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LETTER

Sustainable alternative futures for urban India: the resource, energy, and emissions implications of urban form scenarios

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Abstract

India's rapid urbanisation underscores the need to balance growing consumption patterns, development goals, and climate commitments. The scenarios presented in this paper were created using our Sustainable Alternative Futures for India (SAFARI) model, a system dynamics model that simulates interlinkages between sectors in India and their competition for resources and energy at the national scale. This study presents insights from scenarios based on SAFARI's housing and transport modules, as well as synergies and trade-offs with the industries, water, land, and agriculture modules. It focuses on urban form scenarios and their implications for energy, emissions, and resources. Using a vertically compact residential built form and less energy-intensive materials (such as aerated autoclaved concrete blocks), coupled with greater uptake of public transport and shorter trip lengths, was found to be most beneficial overall. This scenario could reduce residential land consumption by 85%, particulate emissions three-fold, embodied emissions of construction by 11%–13%, and total space cooling energy by 31%–46%, compared to the business as usual scenario. Overall, this scenario could offer a 9.1%–9.6% reduction in cumulative economy-wide greenhouse gas emissions between 2020 and 2050. An urban sprawl scenario (with longer trip lengths) could have the opposite effect, impinging on agricultural land and furthermore, exacerbating food security concerns by 2050. The paper concludes with future research directions, which include exploring the combined potential effects of urban heat islands, alternative materials, and compact urban form on space cooling energy in India.

1. Introduction

That shelter is a basic human need has been recognised globally for the better part of the 20th century, and recently in the United Nations' Sustainable Development Goals (SDGs) [1]. SDG 11 emphasises the importance of access to affordable urban housing, thermal comfort, and accessible transport in facilitating sustainable development by 2030. Ideally, apart from shelter, housing should provide thermal comfort and safety, as well as facilitate a decent quality of life.

India is on a path to rapid urbanisation, with an urban population that is likely to double by 2050 [2, 3]. This, in turn, will increase residential energy demand, especially from space cooling [4, 5], unless considerations around thermal comfort, built form, and urban green space (UGS) are included in the planning process. While there are national and subnational transit-oriented development (TOD) policies in place, thermal comfort is currently neither an explicit criterion in India's affordable housing (AH) policy [35], nor in the SDGs [7].

Urban areas are already responsible for a majority of global greenhouse gas (GHG) emissions [2]. For balancing India's development goals with its climate targets, various synergies and trade-offs will invariably need to be considered. SDG 13 calls for urgent climate action, something that the Paris Agreement and India's Nationally Determined Contribution to the United Nations Framework Convention on Climate

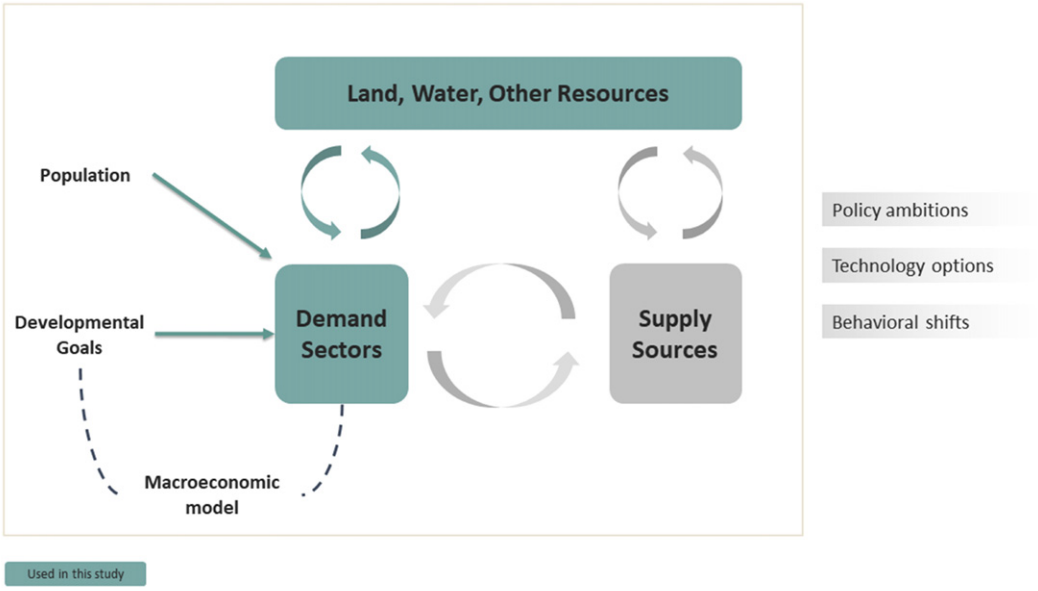

Figure 1. Overview of SAFARI model.

Change (UNFCCC) also emphasise. In view of India's development objectives and climate commitments, it is imperative to find development pathways that can minimise climate impacts while ensuring a basic quality of life for all citizens.

This study examines scenarios generated by an in-house system dynamics model, the Sustainable Alternative Futures for India (SAFARI) model (figure 1). SAFARI explores the implications of meeting India's development goals on materials, energy, resources, and emissions. Built using systems thinking principles, the SAFARI model captures the interlinkages and interdependencies within and between sectors. The interaction between the housing and transport sectors is crucial in determining the structure of a city and, subsequently, in the transition to a low-carbon economy [8, 9]. Densely populated cities typically report lower per capita energy demands for transport but may have an increased space cooling demand due to localised urban heat islands (UHIs) [10–12].

As a first step, in SAFARI, housing demand is estimated on the basis of recalibrated benchmarks corresponding to a reasonable quality of life. Several studies have attempted to explore the lifecycle emissions and energy implications of meeting India's housing shortage [13, 14] but invariably stop at providing a static shortage value. This study examines, for the first time, how an increased housing demand to meet a dynamically computed housing shortage (based on revised benchmarks for area, lifespan, and congestion) impacts energy consumption, emissions, and resource availability.

The building materials used for housing can potentially play a significant role in determining thermal comfort and can also affect the overall carbon footprint of the building. In an ideal scenario, such building materials should be used that can both reduce the overall carbon footprint and increase the thermal comfort of the household [15–17].

This study explores various urban form and building material scenarios to estimate the impact of bridging India's true urban housing shortage. Moreover, it examines the combined impacts of urban densification, open space, and transport policies (urban form scenarios) on energy demand (particularly space cooling), emissions, and land demand. Ultimately, this study aims to provide a first glimpse at the emerging synergies and trade-offs involved in facilitating low-carbon pathways to a good quality of life in urban India.

2. Methods

2.1. SAFARI model logic

The Sustainable Alternative Futures for India (SAFARI) model is essentially a goal-seeking model constrained by the availability of resources such as land, water, and other materials. It projects India's potential development pathways up to 2050 [18] and offers a user input-based simulation platform that allows 'what if?' scenarios to be explored.

Many long-term energy system models, as reviewed by McCollum *et al* [19], use GDP as the primary metric for development and welfare, and to drive sectoral demands. However, to understand demands arising out

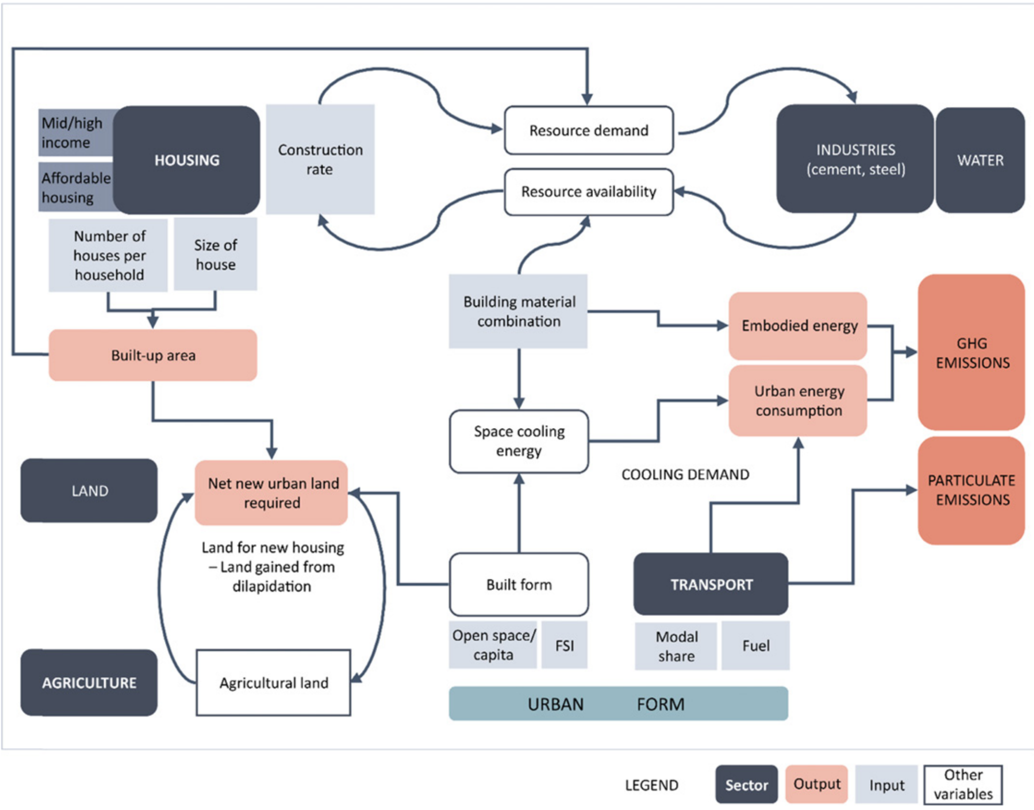

Figure 2. Conceptual model for this study.

of specific development goals and to explore demand-side interventions beyond energy efficiency, a bottom-up analysis of demand becomes important. While studies such as Rao *et al* [20]and Ru du can *et al* take this approach [5], dynamic interlinkages and interdependencies between sectors are rarely captured. For a developing country like India, modelling these interdependencies is important to be able to identify strategies to balance development objectives with climate action. Systems thinking has been shown to be effective in understanding the synergies and trade-offs between such different objectives especially in the context of the SDGs [21, 22]. In system dynamics models, system behaviour is driven dynamically and endogenously by its structure [23]. A system dynamics methodology allows for representation of the dynamic, non-linear interactions between different variables across time, especially in view of the inherently interconnected feedback loops [23] that are present between the modelled sectors. System dynamics models are also useful for conducting policy analysis and analysing decarbonisation pathways [24–26]. To this end, the SAFARI model adopts a systems thinking approach to model interdependencies between sectors and estimates demand in a bottom-up manner, using the modelling software Stella architect. In SAFARI, sectoral growth is primarily driven by development goals such as food and water security, housing for all, sufficient healthcare and education infrastructure, power for all, and access to clean cooking and transport. Sectoral growth is also driven by a computable general equilibrium model, which is soft-linked to SAFARI to ensure macro-economic consistency. The total demand then drives capacity expansion on the power supply side. Figure 1 shows an overview of the SAFARI model framework.

This paper focuses on the ‘housing for all’ goal in urban India, and its interlinkages with urban transport to understand the implications of sustainable urbanisation options. Data sources for the model include IndiaStat, the World Bank, UNdata, and Government of India official reports, and processed data from peer-reviewed literature (see supplementary section 1.3 (https://stacks.iop.org/ERIS/1/011004/mmedia)). We would like to thank the 2050 Pathways Platform of the European Climate Foundation (ECF), and Agence Français

2.2. Conceptual model

This study presents insights from interlinkages between the housing, transport, and land modules of the SAFARI model, as well as the impacts of the industries, agriculture, and water modules on housing, transport and land (figure 2).

2.3. Housing and industries

Based on annual housing construction rate inputs for both affordable and middle/higher income housing, SAFARI computes the resource demand (cement, steel, water) for meeting the total annual housing demand. The industries module consists of bottom-up demand-capacity-supply calculations for steel, cement, and fertilisers, and top-down growth rates for India's remaining major industries. Through its demand for resources, the housing module interacts with the cement and steel segments of the industries module. In turn, the industries module indicates resource availability, which determines the actual, possible construction rate. The industries module simultaneously endogenously ramps up cement and steel production to meet any excess demand that it does not yet have the capacity to produce. In a similar fashion, the water demand for construction derived from the intended housing construction rate interacts with SAFARI's water module, which provides feedback on the available water for construction.

For cement, steel, and water, the desired construction rate and actual construction rate are related as follows: Actual construction rate

$$\text{Actual construction rate} = \text{Min}\,(\text{Desired construction rate},\ \text{Possible construction rate})\,. \tag{1}$$

'Possible construction rate' is calculated as the number of houses that can be constructed taking into account cement, steel, and water constraints. Therefore, in SAFARI, it is the minimum of the number of houses that can be constructed due to each cement, steel, and water availability, as shown in equations (2) and (3).

Possible construction rate

$$\text{Possible construction rate} = \min\left(\frac{\text{cement availability}}{\text{cement required per house}}, \frac{\text{steel availability}}{\text{steel required per house}}, \frac{\text{water availability}}{\text{water required per house}}\right). \tag{2}$$

Cement availability for construction. The same relationship is used for steel and water availability.

$$\text{Cement availability} = \text{Min}\,(\text{Cement demanded},\ \text{Cement produced})\,. \tag{3}$$

Building materials combination (a user input) also impacts cement and steel demand, as different structural blocks require different quantities of cement and steel during production and construction (see materials section).

2.4. Housing and land

Another factor influencing resource demand is total built-up area, which is a function of the number of houses owned per household and the size of each house (both user inputs). Depending on the manner in which this built-up area is spread (built form), SAFARI computes the total land required for residential construction. The net new land required is the difference between the total land required for construction, and the land recycled from dilapidated housing (also computed in SAFARI).

2.5. Housing and agriculture

As the urban periphery expands, the net urban land required is taken away from agricultural land that could otherwise be cultivated (equation (5)). By 2050, this creates land-based pressures on food security.

2.6. Housing and transport

Floor space index (FSI) and open/green space per capita are user inputs. Variations of these produce different residential built forms. This study's urban form scenarios also combine different fuel efficiency measures and modal share changes (user inputs) from the transport sector. Together, residential built form and transport patterns produce the main urban form scenarios explored here. These scenarios have different outcomes in terms of space cooling demand (as a function of materials used in construction, built form, and open space per capita), net land used, residential and transport energy consumption, particulate emissions and GHG emissions.

2.7. Construction rate, land, and floor area

In SAFARI, N_c, also known as construction rate is a function of 'sanction rate', an exogenous variable that indicates how many houses are approved for and may commence construction in a particular year. It is also determined by cement, steel, and water availability, as described in equation (2). For the purposes of this study, two pathways have been examined—a BAU construction rate and a construction rate that allows housing shortage to be met by 2030, in line with the UN SDG targets. In SAFARI, the total floor area per year (A) is dependent on three exogenous variables: floor area per unit (a_h), common space per unit (p_c) (expressed as a fraction), and annual construction rate (N_c) (equation (4)).

Total annual floor area

$$A = a_h \times (1 + p_c) \times N_c. \quad (4)$$

SAFARI also estimates the aggregate net (new) urban land required to fulfil these construction targets. The 'stock' of total net land required, represented in equation (5) as L_n, is calculated using the total land area required for constructing new houses (L_c), total open space (L_o), and the land gained from demolition or from reconstructing old/dilapidated houses (L_d). The scenarios in this study consider two open space per capita options—these are based on the Government of India's recommendation [27] of 12 m^2/capita and the UN's recommendation of 30 m^2/capita [27], as shown in table 3. Equation (5) shows a simplified representation of the relationships between these variables in SAFARI:

Net land required

$$L_n = L_c + L_o - L_d. \quad (5)$$

The total land area required for constructing new houses, L_c is a function of total floor area per year (A), and average FSI. Here, FSI is approximated as the number of floors constructed [28], although in practice, local setback requirements and height restrictions may change this slightly.

Land for construction

$$L_c = \frac{A}{\mathrm{FSI}}. \quad (6)$$

Though FSI is a user input variable, there are three FSI scenarios demonstrated here—high density (average FSI = 8), sprawl (average FSI = 0.75), and business as usual (BAU) (FSI = 1.5).

2.8. Transport

The methodology for calculating the urban transport service demand in terms of passenger-kilometres (pkm) in SAFARI is described in this section. Cities in India were divided into two categories—those with population above 5 million (referred to as urban 1) and those with population below 5 million (referred to as urban 2). Average per capita trip rates and trip lengths in these two categories of cities were taken from secondary data and analyses in literature [29, 30]. Equation (7) was then used to calculate the annual urban pkm/capita.

Annual urban pkm/capita

$$\text{Annual urban pkm/capita} = \frac{\text{number of trips}}{\text{day}} \times \frac{\text{average trip length}}{\text{trip}} \times 365. \quad (7)$$

The average trip length per trip was adjusted for scenarios of densification on the basis of regression analysis conducted between city size and trip length [29]. Using population projections and urbanisation assumptions, the total urban passenger-kilometres for urban 1 and urban 2 were calculated. The passenger-kilometres were split into public transport (bus, suburban rail/metros), private transport (cars, two-wheelers, three-wheelers), and non-motorised transport [28, 30]. The fuel share options considered include petrol, diesel, CNG, and electric. The modal and fuel share assumptions are provided in the supplementary material.

2.9. Materials

SAFARI currently takes into account seven types of structural blocks. These were selected on the basis of current usage trends, policy support for them as alternative housing materials [31], availability as a technology (for newer materials), embodied energy per unit, and material economy [16, 31–33]. On this basis, SAFARI currently considers the following structural blocks: burnt clay brick (BCB), hollow concrete block, solid concrete block, fly ash block, fly ash-lime-gypsum block (FaLG), autoclaved aerated concrete block (AAC), and stabilised earth block (SEB). Aside from these, SAFARI also accounts for cement, steel, sand, aggregate, energy, and water demands for construction [16, 31, 33]. The embodied energy and emissions values used are described in table 1.

Starting from the year 2020, users can input the relative proportion (p_i, where i is the material type) of houses being constructed with each of these material types. SAFARI allows for such user input at flexible intervals up to 2051 to make it possible to explore scenarios with different material combinations for housing construction. The total required quantity of each material ($M_{t,i}$) is computed as a product of material requirement per square metre floor area (M_a), residential floor area (A), and percentage of floor area under that material (p_i).

Quantity of material required

$$M_{t,i} = M_a \times (p_i \quad \times A). \quad (8)$$

Four other materials required for construction were also considered with these blocks—cement (C), steel (S), sand (s), and aggregate (g). Each building block has an associated material requirement per square metre of floor area, namely, $C_{a,i}$, $S_{a,i}$, $s_{a,i}$, and $g_{a,i}$. The required quantities of these materials under any given user input scenario are calculated as the product of p_i, A, and the requirement per metre square floor area

Table 1. Embodied energies and emissions of materials used.

Material/structural block	Embodied energy ($MJ\ m^{-2}$ plinth area) average	Embodied emissions ($g\ m^{-2}$ plinth area)	References
Burnt clay bricks	1499	96 045	[32, 33]
Stabilised earth blocks (SEB)	655	55 458	[32, 33]
Fly ash blocks	569	36 109	[32, 33]
Fly ash-lime-gypsum blocks (FaLG)	594	108 015	[32, 33]
Autoclaved aerated concrete blocks (AAC)	494	66 244	[32, 33]
Solid concrete block	782	66 872	[32, 33]
Hollow concrete block	472	66 999	[32, 33]
Cement	5850	—	[16]
Steel	42 000	—	[16]
Sand	105	—	[16]
Aggregate	175	—	[16]

(i.e., $C_{a,i}$, $S_{a,i}$, $s_{a,i}$, or $g_{a,i}$). The total annual quantity of cement, steel, sand, and aggregate required is the sum of the requirement for construction under each type of building block (equations (9)–(12)).

Total cement required

$$C_T = \sum_{i}^{n} \left(C_{a\cdot i} \times p_i \quad \times A\right). \tag{9}$$

Total steel required

$$S_T = \sum_{i}^{n} \left(S_{a\cdot i} \times p_i \quad \times A\right). \tag{10}$$

Total sand required

$$s_T = \sum_{i}^{n} \left(s_{a\cdot i} \times p_i \quad \times A\right). \tag{11}$$

Total aggregate required

$$g_T = \sum_{i}^{n} \left(g_{a\cdot i} \times p_i \quad \times A\right). \tag{12}$$

A 5% cement wastage was assumed and added to the total computed cement requirement (for urban and rural housing, although the focus of this study is urban housing).

2.10. Aggregate and sand

Aggregate and sand, being materials in high demand and dwindling supply, have the additional user input of percentage ($s_{c\,\&\,d\%}$) gained annually from recycling construction and demolition (C & D) waste, and sand gained from coal mine overburden (s_{coal}). This reduces the demand for new sand/aggregate (equations (13) and (14)).

Sand gained from C & D waste recycling

$$s_{C\,\&\,D} = s_{c\,\&\,d\%} \times s_T. \tag{13}$$

Recycled sand available

$$s_R = s_{coal} + s_{C\,\&\,D}. \tag{14}$$

The annual net demand for sand (or aggregate) is calculated as the difference of the total sand (or aggregate) required for construction and the total sand (or aggregate) available through recycling (equation (15)).

Net annual demand for sand (or aggregate)

$$s_n = s_T - s_R. \tag{15}$$

Embodied energy (E) (equation (16)) is calculated by multiplying the total quantity of each of the 11 materials (cement, steel, sand, aggregate, and seven types of building block) with the corresponding embodied energy per unit of material (e_i) [16, 33].

Embodied energy

$$E_i = \sum_{i}^{n} \left(M_{t\cdot i} \times e_i\right) \tag{16}$$

2.11. Cooling

The cooling demand was calculated using the RETV method, (equation (17)), as described in India's energy conservation building code (ECBC) for the residential sector [31]. RETV, or residential envelope transmittance value, is expressed in terms of watts per square metre (W m^{-2}).

RETV calculation, from ECBC [31]

$$\begin{aligned} \mathrm{RETV} = \frac{1}{A_{\text{envelope}}} \times \Bigg[& \left\{ a \times \sum_{i=1}^{n} \left(A_{\text{opaque}_i} \times U_{\text{opaque}_i} \times \omega_i \right) \right\} \\ & + \left\{ b \times \sum_{i=1}^{n} \left(A_{\text{non-opaque}_i} \times U_{\text{non-opaque}_i} \times \omega_i \right) \right\} \\ & + \left\{ c \times \sum_{i=1}^{n} \left(A_{\text{non-opaque}_i} \times \mathrm{SHGC}_{\text{eq}_i} \times \omega_i \right) \right\} \Bigg]. \end{aligned} \tag{17}$$

The ECBC describes four climatic zones (warm and humid; hot and dry; composite; temperate). To obtain nationally relevant numbers, the number of new houses being constructed each year was divided in proportion to the approximate area of the Indian subcontinent falling under these zones. This worked out to be approximately 50% warm and humid, and 50% hot and dry and composite combined. The RETV equation coefficient values (a, b, c) for hot and dry and composite zones are the same, in the ECBC. The temperate zone was excluded for the purpose of generating estimates at the national level, as it covers a negligible portion of the Indian landmass. Similarly, weighted averages were taken for orientation factors and latitude factors, to provide a nationally relevant estimate. The indoor comfort temperature for most of India has been determined as 24 °C–28 °C [31, 34], and is considered to be 26 °C in this study. The derived RETVs were converted to energy demand for cooling in accordance with Bhanware *et al* [35].

3. Results

3.1. Affordable housing

AH has been a feature of Indian policymaking for decades. A recent addition to this suite of policies is the Pradhan Mantri Awas Yojana (PMAY), which aims to fill India's AH shortage by 2022 with national targets for rural and urban housing [6, 36]. AH, by current definition [14, 37], has a carpet area of under 60 m^2. The PMAY-stipulated area of an urban AH [6] is 30 m^2, whereas studies in the Indian context suggest 20–74 m^2 per house (see supplementary). The scenarios in this paper assume a 'decent quality of life' [13] area of 40 m^2 in 2020, increasing to 60 m^2 per house by 2050.

Adopting an aggressive annual AH construction rate of 3.8 million houses ('SDG scenario'), instead of the BAU average rate of 2.2–2.4 million ('current rate'), was found to help bridge the housing shortage by 2030. The cumulative AH floor area under the two construction scenarios is shown in figure 3.

One of the reasons for the stark difference between the two scenarios is that under the BAU scenario, the construction rate is insufficient to meet the annual, dynamically computed housing shortage. The total floor area in 2030 under AH amounts to 5.5 billion m^2 under the BAU scenario and 6.6–7.2 billion m^2 under the SDG scenario. SAFARI estimates the total floor area (AH + other urban housing) to reach 52.7–69.1 billion m^2 by 2050 depending on the average carpet area of a unit.

3.2. Building materials

Bridging India's housing shortage would increase the demand for construction materials. Depending on the materials chosen, this can have varying effects on energy demand (particularly space cooling) and GHG emissions. This study also accounts for embodied energy and emissions from cement, steel, sand, aggregate, and seven types of blocks—namely, BCBs, hollow concrete, solid concrete (solid CC), autoclaved aerated concrete, stabilised earth (SEB), fly ash, and FaLG.

3.3. Impact on embodied energy and emissions

Three construction material scenarios explored on SAFARI are presented here. The BAU scenario involves 80% new houses being constructed with BCB by 2050. In the alternative materials 1 (AM1) scenario, AAC blocks are used in 50% houses and the share of BCB goes down to 25% by 2050. In the alternative materials 2 (AM2) scenario, BCB is almost completely phased out (∼1%) and AAC is the dominant construction material (∼75%). A 13% increase in steel demand is assumed for vertical construction in the compact urban form scenarios [38]. Details of the material combinations are provided in the supplementary.

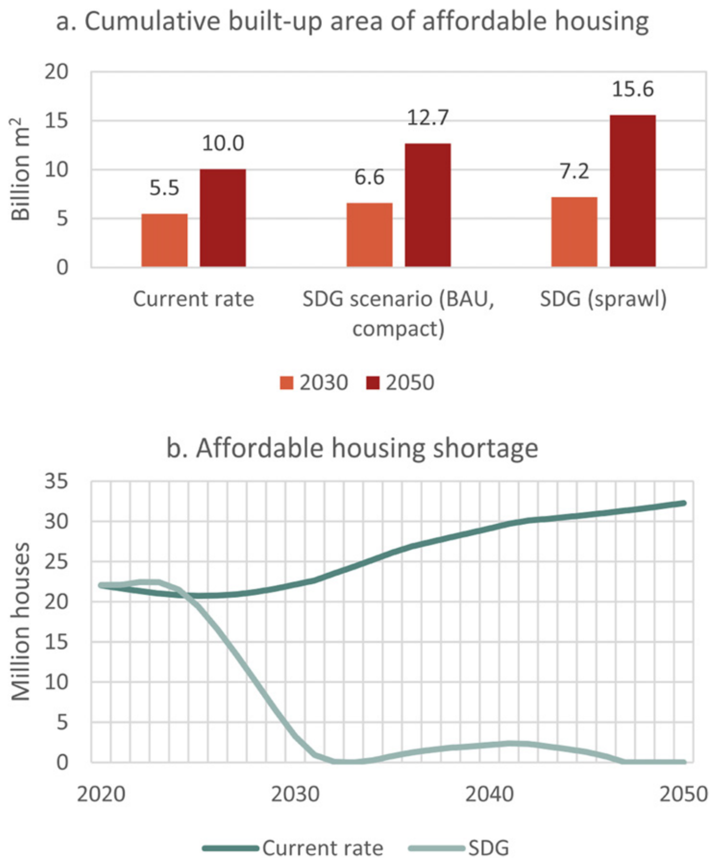

Figure 3. (a) Cumulative built-up area. (b) AH shortage.

Table 2. Embodied energy and emissions per unit area constructed in SAFARI's scenarios.

Year	BAU materials	AM1	AM2
	Embodied energy per unit area constructed (GJ m^{-2})		
2030	3.19	2.95	2.84
2050	3.17	2.47	2.15
	Embodied emissions per unit area constructed (tCO_2e m^{-2})		
2030	0.31	0.29	0.28
2050	0.30	0.24	0.21

Table 2 shows the derived embodied energy and emissions per square metre of constructed area using the three material combinations. Figure 4 shows the cumulative embodied energy and emissions from housing construction under the three material construction scenarios, and the three urban form types explored in this study.

Under the BAU scenario, the cumulative embodied energy of housing construction (while maintaining zero shortage) for 2020–2050 is 139412 PJ. This reduces by 12%–13% and 17%–18% under AM1 and AM2 respectively (figure 4).

In terms of cumulative embodied emissions, AM1 and AM2 lead to reductions of around 1.6–2 $GtCO_2e$, and 2.4–2.9 $GtCO_2e$, respectively, compared to the BAU materials scenario. SAFARI estimates an economy-wide cumulative emissions of 130 $GtCO_2e$ between 2020 and 2050 in the absence of intervention. Based on this, the embodied emissions savings from the adoption of alternative residential building materials alone could amount to a potential 1.2%–1.5% cumulative emissions reduction (AM1) and a 1.9%–2.2% cumulative emissions reduction (AM2) by 2050 at the national level.

3.4. Impact on cooling demand

Of the building blocks considered, AAC has the lowest embodied energy (and emissions) and thermal transmittance (U-value). The use of materials with lower U-values decreases the demand for space cooling [39]. This is an important aspect to consider in the Indian context, especially since the number of air conditioners

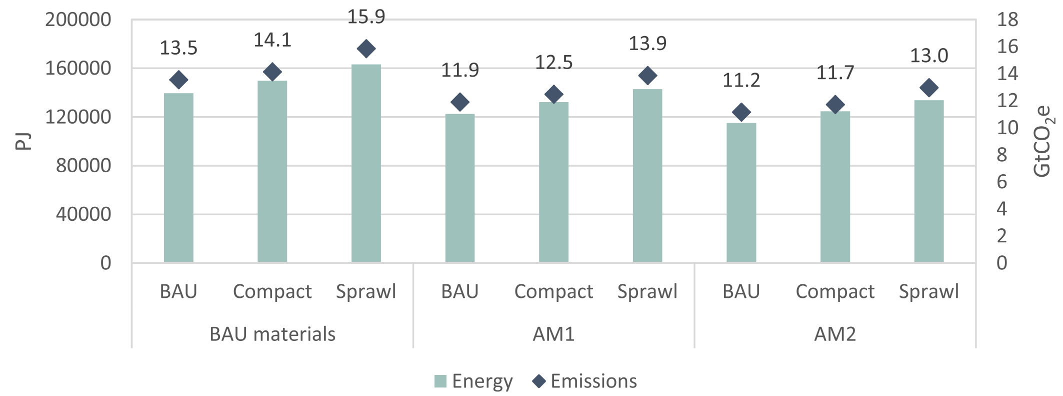

Figure 4. Cumulative embodied energy and emissions from housing construction, (2020–2050, SDG scenario).

in the country is expected to surpass 1 billion units by 2050 [40]. Without intervention, this could result in a 1577 TWh electricity demand for space cooling (ACs and fans) alone.

A major hurdle in adopting AAC blocks has been the high costs involved. However, owing to their superior insulation properties and cost savings from reduced cement and steel requirement in high-rise structures, AAC blocks are gaining popularity in India [32]. Phasing out BCB partially (AM1) or significantly (AM2) could result in a 31%–46% reduction from BAU in residential space cooling energy demand by 2050. With appliance efficiency improvements, this could potentially improve to a 54%–81% reduction. AM1 results in a 20% reduction in cumulative residential emissions by 2050, and a 2% reduction in cumulative economy-wide emissions by 2050. Similarly, AM2 reduces cumulative residential emissions by 30% by 2050, and economy-wide emissions by 3% by 2050.

Space heating demand in India is relatively insignificant (0.1% of final energy use in 2005) and is expected to grow, but remain an extremely small percentage of residential final energy demand, even by the end of the century. Moreover, heating demand is concentrated in the northern and north-eastern parts of India, and for less than a quarter of the year [41]. Therefore, this study focuses only on cooling demand.

3.5. Urban form

Urban form plays an important role in determining energy consumption, GHG emissions, air quality, and ultimately, quality of life. Its two major components are the built environment (building stock) and urban networks (transportation) [42]. The interaction between the housing and transport sectors is crucial in determining urban emissions and energy consumption. Since urban areas are already responsible for over 70% of global GHG emissions [43], they can also play a vital role in the transition to a low-carbon economy [8, 9].

Densely populated cities typically report lower per capita energy demands for transport but may nonetheless have an increased cooling demand due to localised UHIs. While UGS is included in our estimation of land consumption, the combined effect of the UGS urban form on the space cooling demand is a topic for future research in the urban Indian context. A few meta-analyses have suggested that energy demand increases with density and FSI regardless of building typology [44, 45]. They have concluded that sprawl-like urban forms, coupled with decentralised energy sources in the future and urban agriculture, could result in even lower carbon footprints in the long run. In contrast, other studies have found that compact cities offer energy savings from both reduced travel distances as and lower space cooling/heating in buildings [46–49]. The presence of UGS is almost unequivocally considered to help reduce cooling demand and mitigate UHIs, especially in dense urban areas [42, 50, 51].

Urban form scenarios representative of both densification and sprawl were run on SAFARI to understand their repercussions for GHG emissions, energy, land, and resource consumption. For ease of modelling, cities were aggregated into two categories—urban 1 (population greater than 5 million) and urban 2 (population 1–5 million). The population assumptions are based on projections made by the United Nations, Department of Economic and Social Affairs [52]. The urban densification scenarios were combined with transport sector scenarios based on FSI, average UGS per capita, changing fuel shares, travel modes, and distances. The five scenarios are outlined in table 3.

(a) **BAU**, where average trip lengths increase, while the share of private transport and average FSI for buildings follow current trends, and UGS per capita reaches 12 m^2 per capita.

(b) **Sprawl + private transport**, where cities grow in a more spread out manner with lower average FSIs for buildings, still reaching the required UGS levels of 12 m^2 per capita. In line with urban sprawl, the average

Table 3. Urban form scenarios.

Scenario	Trip length in 2050	Share of public transport in 2050	Average urban FSI	House area in 2050 (m^2)		UGS per capita (m^2)
				Affordable	Higher income	
BAU	13 km in urban 1, 6.8 km in urban 2	60% in urban 1, 35% in urban 2	1.5	60	150	12
Sprawl + private	14 km in urban 1, 9 km in urban 2	60% in urban 1, 35% in urban 2	0.75	75	200	12
Sprawl + public	14 km in urban 1, 9 km in urban 2	70% in urban 1, 50% in urban 2	0.75	75	200	30
Compact + private	10 km in urban 1, 5 km in urban 2	60% in urban 1, 35% in urban 2	8	60	150	12
Compact + public	10 km in urban 1, 5 km in urban 2	70% in urban 1, 50% in urban 2	8	60	150	30

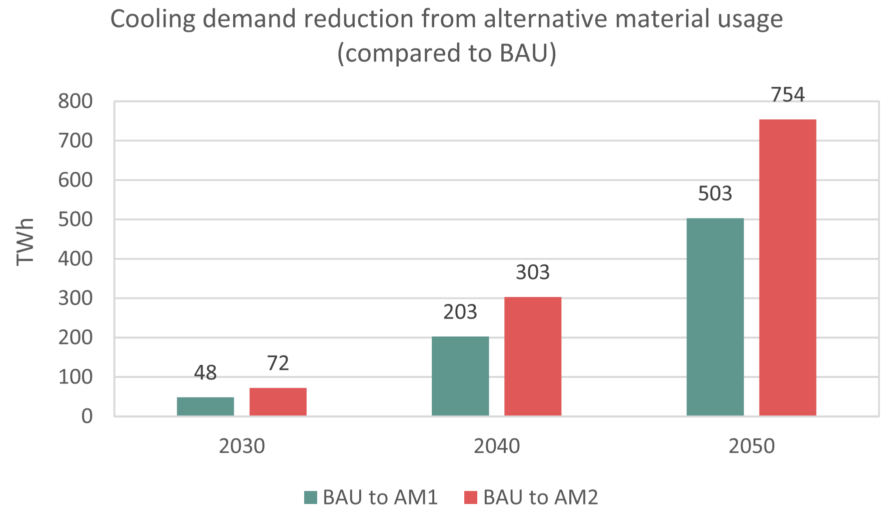

Figure 5. Space cooling demand reduction under different material scenarios.

areas of affordable and higher income houses are higher in this scenario (compared to BAU). Average trip lengths increase compared to the BAU scenario as the city expands.

(c) **Sprawl + public transport**, where policies promoting public transport are implemented in a sprawl scenario to increase the share of public transport (based on the guidelines for an 'ideal modal share' as currently laid out [30, 53]). In this scenario as well, the average areas of houses are higher than in the BAU scenario. However, despite urban sprawl, better public transport and higher average UGS (30 m^2 per capita) levels are assumed to be put in place than in the base-case sprawl scenario.

(d) **Compact + private transport**, where higher average FSIs are permitted, leading to densification. An average UGS of 12 m^2 per capita is assumed. As cities shrink, average trip lengths also reduce [29], but in this scenario, no additional efforts are made to promote public transport. Instead, private vehicle ownership trends continue, resulting in high levels of private transport use by 2050.

(e) **Compact + public transport**, where policies towards TOD are implemented. As in the base-case compact cities scenario, higher average FSIs permit compact residential construction, reducing land consumption. At the same time, with greater average UGS (30 m^2 per capita) and higher levels of public transport and non-motorized transport, combined with reduced trip lengths, a shift towards relatively car-free cities is seen in this scenario.

Additionally, this study considers the impacts of electrification in passenger transport, and the materials scenarios (AM1 and AM2) along with the five main scenarios. In the electrification scenarios, it is assumed that by 2050, all two- and three-wheelers are electrified and 40% of buses and cars passenger-kilometres are electric, which lowers urban GHG emissions. Electrification also has a significant impact on pollutant emissions, as shown in the supplementary material. These reductions amount to 60%–70% in particulate matter (PM), 34%–45% reduction in NO_x, 35%–40% reduction in CO, and 70%–75% reduction in VOC emissions (figure 5).

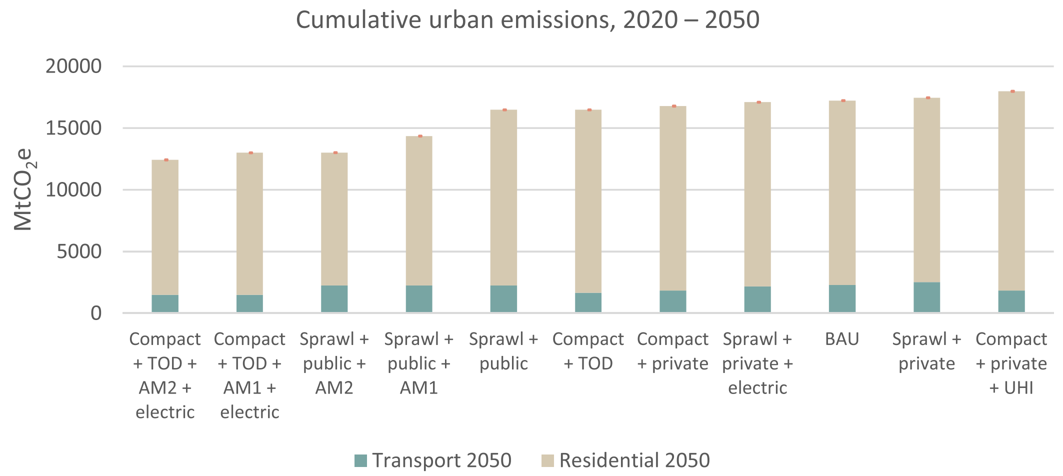

Figure 6. Cumulative urban emissions, 2020–2050.

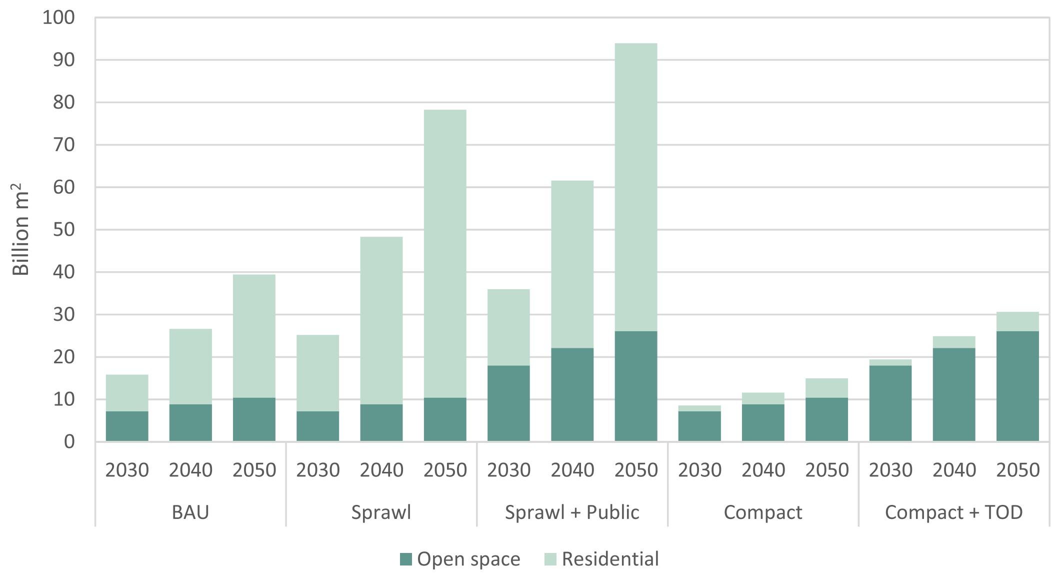

Figure 7. Net land footprint.

Cumulative GHG emissions from urban passenger transport and urban residential energy under the different urban form scenarios are shown in figure 6. Transport has a similar impact on GHG emissions in the BAU and *sprawl + public* scenarios, contributing around 100 $MtCO_2e$ in both cases in 2050 (2.3 $GtCO_2e$ cumulatively between 2020 and 2050). Cumulatively, the TOD scenarios can reduce emissions by 746–4804 $MtCO_2e$ by 2050 when compared to BAU. This amounts to a potential 0.6%–3.7% reduction in cumulative economy-wide emissions in India between 2020 and 2050.

Among the five major scenarios, *sprawl + private* has the highest cumulative urban emissions, surpassing even the BAU scenario. However, if UHI is accounted for, cumulative emissions from the residential sector are potentially greatest in the *compact + private + UHI* scenario, where a combination of high transport emissions, low open space, and UHI result in higher cooling demands. Here, approximately 10% increase in cooling demand due to the UHI effect was assumed [54–56]. Total urban emissions are also consequently highest in this scenario (nearly 1800 $MtCO_2e$ between 2020 and 2050). In the *compact + TOD + AM2* scenario, higher green space [57] and the use of building materials with lower thermal conductivity (AM2 scenario) contribute to lowering residential cooling demands. In this scenario, cumulative emissions are around 30%–34% lower (11 854–12 437 $MtCO_2e$) than BAU urban emissions. This reduction represents a 9.1%–9.6% cumulative emissions savings at the national level between 2020 and 2050 (figure 7).

3.6. Land

The value of urban net additional residential land required is greatest under the two sprawl scenarios (67.8 billion m^2 by 2050) and least under the densification scenario (4.5 billion m^2 by 2050), with the difference amounting to nearly 63.3 billion m^2. This difference could contribute around 8 MT of food grain shortage by 2050, according to SAFARI. Densification reduces pressure on urban land and, consequently, on neighbouring agricultural/forest land that might otherwise be absorbed into the urban periphery. Assuming an average open space of 12 m^2/capita, an additional 10.4 billion m^2 urban (vegetated) land would be needed by 2050. At a more ambitious 30 m^2/capita, an additional 26.1 billion m^2 vegetated urban land would be required by 2050 (see supplementary material).

Sprawl + public and compact + TOD scenarios involve 30 m^2/capita open space, while the others involve 12 m^2/capita.

4. Discussion

This study examined the effects of reduction and increase in space cooling as a result of densification and change in building materials using scenarios from the SAFARI model. Materials, particularly walling materials, impact a building's indoor thermal comfort and space cooling demand [36], embodied and lifecycle energy, and overall carbon footprint. This observation strengthens the case for choosing materials that can reduce the carbon footprint and increase the thermal comfort of residential buildings. AAC is one such material, as is shown in this study. Replacing BCB with AAC could lower a typical dwelling unit's cooling demand by up to 30%–40% (not accounting for other contextual factors that could impact this). Several other emerging alternatives to BCB are proving to be emissions- and cost-effective as they contain waste-based substitutes such as fly ash, rice husk, and paper waste [15–17]. Paper and cotton mill waste and rice husk ash can help address availability concerns associated with fly ash [15]. Further, preliminary studies have found them to be advantageous in lowering space cooling demand [15–17] as well.

Apart from the materials used in construction, built form can play an important role in determining space cooling demand. Several recent studies have shown that with increasing appliance use and changing electricity consumption and travel patterns, traditional densification strategies may inadvertently increase energy demand, especially from cooling to counteract the UHI effect [42, 54, 57–59]. One such study indicated that UHI could increase local temperatures in urban India by 2 °C [3] and, in turn, increase buildings' cooling energy demand [60]. Therefore, some of our scenarios explored the impact of a potential UHI effect arising from dense built form with low open/green space and high transport demand on space cooling demand [55, 57, 61, 62]. Accounting for an increase in cooling demand from UHI, heavy private transport use, lower open space per capita and no construction material changes, our study confirmed that compact forms could result in high urban emissions by 2050, compared with the other scenarios. On the other hand, a compact urban form coupled with modal shifts, better urban planning in the form of greater UGS and building materials, could have important outcomes for urban emissions reduction. Overall, the interaction between the housing and transport sectors is crucial in determining the structure of a city and, subsequently, in the transition to a low-carbon economy [8, 9].

This study's findings further confirm that a compact urban form can reduce pressure on land as a resource. It can reduce trade-offs between food security, housing, and transportation by reducing peripheral vegetated and agricultural land conversion. The direct link between urban expansion and food security is an area that could benefit from further research.

5. Conclusion

This study presents the Sustainable Alternative Futures for India (SAFARI) model, using which, the implications of urban built form and transport on resource demand, energy consumption, and GHG emissions were explored.

The SAFARI model dynamically computes housing shortage in India based on various factors, instead of using a static estimate that other studies have used so far. The analyses presented suggests that to meet the AH shortage in India by 2030, the annual construction rate needs to increase to around 3.8 million from the current average of 2.2–2.4 million. This, along with other housing (for middle and higher income groups) construction, brings the total residential built area in urban India to around 24 billion m^2 by 2030 and around 52.7 billion m^2 by 2050. The ultimate impact of such growth on energy demand, emissions, and land required depends on the kind of construction materials used, as well as urban form. This study shows that phasing out BCBs and using AAC blocks instead can reduce the cumulative (2020–2050) embodied energy for construction in urban India by 12%–18%, and the space cooling demand by 31%–46%. Consequently, the total

GHG emissions reduction possible through the use of better construction materials could be up to 23%–27% compared to BAU.

According to SAFARI, a compact urban form can reduce cumulative GHG emissions from urban transport by 20%–30% due to reduced trip lengths. However, taller and densely constructed buildings have a higher emissions footprint caused by the increased demand for materials (like steel) and the increased cooling demand due to UHIs. To reduce such trade-offs, interventions such as TOD and use of better construction materials can be combined with a compact city scenario, bringing down cumulative GHG emissions by 25%–28% compared to BAU. Similarly, model users can further explore cross-sectoral scenario combinations (like the ones presented in this study) to build alternative strategies for sustainable urbanisation in India. One possible area for future research is to scale down this model to sub-national levels. This could offer further, more contextually nuanced insights, especially in terms of resource competition. The direct relationship between food security, urban form, and land use change is another area of potential research.

Also warranting more research is the correlation between densification and change in cooling demand in the Indian context. As discussed previously, several recent studies in different contexts have shown that with changes in appliance use, electricity consumption, and travel patterns, compact cities may actually increase residential electricity demand, especially from cooling to counteract the UHI effect [42, 54, 57–59]. Moreover, it has been suggested [54] that compact forms are universally less energy efficient when changing insulation standards, household energy use patterns, and energy use in common areas are considered. Introducing different commercial building types and their usage patterns into these studies could add further insight into which urban spaces in their entirety are used in the Indian context. This could be particularly valuable given India's urbanisation rate.

With India's fast-paced urbanisation and growing space cooling demand, it would be useful to empirically investigate how dense urban forms compare with looser urban forms in different climatic zones. This would be useful in shaping urban design strategies with a view to reducing the space cooling demand through passive interventions, particularly in the choice of building materials, fenestration, and UGS. Doing so could help improve thermal comfort and overall living standards, especially in rapidly expanding urban areas.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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