Review of urban building types and their energy use and carbon emissions in life-cycle analyses from low-and-middle income countries

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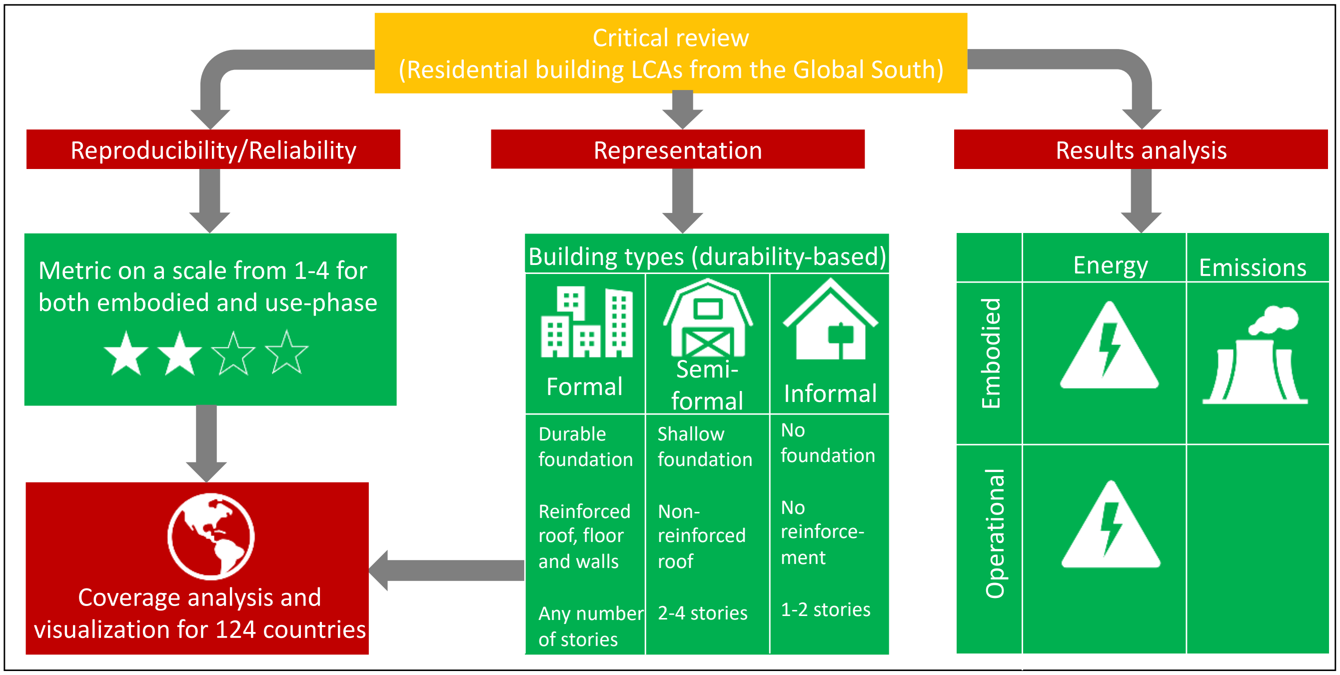
VISUAL ABSTRACT



ABSTRACT

Urbanization, slum redevelopment and population growth will lead to unprecedented levels of residential building construction in 'low-and-middle income' (LMI) countries in the coming decades. However, less than 50% of previous residential building life-cycle assessment (LCA) reviews included LMI countries. Moreover, all reviews that included LMI countries only considered formal (cement-concrete) buildings, while more than 800 million people in these countries lived in informal settlements. We analyze LCA literature and define three building types based on durability: formal, semi-formal and informal. These exhaustively represent residential buildings in LMI countries. For each type, we define dominant archetypes from across the world, based on construction materials. To address the data-deficiency and lack of transparency in LCA studies, we develop a reproducibility metric for building LCAs. We find that the countries with the most reproducible studies are India, Sri-Lanka, Turkey, Mexico, and Brazil. Only 7 out of 54 African countries have reproducible studies focused on either the embodied or use-phase.

Maintenance, refurbishment, end-of-life are included in hardly any studies in the LMI LCA literature. Lastly, we highlight the necessity for studying current, traditional buildings to provide a benchmark for future studies focusing on energy and material efficiency strategies.

INTRODUCTION

According to the conservative benchmark of the low energy demand (LED) scenario, the total residential floorspace in the world is expected to increase from 180 to 260 billion m^2 between 2020-2050[1]. In the shared socioeconomic pathways' SSP1 and SSP2 scenarios, floor space is expected to grow to between 1.5 and 2 times the LED level by 2050[2]. Globally, residential and non-residential buildings have accounted for approximately 35% of final energy consumption and 38% of total direct and indirect CO_2 emissions[3–6]. Residential building energy consumption constituted about 62% of the global building energy consumption[6]. Modern residential buildings contain greenhouse gas (GHG) intensive materials like cement, steel, and concrete[7,8]. Older buildings had less effective insulation and higher air infiltration, increasing energy demand for thermal comfort[9]. The overall importance of the sector for GHG mitigation and energy savings makes it essential to study contemporary residential buildings and possible GHG reduction and energy efficiency strategies. This review proposes ways to streamline this process, by identifying building types, evaluating data availability, and assessing literature quality for previously underrepresented developing regions.

The 135 low-and-middle income (LMI) countries defined by the World Bank, which populate the Global South were home to 81% of the world population in 2020, and are expected to house an estimated 87% of the world population by the end of the century[10–12]. Three of the top ten GHG emitting countries in the world were LMI countries in 2015[13]. While these statistics included China, which may soon be a high-income country, most population growth and consequently residential building construction in the future is expected to take place in South Asia and Africa [14]. One important concern is to provide this growing population with sustainable and durable shelter that meets decent living standards[15]. This will cause significant growth in residential building construction and material and energy demand from the sector[16]. However, there is opportunity to introduce energy and material efficient buildings to contain this increase, as most LMI countries do not suffer from the technological lock-in represented by a large building stock as high-income (also known as developed or industrialized) countries do[17].

Up to 50% of total energy demand in LMI parts of the world stemmed from the residential sector in 2015[13,18]. This was due to two major factors: the fossil-fuel heavy primary fuel mix in residential buildings and the relatively smaller size of other industries[13,18]. Energy intensive buildings are usually concentrated in urban areas, as with high-income countries, but the LMI cities look different. They consist of a range of buildings beyond the usual formal (cement-concrete) buildings, including informal settlements. The proportion of the urban population living in informal settlements worldwide declined from 39% to 30% between 2000 to 2014, but the total numbers increased as LMI countries urbanized[19]. In 2018, more than 1 billion people lived in informal settlements, of which around 800 million lived in LMI countries[19].

Approximately 3 billion people are projected to need access to adequate, affordable and comfortable housing by 2030[20]. Since a majority of these people are in hot, tropical LMI countries, cooling is the fastest growing use of energy, and is expected to drive peak energy demand[21]. Inability to afford energy-intensive cooling appliances and inefficient building envelopes makes residents of informal buildings in LMI countries especially susceptible to heat stress, and necessitate a deeper study into thermal comfort with respect to the energy demand and emissions from residential buildings [22–25].

LIFE-CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a tool used to estimate energy and environmental impacts from the entire lifespan of a product or system. For residential buildings, this includes the production of building materials and components, construction, operation, and end-of-life as described in Figure 1. Production and construction-related impacts are included in the embodied, grey, or upstream impacts, which are further divided into steps (A1-A5) as specified in Fig. 1[18,26]. Operational or use phase (B1-B5) includes all the processes when the building is inhabited by tenants[26]. Maintenance and refurbishment of the building are also included in the use-phase. End-of-life (C1-C4) refers to the impacts from the demolition, and waste disposal after the use-phase of the building is completed[26]. Considering the life-cycle impact is necessary because it includes and compares cumulative effects from the lifetime of buildings, their materials, construction, and use-phase appliances. LCA is used to compare different energy or material efficiency interventions in the product life cycle. In some cases, a scenario may have low embodied impacts but high use-phase impacts, or vice versa, and the LCA approach ensures that all these effects are considered.

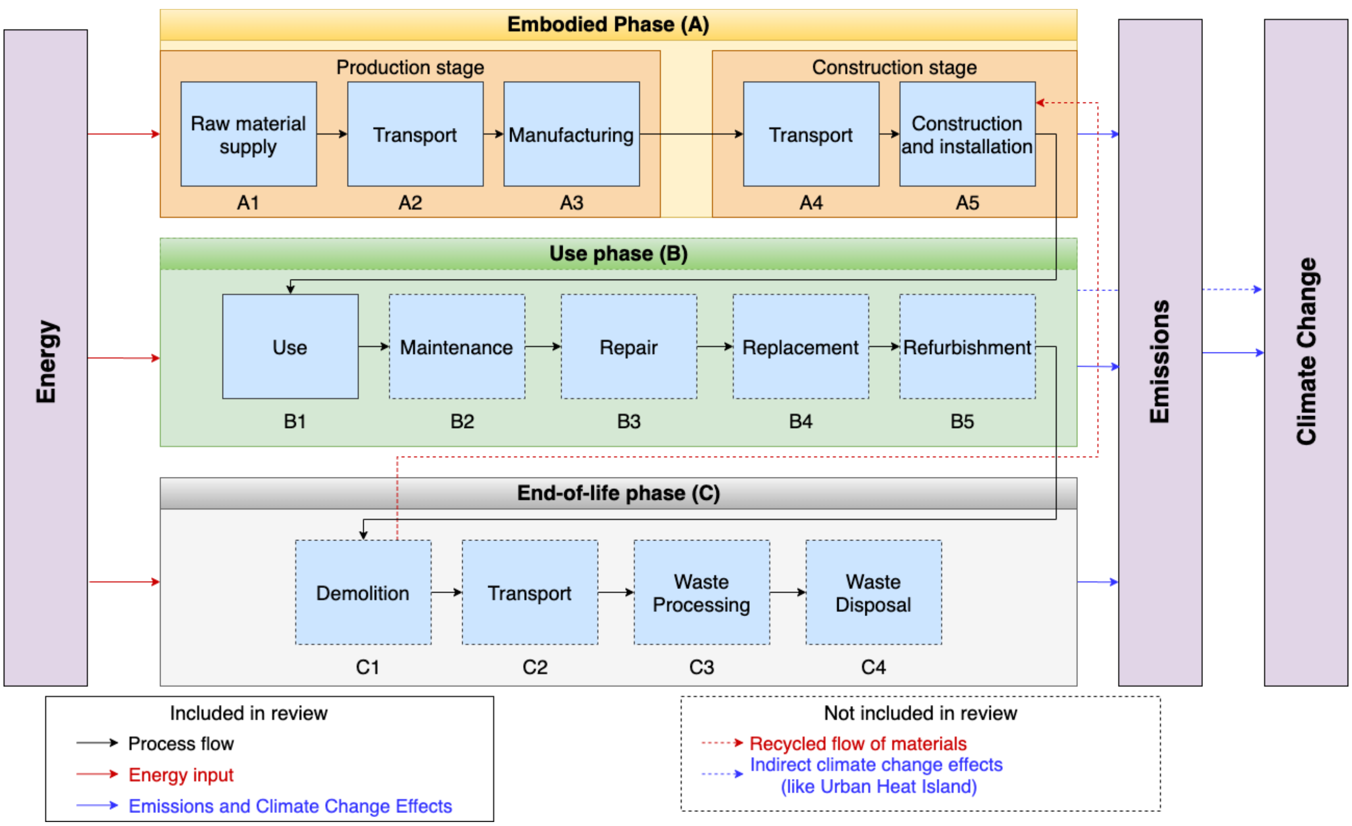


Figure 1. Life-cycle assessment phases for a residential building. [26]

Lately, a number of global scenario studies have focused on residential buildings and investigated their life-cycle energy demand and emissions[16,27,28]. These models and studies often used LCA literature to parametrize representative buildings. This is because LCA studies contain information regarding materials and construction-related impacts, which are not included in most other building studies. In most reports, LMI buildings were crudely represented by adaptations of industrialized-country archetypes [27,29]. These global studies did not fully account for diversity in building type and usage parameters, and primarily focused on urban formal buildings[30], possibly resulting in a misrepresentation of their characteristics. This review investigates whether existing LCAs from LMI countries can provide better information for such global models and identifies gaps in this literature. We focus on LCA literature, as the characteristics we use to classify buildings depend upon several parameters usually only contained in LCAs.

Previous reviews of residential building LCA often did not include LMI countries, and if they did, they only included China, India, and Brazil. This review is undertaken with a goal to fill this gap. Residential buildings in LMI countries are different and more diverse than those in high-income countries. To capture these features, this paper characterizes types of buildings in LMI countries. Are there common characteristics that can be used to create representative types of buildings? What do we know about their embodied energy and use-phase energy? Are studies reliable and transparent and can we use them to represent these buildings in future global studies? We begin to answer these critical questions in this review. We discuss previous review papers, their findings and gaps in literature in our "Synthesis of previous studies" section. We then detail our methods in collecting, analyzing and classifying literature in the "Review methodology" section. We expound on important results in the "Results" section, and discuss major takeaways and future steps in the "Discussion" section.

SYNTHESIS OF PREVIOUS STUDIES

Residential building LCAs have been reviewed in the past on a global scale, but none with a specific focus on LMI countries. Previous studies and reviews recognized the lack of building LCA literature in LMI countries compared to high-income countries[31,32]. Notably, Geng et.al (2017) found that most countries in the African continent had no building LCA studies, India and Brazil had between 10 to 50 studies, China had between 100 to 150 studies, while the US was the focus of more than 400 building LCA studies [33].

When comparing the scope of previous residential building LCA reviews, we found some significant gaps: five out of twelve studied only residential buildings from high-income countries [31,34–37], six of the others considered a maximum of five LMI countries [32,38–42], and only one had a more global scope [43]. Many of these studies found that use-phase was the largest portion of residential building energy demand and environmental impacts [32,35,37,41]. Table 1 lists some relevant review papers since 2010, and their findings.

Table 1. Overview of some salient review papers since 2010

Reference	Countries included	Focus	Findings	Research gaps identified
Ramesh et. al (2010) [32]	High-income countries, India, Thailand and China	All LCA phases, energy demand	Included residential and non-residential buildings Operational phase was 80-90% of life-cycle energy demand Comparison of passive and active technologies to reduce energy demand	Identified lack of building LCAs from LMI countries, and the general bias towards colder countries
Buyle et. al (2013) [41]	High-income countries, India, China, Argentina	All phases, energy demand and other environmental impacts	Heating and/or cooling were the primary drivers in the use-phase causing 90% of total environmental impacts	LCAs need to focus on all phases, new materials and consider economic issues while also being more transparent with data
Karimpour et. al (2014) [38]	High-income countries and India	All LCA phases, energy demand	Reevaluated the importance of embodied energy in the life cycle energy demand of buildings	Highlighted the need for a regional approach to finding energy

				efficient strategies for residential buildings
Cabeza et. al (2014) [43]	Global	All LCA phases, energy, cost, carbon footprint and environmental impacts	Summarized literature on LCAs that study energy demand and carbon footprint for buildings and related industrial sectors	Showed that most LCAs were carried out in "exemplary" buildings, but not in "traditional" buildings Also, most studies were based on urban buildings, and rural buildings are not as widely researched LCAs were not distributed equally across the globe, and were most frequently focused on high-income countries
Chau et. al (2015) [36]	High-income countries only	Functional units of LCAs focused on energy demand, carbon impacts	Looked at LCA studies, and found that shares of different life cycle stages are generally consistent	Commented on the lack of consistency with functional units, goal, scope, boundaries of LCAs
Islam et. al (2015) [35]	High-income countries only	All LCA phases, GHG, water waste	Maximum energy demand, GHG emissions came from the operational or use-phase, and	All values except solid waste changed due to several

		and solid waste	maximum water was used in embodied stage, while most solid waste was generated in the EoL	external factors like maintenance strategy, lifespan and transportation distance
Rashid et. al (2015) [37]	High-income countries only	All phases, energy demand	Use-phase was the largest contributor to life-cycle energy demand	Standardized LCA methodology was needed to create a robust database Functional units changed results
Saynajoki et. al (2017) [44]	High-income countries, China and Turkey	Embodied phase	Looked into 47 relevant articles Differentiated different types of LCAs, and compared results between process LCAs, IO LCAs and Hybrid LCAs	Commented on variability between results of LCAs even while studying similar buildings – due to different scopes, functional units – and lack of policy benefits from existing studies
Finnegan et. al (2018) [39]	High-income countries, India	Embodied energy and carbon	Study of sustainable technologies in construction of buildings Discussed the inaccuracy of some LCA studies	Highlighted the misleading nature of low-energy and sustainable technologies, which may have high embodied

				carbon emissions
Bahramian et. al (2020) [40]	High-income countries, China, Thailand, Iran, India	All life-cycle stages	Review of 230 relevant papers Found that low-rise buildings (1-5 floors) were studied in about twice as many studies as high-rise ones (>5 floors) In high-rise buildings, more than 60% of papers studied commercial buildings In low-rise buildings, more than 70% of papers studied residential buildings	Most frequently studied life-cycle stages were manufacturing and use-related

These studies had different goals for studying building LCAs. Most critiqued some aspect of the existing literature or compared results from specific studies in a meta-analysis. Some identified the absence of uniform characteristics across building LCAs, like functional unit and system boundaries [36]. One study found a significant urban focus found in the LCA literature, specifically on small to mid-sized formal buildings [43]. Some of the reviews also focused on low energy or zero-energy buildings, and found that the embodied phase had a much larger share in the life-cycle energy demand and impacts [45].

In addition to a shortage of studies from LMI countries, building types observed only in these countries, such as informal buildings, were also insufficiently covered. This review begins to study these building types from LMI countries.

REVIEW METHODOLOGY

The LCA studies included in this review were collected through systematic searches on Web of Science and Google Scholar with the following key words: "Residential Building Energy", "Residential Building LCA", "Residential Building Life Cycle Assessment" and "Residential building embodied energy" alongside the names of each of the countries. After going through each of the accessible search results for each country on World Bank's LMI list, we chose those which studied embodied or use-phase of life-cycle energy or emissions for representative current residential buildings. Papers published until 2020 are included in the study.

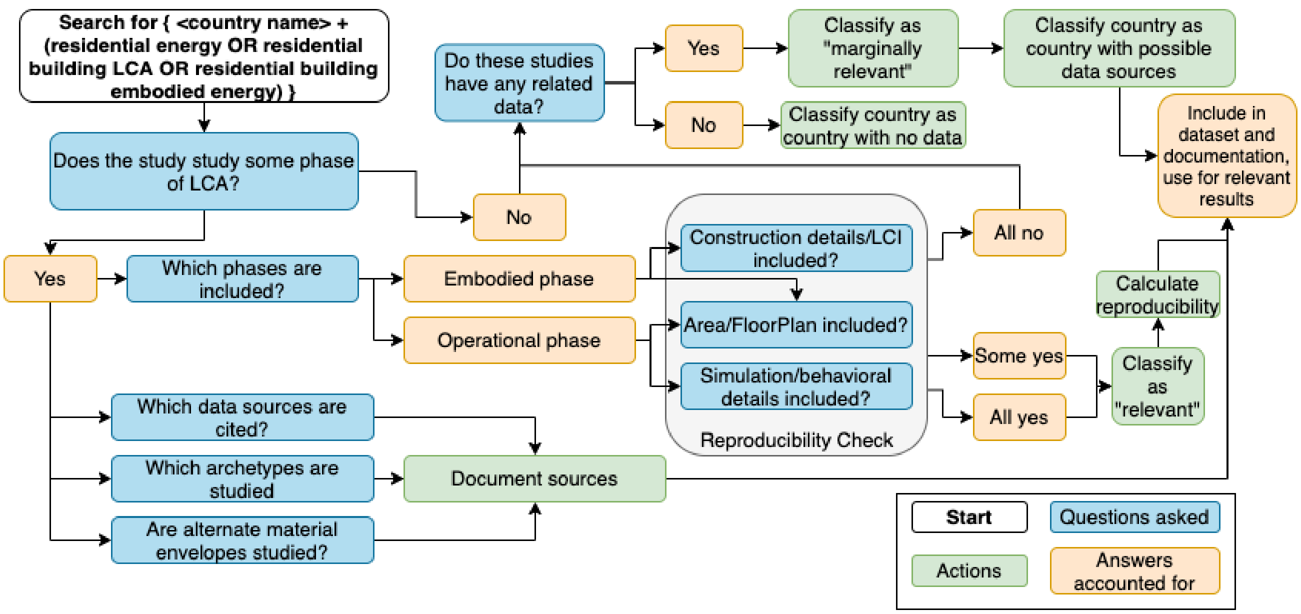


Figure 2. Literature Selection Process

We found that many research articles study energy-efficient, passive or otherwise changed archetypes of the traditional buildings, without studying the traditional, representative buildings themselves, corroborating a finding from a previous review[43]. The goal of this review was to better understand current residential buildings, and as a result, we chose research papers that study these buildings. Studies that included an LCA of representative buildings were classified as "relevant". However, in countries where no relevant LCA studies were found at all, we scoured search results for possible data sources for future LCAs. If studies focusing on other aspects of residential buildings existed and described building characteristics, we classified them as "marginally relevant" and documented as possible data sources for future LCAs. A detailed description of this process is provided in Figure 2. Across the 135 LMI countries of the world, after going through more than 1000 studies, we found 89 studies relevant with a total of 335 individual cases studied. We classified another 88 papers as "marginally relevant".

SCOPE AND FOCUS

Very few studies considered the end-of-life phase across LMI countries, and the few that did, were not transparent regarding this phase[46,47]. As a result, our review does not include the end-of-life phase. Any paper studying energy or emissions from the embodied-phase and energy in the use phase of the LCA was considered relevant and included. In the embodied phase, we included studies that performed some form of embodied energy or emissions analysis for the building. Among use-phase energy studies, we focused on the ones that addressed cooling or heating, among the end-uses, as this is one of the fastest growing and critical end-uses[21]. We included all use-phase studies when considering literature availability, and focused on ones that include cooling and heating in the sections where we compare energy demand from this phase.

DATA SHARING AND REPRODUCIBILITY IN LCAs

ISO 14044 standards define the life-cycle of a product as consecutive and interlinked stages of a product system, from raw material acquisition to final disposal, and LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [48]. An LCA includes several stages of information input and processing. One must establish a product or product system, define the system boundary, a functional unit, and an output unit with a chosen impact calculation method. LCAs are data intensive, meticulous accountings of flows in the system. Learning from or building upon existing LCAs requires transparent sharing of the product details, system boundaries, and impact factor calculations[40,49–51].

The reproducibility and reliability of a building LCA hinges on different types of information[52]. Previous studies enumerate necessary data types and sources for different phases of a life-cycle energy analysis[43,53]. Based on previously recognized data types and requirements, we constructed a metric that measures the sufficiency of shared data to reproduce residential building LCAs (Figure 3). We constructed this metric based on basic, minimum inputs needed for an LCA. More complex LCAs with larger system boundaries will add upon these data type requirements for additional calculations.

Firstly, we find that both embodied and use-phase studies need a floorplan or total area. Secondly, both phases also need construction details like the building envelope materials and lifespan. Thirdly, we need material properties, embodied energy of materials for embodied phase and thermal properties of the materials for the use phase. Fourthly, we need the life cycle inventory or details to calculate the volume or mass of materials for the embodied phase, and input parameters to the model or methodology for the use phase. These are combined to calculate the reproducibility score, between 1-4, described in Figure 3. A study with a score 1-2 is not reproducible, and score 3 or 4 is considered reproducible in the context of LMI countries. 1%, 12%, 25%, 52% and 10% of the 89 relevant studies reviewed here had scores of 0, 1, 2,3 and 4 respectively.

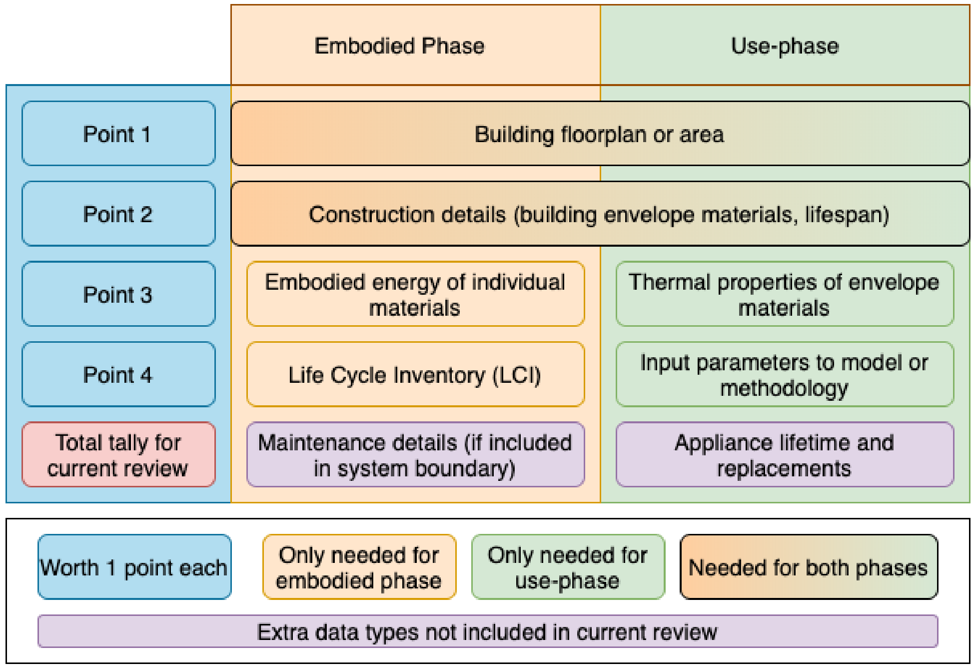


Figure 3. Reproducibility evaluating metric

BUILDING TYPES AND ARCHETYPES

Hossain et. al (2018) noted that difference in building types and location influence the results of residential building LCAs [4]. Building types refer to classes of buildings, which include a range of common characteristics. Archetypes represent specific characteristics of a single building. For example, "formal" is a type referring to a set range of defining features like materials, size, durability, usage parameters. It can include multiple archetypes, that specify the size, number of stories, materials used for different components, appliances and usage intensity. In other projects, the definition of archetype expands beyond material intensity, and includes energy intensity, technology used and efficiency strategies[2,27].

In previous literature reviews, the focus is almost entirely on formal buildings. Types of formal buildings include the single-family, multi-family and high-rise types found in high-income countries [29]. However, formal buildings are not the only type of buildings found in the LMI regions of the world, where informal settlements and other less durable living structures also exist [24,54–57]. Within these, we also make a distinction between traditional, current, and representative residential buildings. Buildings that exist are current residential buildings, but they are traditional if no additional energy or material efficient intervention was modeled in the reference study. This study attempts to streamline attempts towards identifying such representative residential building types in LMI countries.

Characterization of current building types is a necessary step towards understanding the existing stock of buildings and projecting future stocks, their energy use, and opportunities to improve comfort and reduce energy demand. This step will also take us closer to better representing LMI countries in global residential building models. With a view to categorizing buildings in LMI countries, we documented characteristics of buildings in LCA literature. However, completely reproducible papers did not always exist for all types. For instance, in South Asia, we could not glean much in terms of construction materials and home dimensions for informal buildings from the few existing studies. Very few studies compared multiple building types to each other, as most looked at a single building. However, when compared across studies and countries, the buildings showed significantly different characteristics.

RESULTS

In this section, we discuss qualitative and quantitative results and trends from our analysis of the 335 cases studied in the 89 relevant papers.

BUILDING TYPES PROPOSED

We observe four major characteristics that differentiate buildings: construction materials and style, size, durability, and demography of the residents. Variation in these characteristics help define three categories, or types of buildings. We defined formal, informal, and semi-formal categories based on their durability, which is affected by construction elements like foundations and reinforcement of elements.

Formal buildings are the most durable, characterized by sturdy, reinforced walls, strong foundations, and roofs made of reinforced concrete slabs or similar durable materials. These buildings can be classified into low-rise, mid-rise, or high-rise, based on the number of stories. On the other hand, informal buildings are low on durability, characterized by no reinforced elements, no foundation, and non-reinforced roofs made of materials like corrugated metal sheets [58–63]. However, a category of building between the two exists, which includes a range of overlapping characteristics, but not quite fitting in either class [64–70]. This category does not have the same quality of durability in construction and materials as formal buildings, which limits building size and lifespan. These buildings have un-reinforced roofs, and seldom have deep foundations or reinforced walls. However, these semi-formal buildings also are larger than informal buildings. Various names are used for this category, and it is characterized by a range of qualities in different countries. They are similar to chawls in Mumbai, India, social housing in Brazil and embody characteristics of old construction in China and other LMI countries [64,65,71]. The three types are described in Table 2.

Table 2. Building type definitions

Category	Description of characteristic	Formal	Semi-Formal	Informal
Construction materials/ style	Construction (walls)	Reinforced walls and beams	Reinforced or non-reinforced walls/beams (either load bearing or non-load bearing)	Non-reinforced walls/beams (load bearing)
	Construction (roof)	Reinforced slabs or similar durable material	Non-reinforced slabs or corrugated metal sheets	Corrugated metal sheets or other non-reinforced material
	Foundation	Exists	Usually does not exist or is very shallow	Does not exist
Durability		High	Low to medium	Low
Size	Based on number of stories	Any	2-4 stories	1-2 stories
Demographic of residents	Income class	Middle to high	Low to lower middle class	Low

As highlighted earlier, formal buildings are the only type widely represented in international literature and assessment models. For our analysis with formal buildings, buildings with 4 or fewer stories were defined as low-rise, 5 to 12 stories were defined as mid-rise, and all above 12 stories were defined high-rise (adapted from [72]). The definitions for these vary by publication.

ARCHETYPES AROUND THE WORLD

In this section, we define some example archetypes for formal, semi-formal, and informal buildings for LMI countries based on consistent differences in materials in the envelope. We find that for formal buildings, the pillars, beams, external walls are always made of plaster, bricks, reinforced cement concrete (RCC). Interior walls and roofs can be made either of the same layers or with gypsum boards instead of bricks and RCC. Semi-formal were found to have masonry in their walls, but also often with metal sheets supported ceramic tiles in their roofs. Informal buildings either had masonry walls and metal sheet roofs, or were entirely enveloped in metal sheets. Dominant envelopes for each of these types are detailed in Table 3. Some types of buildings, like wood and timber constructions, were not common in the reviewed papers, and were found in very few studies [64,73,74]. Additionally, we found that informal buildings are seldom studied in Latin America.

Table 3. Dominant material-based archetypes for each building type

Type of building	Building Component	Binding agent for paint (Layer 1) (outermost)	Masonry material (Layer 2)	Binding agent (Layer 5) (innermost)	Countries represented	References
Dimensions are in cm						
Formal -1 (RCC reinforced brick-plaster walls)	External Wall	Plaster (1.2)	Clay bricks/ concrete blocks (23 - 30)	Plaster (1.2)	India, Algeria, Brazil, Morocco	[7,71,73,75–80]
	Internal Wall	Plaster (1.2)	Clay Bricks/ concrete blocks (8)	Plaster (1.2)		
	Roof	Plaster (1.2)	RCC (12)	Plaster (1.2)		
	Floor	Plaster (1.2)	RCC (12)	Plaster (1.2) and flooring materials		
Formal – 2 (RCC reinforced Gypsum board -plaster walls)	External Wall	Plaster	Clay bricks		Honduras, Kenya	[81,82]
	Internal Wall	Plaster	Gypsum Board/Plaster (1.2)	Plaster		
	Roof	Plaster	Gypsum	Plaster		

	Floor	Plaster	RCC	Plaster		
Formal - 3 (observed in arid countries with sand and screed binding, and insulation in walls)	External Wall	Extruded polystyrene (5)	Concrete block (20)	Plaster (2.4)	Turkey, Kazakhstan	83,84
	Internal Wall	Extruded polystyrene (5)	Concrete block (20)	Plaster (2.4)		
	Roof	Ceramic tiles (1)	Concrete block (20)	Sand (5) and screed (5)		
	Floor	Concrete (3)	Extruded polystyrene (4)	Screed (5) and parquet (1)		
Semi-Formal -1 (with masonry block walls and aluminum sheet roofs)	External Wall	Plasterboard (1) with or without metal sheet (3)	Concrete block/ mud bricks (10cm)	Plasterboard (1)	El Salvador, Ghana, Nigeria	62,85,86
	Internal Wall	Plasterboard (1)	Concrete block	Plasterboard (1)		
	Roof	Aluminium sheet	Air space	Ceiling tile		
	Floor	Concrete floor slab (30)		Plasterboard (1)		
Semi-Formal – 2 (with masonry block walls and ceramic tile roofs)	External Wall	Plaster (2.5)	Red ceramic blocks – one layer filled with RCC (14)	Plaster (2.5)	Brazil	66
	Internal Wall	Plaster (2.5)	Red ceramic blocks – one layer filled with RCC (14)	Plaster (2.5)		
	Roof	Ceramic tiles	Wooden structure	PVC Sheets		
	Floor		Concrete (5)	Ceramic plates		
Informal – 1 (with non-reinforced masonry walls and metal sheet roofs)	External Wall	Mortar (40)	Brick (35)	Mortar (4)	Iran, Nepal, Iraq	87,88
	Internal Wall	Mortar (30)	Brick (35)			
	Roof	Metal sheets				
	Floor	Mortar (40)	Brick (30)			
Informal – 2 (with metal sheet elements throughout)	External Wall	Aluminium (0.3)			Madagascar, India**	89
	Internal Wall	Aluminium (0.3)				
	Roof	Aluminium (0.3)				
	Floor	unknown				

All dimensions are in cm
** Based on data collected by author

Foundation specifications were not included in these archetypes, because these varied vastly even between similar buildings. Foundations typically contain reinforced cement concrete (RCC) for formal buildings, but the dimensions, proportions and types are determined on a case-to-case basis.

Formal construction in most countries had similar building blocks. Most studies found burnt clay or fired clay bricks, cement and steel as the top 3 highest emitters [7,8]. Various studies showcase that changing the material composition of the residential building by using energy efficient alternative materials can reduce total life-cycle energy demand and environmental impacts from a building [40,65,90]. This helped us compile a list of common materials used and types of improved alternatives for these materials, which we included in Table 4.

Materials mentioned in this table have not only the strength and durability to replace the traditional material, but they also usually have lower production energies and desirable thermal properties. These are conservative interventions that build upon materials that already exist in many LMI countries. More energy-efficient changes could include integration of passive cooling methods, zero or low-energy buildings and design-for-disassembly to transition to a circular economy. For steel, which is the most energy intensive material in the embodied phase, we did not find any substitutes, but some studies mention alternate construction styles that use more concrete instead of steel. Others discuss the possibility of adding scrap metal to steel production, to reduce the total embodied energy [91–93].

Table 4. Properties of traditional and alternate materials [7,46,75,94–101]

Category of material	Materials	Production Energy (GJ/m^3)	Production Energy (MJ/kg)
Masonry	Clay Bricks*	2.23-5.185	1.64
	Hollow Concrete blocks	0.81-1.216	0.41
	Solid Concrete blocks	1.465	0.48
	Autoclaved cellular concrete blocks	1.536	0.6-0.745

	Fly ash bricks	0.184-1.341	0.56
	Soil-cement block	0.646	
	Stabilized Soil Block	0.938	
Cement	Portland Cement	9.65	3.32-7.8
	Blended cement (with fly-ash, pozzolana, limestone and/or blast furnace slag)		1.75-2.11
Reinforcement	Steel	314	28.2-56.7

LITERATURE AVAILABILITY AND RELIABILITY ACROSS LMI COUNTRIES

This review shows that LMI countries are generally data-scarce, and this is at odds with the data-intensive nature of LCA studies. However, within the reproducible studies, we find that the types of data sources for specific characteristics are consistent across most studies. Physical characteristics of the building are usually collected based on observations and on a local level. The bill of materials or life-cycle inventory is usually calculated based on local observations too, with a few studies referencing international literature for assumptions. The embodied energy of materials come from a mix of international datasets, articles or benchmarks, and local studies, because in several countries, local material production data and information regarding construction practices do not exist. Several studies refer to the Inventory of Carbon and Energy (ICE), a European dataset for embodied energy and carbon values[102], but there have been studies showing the difference between this data and locally sourced data [46,102]. Usage behavior for cooling appliances is widely based on assumptions or locally sourced data. No standards exist for these parameters for hot, LMI countries.

However, the thermal comfort standards are different from those used in high-income countries. Our results shows us that the range of set-point temperatures is much wider and higher in LMI countries, than the 18-22°C used in industrialized countries. This indicates a necessity to have a better understanding of the thermal comfort expected in LMI countries, in addition to a better understanding of appliances used.

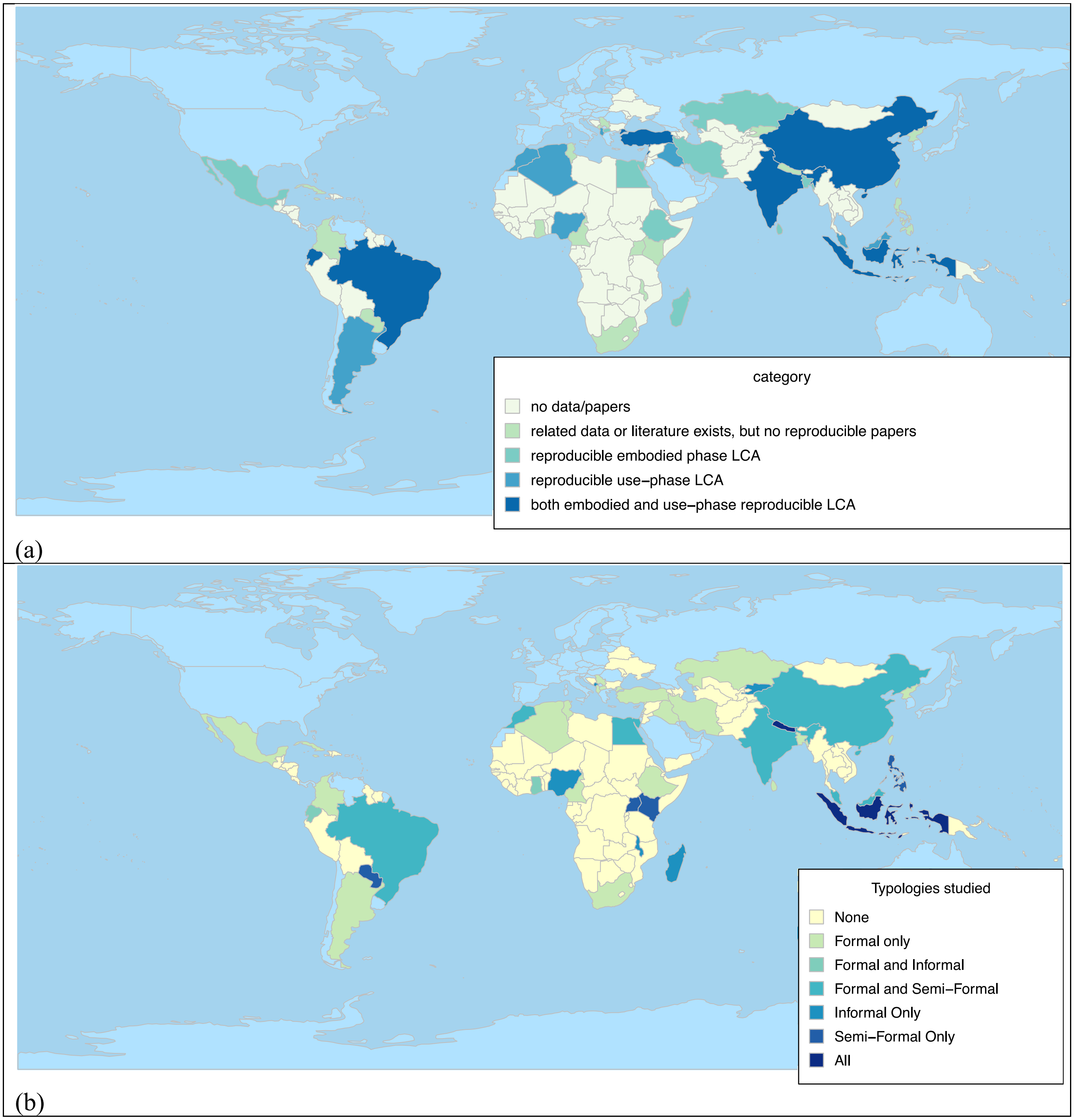


Figure 4: (a) Reproducible literature availability in LMI Countries (b) Building types mentioned in literature from LMI countries

Figures 4a and 4b summarize regional findings and showcase literature availability from different countries, and the types studied in each, respectively. In Figure 4a, we observe that there are countries with reproducible LCAs for both embodied and use-phases in South America and the Caribbean, and in

Asia. Brazil, China, Ecuador, Indonesia, India, Israel, Lebanon, and Turkey were the eight countries with reproducible studies in both phases. On these two continents, there were also several countries with either embodied or use-phase reproducible LCAs. Bangladesh, Iran, Sri Lanka, and Mexico had reproducible embodied energy studies. Reproducible use-phase studies existed for , Malaysia, Iraq and Argentina.

No countries in the African continent had reproducible studies for both embodied and use-phase. 40 of the 54 LMI countries on the African continent did not have any residential building LCA studies or any related literature. Egypt, Ethiopia, and Madagascar had reproducible embodied energy studies, while Algeria, Morocco, Mauritius, and Nigeria had reproducible use-phase studies.

The countries recognized in the above section had reproducible studies on one or two of these life-cycle phases, and were rich in data, findings, and results particular to this region. These countries can now be used as starting points for neighbours with similar buildings, without imputing data from high-income countries, like many previous studies do.

As depicted in Figure 4b, formal buildings were the most widely represented type, followed by semi-formal and informal buildings. For this part of the analysis, we included studies that had details of residential building construction, even if the LCA analysis in them not reproducible. Majority of the LMI countries in the world only had LCA studies focused on formal buildings. Several countries had some representation of formal and semi-formal construction, like Egypt, Morocco, China, Malaysia, India, and Brazil. Formal and informal types were represented in Ghana. Kenya, Uganda, Ecuador, The Philippines, and Paraguay had studies only looking into semi-formal building types, and Madagascar, Malawi, and Nigeria only had studies representing informal houses.

EMBODIED AND USE-PHASE ENERGY AND CARBON

All reproducible life-cycle energy analyses we found were based on formal buildings, and only these are included in the results in this section. Numerous times, a single research paper studied several buildings or cases. The 89 papers thus covered 335 case studies, of which, 40% were single-family homes (SFH), 56% were multi-family homes (MFH), and the remaining 4% did not specify the type. Most studies assumed a lifespan of 50-75 years. 87% of the case studies focused on formal buildings, 9% on semi-formal buildings and 4% on informal buildings. However, almost 100% of the reproducible case studies were focused on formal buildings. Variations in areas of studied homes, and the number of case study buildings for each country can be found in Figure A1 in the Supplementary Information.

The range of results in both embodied and use-phase energy demand in Figures 5, 6 and 7 also come from differences in the LCAs conducted. In the embodied stage, some studies include construction processes (A5 from Figure 1), transportation (A2 and A4) and other non-production embodied processes. In all studies, production of materials presented the largest portion of embodied energy, and often is the only part of the embodied phase that is included. Most commonly, this is dominated by bricks, cement and steel [7,8]. Maintenance and refurbishment (B2 and B5) are also included in the embodied energy in some studies. As a result, the scope of LCAs and system boundaries varied, and this explains a lot of the variation in results amongst the reviewed papers.

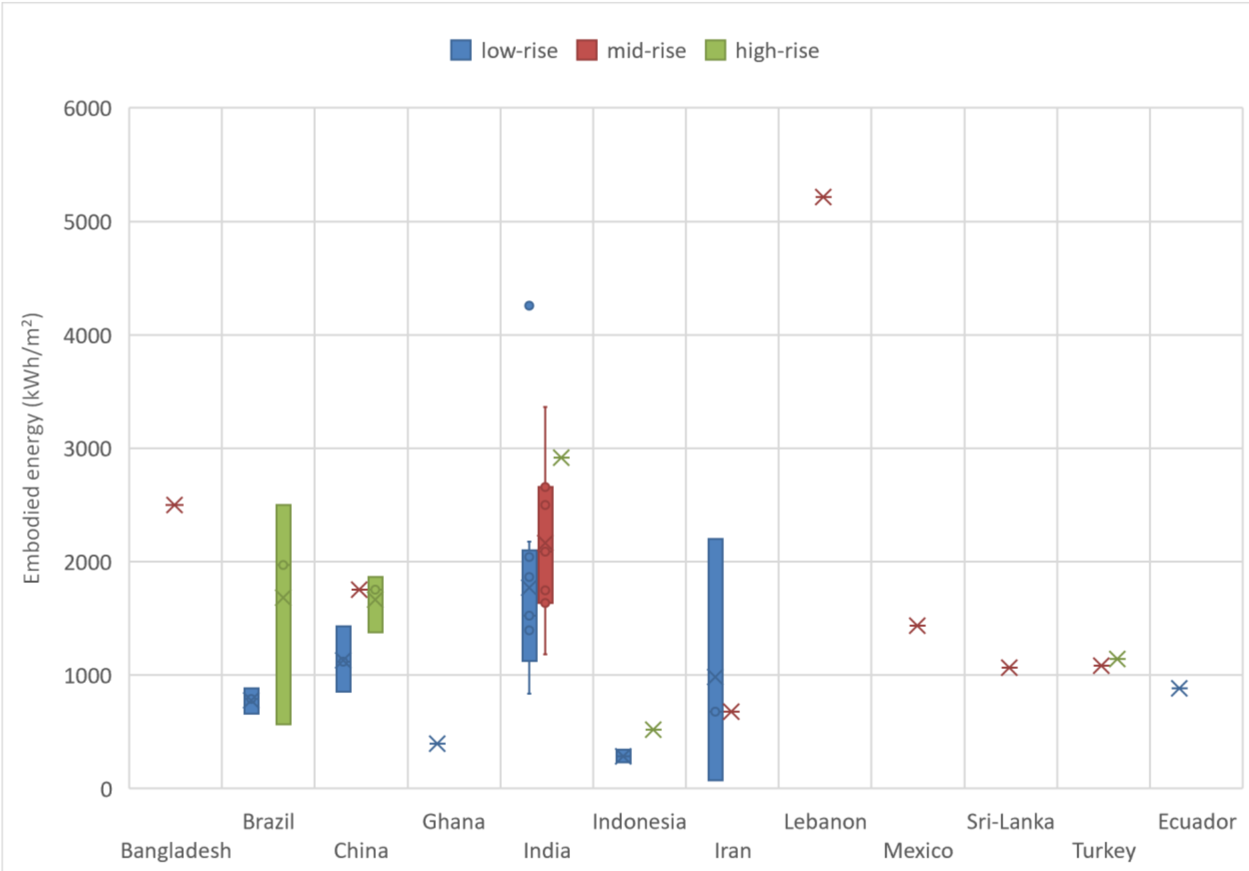


Figure 5. Specific embodied energy by height of formal buildings
low-rise: <4 stories, mid-rise: 5-12 stories, high-rise: >12 stories;
In boxplot: x: mean, box: first to third quartile, circles: mean markers

There is a consistent trend of increasing embodied energy per unit floorspace with height of formal buildings. Figure 5 shows mean embodied energy for low-rise buildings, which we observe is mostly consistent between 700-2000 kWh/m^2. Other variations are explained by inclusion and exclusion of foundation, and system boundaries for the embodied analysis. Within countries like India, Indonesia, Brazil, China, Turkey, there is an increase in embodied energy intensity with height. Figure 5 depicts that within formal buildings, there is value to further characterizing archetypes, to better describe embodied energy demand.

Figure 6 shows the specific embodied carbon by size, and we find that among the few countries that reported embodied carbon mid and high-rise buildings seem to have higher embodied carbon than low-rise buildings. This reinforces trends of increasing impacts with increasing height of formal buildings, and the benefits of classifying formal buildings by height.

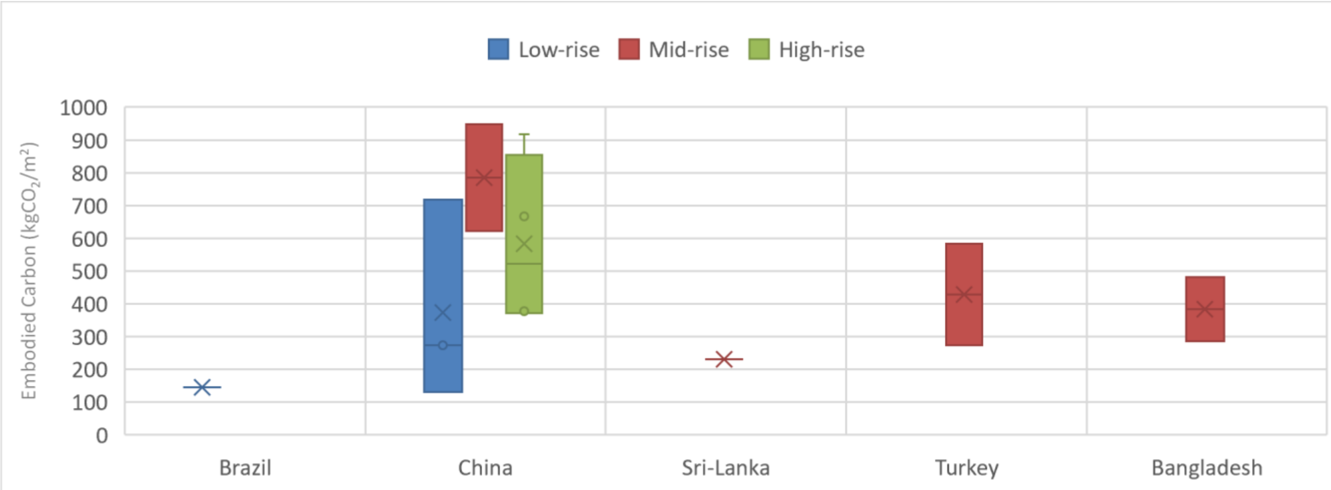


Figure 6. Specific embodied carbon by height of formal buildings
low-rise: <4 stories, mid-rise: 5-12 stories, high-rise: >12 stories;
In boxplot: x: mean, box: first to third quartile, circles: mean markers

For use-phase energy results shown in Figure 7, no single factor driving use-phase was found, in contrast to the embodied phase. Some variations in results were found to stem from the different number of appliances and end-uses considered in studies [70]. For India, Ramesh et. al (2012) considered the use of all appliances, including water heaters, and cooling for both bedrooms and living rooms, with heating also incorporated for the cooler parts of the country[7]. Consequently, their results were towards the higher end of the spectrum. Praseeda et. al (2016) considered natural ventilation and fans as a cooling method for less hot parts of the country, and were towards the lower end of the operational energy estimates for India[65]. Similar variations were observed for lower operational energy demand values for Indonesia in studies such as Surahman et. al (2013)[70]. Also, use of appliances varied, especially in cooling behavior, assumptions of set-point temperature and hours of use varied between studies and countries, due to different driving factors like climate and income. Figure 7 also showcases the set-point temperature across studies where this data was available, which helps explain some of the variation in use-phase energy demand, but also illustrates that it is not the only factor influencing the energy demand in this phase.

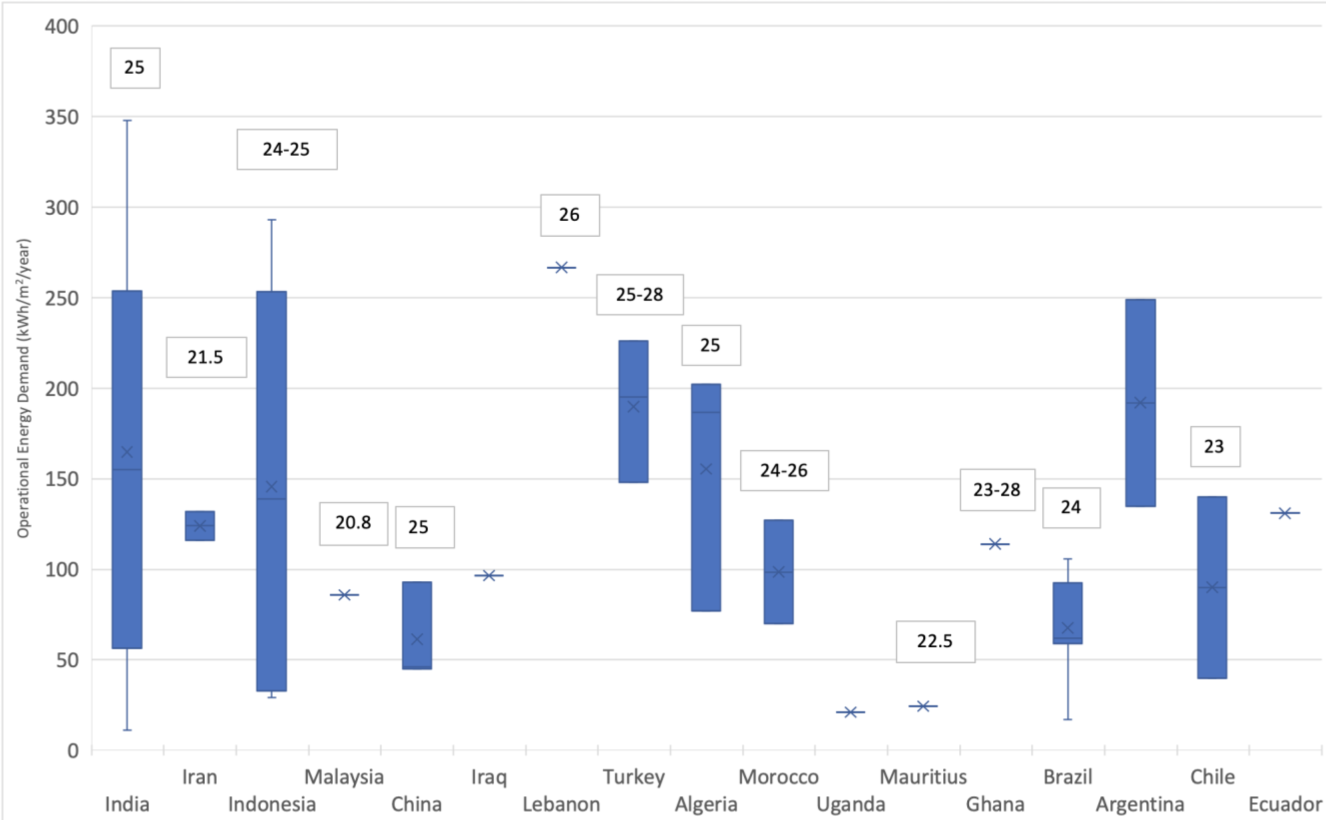


Figure 7. Operational energy demand of formal buildings (ordinate) and cooling set-point temperatures in degree Celsius, label.

DISCUSSION

This review is the first to exclusively focus on residential building LCAs in low-and-middle income countries. We find that current LCAs tell us far more about buildings in LMI countries than previously considered in global reviews or utilized in scenario models. However, we also confirm the continued shortage of studies in these countries in a more nuanced and detailed way, identifying regions without studies and avenues for future research.

LCA results are often used in global studies as the representative reference case for that region, but LCA studies rarely aim to represent contemporary buildings. Instead, many focus on individual energy efficient buildings which are different from traditional buildings, such as buildings with cool-roofs, heat pumps, solar PV panels, added insulation or other passive cooling methods [43]. However, a reference case is needed to quantify reduction in energy demand or improvements in comfort, and to better characterize benefits of such different interventions. Many LCAs also focus on other environmental impact indicators such as eutrophication, ocean water acidification and deforestation, which are important avenues to be researched as well.

The classification system proposed in this paper with durability-based types and material-based archetypes is a framework for future LCA studies from LMI countries and for studies representing these countries on a global level. This will help not only with global studies and other research seeking representative building types, but also with other end-uses of LCA studies. In addition, LCAs are used by building consultants, municipalities, urban designers, property developers, tenants, architects and engineers, and inspire choices made by different stakeholders [35,103]. Better understanding current and future stocks for each building type, and LCAs of common archetypes for each region will also improve resource and energy demand projections for residential sectors in the LMI countries.

LCA studies are used to parametrize buildings for other LCAs and global reports alike. However, to inform any future research, LCAs must be transparent in sharing data and calculation processes. Data transparency in LCAs and industrial ecology methods has been advocated previously in a number of publications [40,49–51,104]. We introduce a reproducibility metric that ranks studies based on different forms of input data for embodied and use-phase LCA calculations. Most LMI countries do not have any reproducible studies, especially those on the African continent.

The African continent will see the largest population growth in future decades [105]. However, the fewest studies are found on this continent. Of these, there are more operational energy studies than embodied energy or carbon studies. Few studies focus on embodied impacts of different materials in African countries, and can be used as a starting point for future studies for the life-cycle of buildings[98,106]. LCAs in these LMI countries will help identify energy-efficient alternatives to the current buildings and can help avoid the technological lock-ins of the high-income world.

In our review, our reproducibility metric analysis identified a select few countries with reproducible studies. Journal guidelines for future LCAs requiring transparency would help encourage reproducible

LCA literature from the LMI world. In addition to mandated sharing of goal, scope, functional unit, system boundaries for the LCA, specific formats for sharing data can be imposed. For example, for residential buildings, the floorplan, building parameters such as size, area, number of stories, lifespan, building envelope thickness and material details, datasets for embodied energy or carbon values of materials, and any assumptions or inputs to software or models are necessary for embodied energy or carbon studies. Use-phase studies are often more complex, needing data on appliance use and ownership, building envelope properties, usage schedule, comfort parameters, and carbon intensity of the power grid. These depend on more general characteristics like occupation, income, social conditions, behaviour and climate, and presumably why we found fewer use-phase studies. LCA literature can benefit from richer use-phase studies, and a concerted data collection effort is needed in most LMI countries to inform these. Social science studies, which focus on socioeconomic characteristics, appliance ownership and usage behaviour will be key to future studies.

Maintenance, refurbishment, and end-of-life are life-cycle phases previously not included in most LMI studies. Refurbishment and retrofits can help reduce life-cycle impacts and prolong the lifespan of a building, and need to be studied carefully in the future [107]. End-of-life is critical as we move towards a material-efficient world and promote circular economy across sectors. Design-for-disassembly and reuse of construction materials, appliances and other products in the life-cycle of a building can help reduce waste from one of the largest inert waste-generating sectors in the world. Reuse of materials from one building to another, and across building types, can help reduce total material input into the building sector. Especially, studies focusing on the existing informal economy in LMI countries, wherein reuse and downcycling of materials is common, would be a key starting point to explore such avenues. Data scarcity remains a central issue, particularly when estimating material stocks across building types, especially in informal settlements [24,108]. Apart from on-ground surveys, remote sensing and other satellite-based techniques can be employed while attempting to estimate these dynamic building stocks, and service future reuse and recycling efforts [109–112].

Representation of residential buildings and their types in energy reports and in other fields of study would be easier with a set of types recognized and policies ratified by the governments. However, building energy codes (BECs) are not very well defined or implemented in many LMI countries. A 2010 paper finds that 25 out of 60 LMI countries studied had no BECs[113]. Countries where standards do exist, have government-created policies without inputs from other stakeholders in the building sector, which impedes development and implementation of policies [113]. Africa and Latin America have the highest percentage of countries without any BECs, and most LMI countries are plagued with non-compliance in the building construction sector.

In summary, LMI countries represent 80% of world population and 99% of projected global growth in the next decade[114]. They are sites for major development and construction in the future. These countries and their residential buildings will play a key role in our climate change mitigation plans. Previous LCA reviews in the residential buildings sector largely disregard LMI countries. This study enables researchers to understand the state of existing literature, better evaluate quality and reproducibility of LCAs, and identify future avenues for research.

ASSOCIATED CONTENT

Supporting Information

Country by country Analysis (docx)

List of reviewed papers and data (xlsx)

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Author Contributions

The work was conceptualized by all authors. AI conducted the literature review, produced the figures and provided an initial draft. NR and EH edited the draft and provided feedback. All authors have given approval to the final version of the manuscript.

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ABBREVIATIONS

Abbreviation	Meaning	Abbreviation	Meaning
LCA	Life Cycle Assessment	MFH	Multi-family home
LMI	Low-and-middle income, that is the same as developing	SFH	Single-family home
IAM	Integrated Assessment Model	GHG	Greenhouse gases
RCC	Reinforced Cement Concrete	SSP	Shared socioeconomic pathways

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