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Targeted Embodied Energy Mitigation in Ethiopian Housing: A Sensitivity Analysis for Sustainable Material Optimization

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Abstract—**Building sustainability can be improved by systematically applying low-impact material selection and strategic substitution, informed by robust environmental performance analysis. This study uses a process-based quantification combined with Morris's sensitivity analysis to investigate Embodied Energy (EE) minimization in Ethiopian IHDP housing. Analysis of a case housing building revealed that hollow concrete blocks, concrete, finishes, and steel are the predominant contributors to total EE. Sensitivity analysis identified these categories as priority targets for intervention. Scenario modeling demonstrated that reducing and replacing steel and other high contributors to conventional materials offers cumulative EE reductions exceeding 330,000 MJ, a 3.63% improvement over baseline energy. These findings highlight the significant opportunity for advancing the Climate Resilient Green Economy strategy and support rapid urban housing objectives while significantly reducing the environmental footprint. The research establishes actionable pathways for material optimization in large-scale housing, bridging critical gaps in lifecycle assessment data and informing Ethiopian policy and practice toward more resilient, sustainable urban development.**

Keywords—**alternate materials, embodied energy, ethiopian housing, sensitivity analysis, sustainable construction**

I. INTRODUCTION

The housing sector in Ethiopia, shaped mainly by the Integrated Housing Development Program (IHDP), is undergoing transformation to address urban housing shortages by deploying affordable condominium units through semi-prefabricated methods that include locally sourced materials such as compressed stabilized earth blocks and agrostone panels [1–3]. Prefabricated components, including ribbed slabs and on-site partial prefab construction, significantly reduce concrete usage and enhance embodied energy efficiency. Despite these advances, pressing concerns remain regarding environmental sustainability [4, 5]. The government's current focus on prefabricated concrete cast housing aims to meet high housing demand and reduce construction delays. Still, this approach may overlook environmental considerations, potentially causing undesired ecological impacts due to material wastage, pollution, and lifecycle carbon emissions [6].

National policies, such as the Climate Resilient Green Economy strategy, underscore the importance of integrating green building practices with renewable energy and efficient resource use [7, 8]. However, comprehensive assessments of embodied energy and complete environmental impacts for IHDP housing are still lacking. There is a critical gap in research regarding detailed material-wise embodied energy quantification and the evaluation of phased material substitution for improved sustainability. Bridging this gap is essential to ensure Ethiopia's rapid urban housing development effectively aligns with long-term sustainability targets. Accordingly, this study applies Morris sensitivity analysis to accurately identify materials with the highest embodied energy consumption and quantify the potential for low-impact alternatives, providing a much-needed evidence base to guide material optimization and policy for sustainable, resilient housing construction within the national development agenda [9].

II. LITERATURE REVIEW

The building sector is a major driver of global CO_2 emissions and energy consumption, making advancing and adopting alternative sustainable building materials critical for reducing the built environment's Embodied Energy (EE) footprint [10]. This sector's lifecycle impact spans raw material extraction, processing, construction, maintenance, demolition, and disposal, where embodied energy can often exceed operational energy, especially in energy-efficient designs such as Nearly Zero Energy Buildings (NZEB), with EE representing 53–61% more energy than operational energy in studied cases [11]. EE estimation is commonly employed to quantify these impacts, providing standardized energy efficiency measures for better sustainability [12, 13]. Research highlights multiple promising sustainable materials, including biobased resources such as bamboo and timber, geopolymer-based concrete, and clay roofing tiles, which offer considerable reductions in embodied energy when substituted for traditional steel or OPC concrete [14–16]. For instance, dak clay tiles reduce roofing EE by over 92% compared to steel, and geopolymer concrete cuts structural concrete EE by nearly 40%.

Furthermore, Industrialized Building Systems (IBS) demonstrate lower EE than cast-in-situ methods, facilitated by prefabrication efficiencies and optimized material use, especially in steel-intensive components [17]. Moreover, Environmental benefits must be balanced against economic and practical constraints, as bioplastics and other innovative bio-based materials often face hurdles in cost and scalability [10]. Studies further emphasize the importance of data quality, representativeness, and uncertainty analyses to model EE across geographic regions and material typologies robustly. New methodologies like the STIRPAT model link socio-economic drivers to energy use patterns in construction, aiding policy formulation [18, 19]. Cumulative EE reduction strategies focus on component-level substitutions—such as replacing steel materials with timber or bamboo [20], or conventional cement screed with low EE variants that, while individually modest, collectively compound into substantial reductions in building lifecycle embodied energy [12, 21].

III. MATERIALS AND METHODS

Sustainability in the built environment is essential for mitigating climate change and conserving resources. Embodied Energy (EE), comprising all energy consumed in material extraction, production, transportation, construction, and disposal, significantly contributes to buildings' life cycle energy use. However, challenges persist in accurately estimating EE due to data variability, material diversity, and regional construction practices. High embodied energy materials like steel and concrete substantially impact environmental footprints, making their substitution or optimization critical for sustainable development [10, 22]. Addressing these issues through EE Assessment combined with sensitivity analysis enables the identification of key influence factors. It supports selecting low-embodied-energy materials and efficient design strategies, particularly in contexts like Ethiopian housing [17, 23].

A. System Boundary

The study's system boundary includes only the Product Stage (A1–A3) and Construction Stage (A4–A5), focusing exclusively on material extraction, transport, manufacturing, and construction activities, and excludes the use Stage and End-Life Stage (maintenance, demolition, disposal), as shown Fig. 1. This scope is consistent with ISO 14040/44 Life Cycle Assessment standards and ASHRAE 189.1 recommendations, which emphasize up-front embodied energy impacts in benchmarking the sustainability of building materials [24, 25].

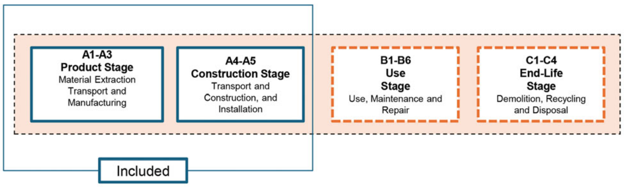

Fig. 1. System boundary.

B. Sensitivity Analysis

Morris's sensitivity analysis applied post-estimation of Embodied Energy (EE) for case buildings to quantify the influence of individual material parameters on total EE and identify critical contributors. This method enabled the systematic screening of parameters, facilitating targeted selection of materials for low-energy substitution to optimize environmental performance. The approach provides a robust framework for prioritizing interventions in sustainable building material design [26, 27].

C. Case Building and Material Intensity

The case building, depicted in Fig. 2, is in Addis Ababa, Ethiopia, at the IHDP Project 10 (Gelan Site), with a gross floor area of 1557.5 m², constructed using semi-prefabricated reinforced concrete techniques. Material intensity and embodied energy coefficients were primarily adapted from regionally recognized studies. At the same time, parameters lacking local data were supplemented using the locally recognized life cycle inventory database, Ecoinvent, ensuring comprehensive and context-specific embodied energy assessment [28–30].

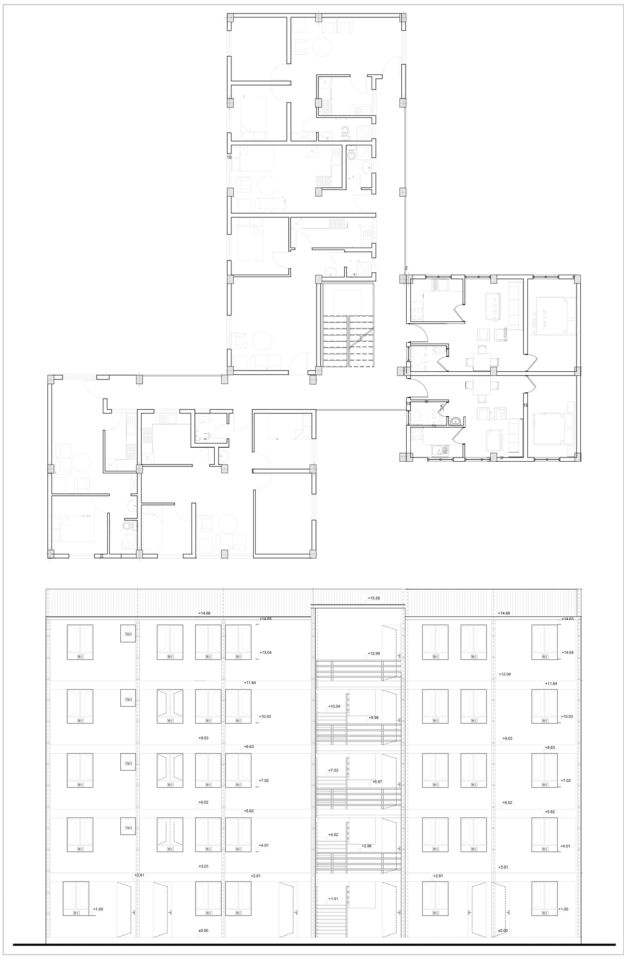

Fig. 2. Case building layout (Source: Addis Ababa Housing Agency).

The construction material quantities used for the case building were derived from the bill of quantities provided by the Addis Ababa Housing Agency. It is summarized alongside their corresponding embodied energy coefficients in Table 1.

Table 1. Material intensity and EE factors (Ref: [28, 30])

Material	Total Quantity (kg)	EE Coeff (MJ/kg)
Stone Hardcore & Masonry	16,585	0.5
Concrete	195,352.55	3.32
Reinforcement & Steel Elements	15,726.25	15.97
Polystyrene Insulation	140	92
Hollow Concrete Blocks (HCB)	588,780	7.96
Precast Elements	20,080	1.8
Galvanized Metal (Roof & Pipes)	3443.75	20
Aluminum Windows	4170	155
Steel Doors	2100	40
Timber Doors	875	14
Glass (Glazing)	3068.75	22
Paint	1597.50	85
Cement Screed (Mortar)	104,122.50	1.4
Ceramic Tiles & Terrazzo	18,543.75	~10.25
PVC Pipes	1757.50	75
Fixtures & Electrical	7815	280

IV. RESULT AND DISCUSSION

Embodied Energy estimation (Table A1), utilizing detailed BOQ material quantities for the five-story IHDP

M1-Typlogy housing type (1557.5 m²), revealed that the superstructure overwhelmingly dominates total embodied energy, with Hollow Concrete Blocks (HCB) contributing 52.1%, finishes 29.4%, concrete 7.4%, steel 7.2%, and aluminum 4.2% (Fig. 3). The result reveals that high material intensity in wall work and finishing elements is the principal driver of EE, indicating that targeted substitution in these categories would most effectively reduce the building's overall environmental impact.

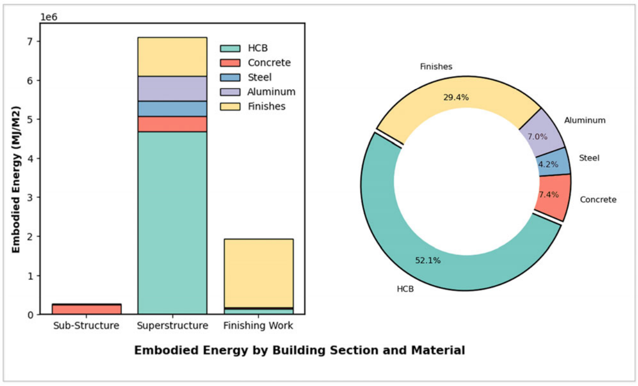

Fig. 3. Embodied energy level.

These results underscore significant opportunities to enhance sustainability in IHDP housing construction by substituting conventional steel, finish materials, and standard concrete with lower EE alternatives. Adopting advanced low-energy concrete technologies, utilizing recycled steel or bamboo for stair elements, and optimizing finishes with eco-friendly products can dramatically reduce total embodied energy, supporting Ethiopia's transition to environmentally responsible urban development.

A. Scenario for Embodied Energy Reduction

Morris's sensitivity analysis was applied to define the possible material substitution scenario for EE reduction. The study reveals that Hollow Concrete Blocks (HCB) and concrete exhibit the highest overall influence (μ^*) on total embodied energy, 0.82 and 0.78, respectively, with moderate Nonlinearity (σ = 0.15 – 0.18). Steel and aluminum contribute notable influence (μ^* = 0.48 and 0.37) and display greater Nonlinearity ($\sigma > 0.2$), indicating more complex sensitivity patterns. Despite a lower influence (μ^* = 0.23). These results robustly prioritize HCB and concrete as prime targets for low-energy material substitution, with steel and aluminum also offering impactful secondary opportunities for reduction (Table 2 & Fig. 4).

Table 2. Morris sensitivity result

Category	Total EE (MJ)	μ^* Influence	σ Nonlinearity
HCB	4,832,460.30	0.82	0.15
Concrete	684,714.30	0.78	0.18
Steel	388,053.20	0.48	0.22
Aluminum	646,350.00	0.37	0.21
Finishes	2,725,333.10	0.23	0.17

A. Minimizing Embodied Energy

In this study, replacing conventional materials with low-embodied energy alternatives can significantly reduce the overall Embodied Energy (EE) of a case building. The result revealed that substituting galvanized steel roofing (EE ≈ 20 MJ/kg) with clay tiles (EE ≈ 1.5 MJ/kg) can reduce roofing-related EE by over 85%, as confirmed by a similar report by CECP-EU's review on Indian building materials [31]. For stair balusters and handrails, engineered bamboo (EE ≈ 8 MJ/kg) presents nearly a 50% reduction compared to conventional steel (EE ≈ 16 MJ/kg), offering ecological benefits. Additionally, adopting low-clinker and geopolymer concrete (EE ≈ 2 MJ/kg) in place of standard RC C-25/30 mixes (EE ≈ 3.3 MJ/kg) leads to a 40% decrease in the embodied energy (Table 3).

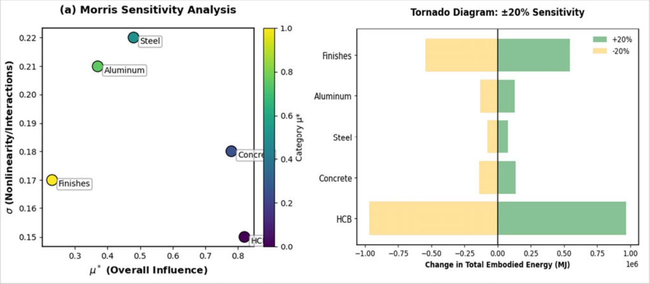

Fig. 4. Key material affecting EE.

Table 3. EE reduction with alternate materials

Component	Qty (kg)	Original EE (MJ)	Replacement EE Coeff (MJ/kg)	New EE (MJ)	Reduction (MJ)
Roofing (steel/metal)	3262.50	65,250	1.5 (clay tile)	4893.75	60,356.25
Handrail/stairs	1993.75	31,840.19	8 (bamboo)	15,950	15,890.19
RC Concrete (struct)	119,903.75	398,080.45	2.0 (geopolymer)	239,807.50	158,272.95
Steel Doors	2100	84,000	14 (timber/bamboo)	29,400	54,600
Cement Screed	104,122.50	145,771.50	1.0 (low-EE screed)	104,122.50	41,649

Material substitution scenarios reveal substantial Embodied Energy (EE) reductions across key building components. Specifically, replacing steel/metal roofing (EE: 65,250 MJ) with clay tiles (EE: 4893.75 MJ) results in a dramatic 92.5% decrease in EE for the roofing system. Substituting bamboo for steel in handrails and balusters lowers EE by 49.9%, while adopting geopolymer concrete for structural elements instead of conventional reinforced concrete achieves a 39.8% reduction.

Transitioning steel doors to timber or bamboo reduces EE by 0.51%, and switching cement screed to a low-EE variant yields a 0.39% decrease (Fig. 5). These strategic substitutions collectively produce a cumulative reduction of over 330,768 MJ (3.63% of the baseline EE), highlighting the potential of alternative materials to mitigate environmental impact in Ethiopian IHDP housing construction. These findings align with established literature, underscoring the effectiveness of targeted, component-based EE interventions for sustainable built environments.

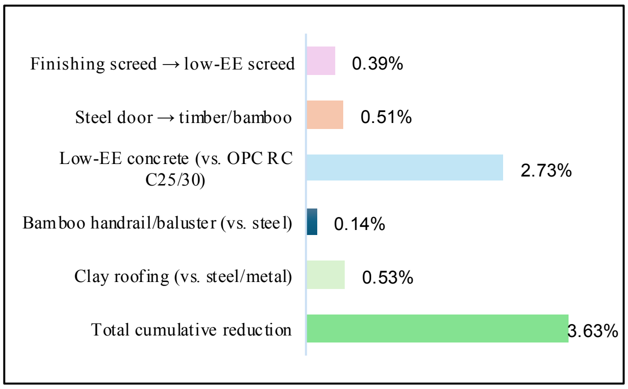

Fig. 5. Alternate materials reduction percentage from the baseline EE.

V. CONCLUSION

The comprehensive assessment of Embodied Energy (EE) in a five-story case IHDP housing building, using a process-based methodology and Morris sensitivity analysis, reveals that Hollow Concrete Blocks (HCB), concrete, finishes, steel, and aluminum are the dominant contributors to the building's total embodied energy. Sensitivity screening confirms HCB and concrete as the highest-impact categories ($\mu^* > 0.78$), with steel and aluminum showing appreciable EE influence and greater Nonlinearity. Scenario analyses demonstrate that substituting key components with low-EE alternatives—such as replacing steel/metal roofing with clay tiles, steel handrails and doors with bamboo and timber, ordinary Portland cement concrete with geopolymer mixes, and conventional screed with low-EE variants—can yield cumulative EE reductions exceeding 330,000 MJ, representing a 3.63% decrease relative to the baseline energy. The results highlight that targeted interventions in steel consumption and finishing materials substitutions present substantial opportunities for EE mitigation, particularly through local adaptation of alternative technologies and renewable resources. These findings substantiate the value of sensitivity analysis in guiding material prioritization for sustainable housing construction, offering actionable insights for policymakers and practitioners to integrate green design principles. Ultimately, this study underscores that strategic material substitution, supported by robust quantitative frameworks, is essential for minimizing environmental impacts and advancing Ethiopia's sustainable urban development agenda within the IHDP framework.

A key limitation of this study is the focus solely on embodied energy, without integrating detailed cost analyses or evaluating potential trade-offs arising from large-scale material substitution. Future research should encompass comprehensive economic assessments, include operational energy impacts, and examine the feasibility and adaptability of proposed low-impact material alternatives within local and regional Ethiopian housing contexts, ensuring recommendations are practical, affordable, and scalable for broader implementation.

APPENDIX

Table A1. Detailed embodied energy estimation

Building Section	Material	Total Quantity (kg)	EE Coeff (MJ/kg)	Final EE (MJ)
Sub-Structure	Stone Hardcore & Masonry	16,585	0.5	8293
	Concrete (Lean + Ground Slab)	75,448.75	3.32	250,490
	Reinforcement Bars	1441.25	15.97	23,017
	Polystyrene Insulation	140	92	12,880
	Sub Structure Total			294,679
Superstructure	Structural Concrete	119,903.8	3.32	398,080
	HCB Walls	519,660	7.96	4,136,494
	Ribbed Slab HCB	69,120	7.96	550,195
	Precast Elements	20,080	1.8	36,144
	Reinforcement Bars	11,291.25	15.97	180,321
	Galvanized Roofing & Metal	3262.5	20	65,250
	Aluminum Windows	4170	155	646,350
	Steel Doors	2100	40	84,000
	Steel Structure & Handrail	1993.75	15.97	31,840
	Timber Doors	875	14	12,250
	Glass (Glazing)	3068.75	22	67,513
	Paint	1597.5	85	135,788
	Super Structure Total			6,344,224.7
Finishing Work	Cement Screed (Mortar)	104,122.5	1.4	145,772
	Ceramic Tiles (Floor & Wall)	9877.5	10	98,775
	Terrazzo (Flooring & Steps)	8666.25	10.5	90,996
	PVC Pipes	1757.5	75	131,813
	Galvanized Steel Pipes	181.25	20	3625
	Fixtures & Electrical Components	7815	280	2,188,200
	FINISHING TOTAL			2,659,180
	TOTAL Initial EE			9,298,083
	Recurrent 15% EE			1,394,712.52
	TOTAL EE			10,692,796
	1557.5 M2 Floor Area- Normalized EE (MJ/M2)			6865.36

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

Getahun Ayele Tessema contributed to the original draft writing, data curation, methodology development, investigation, formal analysis, validation, software application, and study conceptualization. P. S. Chani and E. Rajasekar contributed to methodology, conceptualization, and supervision. All authors had approved the final version.

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