Decent housing in the developing world: reducing life-cycle energy requirements

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Abstract

Developing countries face a crisis of deteriorating and unsafe human settlements conditions. Few studies examine the resources and energy required to provide everybody with decent housing. This study presents a generic methodology for the estimation of Life Cycle Energy (LCE) requirements to meet the housing gap and provide basic comfort to everybody in a developing country, based on standards of safety, durability and indoor temperature and humidity limits. The methodology includes the operationalization of this decent housing standard into materials and equipment; development of appropriate building archetypes; calculation of embodied and operating energy using a building simulation model; a parametric analysis to investigate the range of uncertainty in LCE and the attribution to different contextual conditions and energy savings measures.

Results for the test case India showed that LCE of decent housing can significantly vary depending on climatic conditions, building typology, construction materials, technical equipment for space cooling-dehumidification and user behaviour. Embodied energy accounts for 27-53% of the LCE, depending on the building type and climate. LCE savings up to -44% can be achieved by implementing low embodied energy materials, building envelope insulation, ceiling fans usage and improved energy efficiency of air-conditioning systems.

Keywords

Decent housing; Developing countries; Poverty; Policy decision support; Life cycle energy; Dynamic energy simulation; Energy savings; Uncertainty; Parametric analysis.

Abbreviations

A/C: Air Conditioning

COP: Coefficient of Performance

EE: Embodied Energy

LCE: Life Cycle Energy

OE: Operational Energy

PPD: Percentage of People Dissatisfied

PMV: Predicted Mean Vote

RC: Reinforced Concrete

RH: Relative Humidity

T_{air}: Air Temperature

T_{op}: Operative Temperature

1. Introduction

Developing countries are facing an increasing emergency related to the continuing deterioration of shelter and human settlements conditions [1]. Dwellers living in poor housing conditions are estimated to reach 2 billion by 2030 as the rapid urbanization process in the Global South makes it difficult for the poorer section of the society to find adequate shelter and security of tenure [2]. Ensuring adequate shelter for all is a universal goal endorsed by the Istanbul Declaration on Human Settlement [1] and providing adequate and affordable housing remains a key priority for all governments [3]. However, few studies assess the resources and energy required to provide everybody with 'decent' housing, based on a normative standard of safety and comfort, in developing countries. A life cycle approach to such an assessment – Life Cycle Energy (LCE) – provides a holistic assessment by including all energy inputs in the major stages of building life cycle [4].

LCE is a version of Life Cycle Assessment (LCA) evaluating the energy inputs for different phases of the life cycle [5,6]. The total LCE of buildings consists of: embodied energy (EE) derived from materials production, construction and final disposal; operational energy (OE) used for building operations such as heating, cooling, lighting and appliances.

Most LCE studies focus on developed countries, while only a few address developing countries [7–9]. Calculation methods used in developed regions might not be equally applicable to developing areas [10]. In particular, the calculation of embodied energy (EE) may be challenging due to scarcity of specific data on the energy related to the production and manufacturing of construction materials [11] as well as traditional and non-conventional materials [8], e.g. rammed-earth or bamboo construction. Operational energy (OE) requirements might also be difficult to estimate because of unique climate conditions [12], indoor thermal comfort considerations [13,14], user behaviour as a result of culture and social context [15] and energy mixes [8]. Many developing countries are located in tropical areas and characterised by hot and humid climates. However, humidity-related aspects and latent loads are rarely addressed [16]. In addition, technologies alternative to or complimenting air conditioning (A/C) systems, such as ceiling fans, which have been scarcely considered in scientific literature [17], should be further investigated for their potential to reduce energy consumption.

In recent times, a new research stream addresses the LCA of large building stocks for policy decision support [18]. However, only few papers focus on developing countries [19,20] and, to the best of our knowledge, only one addresses poverty eradication issues [21]. Furthermore, most of the studies on the energy requirements of low-income houses in developing countries involve specific case studies (see e.g. [22–25]). Current limitations include the consideration of only one single building typology, fixed building size and design, and standard operation schedules, all of which might limit the range and validity of outcomes on a large scale assessment, potentially leading to partial or misleading conclusions.

This study aims at filling the above gaps by developing a generic bottom-up approach to assess the LCE required to provide everybody with decent housing in a developing country. This methodology also enables the analysis of LCE reduction strategies, to support both housing policies and climate mitigation strategies. We apply the methodology as a test case to India. This case is highly relevant as the housing shortage in India is estimated at more than 50 million units in both urban and rural areas due to the obsolescence, non-durability and congestion of a large part of the current stock [26]. The presence of multiple climatic zones, including hot-humid conditions, makes the study of particular interest for determining the range of energy needed to provide sufficient cooling to meet a particular standard nationwide. The results provide an insight in the range of LCE associated with decent housing, accounting for the different contextual conditions and energy savings opportunities, to support decision makers in the development of poverty eradication policies.

2. Methodology

The generic methodology consists of a series of steps as shown in Figure 1. The first step involves the identification and operationalization into material requirements of a decent housing standard. Second, we develop a series of archetype buildings to represent the main housing types that meet the standard (*Reference* case). We then calculate the LCE associated with the several stages of the life-cycle of buildings. We finally use parametric analysis to investigate the influence of relevant parameters related to contextual conditions and energy savings measures on the results. The following sections detail the steps of the methodology and the application to the pilot case of India.

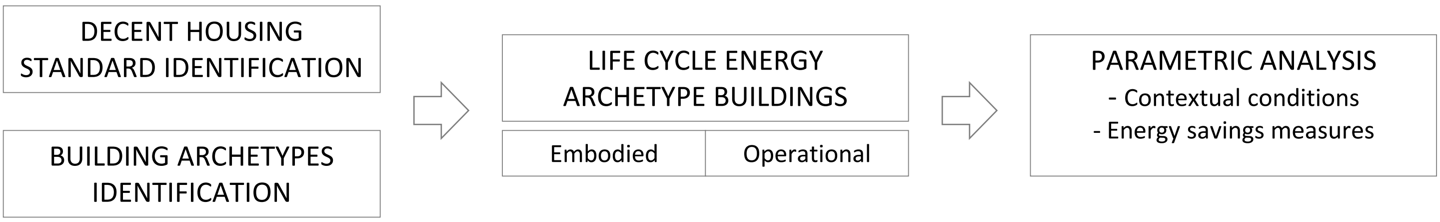

Figure 1 Overview of the methodology.

2.1. Decent housing standards

The first step consists in the identification of decent housing standard. This part is supported by previous studies on material requirements and decent living emissions [27,28]. The minimum standards are presented in Table 1 and further discussed in the following sections. Three components of decent housing were identified as universal basic needs: floor space sufficient to live an uncramped life; safe and durable construction; shelter from inclement weather conditions. Basic needs are translated into requirements for housing. In contrast to basic needs that are universal, housing material requirements are specific to the context addressed by the analysis to respond to the variety of social, economic, climatic conditions and construction practice.

Table 1 Identified decent housing standards.

Basic needs	Housing requirements	References
Sufficient space	Minimum floor surface (10 m^2 per person, minimum 30 m^2 up to 3 persons).	[26–28]*
Safety and comfort	Permanent construction.	[29,30]*
	Adequate thermal insulation and proofing. Minimum indoor thermal comfort level.	[29,31]* [32,33]

Notes: the symbol * denotes Indian sources.

2.1.1. *Sufficient space*

The provision of a house with adequate space and privacy is a constitutive element of a healthy built environment [26]. A minimum floor surface area per inhabitant assures a minimal space required for conducting an uncramped life [27,28]. While the minimum space requirement should be decided at local level, some guidelines for minimum living space may be drawn. Rao & Baer propose a minimal value of 10 m^2 per person based the average size of upper quartile Indian households. Similar values were suggested by Tiwari *et* al. [26] in their study on Indian housing. This value is consistent with the minimum floor surface requirements in the national housing guidelines of densely populated countries. As an example, Taiwan recommended a minimum living space between 7-13 m^2 per person, depending on number of occupants. A minimum standard of 12 m^2 for one person and 8-10 m^2 for each additional person is recommended for South Korea. The minimum of 30 m^2 per households up to three persons is also in the range of the average floor surface of households in China. The identified minimum is still higher than thresholds suggested in emergency conditions. For instance, the Red Cross defined a minimal floor surface of 3.5 m^2 for shelters during humanitarian emergencies. This is motivated by the fact that more space is needed in ordinary life conditions than during emergencies.

2.1.2. *Safety and comfort*

Durable construction and materials should be chosen to ensure the safety of dwellers. The construction should provide protection against major extreme events, such as earthquakes, floods and monsoons. Definition of risks and suitable structures and materials for buildings are often defined at the country or regional level, e.g. vulnerability atlas for buildings in India [30].While non-durable constructions are not uncommon in developing countries (e.g.: use of plastic, tissues, leaves, etc. for building elements), especially in slum areas, we consider these constructions as not respondent to the minimal requirements for decent living conditions as they do not permanently ensure the safety of occupants. We therefore require permanent, durable structures able to offer adequate resistance to extreme events and safety for occupants. Implications for decent housing include the choice of structure type (e.g. masonry, framing, etc.), materials and components with adequate properties (e.g. min. thickness, resistance, etc.).The houses should protect against inclement weather conditions. Minimum thermal comfort conditions are therefore part of a decent living standard, which would require that houses be equipped with mechanical systems if passive strategies, such as natural ventilation, thermal insulation, solar shadings, do not suffice to achieve these comfort conditions. Since many developing countries are within around the tropics, where severe temperatures and/or humidity are commonplace, the use of fans, air conditioning and other devices may be an essential part of decent housing.

Several indices for indoor thermal comfort conditions have been developed, such as Predicted Mean Vote (PMV) [33], adaptive method [34], etc. We selected the PMV index as this is an internationally recognised standard. The acceptable range of PMV conditions for new buildings is established at ±0.5, corresponding to a percentage of dissatisfied people of 10%, according to the international standard ISO 7730 [33]. The PMV method tends to underestimate people’s adaptability to high temperatures and humidity [35]. Nicol using a meta-analysis confirms that in high humidity conditions people tend to require a lower temperature setting, but on average the difference is just one degree centigrade. However, the range of temperatures covered in this analysis do not cover temperatures above 28 degrees C, which would omit large portions of hot-humid conditions in the tropics. Some authors argued that alternative methods, such as the adaptive method based on the operative temperature, might be more appropriate in cooling conditions. However, relative humidity conditions are not considered in this method, resulting in potential underestimation of thermal discomfort due to high relative humidity. As a significant part of the developing countries lies in the tropical region with severe relative humidity conditions, we include a restriction on humidity as part of the comfort conditions. We stick with PMV method, in the absence of reasonable alternatives, but allow for the use of ceiling fans where feasible and use conservative set-points in order to allow for some adaptation, as we discuss in more detail later.

2.2. Building archetypes

Building archetypes have been widely used as a bottom-up technique to model entire building stocks [36–38]. In this technique, a limited set of buildings called *archetypes* are identified to represent classes of houses in the residential sector. An energy model is developed for each archetype based on the identified characteristics of the respective class of buildings, enabling the upscale of results.

We identified three main archetype buildings for India (Figure 1), consistent with the previously defined minimum requirements (*Reference* case). The first archetype is a one-storey building with masonry structure and flat concrete roof, typically found in rural areas [39,40]. The second archetype is a two-storey building with masonry structure, reinforced concrete (RC) flooring and flat roof, common for both rural and urban areas [41]. The third archetype is a four-storey building with RC framing structure and flat roof common for low-income housing in urban areas [22], which we assume as representative of multi-storey buildings.

We defined the characteristics of building archetypes based on the current construction practice in India, as described by other authors [22,31,42,43] and according to the national building code [29]. The main characteristics of the archetype buildings for India are reported in Table 2. For all archetypes, we used a reference net floor area (defined as *carpet area* in India) of 40 m^2 per dwelling, representing the average household size of 4 persons in both urban and rural areas in India [44] (see Supplementary Material Figs. SM1-SM2). The building elements and components for the *Reference* case for all archetypes are shown in Table 3. The configuration and thickness of the building structure and envelope components were defined according to the minimum requirements of the national building code [29]. The amount of glazed surface was sized in accordance with the minimum requirements for ventilation and lighting of the code.

Table 2 Main characteristics of building archetypes for India (reference case).

Description	R	U	N. dwellings	Total floor surface *(m^2)*	Structure	Walls	Roof
Single-storey	✓		1	40	Masonry	Fired bricks	RC
Two-storey	✓	✓	2	80	Masonry	Fired bricks	RC
Multi-storey		✓	16	640	RC Framing	Fired bricks	RC

Notes: R = typically rural; U = typically urban.

Figure 2 Plans and elevations of the housing archetypes for India.

Table 3 Building elements and components in the reference case and for affordable construction (see section 2.4.1.2).

Type	Case	Description	Composition *(Thickness cm)*	U-value *(W/m²K)*
External and load-bearing walls	R	Fired brick masonry with cement mortar.	Plaster (1.5), Fired bricks (32.0), Plaster (1.5).	1.29
	A	Rammed earth masonry.	Plaster (2.0), Rammed earth (46.0), Plaster (2.0).	0.86
Internal non load-bearing walls	R	Fired brick masonry with cement mortar.	Plaster (1.5), Fired bricks (23.0), Plaster (1.5).	1.58
Vertical structure*	R	RC pillars.	Plaster (1.5), RC (32.0), Plaster (1.5).	2.47
Flat roof	R	RC slab.	Plaster (1.5), RC (12.0), Screed (5.0), Bitumen (0.5), Clay tiles (1.0)	2.78
Pitched roof	A	Wooden structure with clay tiles covering.	Clay tiles (2.0), Screed (3.0), Clay tiles (2.0). Wooden truss structure.	4.24
Standard floor	R	RC slab.	Plaster (1.5), RC (12.0), Screed (5.0), Clay tiles (1.0)	2.96
Ground floor	R-A	Concrete slab.	Gravel (20.0), Cast concrete (10.0), Clay tiles (1.0).	1.68
Foundation	R	Fired bricks foundation.	Fired bricks (35.0)	-
	A	Rubble stone foundation.	Rubble stones (46.0)	-
Windows	R-A	Single-glazing in a wooden frame.	Glass (0.3). Wooden frame (4.0).	5.78**
Doors	R-A	Wooden panels.	Wood (4.0)	2.29

Notes: R = Reference case. A = Affordable construction. *For RC framing structures. **Glazing U-value.

2.3. LCE analysis

The life cycle of buildings can be divided into three main stages: product/construction, use and end-of-life. In current conventional buildings, the OE dominates the LCE while EE accounts for 5-6% of total LCE [4]. Other stages account for less than 1% of the total LCE [11]. Accordingly, we included the product and use stages within the boundaries of the analysis. We included the following end-uses in the analysis: space heating, cooling, dehumidification and lighting. Other uses, such as cooking and other appliances are out of the scope of this study. We assumed a service life of 50 years, in accordance with other studies [4,45,46]. The functional unit assumed for this analysis is the useful floor surface unit (m^2) of dwelling, excluding common areas of the building (e.g. staircases).

2.3.1. Production stage

The energy embodied in building materials and components can be calculated in three subsequent phases: 1. Estimation of the amount of different materials in the building archetypes; 2. Identification of suitable embodied energy intensity coefficients for all materials and components; 3. Multiplication of the amount of materials by the respective embodied energy intensity coefficients.

We estimated the volume of materials embodied in the building archetypes from the drawings (Figure 2) and multiplied by the respective density values (Table 4) to obtain the total amount. For openings, including window and doors, we estimated the surface instead of the material amount. Embodied energy intensities, expressed as GJ per tonne of material or per surface unit, were obtained from literature for India (Table 4). The selected embodied energy intensities were compared against values for similar materials from international databases, such as Ecoinvent 3 [47], to check for consistency.

Table 4 Properties and embodied energy intensity of building materials and components assumed for India.

Material	Density	Thermal conductivity	Specific heat	Embodied energy intensity		References*
	(kg/m3)	(W/m K)	(J/kg K)	(GJ/ton)	(GJ/m2)	
Fired brick	1700	0.84	800	1.31	-	[31]
Cement mortar	2800	0.88	896	0.45	-	[31,48]
Cast concrete	2000	1.13	1000	0.73	-	[31]
Gravel (Crushed stones)	2600	0.7	1800	1.14	-	[31,49]
Reinforced concrete (2% Steel included)	2400	2.5	2400	2.77	-	[31]
Plaster (Cement-sand)	1200	0.16		1.27	-	[48]
Block - Hollow Concrete	1200	0.63	1000	0.41	-	[22,31]
Block - Soil-cement	1920	0.55	835	0.55	-	[22,31]
Block - Fly-Ash concrete	1270	0.36	857	0.56	-	[22,31]
Block - Aerated concrete	750	0.24	1000	1.09	-	[31]
Rammed earth	1700	0.57	840	0.00		[31]
Expanded polystyrene (EPS)	25	0.035	1400	100.00	-	[31]
Bitumen	1000	0.23	1000	2.98	-	[31]
Wood	700	0.15	608	-	0.16	[49]
Glass (Single Glazing)	2500	0.9	-	-	0.54	[49]

*All sources are Indian.

2.3.2. Use stage

We estimate the energy required for the use stage by modelling and simulating the dynamic state in hourly time-steps using the software EnergyPlus [50] and the OpenStudio suite [51], launched with the software jEplus [52] for multiple runs and efficient results gathering.

India has five climatic zones [29]: warm-humid, hot-dry, composite, temperate and cold. Similar to other authors [31], we selected five representative locations for each of the climatic zones (Table 5) and run simulation using the EnergyPlus weather data [53]. Using a multi-zonal approach, we distinguished three types of space: living room, bedrooms, and unconditioned spaces. Common areas in multi-family buildings (e.g. staircases, corridors, etc.) were assumed as not conditioned, and not lit. We adapted activity schedules from other studies for India [54], as shown in Table 6.

Table 5 Climatic zones and monthly statistics for daily average air temperature and relative humidity. Data elaborated from [55].

Climatic zone	Location	T_{air}* (°C)	RH* (%)
Warm-humid	Chennai	24.2-31.5	68-84
Hot-dry	Jodhpur	16.9-33.9	30-70
Composite	Allahabad	14.7-33.1	37-86
Temperate	Bangalore	20.5-27.6	45-85
Cold	Dehradun	11.2-28.8	54-86

Note: *Minimum and maximum monthly statistics for daily average air temperatures and relative humidity. See Supplementary Material for complete monthly statistics (Table SM1).

Table 6 Activity schedules.

Space type	Activity schedules			
	Occupation (% occupied)	Heating	Cooling*	Lighting
Living room	W: 8:00-18:00 (50%); 18:00-22:00 (100%) WE: 8:00-22:00 (100%)	W: 18:00-22:00 WE: 13:00-22:00	-	7:00-8:00; 19:00-23:00
Bedrooms	22:00-08:00 (100%)	W-WE: 22:00-8:00	W-WE: 22:00-6:00	7:00-8:00; 19:00-23:00
Non-conditioned spaces	-	-	-	7:00-8:00; 19:00-23:00

Note: W = weekdays; WE = weekends. *Ceiling fans operate in Living rooms.

Most of the studies on the energy use of buildings in India considered only space cooling. However, dehumidification is a key issue for providing indoor thermal comfort, as discussed earlier. For the reference set of simulations, we assumed that space cooling and dehumidification are provided by a single speed air conditioner for bedrooms. The coefficient of performance (COP) was set to 3.26 corresponding to an average performance of air conditioning systems in India [56]. In addition, ceiling fans of 55 W rating are provided for living rooms [45]. For the reference case, we assumed that no ceiling fans are used in the bedroom beacause A/C is available throughout most of the occupation period. For rooms served by A/C, we fixed operative temperatures at 26°C and relative humidity at 60%, which several studies suggest are optimal thermal comfort settings for tropical countries [15,57,58] Assuming indoor air velocity at 0.1 m/s, metabolic activity typical for housing (MET = 1.1) and summer clothes (CLO = 0.5), this set of parameters leads to PMV within ±0.5, corresponding to the standard level for new buildings according to ISO 7730 [33].

Hourly results of simulations were postprocessed in R to add the operation of ceiling fans and related electricity consumption. We assumed that ceiling fans start operating when indoor air temperature exceeds 26°C and the air conditioner is off. Space heating is assumed to be provided by an electric heater with efficiency 0.9 similarly to other studies [11]. While using an electric heater is not an efficient solution for space heating, this is quite common in India as the winter season is very short and temperatures are quite mild in most of the climatic zones. The set-point temperature for space heating was assumed at 20°C with setback at 18°C out of the activity schedule. We used a primary energy conversion factor of 3.4 for electricity [11,31].

2.3.3. Life cycle energy

We express LCE as an intensity per floor surface unit (m^2) per year according to the following equation: $LCE = EE/SL + OE$, where SL is the service life of buildings. We assess, using a contribution analysis, the relative share of EE and OE for different building archetypes and climates.

2.4. Parametric analysis

Due to the large number of input parameters with a high degree of uncertainty in each, we used a parametric analysis to investigate the most influential input parameter values on the LCE results. We categorized parameters in relation to contextual conditions and general energy savings measures (Table 7). The former includes characteristics of building geometry, construction, and usage, the latter energy savings measure for the building envelope and equipment, as detailed in the following sections. For each set of parameters, we show the *Reference* case assumptions and the sensitivities. We run all cases for all five climatic zones.

Table 7 Overview of the parametric analysis.

Category	Description	Parameters
Contextual conditions		
Building location	Investigate the building location in different climatic zones.	- Climatic conditions
Building geometry	Assess the effect of different configurations for the building.	- Building archetypes - Size of dwellings
Building construction	Compare conventional and traditional materials.	- Building structure and materials
Building usage	Evaluate the effect of different behaviours of occupants.	- Set-point for indoor temperature and relative humidity - Schedules for space cooling
Energy savings measures		
Building envelope	Investigate the effect of several measures on building envelope to reduce EE and OE.	- Masonry material - Walls insulation - Roof insulation
Building equipment	Investigate the effect of efficiency measures for technical systems on OE.	- Efficiency of A/C systems - Lighting technology - Use of A/C in combination with ceiling fans

2.4.1. Contextual conditions

2.4.1.1. Building geometry and dwelling size

India has a range of household sizes, with an average of about 4, but with a right-tailed distribution that includes sizes above ten inhabitants. As discussed above, we increase dwelling size in proportion to the number of household members. But both embodied and operational energy are not necessarily linear with the floor surface area. As the size of dwelling influences the conformation, geometry and size of the building, we investigate their effects on both EE and OE requirements. To the best of our knowledge, only one previous study estimates the influence of the building size on EE for India [49]. The findings of this study showed that, for a given housing typology, increasing the building size typically results in decreased EE intensities. We extend the results to different dwelling sizes and encompassing both EE and OE requirements. To this goal, we varied the dwelling size up to six members, ranging from 30 m^2 to 60 m^2 of floor surface (Table 8).

Table 8 Building geometry and dwelling sizes by archetype.

Archetype	Inhabitants per dwelling	Floor surface of dwellings *(m^2)*	N. main rooms per dwelling*	Total floor surface of the building***(m^2)*
	Min-Max (Ref)	Min-Max (Ref)	Min-Max (Ref)	Min-Max (Ref)
Single-storey	3-6 (4)	30-60 (40)	1-4 (2)	30-60 (40)
Two-storey	3-6 (4)	30-60 (40)	1-4 (2)	60-120 (80)
Multi-storey	3-6 (4)	30-60 (40)	1-4 (2)	480-960 (640)

*Living room and bedrooms. **Excluding common areas (Staircase, atrium, etc.).

We adapted the conformation of dwellings to their size. The minimum size ($30 m^2$) dwelling includes only one main room serving as living room and bedroom. For dwellings of bigger size, we added one bedroom for each additional person. A/C units were added to serve all bedrooms and the same availability schedule as of the reference case was assumed (Table 6).

2.4.1.2. Affordable building construction

Affordability is of paramount concern in India, since over 700 million live on less than $3.10/day.[1] We considered a set of traditional materials and construction techniques for single-storey buildings in rural areas [59], as shown in Table 3. The building has a thick masonry structure in rammed earth and pitched roof with wooden structure and clay tiles covering. The plan of the building is the same as the single-storey archetype (Figure 2). While this set of construction elements might not be suitable for every region in India due to its limited resistance to extreme conditions, such as earthquakes and floods [30], this type of building represents the continuity with traditional local construction practices and may be suitable for self-construction. Traditional materials, such as mud and stone, typically have low embedded energy [45]. However, the effect on OE is unclear, since the light roof covering is likely to have lower thermal resistance than the *Reference* case, while the thick masonry offer increased thermal inertia whose effect is beneficial to shift and attenuate cooling loads. The results might also depend on ambient and usage conditions.

Beside energy requirements, estimation of global costs is another key element to effectively support policy decision for decent housing development. Although a thorough economic analysis is beyond the scope of this paper, here we addressed a simple Life Cycle Cost (LCC) analysis [5,60–63] to compare conventional and affordable construction for rural housing (see Supplementary Material for more details).

2.4.1.3. Building usage

In this study, we considered two main aspects related to building usage: indoor thermal comfort level; A/C availability and schedules. The analysis of the building usage was limited to cooling and dehumidification. Schedules for heating were not varied because of its relatively small demand in Indian climates.

Two alternative sets of design indoor thermal conditions were tested against the *Reference* set described in section 2.3.2 (Table 9): a more stringent set-point, corresponding to the comfort category *A* in the standard ISO 7730 (25 °C, 55% RH), which incorporates the observation that people overuse air conditioning when available [33]; and a less stringent set-point, corresponding to high adaptability and cost-conscious behaviour. For this set, we used the upper limit of T_{op} (27 °C) according to the European standard EN 15232 [64] and the upper limit for RH (65%) recommended by ASHRAE [65].

Table 9 Design conditions for indoor thermal comfort.

Thermal comfort level	T_{op}* (°C)	RH (%)	PMV	PPD (%)
More stringent	25	55	0.12	5.3
Reference	26	60	0.46	9.4
Less stringent	27	65	0.80	18.5

Table 10 Variation of the activity schedules.

Space type	Activity schedules: Cooling (time)	
	Reference	Extended

[1] World Bank Development Indicators. http://povertydata.worldbank.org/poverty/country/IND, accessed February 28, 2017.

Living room	-	W: 18:00-22:00 WE: 13:00-22:00
Bedrooms	W-WE: 22:00-6:00	W-WE: 22:00-8:00

Note: W = weekdays; WE = weekends.

The activity schedules and availability of A/C were varied to analyse the impact of extended operation times and availability for both bedrooms and living room (

Table 10). In the *extended* set, A/C was made available for living rooms as well, and the availability of A/C was extended for the bedrooms in comparison to the *Reference* case.

2.4.2. Energy savings measures

2.4.2.1. Building envelope

The parameters representing the building envelope are shown in Table 11. Previous studies highlight that the material for masonry can significantly change the embodied energy [49]. Moreover, different conductivity values also change the space heating and cooling requirements. The following alternatives to fired bricks are available in India [31]: hollow concrete blocks, soil-cement blocks, fly-ash concrete blocks and aerated concrete blocks. We selected only hollow concrete and aerated concrete blocks for the parametric analysis, since they have the lowest embodied energy intensity and the lowest thermal conductivity (Table 4), respectively.

Wall and roof insulation can contribute to lower operational energy requirements for space heating and cooling at the cost of increased embodied energy, due to the use of additional material. Previous studies have shown that the optimal thickness for EPS insulation boards is 5.0 cm for both walls and roof in most of Indian climatic zones [31]. Accordingly, we introduced wall and roof insulation with 5.0 cm thick EPS boards into the parametric analysis.

Table 11 Building envelope energy savings measures.

Parameter	Reference	Improved options		U-value building element*(W/m^{2}K)*
		Denomination	Description	
Masonry material	Fired bricks	P1 P2	Hollow concrete blocks Aerated concrete blocks	1.10
External walls insulation (cm)	0.0	P3	5.0	
Roof insulation (cm)	0.0	P4	5.0	

2.4.2.2. Building equipment

Three variations to the building equipment were tested to reduce OE requirements: improvement of COP for A/C systems (efficiency); use of ceiling fans with A/C in the bedrooms (adaptability); and efficient lighting technology. For the high efficiency case, COP was set at 3.90, corresponding to an improvement of 20% over the current mandatory COP of 3.26. In addition, the use of fans increases the air velocity, which enables the A/C set-point to be increased by up to 2 degrees, as shown in other studies [66,67]. The ASHRAE 55-2013 standard [32] specifies an extension of the summer comfort zone with high air movement with velocities up to 0.8 m/s. The introduction of ceiling fans in bedrooms in addition to A/C was therefore modelled and the set-point temperature increased by 2 °C to obtain similar levels of PMV as in the *A/C only* case (Table 12). With regard to lighting, in the Reference case, we use 50 percent compact fluorescent lights and 50 percent LED. In the energy savings case, we use only LED.

Table 12 Design conditions for indoor thermal comfort in presence of A/C and fans in bedrooms.

Design set (bedroom)	Thermal comfort level	T_{op}* (°C)	Air velocity (m/s)	PMV	PPD (%)
A/C + Ceiling Fans	More stringent	25+2	0.8	0.03	5.0
	Reference	26+2	0.8	0.48	9.8
	Less stringent	27+2	0.8	0.94	23.7

2.4.3. LCE ranges for urban and rural housing

With the results of the parametric analysis, we generated ranges of LCE requirements for decent housing considering various contextual conditions and energy savings opportunities in India. We first present results for individual parameters for all archetypes and then combine variations on contextual conditions and energy saving to provide ranges per building archetype and climatic zone.

To summarize, this range encapsulates variations in the following contextual characteristics: climatic zones, building archetypes, dwelling size, construction methods, user behaviour, and energy savings measures for the building envelope and equipment. The option of affordable construction (see section 2.4.1.2) was included only for the single-storey archetype.

3. Results

3.1. Reference Case

3.1.1. Embodied energy

Results of the material amount and embodied energy analysis are shown in Figure 3. The mass intensity is higher for the single-storey building and shrinks with the increase in the number of storeys. Inert materials, such as fired bricks, concrete and cement-based materials, account for the biggest share of material mass intensity. The contribution of masonry is higher for archetypes with masonry structure (single-storey and two-storey) and less for the reinforced concrete framing structure (multi-storey). Conversely, reinforced concrete is the highest for the multi-storey archetype. Materials other than inert have a minor influence on results due to both lower densities and volumes in the construction.

Results of the EE intensity calculation show a similar trend compared to material mass intensities, namely that EE intensity decreases with the number of storeys and inert materials represent the bulk. However, the relative impact of reinforced concrete is significantly larger compared to material mass intensity due to its high EE intensity. Accordingly, the relative difference in intensity between the multi-storey archetype and the other two archetypes is lower for EE as compared to material mass.

Figure 3 Mass intensity and EE intensity per floor surface unit of different archetypes (reference case).

We compared the estimated EE intensities against similar studies for India [11,22,31,42,46] for validation purposes. Case studies from other works were classified according to the number of storeys, structure type (masonry structure with concrete roof, reinforced concrete framing) and type of masonry (high EE, e.g. fired bricks, and low EE, e.g. rubble stones). We find high agreement in the EE intensities for the same combination of housing type, structure and materials (Figure 4).

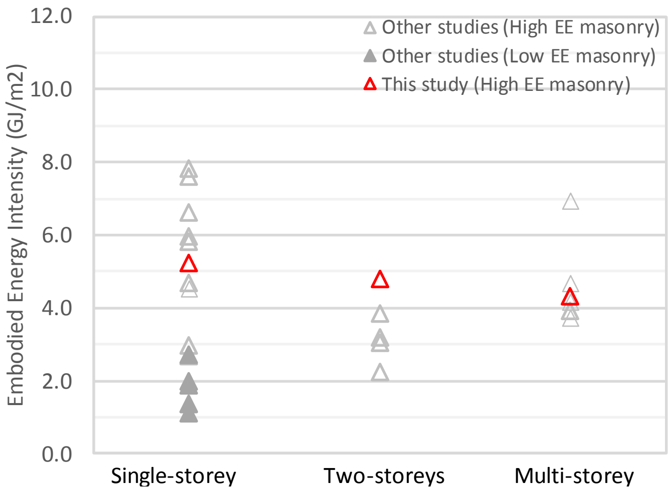

Figure 4 Comparison of embodied energy results (reference case) with other studies in literature.

3.1.2. Operational energy

Figure 5 shows the results of the OE calculation for different building archetypes and climatic zones. As with other studies [11], energy for space cooling and dehumidification dominates OE. The OE per floor surface unit is higher for the single-storey archetype and decreases for the two-storey and especially the multi-storey archetypes. This is because with more storeys, the shape of the multi-storey archetypes are more compact, thus reducing the heat exchange by transmission with the outdoor environment. Cooling and dehumidification loads are particularly large for warm-humid, composite and hot-dry climatic zones, due to more severe outdoor temperature and humidity conditions. Energy consumptions for heating are low or null in most of the climatic zones, with the exception of the cold zone where it contributes for 25-36% of the OE. Lighting contributes only to a minor portion of the total OE (6-13%).

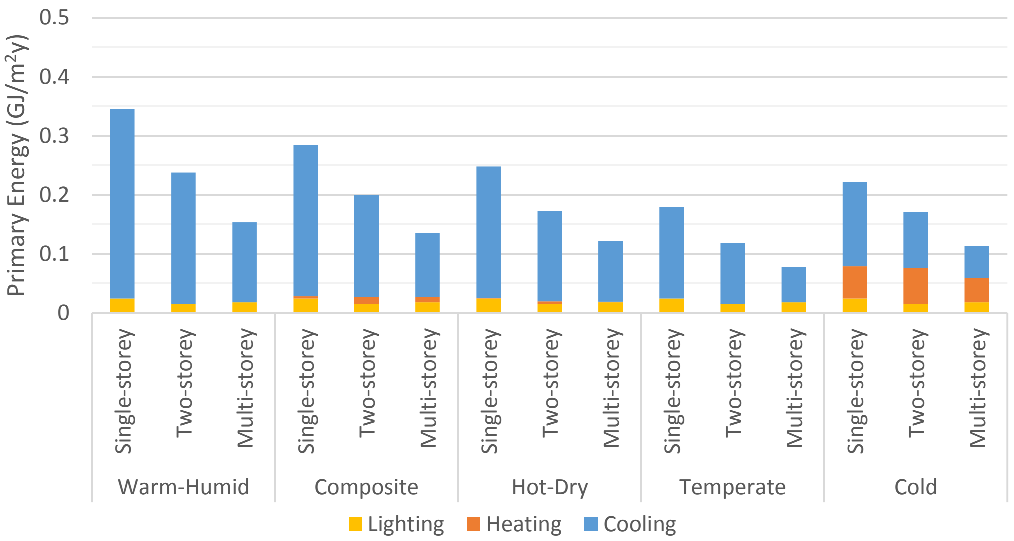

Figure 5 Operational energy need for different housing types and climatic zones in India (reference case).

Results of OE were compared in terms of final energy intensity with similar studies in literature, which typically have cases in composite climatic zones [11,31,42,46]. We found good agreement with OE as well (Figure 6). Notably, some of the past studies rely on measured energy consumption and a part on calculated energy consumption. Many authors underscore the potential overestimation of calculated energy consumption over measured values (see e.g. [54,68,69]) for assumptions on building characteristics and occupants related variables [70]. Our comparison seems to confirm this trend for other existing studies, as our results are generally placed in-between the two.

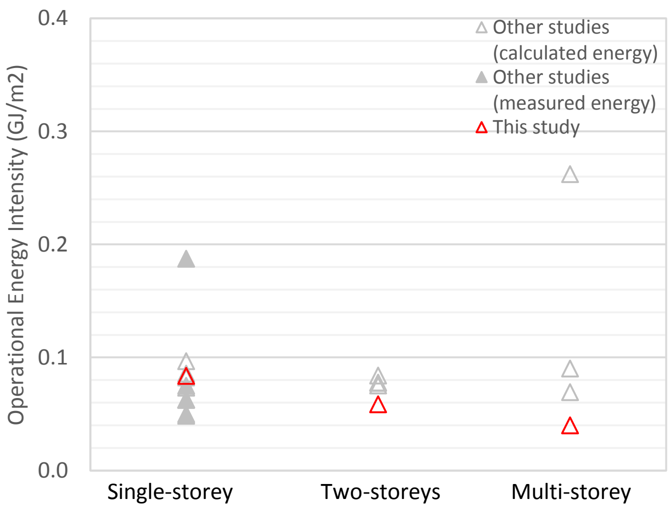

Figure 6 Comparison of operational energy results (reference case) with other studies in literature. Results for composite climate.

3.1.3. Life cycle energy

LCE requirements for buildings demonstrated significant variations across different building archetypes and climatic zones (see the Supplementary Material - Table SM2 for detailed results). The single-storey archetype showed the highest LCE intensities (0.43 GJ/m^{2}y for the composite climatic zone) as a result of higher EE and OE intensity. At the lower extreme stands the multi-storey archetype (0.23 GJ/m^{2}y) with the two-storey archetype in between (0.31 GJ/m^{2}y). The OE requirements drive differences across the climatic zones, causing the highest values to occur in the warm-humid climate and the lowest for the temperate climate.

The relative contributions of different life-cycle stages to the LCE were also analysed. The OE dominates the LCE of the single-storey archetype, ranging from 58% (temperate climate) to 72% (warm-humid climate). While the contribution of OE is lower for other archetypes, it exceeds the EE in almost all cases, being 55-71% for the two-storey archetype and 47-64% for the multi-storey archetype. The contribution of EE on the LCE is lower for climatic zones with more severe conditions (27-36% for the warm-humid climate, 32-39% for the composite climate) and higher for cold (36-43%) and temperate zones (42-53%).

3.2. Parametric analysis

3.2.1. Contextual conditions

3.2.1.1. Building geometry

Results of changes in dwelling size on EE and OE intensities are shown in Figure 7. EE intensities decrease slightly with dwelling size, more noticeably for the two-storey and multi-storey archetypes. For practical purposes, in comparison to OE in particular, one could consider EE as invariant to dwelling size, per archetype. On the other hand, OE intensities increase with dwelling size from

40 m^2 to 50 m^2 and 60 m^2, more significantly for the single-storey archetype. This effect can be explained by the addition of new bedrooms, which increase the relative weight of A/C cooling per m^2 of floor surface. The increase in OE intensities when reducing the dwelling size from 40 m^2 to 30 m^2 is due to the fact that living room and bedroom are merged in one room, resulting in an increased floor surface served by A/C (the operation schedules being equal). Nevertheless, the share of households with size below 4 persons is relatively low when looking at the national Indian distribution (see Supplementary Material - Figs. SM1-SM2), indicating that the required houses will be mostly of 40 m^2 or more and with lower energy intensity requirements.

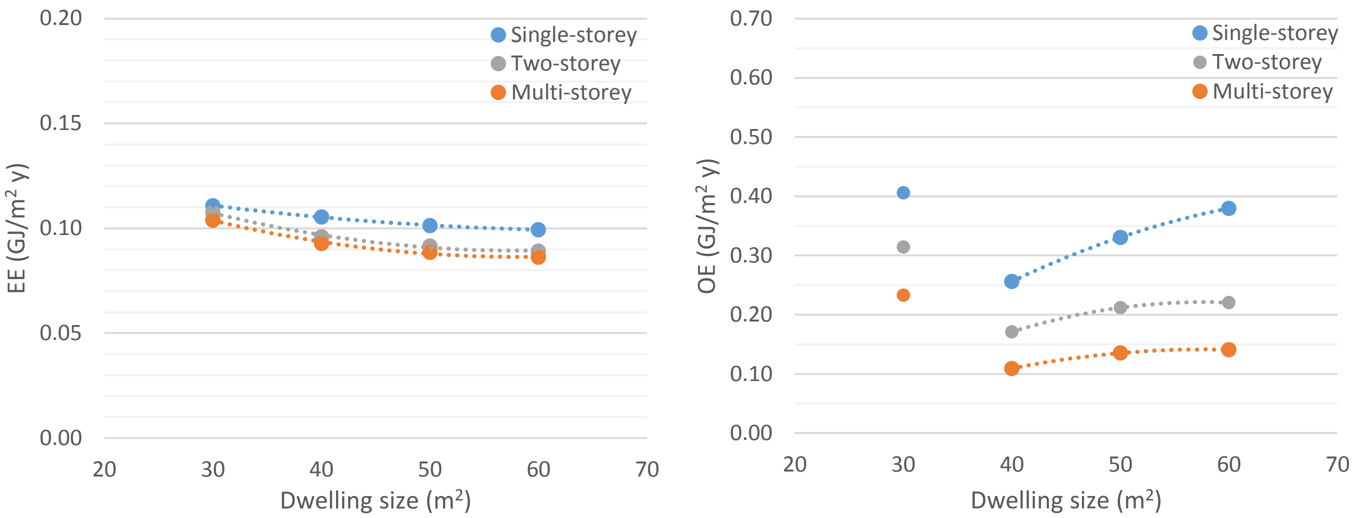

Figure 7 Influence of the dwelling size on the EE intensity (left) and OE intensity in composite climate (right) per floor surface unit.

3.2.1.2. Affordable building construction

Figure 8 shows the results of varying the set of construction materials from conventional (reference) to affordable solutions for the single-storey archetype. The EE intensity reduces significantly due the use of materials requiring a low amount of energy for production, such as rammed earth and wood. In contrast, OE intensity increases slightly as a result of higher U-values for the traditional envelope (reference A/C schedule). This shift is particularly evident for heating in the cold climatic zone. This effect is partially counterbalanced by the beneficial behaviour of the increased thermal mass provided by rammed earth walls in attenuating and delaying the cooling peak loads. Additional simulations run for extended A/C availability schedules (

Table 10) showed that the increase in cooling consumption compared to the reference case is even higher, leading to comparable LCE values. Thus, increased use of A/C during the daytime erodes the benefit of traditional materials in construction. The trade-off between the reduction in EE and increase in OE increase for affordable construction should be therefore carefully evaluated in context, as also confirmed by other studies for India [45].

Results of the cost calculation show that the conventional solution has a construction cost 25% higher than the affordable solution. However, this difference reduces to 8-21% when LCC are considered (construction and operational phase). The low (high) limit corresponds to a low (high) discount rate and an extended (reference) cooling schedule under composite climate conditions.. This difference shrinks further if affordable housing were to have a shorter life (e.g. 40 years), due to the reliance on unconventional materials, and would be negligible when considering low discount rate and extended schedules (see the Supplementary Material for detailed results).

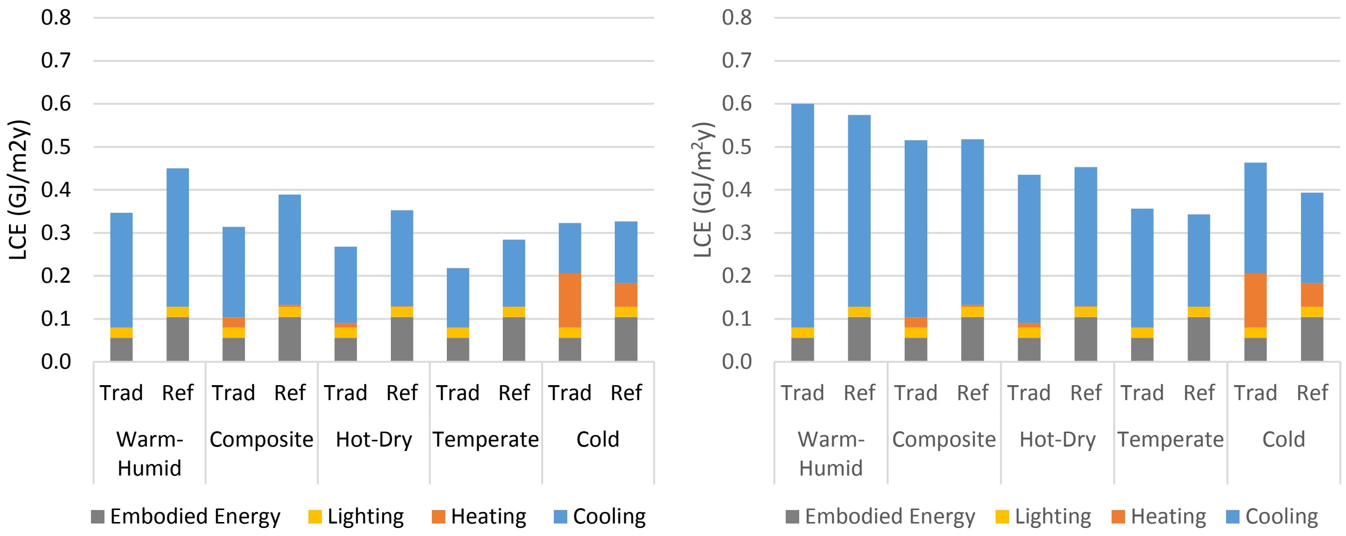

Figure 8 Comparison of the results for the one-storey archetype in the case of affordable construction (Trad) and reference (Ref) in different climatic zones and for different cooling schedules: reference (left) and extended (right). See Table 3 for building elements and components in the two cases and Table 10 for cooling schedules.

3.2.1.3. Building usage

Increasing the thermal comfort level (more stringent case) entails an increase in OE of 19-20% compared to the reference conditions in a composite climate (Table 13). Conversely, reducing the thermal comfort level (less stringent) results in a reduction of 13-14% in OE. The absolute amplitude of these variations is the largest for the single-storey archetype and the lowest for the multi-storey archetype, in proportion to the magnitude of their OE requirements.

The effect of extending the user schedule for A/C is even more remarkable. The OE increases by 42-68% in a composite climate. Reasons for such a significant increase lie in the additional hours of operation for A/C, but also in the higher temperatures that the living room experiences during the day (weekend) and the evening (all days). Similarly to previous studies [54], these results prove that the hours of A/C availability play a major role in the OE requirements of residential buildings in India, which should be further investigated by future studies.

Table 13 OE for cooling and dehumidification for different design conditions of indoor thermal comfort in bedrooms with A/C only (composite climate).

Archetype	Thermal comfort level	T_{op}* (°C)	RH (%)	OE cooling (GJ/m^2y)	OE difference with reference (GJ/m^2y)	(%)
Single-storey	More stringent	25	55	0.308	0.052	+20
	Reference	**26**	**60**	**0.256**	**-**	**-**
	Less stringent	27	65	0.220	-0.036	-14
Two-storey	More stringent	25	55	0.201	0.032	+19
	Reference	**26**	**60**	**0.169**	**-**	**-**
	Less stringent	27	65	0.140	-0.029	-13
Multi-storey	More stringent	25	55	0.131	0.022	+19
	Reference	**26**	**60**	**0.109**	**-**	**-**
	Less stringent	27	65	0.089	-0.020	-13

3.2.2. Energy savings measures

3.2.2.1. Building envelope

Results of the parametric analysis for energy saving measures implementation in a composite climate are shown in Figure 9. The diagrams report the difference in the results for each variation from the reference case. Changing the material for masonry from fired bricks to hollow concrete blocks (P1) entails a significant reduction in the EE of the three archetypes, while variations in the OE are smaller. Aerated concrete blocks (P2) are more effective in reducing the OE than hollow concrete blocks due to their lower conductivity. Nevertheless, the reduction in EE exceeds the decrease in OE associated with this measures for the single-storey and two-storey archetypes, while the reduction is comparable for the multi-storey archetype. In general, the implementation of aerated concrete blocks is more effective than hollow concrete blocks in attenuating the LCE intensity for the three archetypes in the reference case.

The insulation of external walls (P3) and roof (P4) entails an increase in EE, albeit small, as an effect of the additional insulation material required. In contrast, both measures entail a significant reduction in OE due to the reduction in heat exchange through the building envelope. Roof insulation is more effective in reducing the OE intensity of the single-storey archetype, while wall insulation yields the best results for the multi-storey archetype as a result of different surface extensions related to specific building shapes.

In general, the most effective measures to reduce the LCE of the single-storey and two-storey archetypes include roof insulation and replacement of fired bricks with lower EE materials. In the case of the multi-storey archetype, replacing fired bricks with aerated concrete blocks and insulating external walls are the measures with associated higher LCE savings.

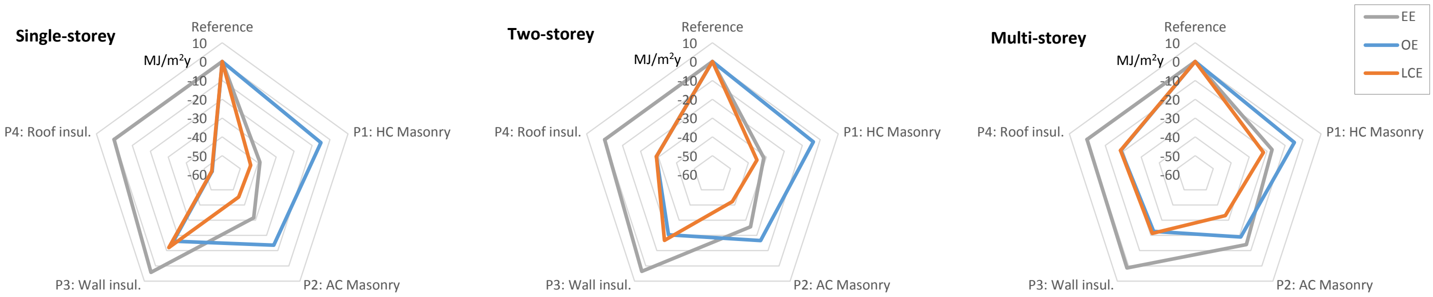

Figure 9 Results of the parametric analysis on the building envelope for the three archetypes (composite climate): difference with the reference case in EE, OE, and LCE for individual energy savings measures.

In addition to the analysis of individual measures on the LCE, combination of different measures was also tested. Interaction were detected, in particular in the combined effect of external wall materials and addition of insulation. In this case, a bigger reduction in EE is preferred for the masonry (instead of lower conductivity) as larger savings in OE are offered by the thermal insulation layer. Hollow concrete blocks are then preferred to aerated concrete blocks when used in combination with thermal insulation. We found that the best combination of measures includes hollow concrete masonry, wall insulation and roof insulation for all building typologies. This combination of measures entails energy savings in the range of 17% to 33% on the LCE depending on the archetype, being the minimum for the multi-storey building and the maximum for the single storey building (mainly as an effect of their different shape ratios).

3.2.2.2. Building equipment

Table 14 presents the results of the energy savings analysis for different measures on building equipment. Increasing the COP of the A/C system entails a major reduction in the total OE with a reduction of 12-17%. This measure is more effective when implemented for the single-storey archetype. The use of ceiling fans in combination with the A/C system and the consequent lowering of the set-point temperature provides energy savings in the measure of 4% of the total OE. Changing the lighting technology to full LED offers additional energy savings of 1-3% depending on the housing archetype.

Table 14 OE reduction potential for different energy savings measures on building equipment (composite climate).

Archetype	OE total (GJ/m^2y)	OE reduction COP A/C (GJ/m^2y)	Ceiling fans (GJ/m^2y)	Lighting (GJ/m^2y)
Single-storey	0.294	-0.050 (-17%)	-0.010 (-4%)	-0.004 (-1%)
Two-storey	0.208	-0.029 (-14%)	-0.008 (-4%)	-0.004 (-2%)
Multi-storey	0.135	-0,016 (-12%)	-0.006 (-4%)	-0.004 (-3%)

3.2.3. LCE ranges for decent housing in India

Here we present an overview of the range of LCE results grouped by parameters related to contextual conditions (Figure 10) and energy savings measures (Figure 11) separately. Both figures show the range of variation in LCE for each parameter individually and for all combined together, for each archetype, and just for the composite climate zone. Figure 12 shows the total range of variation for the three housing archetypes for all the climatic zones having fixed the dwelling size to 40 m^2.

Notably, among contextual conditions, the effects of users-related parameters are comparable to those of climatic conditions, and building and construction characteristics. In particular, indoor set-points for cooling-dehumidification and operation schedules for A/C have a key impact on the LCE intensity. The amplitude of the variations is generally the largest for the single-storey archetype and the lowest for the multi-storey archetype. The total range of uncertainty varying all contextual parameters is 0.20-1.29 GJ/m^2y for single-storey, 0.15-0.87 GJ/m^2y for two-storey and 0.12-0.67 GJ/m^2y for multi-storey buildings. Maximum values correspond to buildings in warm-humid climate, with 60 m^2 dwellings, high set-points and extended operation schedules. Minimum values refer to buildings in temperate climate, with 40 m^2 dwellings, low set-points and reference operation schedules. The maximum variation is higher than the sum of combined single parameters effect due to parameters interactions. In particular, the combination of severe climatic condition (warm-humid) with high set-points and extended schedules result in much higher energy consumption.

As shown in Figure 11, efficiency measures on the building envelope prove to be effective in reducing energy use for all archetypes. Regarding building equipment, improving the efficiency of the A/C system turned out to be the most effective action. Combining all measures on building envelope and equipment allows for significant energy savings. The best savings in LCE can be achieved for the single-storey archetype (-44%), followed by the two-storey archetype (-40%) and the multi-storey archetype (-37%). The total energy reduction is slightly lower than the sum of the single effects of individual measures due to their interaction (e.g. wall insulation and masonry type).

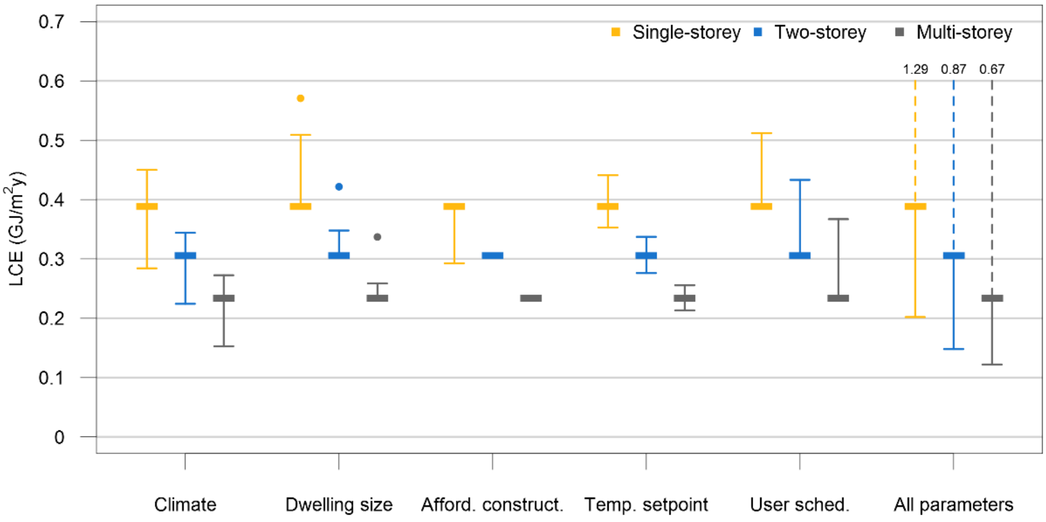

Figure 10 Results of the parametric analysis on contextual conditions. Note: marks indicate maximum, reference and minimum values; "·" denotes values for the archetypes with dwelling size 30 m^2.

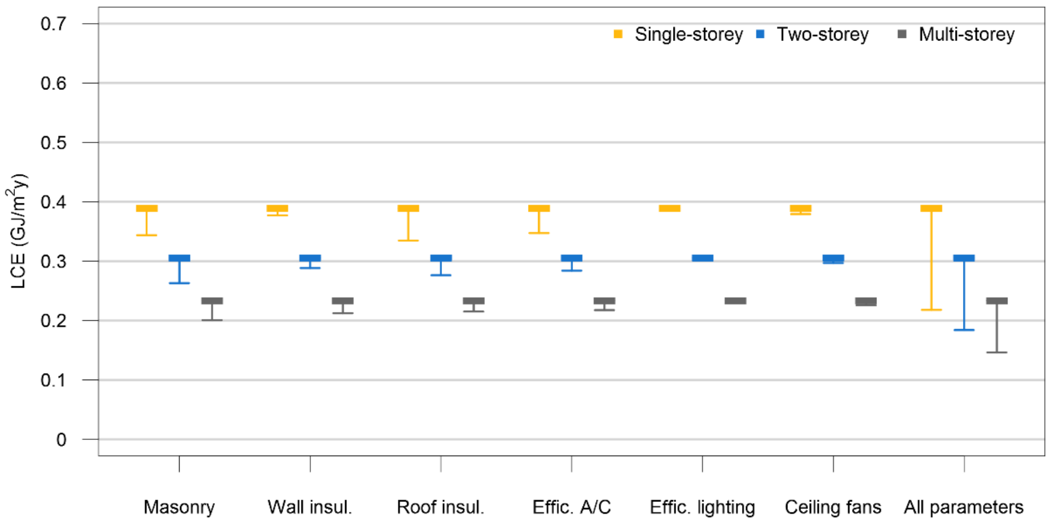

Figure 11 Results of the parametric analysis: energy savings measures. Note: marks indicate reference and minimum values.

The total range of LCE intensity (Figure 12), fixing the dwelling size at 40 m^2 while varying all other parameters, is between 0.19-0.61 GJ/m^{2}y for single-storey buildings, 0.15-0.58 GJ/m^{2}y for two-storey and 0.12-0.40 GJ/m^{2}y for multi-storey buildings. The range of variation is the lowest for multi-storey buildings and for temperate climatic zones. Conversely, the range of variation is the highest for single-storey buildings and warm-humid climatic zone.

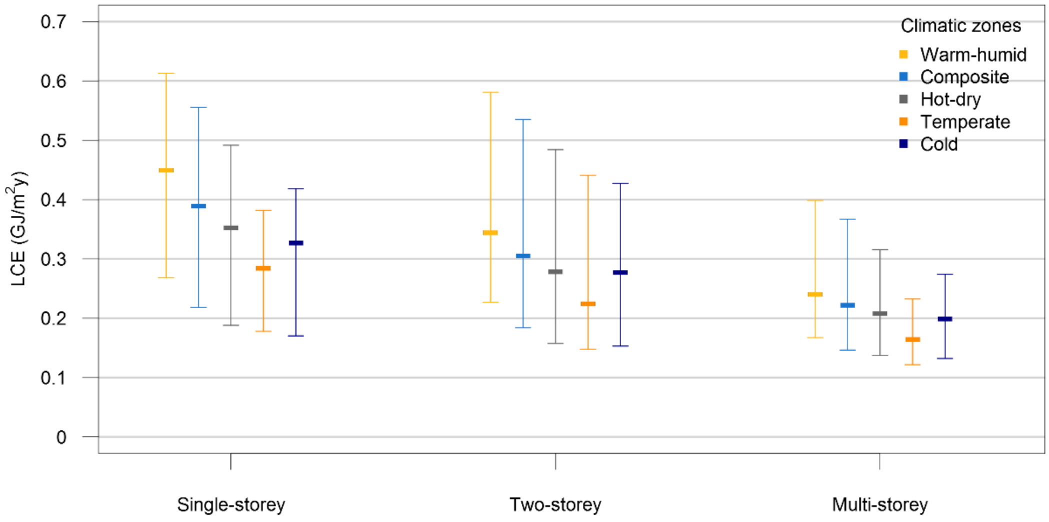

Figure 12 Ranges of LCE for different archetypes (Dwelling size 40 m^2). Note: marks indicate maximum, reference and minimum values.

4. Discussion

This paper applies LCE analysis for the first time to examine one core aspect of the resource implications of poverty eradication – estimating the energy needs for providing decent housing. The methodology, combining dynamic simulation of building operation with estimates of the related construction energy, provides ranges of LCE estimates for decent housing in India considering the potential for energy savings and important contextual conditions, such as climate and construction methods. The construction and use of building archetypes provides the flexibility to adapt and replicate the analysis to different contexts with limited additional computation effort.

The study has demonstrated the potential of using LCE for the holistic estimation of housing energy requirement encompassing several life cycle stages to provide everybody with decent housing. Using a dynamic energy model made it possible to comprehensively analyse the energy demand for heating, cooling, dehumidification and lighting, properly accounting for severe weather conditions, including humidity, while controlling the indoor thermal comfort level. The analysis confirmed that the OE requirements dominate the LCE in most of the Indian climatic zones when space cooling and dehumidification are considered. Nevertheless, the EE accounts for 27-53% of the LCE, depending on the building type and climate.

Parametric analysis captured uncertainty in LCE related to a number of contextual conditions and energy savings measures, different housing typologies and climatic conditions, in contrast to previous studies than typically provide single reference values. In particular, changing the size of the dwellings entails a modest decrease in the EE intensity and a moderate increase in OE intensity due to floor area expansion for bedrooms served by A/C. The affordable construction option for rural housing has a significantly lower EE compared to modern construction, however these benefits may be offset by increases in OE to the extent daytime cooling usage increases. On a lifecycle basis, the advantage of providing affordable construction reduces the more the need for cooling and the shorter the life of the building, Household behaviour, encompassing indoor set-points and schedules for cooling and dehumidification, emerged as one of the key influences on OE. The implementation of the selected energy savings measures for the building envelope can reduce the LCE by 17-33%. The additional implementation of building equipment measures further pushes the LCE savings potential to 37-44%, and should be therefore encouraged by decent housing policies.

A number of limitations of this study should be addressed in future work. The limitation in the number of archetype might result in missing typologies of buildings and consequent deviation of results. While the selected materials and building components reflect common choices in India, as documented in literature, local material availability and transportation distances might entail different choices and consequently EE requirements. Being masonry one of the major contributors to the EE of buildings in India, we limited the investigation of different material choices to this element in our parametric analysis. The choice of different material options depending on their availability and respective implication on the LCE requirements will be investigated in future work.

Uncertainty in the EE intensities of building materials and components should be also further addressed. While we used EE values specific for India, different production processes for specific regions might influence the results. Application to other contexts with limited data availability could be overcome by considering international databases and possible adaptations to improve their consistency with local specificities.

Regarding the OE evaluation, one of the major barriers lies in the validation of results due to the limited availability of measured energy records and potential differences in the current pattern of consumption compared to the decent living standard. Whilst we took into account a wide range of variations for the parametric analysis, additional investigation would be needed to take into account other aspects, e.g. location-specific parameters for buildings, including shading from neighbouring buildings and orientation. In addition, future climate change and energy mix variation should be considered in the development of future scenario.

Finally, the cost and environmental dimensions are of paramount importance in relation to decent housing development policies. Although a thorough economic analysis is beyond the scope of this paper, we recommend the coupling of LCE and LCC analysis for future studies in order to foster an informed knowledge for policy decision. The environmental impact of decent housing, including carbon emissions and other potential burdens, should also be addressed in future studies for a better understanding of the implications on environmental sustainability.

Despite these limitations, this study provides a first estimation of the LCE requirements for decent housing in India, and contributes insights on design features that can support policies for sustainable and affordable housing in developing countries.

5. Conclusions

We developed a generic methodology for the estimation of LCE requirements to provide everybody with decent housing in developing countries. The methodology includes the operationalization of a decent housing standard, development of building archetypes, calculation of LCE requirements and parametric analysis to investigate the effect of different contextual conditions and energy savings measures.

Results show that LCE can significantly vary depending on climatic conditions, building typology, construction materials, technical equipment for space cooling-dehumidification and user behaviour. Significant energy savings up to -44% of the LCE can be achieved by implementing low embodied energy materials, building envelope insulation, ceiling fans usage and improved energy efficiency of air-conditioning systems.

This study shows the suitability of the developed methodology in providing reference LCE values and ranges to support policies aiming at both covering housing gaps and eliminating poor housing conditions. Future developments include the application of the methodology to other developing countries, the expansion of the methodology to extrapolate results at the country scale by considering housing gaps and the development of future scenarios for decent housing provision.

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References

[1] United Nations Centre for Human Settlements (Habitat), The Habitat Agenda - Istanbul Declaration on Human Settlements, (2001). http://www.un.org/ga/Istanbul+5/declaration.htm.

[2] J. Bredenoord, P. van Lindert, P. Smets, Affordable housing in the urban global south, Routledge, 2014.

[3] UN Habitat, Sustainable Housing for Sustainable Cities: A Policy framework for Developing Countries, 2012.

[4] P. Chastas, T. Theodosiou, D. Bikas, Embodied energy in residential buildings-towards the nearly zero energy building: A literature review, Build. Environ. 105 (2016) 267–282. doi:10.1016/j.buildenv.2016.05.040.

[5] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review, Renew. Sustain. Energy Rev. 29 (2014) 394–416. doi:10.1016/j.rser.2013.08.037.

[6] C.K. Chau, T.M. Leung, W.Y. Ng, A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings, Appl. Energy. 143 (2015) 395–413. doi:10.1016/j.apenergy.2015.01.023.

[7] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: A critical review, Renew. Sustain. Energy Rev. 67 (2017) 408–416. doi:10.1016/j.rser.2016.09.058.

[8] T. Ramesh, R. Prakash, K.K.K. Shukla, Life cycle energy analysis of buildings: An overview, Energy Build. 42 (2010) 1592–1600. doi:10.1016/j.enbuild.2010.05.007.

[9] M.M. Khasreen, P.F.G. Banfill, G.F. Menzies, Life-cycle assessment and the environmental impact of buildings: A review, Sustainability. 1 (2009) 674–701. doi:10.3390/su1030674.

[10] C. Peng, Calculation of a building’s life cycle carbon emissions based on Ecotect and building information modeling, J. Clean. Prod. 112 (2016) 453–465. doi:10.1016/j.jclepro.2015.08.078.

[11] T. Ramesh, R. Prakash, K. Kumar Shukla, Life Cycle Energy Analysis of a Multifamily Residential House: A Case Study in Indian Context, Open J. Energy Effic. 2 (2013) 34–41. doi:10.4236/ojee.2013.21006.

[12] R.A. Mangkuto, M. Rohmah, A.D. Asri, Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics, Appl. Energy. 164 (2016) 211–219. doi:10.1016/j.apenergy.2015.11.046.

[13] B. Wittstock, J. Gantner, K.L.T. Saunders, J. Anderson, C. Carter, Z. Gyetvai, J. Kreißig, A.B.S. Lasvaux, B. Bosdevigie, M. Bazzana, N. Schiopu, E. Jayr, S. Nibel, J. Chevalier, J.H.P. Fullana-i-Palmer, C.G.J.-A. Mundy, T.B.-W.C. Sjostrom,

EeBGuide Guidance Document Part B: BUILDINGS , Oper. Guid. Life Cycle Assess. Stud. Energy-Efficient Build. Initiat. (2012) 1–360. http://www.eebguide.eu/eebblog/wp-content/uploads/2012/10/EeBGuide-B-FINAL-PR_2012-10-29.pdf%5Cnpapers2://publication/uuid/08A1A363-8E01-4CBB-B710-4ADBDFB14EBB.

[14] H. Djamila, C.M. Chu, S. Kumaresan, Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia, Build. Environ. 62 (2013) 133–142. doi:10.1016/j.buildenv.2013.01.017.

[15] Q.J. Kwong, N.M. Adam, B.B. Sahari, Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: A review, Energy Build. 68 (2014) 547–557. doi:10.1016/j.enbuild.2013.09.034.

[16] Z. Lin, S. Deng, A study on the characteristics of nighttime bedroom cooling load in tropics and subtropics, Build. Environ. 39 (2004) 1101–1114. doi:10.1016/j.buildenv.2004.01.035.

[17] R. Bassiouny, N.S. Korah, Studying the features of air flow induced by a room ceiling-fan, Energy Build. 43 (2011) 1913–1918. doi:10.1016/j.enbuild.2011.03.034.

[18] A. Mastrucci, A. Marvuglia, U. Leopold, E. Benetto, Life Cycle Assessment of building stocks from urban to transnational scales: A review, Renew. Sustain. Energy Rev. 74 (2017) 316–332. doi:10.1016/j.rser.2017.02.060.

[19] W. Yang, N. Kohler, Simulation of the evolution of the Chinese building and infrastructure stock, Build. Res. Inf. 36 (2008) 1–19. doi:10.1080/09613210701702883.

[20] A. Afshari, C. Nikolopoulou, M. Martin, Life-Cycle Analysis of Building Retrofits at the Urban Scale—A Case Study in United Arab Emirates, Sustainability. 6 (2014) 453–473. doi:10.3390/su6010453.

[21] X. Zhu, J. Pan, Energy requirements for satisfying basic needs: China as a case for illustration, Chinese Acad. Soc. Sci. (2007) 77.

[22] D. Bansal, R. Singh, R.L. Sawhney, Effect of construction materials on embodied energy and cost of buildings - A case study of residential houses in India up to 60 m2 of plinth area, Energy Build. 69 (2014) 260–266. doi:10.1016/j.enbuild.2013.11.006.

[23] J.S. Paulsen, R.M. Sposto, A life cycle energy analysis of social housing in Brazil: Case study for the program "mY HOUSE MY LIFE," Energy Build. 57 (2013) 95–102. doi:10.1016/j.enbuild.2012.11.014.

[24] J.E. Ramsdell, L.W. Burkett, C.R. Davis, R.D. Neri, E. Jacobs, J.J.P. Verster, Value of Energy Efficiency Improvements for Low-Income Housing in Developing Countries, Energy Procedia. 78 (2015) 1021–1026. doi:10.1016/j.egypro.2015.11.050.

[25] X. Hu, W. Zhu, Analysis of application of external wall thermal insulating technology in affordable housing in tonglu county, Energy Procedia. 14 (2012) 488–492. doi:10.1016/j.egypro.2011.12.963.

[26] P. Tiwari, J. Rao, J. Day, Development Paradigms for Urban Housing in BRICS Countries, 2016. doi:10.1057/978-1-137-44610-7.

[27] N.D. Rao, J. Min, Decent Living Standards : material prerequisites for human wellbeing, IIASA Work. Pap. (2017). doi:10.1007/s11205-017-1650-0.

[28] N.D. Rao, P. Baer, “Decent Living” emissions: A conceptual framework, Sustainability. 4 (2012) 656–681. doi:10.3390/su4040656.

[29] Bureau of Indian Standards, National Building Code of India 2005, 2005.

[30] G. of I. Building Materials and Technology Promotion Council Ministry of Housing & Urban Poverty AUeviation, Vulnerability Atlas of India, (2006).

[31] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle energy analysis of a residential building with different envelopes and climates in Indian context, Appl. Energy. 89 (2012) 193–202. doi:10.1016/j.apenergy.2011.05.054.

[32] American Society of Heating Ventilation Refrigerating and Air Conditioning Engineers, ANSI/ASHRAE/IES Standard 55-2010. Thermal environmental conditions for human occupancy., (2010).

[33] ISO, International Standard ISO 7730:2005 - Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, (2005).

[34] CEN, European standard EN 15251:2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, (2007).

[35] F. Nicol, Adaptive thermal comfort standards in the hot-humid tropics, Energy Build. 36 (2004) 628–637. doi:10.1016/j.enbuild.2004.01.016.

[36] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, Renew. Sustain. Energy Rev. 13 (2009) 1819–1835. doi:10.1016/j.rser.2008.09.033.

[37] M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfeld, Z. Stevanovic, M. Djurovic-Petrovic, A review of bottom-up building stock models for energy consumption in the residential sector, Build. Environ. 45 (2010) 1683–1697.

[38] S. Moffatt, Stock Aggregation. Methods for Evaluating the Environmental Performance of Building Stocks, 2004. http://www.iisbe.org/annex31/index.html.

[39] A. Kumar, World Housing Encyclopedia. Housing report N.22 (India) - Unreinforced brick masonry walls with pitched clay tile roof (Last consulted: February 2017), (n.d.). http://db.world-housing.net/building/22/.

[40] A.A. Khan, M. Khalid, World Housing Encyclopedia N.20 (India) - Unreinforced brick masonry with flat roof (Last consulted: February 2017), (n.d.). http://db.world-housing.net/building/20/.

[41] R. Sinha, S. Brzev, World Housing Encyclopedia. Housing report N.21 (India) - Unreinforced brick masonry building with reinforced concrete roof slab. (Last consulted: February 2017), World Hous. Encycl. (n.d.). http://db.world-housing.net/building/21/.

[42] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle approach in evaluating energy performance of residential buildings in Indian context, Energy Build. 54 (2012) 259–265. doi:10.1016/j.enbuild.2012.07.016.

[43] D. Bansal, (Single Storied) Up to 50 Sqm Plinth area 3 . Embodied Energy Values for Materials of Construction, (2010) 13–14.

[44] IHSN - International Household Survey Network, India - National Sample Survey 2011-2012 (68th round) - Schedule 1.0

(Type 1) - Consumer Expenditure, (2013). http://catalog.ihsn.org/index.php/catalog/3281.

[45] K.I. Praseeda, M. Mani, B.V.V. Reddy, Assessing impact of material transition and thermal comfort models on embodied and operational energy in vernacular dwellings (India), Energy Procedia. 54 (2014) 342–351. doi:10.1016/j.egypro.2014.07.277.

[46] K.I. Praseeda, B.V.V. Reddy, M. Mani, Embodied and operational energy of urban residential buildings in India, Energy Build. 110 (2016) 211–219. doi:10.1016/j.enbuild.2015.09.072.

[47] Ecoinvent Centre, The ecoinvent 3 database, (n.d.). http://www.ecoinvent.org/database/database.html.

[48] B. V. Venkatarama Reddy, K.S. Jagadish, Embodied energy of common and alternative building materials and technologies, Energy Build. 35 (2003) 129–137. doi:10.1016/S0378-7788(01)00141-4.

[49] A. Debnath, S.V. Singh, Y.P. Singh, Comparative assessment of energy requirements for different types of residential buildings in India, Energy Build. 23 (1995) 141–146. doi:10.1016/0378-7788(95)00939-6.

[50] U.S. Department of Energy’s (DOE), EnergyPlus Documentation, v. 8.5, (2016). https://energyplus.net/.

[51] National Laboratory of the U.S. Department of Energy NREL, Open Studio 1.12.0 User Documentation, (2016). https://nrel.github.io/OpenStudio-user-documentation/.

[52] Y. Zhang, CIBSE ASHRAE Technical Symposium, Imperial College, London UK – 18 and 19 April 2012, CIBSE ASHRAE Tech. Symp. (2012) 1–12.

[53] Indian Society of Heating Refrigerating and Air-Conditioning Engineers (ISHRAE), Indian Weather Data, (2005). https://energyplus.net/weather.

[54] R. Rawal, Y. Shukla, Residential Buildings in India : Energy Use Projections and Saving Potentials, Gbpn. (2014).

[55] Indian Society of Heating Refrigerating and Air-Conditioning Engineers (ISHRAE), Indian Weather Data, (2005).

[56] Bureau of Energy Efficiency, Schedule – 3 (A) Room Air Conditioners, 3 (2006) 1–15.

[57] N. Yamtraipat, J. Khedari, J. Hirunlabh, Thermal comfort standards for air conditioned buildings in hot and humid Thailand considering additional factors of acclimatization and education level, Sol. Energy. 78 (2005) 504–517. doi:10.1016/j.solener.2004.07.006.

[58] J.W. Wan, K. Yang, W.J. Zhang, J.L. Zhang, A new method of determination of indoor temperature and relative humidity with consideration of human thermal comfort, Build. Environ. 44 (2009) 411–417. doi:10.1016/j.buildenv.2008.04.001.

[59] A. Kumar, World Housing Encyclopedia. Housing report N.23 (India) - Rural mud house with pitched roof. (Last consulted: February 2017), (n.d.). http://db.world-housing.net/building/23/.

[60] S. Geng, Y. Wang, J. Zuo, Z. Zhou, H. Du, G. Mao, Building life cycle assessment research: A review by bibliometric analysis, Renew. Sustain. Energy Rev. 76 (2017) 176–184. doi:10.1016/j.rser.2017.03.068.

[61] P. Moran, J. Goggins, M. Hajdukiewicz, Super-Insulate or use Renewable Technology? Life Cycle Cost, Energy and Global Warming Potential Analysis of Nearly Zero Energy Buildings (NZEB) in a Temperate Oceanic Climate, Energy Build. 139 (2017) 590–607. doi:10.1016/j.enbuild.2017.01.029.

[62] F. Stazi, E. Tomassoni, C. Bonfigli, C. Di Perna, Energy, comfort and environmental assessment of different building envelope techniques in a Mediterranean climate with a hot dry summer, Appl. Energy. 134 (2014) 176–196. doi:10.1016/j.apenergy.2014.08.023.

[63] J. Nässén, F. Hedenus, S. Karlsson, J. Holmberg, Concrete vs. wood in buildings - An energy system approach, Build. Environ. 51 (2012) 361–369. doi:10.1016/j.buildenv.2011.11.011.

[64] B. Kursun, B.R. Bakshi, M. Mahata, J.F. Martin, Life cycle and emergy based design of energy systems in developing countries: Centralized and localized options, Ecol. Modell. 305 (2015) 40–53. doi:10.1016/j.ecolmodel.2015.03.006.

[65] American Society of Heating Ventilation Refrigerating and Air Conditioning Engineers, ASHRAE Standard 62.1-2013 - Ventilation for Acceptable Indoor Air Quality, (2013).

[66] Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens, Q. Meng, Human comfort and perceived air quality in warm and humid environments with ceiling fans, Build. Environ. 90 (2015) 178–185. doi:10.1016/j.buildenv.2015.04.003.

[67] Y. Zhu, M. Luo, Q. Ouyang, L. Huang, B. Cao, Dynamic characteristics and comfort assessment of airflows in indoor environments: A review, Build. Environ. 91 (2015) 5–14. doi:10.1016/j.buildenv.2015.03.032.

[68] A.G. Entrop, H.J.H. Brouwers, A.H.M.E. Reinders, Evaluation of energy performance indicators and financial aspects of energy saving techniques in residential real estate, Energy Build. 42 (2010) 618–629. doi:10.1016/j.enbuild.2009.10.032.

[69] R. Nouvel, A. Mastrucci, U. Leopold, O. Baume, V. Coors, U. Eicker, Combining GIS-based statistical and engineering urban heat consumption models: Towards a new framework for multi-scale policy support, Energy Build. 107 (2015). doi:10.1016/j.enbuild.2015.08.021.

[70] A. Strzalka, J. Bogdahn, V. Coors, U. Eicker, 3D city modeling for urban scale heating energy demand forecasting, HVAC&R Res. 17 (2011) 37–41. doi:10.1080/10789669.2011.582920.