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Assessment of Cost and Sustainability of Building Materials in Residential Buildings of Bhutan

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ABSTRACT

The construction industry contributes significantly to global energy and CO_2 emissions. Besides, the construction model in Thimphu, Bhutan, is expensive. This study appraised the prevalent construction material of a typical multi-storied residential structure from the cost and sustainability perspective. The cost assessment revealed almost 300% cost escalation of sand in Thimphu, followed by common infill wall material of autoclave aerated concrete blocks and red bricks, all impacting the construction costs. Using the process-based method, sustainability assessment estimated production embodied energy and CO_2 emissions of $2.5GJ/m^2$ and $203KG/m^2$, respectively. This estimate implies the energy and carbon-intensive nature of the urban building stock, a trend likely to be aggravated increasing similar construction activities unless alternatives become available. Our investigation provided scientific evidence of construction issues from specific lenses. Further comprehensive studies are needed to provoke innovative restructuring of conventional inadequacies into a more productive, cost-effective, and sustainable building industry.

1. INTRODUCTION

The building industry consumes 40% of global energy and contributes to about one-third of the overall carbon dioxide emission [1]. By 2060, CO2 emission and energy demand will increase by 10% and 30%, respectively [2]. For this reason, the construction sector is increasingly encouraged to utilize renewable materials with low embodied energy and less carbon-related emissions, thereby helping reduce global environmental impact. In addition, the construction industry drives the economic engine and subsequent national development [3]–[5]. Khan et al. [4] illustrated the contribution to Malaysia's revenue generation, capital growth and employment creation, which eventually contributed to the GDP (Gross Domestic Product) and socioeconomic status. Besides its direct involvement, the construction industry has substantial multiplier effects via forward and backward links with other economic sectors [4]–[6].

But the construction industry, particularly building construction, has been critiqued for lackluster performance, such as low productivity and quality [7]–[9], and for its inability to adopt sustainable technologies [8]. Industry practitioners prefer a conservative approach to developing and adopting new technologies, favoring well-established practices over innovative construction methods [10], [11]. The on-site conventional construction practice in Bhutan depends mostly on mineral-based building materials. The 11th Five-Year Plan (FYP) acknowledged the repercussions of the existing construction method, which incurs high construction costs, delivers poor quality work, and requires expensive maintenance. Bhutan's Ministry of Works and Human Settlement (MoWHS) suggested similar narratives. Besides the anecdotal criticism, scientific studies to recognize the possible causes or potential solutions to the apparent high construction cost are lacking in Bhutan.

The sustainability of construction, another pertinent concern, has received less attention in the country. Dixit et al. [12] reckon that until recently, only operating energy received attention due to its more significant fraction of the overall life cycle energy. Following substantial efforts in energy efficiency studies worldwide in recent years, the focus in current environmental studies has shifted to embodied energy and emissions [12]–[14]. Despite the growing significance of embodied impacts, efforts to lessen building's environmental footprints have primarily focused on their operating effects [2], [15], [16]. Developing countries such as Bhutan lack assessment studies relating to building energy and carbon, although, from anecdotal evidence, they have proven problematic. Kumanayake et al. [14] reiterated the significant gap in the current research on the environmental issues of buildings in developing

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countries.

This study appraised prominent construction materials from the perspective of material cost analysis and sustainability quantification. The former identified the impact of construction material costs. At the same time, the latter provides, probably the first of its kind in the country, quantification of sustainability metrics in terms of embodied energy and embodied CO_2 emissions on a contemporary building. In contrast, Chettri et al. [17] performed a sustainability assessment on a vernacular building with wattle and daub construction. Efforts to reduce embodied energy and carbon emission demand quantification studies [18]. In a broader sense, this study will investigate the shortcomings and ramifications of the current construction practices and, as a result, promote initiatives and studies for a productive and sustainable built environment.

2. LITERATURE REVIEW

Project objectives of cost, time, and quality, along with sustainability in recent times, have been acclaimed as essential performance criteria in the literature [19]–[25]. These studies have demonstrated the adoption of these indicators in their assessment and selection of appropriate construction materials and methods. Nonetheless, owing to the construction process's highly complex and variable nature [26], [27], each of these parameters can comprise many factors and thus might require study in isolation. Therefore, this paper has contextualized the assessment of construction materials only from the perspectives of cost and sustainability.

The selection of cost indicator is due to its significance as a primary objective, at least in developing countries like Bhutan. In addition, anecdotal evidence suggests that the building materials can account for about 60% to 70% of the total construction cost of a typical RCC (reinforced cement concrete) framed structure. Thus, to uncover the possible causes of this apparent high construction cost, this research chose material rate analysis as the building materials constitute a significant fraction of the construction cost.

Concerning sustainability, this study adopted the Life Cycle Assessment (LCA) concept to evaluate the sustainability of construction materials. LCA is broadly accepted and enables quantifying material use—environmental concerns in terms of explicit indicators like energy consumption and carbon emission—under different life cycle phases [28], [29]. The LCA methodology can assess the environmental impact of processes and products (goods and services) from the cradle to the grave [30]–[32]. Such sustainability assessment primarily intends to gather and report information for decision-making during various stages of a building-construction, design, and use [33], [34]. Ortiz et al. [32] opine that applying LCA is essential for building and construction sustainability and improvement. LCA can target various scales of analysis ranging from small systems like building materials, building products and construction elements to more extensive systems comprising independent zones, buildings, and neighborhood levels [33]. For instance, Koroneos and Dompros [29] demonstrated the application of integrated LCA in the building material category of brick production in Greece.

Within the LCA methodology, this research targeted the sustainability metric of embodied energy (EE) and embodied CO_2 (ECO_2) emissions to achieve appropriate *research scope* and due to their *significance* as highlighted subsequently. According to Chau et al. [35], Life Cycle Assessment (LCA), Life Cycle Energy Assessment (LCEA), and Life Cycle Carbon Emissions Assessment ($LCCO_2A$) constitute three types of LCA studies. These are widely employed to evaluate the environmental impacts of buildings. However, implementing environmental LCA in buildings and construction is complicated and onerous [33], [34]. Moreover, data for developing and emerging countries (including Bhutan) are still lacking, leading to the use of European and American databases, which may not lead to correct decision-making [32]. Therefore, this paper has adopted only the sustainability metric of EE under LCEA and ECO_2 emissions under $LCCO_2A$ in a cradle-to-site boundary. Related literature contains studies focusing similarly on EE and CO_2 [36]–[38]. ECO_2 is the sum of emissions in the production and transportation stage [18], [35], while EE represents the energy used in the mining, production, assembly and transportation of a specific product [39].

Secondly, this study targeted EE and ECO_2 indicators due to their considerable environmental impacts; the building industry contributes to about 40% of global energy intake and about one-third of the overall carbon dioxide emission [1]. CO_2 is a prominent GHG, contributing to roughly 80% of global warming [14]. The production of building materials requires substantial energy and is similarly associated with high CO_2 emissions.

Besides, their subsequent transportation and assembly contribute to the overall embodied estimation of energy and CO_2 emissions, although to a comparatively lesser degree. Tirth et al. [40] found that the GHG emissions from transportation and construction equipment were 12% and 10%, respectively.

The extant literature suggests that common materials such as steel, bricks and cement constitute a considerable fraction of the aggregate EE and ECO_2. Every ton of cement and steel produces approximately 1 ton and 1.85 tons of CO_2, respectively [2]. The EE and embodied carbon of cement, steel, and brick contribute to no less than 70% of all EE and carbon of all building materials [14], [18]. In the Indian context, Debnath et al. [41] found that around 95% of EE is associated with the cement, steel, bricks and stone in the four-story residential building studied, leaving only 5% attributable to other materials. These materials represent the most prominent bulk application in the Indian construction industry [36]. Likewise, they accounted for about 66% of the aggregate emissions [40] in a cradle-to-service boundary condition. Yan et al. [42] concluded that steel and concrete contribute 94-95% of the embodied GHG emissions from production till the construction stage. These studies suggest that common building materials such as steel, cement and clay bricks constitute a significant proportion of conventional buildings and are associated with high embodied energy and CO_2 emissions.

3. METHOD

This research aimed to assess prominent conventional building materials from the cost and sustainability perspective. The former compares common building materials costs based on Thimphu (the capital of Bhutan) and the base town, Phuentsholing. The latter quantifies embodied energy and CO_2 using a three-step process-based analysis: material analysis, quantitative analysis of material, and then embodied energy and CO_2 estimation by multiplying material quantities with respective coefficients. The predominant quantitative assessment originates from a typical residential building in Thimphu, Bhutan.

3.1. Case study

The case study building constitutes a four-story residential with a typical Bhutanese attic feature known as *Jamthog*. Table 1 summarizes the main characteristics of the building, while Fig. 1 supplements the actual architectural drawing. In addition, Table 2 illustrates the quantification of RCC and wall systems into their constituent material, adopting a bill of quantities (BOQ) methodology.

The building studied represents the archetype of residential construction currently prevalent in Thimphu. Although contemporary architectural typologies include all sorts of building uses, most of these structures conform to 4 to 6-storied repetitive box-like structures (Fig. 2) of RCC framed structures with brick infill walls adorned with corrugated sloping roofs. Such residential structures, in particular, are becoming increasingly omnipresent in Thimphu and are currently shaping the urban landscape of Bhutan, much like the traditional rammed earth dwellings that once populated the historical rural landscape of Bhutan.

A survey revealed a significant proportion of nearly 60% of the urban structures have walls made of cement/RCC wall, bricks, or cement blocks [43]. Therefore, the selected case study shares many similarities with other residential buildings and, arguably, with additional building typologies. For this reason, the findings from this study can be generalized to Bhutan's building industry.

Table 1: General characteristics of the residential buildings in Bhutan

Characteristics	Description
Gross floor area	763.2m2 (Ground Floor; 153, Frist Floor:183.4, Second Floor: 183.4, Third Floor: 183.4, *Jamthog*: 60)
Building height	16.7m
No. of floors	G+3+attic (*jamthog*)
Building structure	Reinforced concrete framing with Brick wall infill
Type & Use	7/8 units: Residential (Rental); 1/8 unit: Commercial
Material	Reinforced concrete, burnt bricks, Tiles, timber, Corrugated roofing sheets, glass and wood
Wall (brick) thickness	External: 250mm; Internal: 125mm
RCC column size	400mmX400mm
Column spacing (c/c)	2.9m-5.3m
RCC beam size	Main: 300mmX450mm
Construction time	Approx. 2years
Architectural features	Sloping roofs, Box design, Façade design as per the regulation (Bhutan Building Rules, 2018), Projecting balconies.

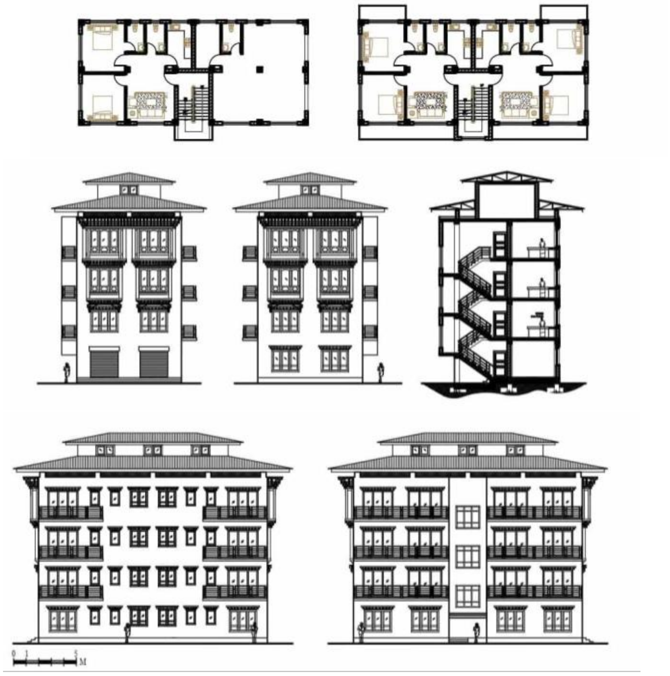

Fig. 1: Plans, a section and elevations of case study building. *Top row. left*: Ground floor plan. *Right*: Typical floor plan. *Middle row. Left & Middle*: Side elevations. *Right*: Section. *Bottom row*: Elevations.

Fig. 2: Typical box-like structures define the urban landscape of Thimphu.

Table 2: Summary of material quantification of the case study building

Building assemblage	Material	Quantity in m^3	Quantity in KG
RCC	Cement (tons)	*71.85	71846.77
	Sand (m^3)	74.84	119744.62
	Aggregates (m^3)	149.68	224521.17
	Steel (tons)	*19.82	19824.08
Wall	Clay bricks (m^3)	181.65	**90824.06
	Cement (tons)	*18.40	18403.51
	Sand (m^3)	51.12	81793.39
	Lintels		
	Cement (tons)	*3.23	3234.35
	Sand (m^3)	3.37	5390.59
	Aggregates (m^3)	6.74	10107.35
	Steel (tons)	*1.27	1270.13

*Quantity of cement and steel in tons,
**Quantity of clay bricks in numbers
Assumptions: Steel density= 7850Kg/m3, Cement density= 1440Kg/m3, Sand density= 1600Kg/m3, Aggregate density= 1500Kg/m3, Weight of one brick= 2.25kg

3.1. Material cost analysis

To reveal the probable causes of the high construction cost in Thimphu, this study undertook a comparative cost analysis of principal building materials representing the voluminous building assemblage, wall systems and structural systems. We compared the rates (in Bhutanese Ngultrum) in Thimphu with the base town, Phuentsholing (155 km southwards) since most materials originate from the latter. Due to the intrinsically dynamic nature of the material rates, this study sourced material rates from the Bhutan Schedule of Rates (BSR), 2021 [44]: Bhutan Schedule of Rates is a national document with material and built-up rates used for drawing up bills of quantities and projects estimates.

3.2. Sustainability analysis: Estimation of embodied energy and CO2 emissions

The main methods for estimating EE and ECO_2 emissions are input-output, process-based, and hybrid analysis [38], [45]. This paper employed a widely adopted process-based analysis comprising a three-step (bottom-up) process: material analysis and quantitative materials analysis of materials, followed by EE and ECO_2 calculations [38]. First, the material and quantity analysis involved a breakdown of building components (wall and structural systems) into their constituent materials [14], [37]–[39]. After that, we determined EE and ECO_2 emissions by multiplying material quantities with their respective coefficients, MJ/Kg and $KgCO_2$/Kg, respectively [14], [18], [35], [37]–[39], [42], [45], [46]. Due to its inability to account for complete boundary conditions, various truncation errors plagued the process-based analysis [12], [38], [45]. However, Dixit et al. [12] assert that none of the methods are fully efficient. The hybrid analysis combines the merits of input-output and process-based methods; however, even its accuracy is debated in the literature. For instance, Yang et al. [47] demonstrated that aggregation error could limit the accuracy of the hybrid LCA.

Without local coefficients, this study, like previous studies, referenced foreign values. We attempted to adopt the most relevant, recognized, and applicable database (Table 3). For instance, EE estimation is based on the India database by Reddy and Jagadish [36] due to commonalities in the construction sector. Likewise, the ECO_2 emission coefficient referenced the widely recognized Inventory of Carbon and Energy (ICE) assembled by the University of Bath [48]. They provide valuable indicative estimates despite the energy and CO2 emission quantification from foreign databases.

Due to the complexity and diversity of the analysis process, including comprehensive building materials in a building would be difficult [49]. Therefore, this study focused on components with a bulk contribution, such as wall and structural systems. Excluding the foundation, these two account for a significant fraction of the materials in a conventional building, if not the entirety. Previous studies have narrowed the focus to include essential materials or products [18], [39], [45].

Table 3: Embodied energy and CO2 emission coefficients

Material	EE (MJ/unit)	Transportation EE (MJ/KM/Cu.m)	ECO_2 ($KGCO_2$/KG)	Transportation ECO_2 ($KGCO_2$/T*KM)
Cement	5850/ton	1	0.83	0.057
Sand	0	1.75	0.005	0.057
Aggregates	20.5/m^3	1.75	0.005	0.057
Steel	42000/ton	1	1.71	0.057
Clay bricks	2550/m^3	2	*427.99	0.179

Production EE (embodied energy) & Transportation EE from [36].
ECO_2 (embodied CO_2) from [48]. Transportation ECO_2 from [18]
*ECO_2 coefficient in $KGCO_2$/1000 bricks from [50]
Assumptions: Cement, clay bricks, and steel transported from Phuentsholing (155KM): Sand from Wangdue (70KM): Aggregates within the vicinity (25KM) of Thimphu.

4. RESULT AND DISCUSSION

4.1. Material cost analysis

This analysis excludes locally available aggregates, while sand transported from another district of Wangdue (70 km eastwards) is reported separately in the subsequent paragraph.

Table 4 compares the unit price of prominent building materials that constitute the wall and structural assemblages. This analysis excludes locally available aggregates, while sand transported from another district of Wangdue (70 km eastwards) is reported separately in the subsequent paragraph.

Table 4: Material rate analysis of principle building materials

Description	Units	Phuentsholing (A)	Thimphu (B)	Diff (%)
Cement (OPC/PSC)	tonne	6627.5	8147.5	22.93%
Reinforcement steel	Kg	51.29	61.09	19.11%
Autoclaved aerated cement (AAC block)	Cu.m	4000	6500	62.50%
Bricks 2nd class	1000#	9666.67	14166.7	46.55%

Bhutan has a vast deposit of materials to produce stone aggregates and sand in quarries and riverbanks [51]. The sand in the capital comes from the Wangdue district, and nearly 60-65% of the sand supply to 11 central and western Bhutan districts comes from this region [52]. Like other natural resources, since early 2018, the sand supply has been streamlined by the government corporation Natural Resource Development Corporation (NRDCL). As of 2021, NRDCL maintained the commercial rate of sand from the dredging site of Wangdue at Nu. 287.80 per cubic meter (cu.m.), whereas in Thimphu, the same quantity costs Nu. 1124.15/cu.m, a significant escalation of roughly 290%.

In addition, prominent infill wall materials in AAC (autoclave aerated concrete) and red bricks contribute about 62.5% and 46.5% additional charges in the capital, respectively. Conservatively, similar impacts in varying degrees can be concluded for other construction materials not covered here - because most of the building materials originate from Phuentsholing, including imported materials and those manufactured nationally. Moreover, the city is known as the country's economic gateway. According to Bhutan Trade Statistics 2020, nearly 70% of imports entered through the city, and construction-related materials accounted for one-third of the total imports [53]. Consequently, the inflated material rates in the capital, contributing substantially in some cases, can be, amongst others, associated with transportation.

4.2. Sustainability analysis: Embodied energy

Fig. 3 and Fig. 4 present a breakdown of embodied energy for production (1896GJ) and transportation (97GJ) in gigajoules (GJ), respectively. Fig. 3 excludes the production EE of sand and aggregates due to negligible values.

Steel, cement, and clay bricks account for a significant proportion of EE in the case study building. Steel has the highest contribution at 47%, followed by cement and clay bricks, with a roughly equal contribution at nearly half that of steel (Fig. 3). Although the total EE estimate accounts for only the wall and structural systems, it represents the bulk and most energy-intensive materials (cement, steel & clay bricks) in a conventional residential building. For instance, Chen et al. [18] found that conventional materials account for more than 70% of the total embodied energy of most common building materials. Moreover, Debnath et al. [41] concluded that these materials represent nearly 85% of the overall embodied energy in a four-story RCC structure with clay brick infills. Therefore, it is clear that the buildings in Bhutan contribute considerably to the production EE.

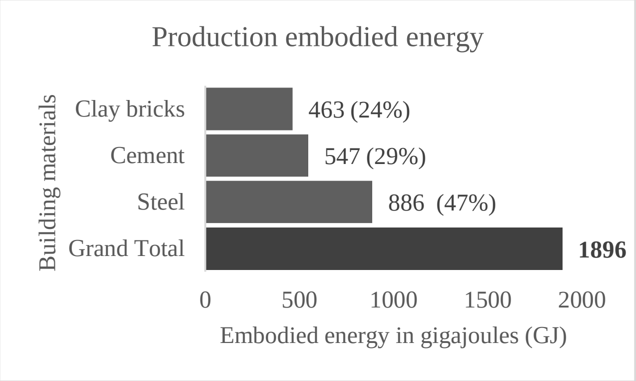

Fig. 3. Breakdown of production energy contribution.

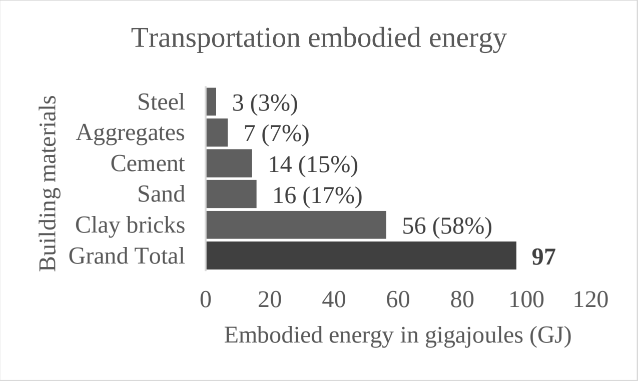

Fig. 4. Breakdown of transportation energy contribution.

The EE of 1896 GJ for the case study building translates to 2.5GJ/m^2 after dividing by the gross floor area of 763 m^2. Reddy and Jagadish [36] found that the EE of an RCC-framed structure in India with infill burnt clay brick masonry walls of an 8- storied building was 4.2GJ/m^2. Similarly, [37] found 4.24GJ/m^2 production EE from their study of a five-story residential building in Bangladesh. Elsewhere, Dixit et al. [12], after reviewing several similar studies with significant variations in EE figures, suggested a mean of 5.506GJ/m2 with a standard deviation of 1.56GJ/m^2. Therefore, considering the expected variations and exclusions such as foundation and other building assemblages, this finding shows close agreement with the EE described above from the literature.

4.3. Sustainability analysis: Embodied CO2 emissions

Fig. 5 and Fig. 6 represent the breakdown of embodied CO2 emissions in the production (154743Kg) and transportation stages (7842 kg), respectively.

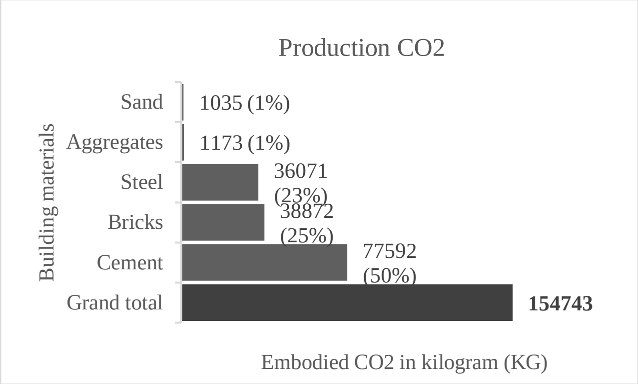

Fig. 5. Breakdown of production CO2 emission.

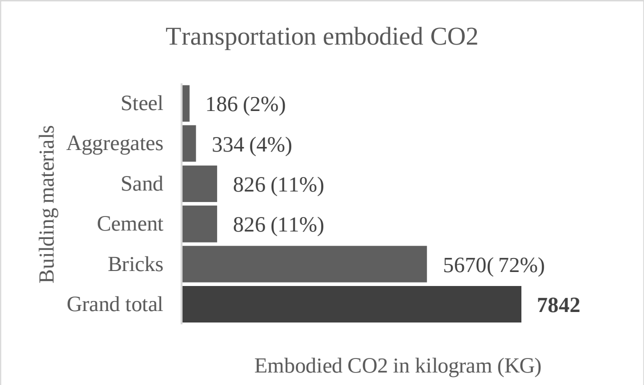

Fig. 6. Breakdown of transportation CO2 emission.

Like embodied energy, steel, cement, and clay bricks are substantially responsible for embodied CO_2 emissions. Cement has the highest CO_2 emission of about 50% of the aggregate ECO_2 emission, followed by clay bricks and steel, with a nearly similar proportion of about a quarter (Fig. 5). These materials constitute more than 70% of all carbon emissions of an entire building [14]. Buildings in Bhutan similarly contribute significantly to embodied CO_2 emission.

The production ECO_2 of 154.7T (154743KG) represents about 203KG/m^2 after accounting for its gross floor area. This estimate is lower than the related studies in the literature. For instance, Shams et al. [37] reported 340KG/m^2 of embodied CO_2 emissions and Kumanayake et al. [14] found 629.6KG/m^2 from a three-story office building in Sri Lanka. These differences can be associated with higher CO_2 coefficients. Also, the former study considered a wider range of materials and the latter case study from Sri Lanka was a commercial building.

4.4. Discussion

The preceding sections have presented and interpreted the results, compared to existing literature. In contrast, this section will discuss the findings' overall implications and provide possible future research directions.

This investigation revealed that the typical residential buildings in the capital consume energy-intensive and carbon-intensive mineral-based materials. This is in addition to the apparent issue of construction cost escalation predominantly originating from construction materials. The Housing Market Demand Survey 2021 [54] estimated Thimphu's housing stock at 28,956 units. These units translate to 3620 four-storey buildings containing eight units (like our case study building) due to a similar ubiquitous RCC archetype construction method with an infill wall system. That would mean that Thimphu's residential sector's total embodied energy and embodied CO_2 emissions are responsible for 7215 TJ (Terajoules) and 590 KT (Kilotonnes), respectively.

Similarly, Thimphu sees the equivalent of 441 four-storey buildings annually constructed [54], which implies that the residential sector alone contributes annually to 879 TJ of embodied energy and 72 KT of embodied CO_2. The projections suggest that the urban building stock is underwhelmingly unsustainable, and the trend will likely continue with increasingly similar construction activities unless alternatives become available. These explicit sustainability quantifications from the Bhutanese context further confirm and expand the existing studies from other regions. At the same time, these estimates can show relatable insights, especially in emerging countries with similar on-site conventional construction practices.

Several strategies are suggested in the literature to reduce embodied energy and CO_2 emission. These include using low-carbon and renewable materials, material minimization, local sourcing of materials and components, designs that save material, modifying concrete properties, and construction optimization strategies [14], [55]. For Bhutan, the Economic Development Policy 2016 and Draft National Construction Industry Policy 2018 have prioritized two schemes: mechanization of construction methods and domestic production of construction materials.

As a result, Bhutan recently embarked on a systematic transformation of the construction sector employing mass timber construction and sustainable forest management. Three mass timber pilot projects are underway in the capital to demonstrate sustainable timber construction. Mass timber construction comprises engineered wood products—laminated from smaller boards or lamella [56] using glue or non-glued methods like nails and dowels—which offers alternatives to steel and concrete [2], [57]. The sustainability evidence from this research justifies Bhutan's ongoing construction restructuring efforts. As an advocator and executant of the holistic Gross National Happiness development model [58], coupled with the construction sector being increasingly encouraged to adopt sustainable construction practices, Bhutan merits authenticity to shift to a sustainable construction sector.

MTC benefits from the marriage of prefabrication and the renewability of the construction material, wood. Firstly, MTC is an attractive and viable 21st-century construction material owing to its low embodied energy, renewability, and carbon sequester capability [59]. Secondly, MTC can reap several prefabrication-related benefits, the most notable being the reduction in construction time, comprehensive cost reduction, and improved quality of the products [7], [60]–[65]. Likewise, its environmental benefits include waste reduction, reduced transportation, and pollution [7], [64]–[67].

Despite its strengths, MTC has inherent disadvantages and barriers, including knowledge and labor, research, logistics, planning, acoustics & vibration, job displacement, code permits, wind, and component flexibility [59]. Apart from a Glulam manufacturing unit, Bhutan does not have other mass timber products such as commonly adopted CLT (cross-laminated timber). Although other mass timber products like DLT (dowel laminated timber) and NLT (Nail-laminated timber) provide cheaper promises without the dedicated manufacturing units, a precedent must first be proven in Bhutan. Likewise, the success of MTC would depend on the sustainable supply of forest resources. Bhutan has a great forest cover of 71% [68], and its constitution mandates a minimum coverage of 60% for all times to come. The forest resource is considered renewable, and with proper management (sustainable forest management), a steady supply of wood products can be achieved [56], [69]. Demonstration projects could provide valuable insights into these uncertainties. In parallel, future researchers could also explore the appropriate level of mass timber construction adoption and related studies within the country's settings. Ultimately, the authors argue that the essential factor in the successful adoption of MTC could depend on the construction costs of the MTC. Therefore, our subsequent study compared the existing concrete building with the MTC alternative regarding sustainability and construction cost assessment [70].

5. CONCLUSION

This study appraised the prominent building materials from the perspective of material cost analysis and sustainability metrics comprising embodied energy and CO_2 emissions. The material cost analysis revealed a staggering 300% cost escalation for sand, followed by infill wall materials of autoclave aerated concrete blocks and red bricks at approximately 62.5% and 46.5%, respectively, potentially impacting the overall construction costs. Similarly, the sustainability evaluation reported that Bhutan's primary building materials contributed significantly towards embodied energy and CO_2 emissions of $2.5GJ/m^2$ and $203KG/m^{2,}$ respectively. These estimates suggest that the urban building stock is economically and environmentally unsustainable. In addition, this trend will likely worsen unless alternatives appear due to the expected rise in construction activities. In response, the adoption of prefabrication, using wood for mass timber construction, is discussed as a possible strategic intervention to restructure the construction industry and its related inadequacies to be productive, cost-effective, and sustainable.

This research is based on a typical multi-story residential building and is limited to the materials of a superstructure building assemblage with a substantial contribution, wall system, and structural system with the expectation that they represent the significant characteristics of the analysis. Future studies should include comprehensive building assemblages and materials over multiple case study buildings for a better-representative value. Furthermore, this study adopted a foreign database for sustainability. Future researchers should use a local database, whenever developed, for a more accurate value.

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