of high-resolution satellite imagery of major brick-producing districts in India using Google Earth Pro, Right to Information (RTI) petitions registered with state pollution control boards, and information available on government websites. On the basis of these, we developed a list of over 150 districts and the number of kilns present in each. Remotely enumerated districts together with decadal changes in brick-walled houses, derived from the census data, were used to develop a model to estimate brick production at the state level. Regional mean coefficients from field surveys were used to parse production by key operational characteristics, and they were combined with the corresponding energy performance metric to yield total and sub-national energy consumption by kiln technology and fuel-mix.
Research sample	Kilns manufacturing fired clay bricks
Sampling strategy	Sampling was done to select districts for field survey and geo-tagging. The brick survey aims to cover the regional differences in the production capacity, distribution of various kiln technologies and fuel mixes used across the nation. Following this, first step is to identify the states which cover i) maximum production ii) all prominent kiln technologies and iii) different fuel mixes. Three different lists of states are prepared fulfilling each criterion individually through different sources such as journal articles, government reports and websites. The final list is compiled by clubbing the states in the lists. This ensured that regions with higher probability of brick manufacturing as well diversity are selected to capture a nationally representative sample. The location of the survey is narrowed down from state-level by identifying three to four districts or regions from each identified state using the above resources, Google Maps and expert consultation. District selection was random. After preparing the list of districts, a ground truthing of existence of brick kilns is done through local investigation (presurvey visits and contacting the respective state pollution control board). Further, within a district 20-25 kilns were visited randomly. The brick entrepreneurs are contacted and their consent is obtained prior to survey. Brick industry is a very sensitive sector and many owners/manufacturers are reluctant to participate in such surveys. So it was only possible to visit kilns for which permissions was granted. However, it was ensured to cover as much different regions as possible. Regional variation was more important than quantity per region for the analysis presented here. In regard to geo-tagging, major brick producing regions were identified in consultation with experts from this industry. District were then selected randomly across the country.
Data collection	Survey data was collected using a custom made android application. Geotagging was done using Google Earth Pro.
Timing and spatial scale	The field visits were carried out in multiple phases during the brick making season from 2019 to March-2020 (before the pandemic). Geotagging was carried out by scanning satellite images for the same period. Both field survey and geotagging were spread across various locations in India.
Data exclusions	Data from field surveys were excluded when the responses seemed unrealistic and did not adhere to the consistency checks.
Reproducibility	*Describe the measures taken to verify the reproducibility of experimental findings. For each experiment, note whether any attempts to repeat the experiment failed OR state that all attempts to repeat the experiment were successful.*
Randomization	All kilns were selected in random. During analysis of survey responses, these were grouped into 6 regions which showed significant differences in key operational parameters based on the correlation test.

Blinding	Personal information of kiln owners are kept anonymous and not included in the analysis.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Field visits to various brick kilns were made to conduct questionnaire-based survey for collecting kiln information. The field-condtion such as temperature/rainfall etc. are not relevant to the analysis.
Location	The field visits were carried out at various locations across India (nearly 25 districts of India and around 10-25 kilns per district)
Access & import/export	Since brick industry in India is a very sensitive and unorganized sector, prior permissions from the local brick associations/groups/ communities were obtained.
Disturbance	*Describe any disturbance caused by the study and how it was minimized.*

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