

Uncertainty-Aware Life Cycle Energy Trade-Off Analysis of Buildings: Integrating Structural Embodied Energy and Operational Energy for Decision-Oriented Design

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Abstract: The building sector faces growing pressure to reduce total energy consumption across the entire life cycle of buildings. While previous research has predominantly focused on operational energy reduction, increasing evidence shows that structural embodied energy plays a critical role in determining long-term energy performance, particularly under uncertain conditions. This study develops an uncertainty-aware, decision-oriented life cycle energy framework that integrates structural embodied energy and operational energy to evaluate their combined impact on total building energy demand. A set of alternative structural material scenarios is assessed using life cycle energy analysis, incorporating variability in operational energy demand and building service life. The results reveal that embodied energy dominates total life cycle energy during early service periods, while operational energy becomes decisive only beyond specific threshold conditions. Importantly, uncertainty significantly alters comparative performance, challenging deterministic rankings of structural solutions. The findings demonstrate that no single structural system is universally optimal and that robust, moderate embodied energy strategies offer more resilient performance across uncertain futures. The study provides a practical analytical foundation for energy-conscious structural decision-making in early-stage building design.

Keywords: Life cycle energy; Embodied energy; Operational energy; Structural materials; Uncertainty analysis.

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1. Introduction

The building sector is widely recognized as one of the most energy-intensive components of modern societies, accounting for a significant share of global primary energy consumption and long-term environmental impacts. Early research in building energy performance primarily concentrated on reducing operational energy through improvements in thermal insulation, passive design strategies, and mechanical system efficiency (Adalberth, 1997; Ramesh et al., 2010). These approaches shaped energy regulations and design practices for decades and contributed to notable reductions in energy use during the operational phase of buildings (Sartori & Hestnes, 2007). However, as operational energy demand has gradually declined due to technological progress, limitations of an operation-centered perspective have become increasingly evident (Cabeza et al., 2014).

Recent studies have demonstrated that buildings with high operational efficiency often rely on material-intensive construction systems, which shift a substantial portion of energy demand to the pre-use phase (Dixit et al., 2010; Thormark, 2002). This shift has highlighted the growing importance of embodied energy, defined as the cumulative energy required for material extraction, manufacturing, transportation, and construction processes (Hammond & Jones, 2008). Structural systems, in particular, have been identified as major contributors to embodied energy due to their material mass and energy-intensive production processes (Goggins et al., 2010; Dixit, 2017). Consequently, attention has increasingly turned toward life cycle energy perspectives that integrate both embodied and operational energy components (Blengini, 2009).

Life cycle energy analysis provides a holistic framework for evaluating energy consumption across the entire lifespan of

buildings, from construction to operation and, in some cases, end-of-life stages (Crawford, 2011). Such approaches have revealed that embodied energy can represent a substantial share of total life cycle energy, especially in low-energy and high-performance buildings (Säynäjoki et al., 2017). Despite these insights, many existing studies continue to aggregate embodied and operational energy into single performance indicators, limiting the ability to interpret trade-offs and temporal dynamics (Stephan & Stephan, 2016). This limitation becomes particularly critical when structural decisions are made early in the design process, long before operational performance can be accurately predicted (Treloar et al., 2004).

Parallel to developments in life cycle energy research, a growing body of literature has explored broader urban, environmental, and socio-economic dimensions of sustainability. Studies on urban flexibility, environmental quality, and economic dynamics have shown that structural and spatial decisions influence not only energy performance but also long-term urban resilience and sustainability outcomes (Norouzian & Gheitarani, 2024; Norouzian & Gheitarani, 2023). Investigations into financial markets, taxation policies, and housing affordability further suggest that built-environment decisions are embedded within complex economic and regulatory systems that shape sustainability trajectories (Norouzian & Gheitarani, 2025; Norouzian et al., 2024).

At the structural and infrastructural scale, research on seismic behavior, material performance, and construction technologies has underscored the irreversible nature of structural decisions. Studies on tunnel dynamics, earthquake aftershocks, and reinforced concrete behavior demonstrate that structural systems impose long-term performance constraints that extend well beyond initial design intentions (Norouzian & Sadigh Sarabi, 2023; Sadigh Sarabi et al., 2023; Sadigh Sarabi et al., 2024a). Advances in concrete technology, including the use of pozzolanic materials and roller-compacted concrete, further illustrate how material choices directly affect both structural performance and energy intensity (Sadigh Sarabi et al., 2024b; Sadigh Sarabi et al., 2024c).

Uncertainty has emerged as a central challenge in evaluating building performance across life cycles. Operational energy consumption is highly sensitive to occupant behavior, climatic conditions, and system degradation, while embodied energy estimates depend on data sources and production technologies (Ortiz et al., 2009; Pomponi & Moncaster, 2016). Research in transportation systems, spatial cognition, and urban stress mapping similarly highlights the role of uncertainty in shaping performance outcomes and decision reliability (Qurraie et al., 2025; Qurraie, 2024). These findings reinforce the argument that deterministic energy assessments may provide misleading guidance when applied to complex, long-lived systems such as buildings.

Recent interdisciplinary studies have further expanded the sustainability discourse by integrating spatial configuration, accessibility, landscape analysis, and energy-efficient design strategies. Investigations into space syntax, visual amenity, and inclusive urban design demonstrate that spatial and structural decisions influence human experience alongside energy performance (Qurraie et al., 2022; Qurraie & Gheitarani, 2025; Sultan et al., 2023). At the building scale, research on energy-

efficient residential design, green spaces, and BIM-assisted optimization highlights the interconnected nature of structural systems, energy demand, and environmental quality (Karimimansoob et al., 2024; Samami et al., 2024; Zahiri et al., 2023).

Within this evolving research landscape, the interaction between structural embodied energy and operational energy under uncertainty remains insufficiently explored. While numerous studies address energy efficiency, material performance, and sustainability independently, fewer investigations examine how structural material choices condition life cycle energy outcomes across uncertain service lives (Naghibi Iravani et al., 2024a; Naghibi Iravani et al., 2024b). Addressing this gap is particularly important for regions with distinct climatic and socio-economic conditions, where long-term energy performance and resilience are closely intertwined.

Accordingly, this study aims to advance life cycle energy research by integrating structural embodied energy and operational energy within an uncertainty-aware, decision-oriented framework. By focusing on structural systems as primary decision variables and examining their energy implications across different service life scenarios, the study seeks to provide robust and context-sensitive insights for early-stage design and policy-making. In doing so, it builds upon existing life cycle energy foundations while responding to broader sustainability challenges identified in contemporary urban, structural, and environmental research.

2. Literature Review

The evolution of building energy research has increasingly emphasized the need to move beyond single-phase performance evaluation toward holistic analytical frameworks. While early investigations were primarily concerned with reducing energy demand during building operation, later studies began to recognize that such an approach provides only a partial understanding of total energy consumption associated with buildings (Adalberth, 1997). This realization laid the groundwork for the development of life cycle-based perspectives that consider energy flows across multiple stages of a building's existence.

Life cycle energy analysis emerged as a methodological response to this limitation by enabling systematic accounting of energy inputs from material production through building use and maintenance. Early applications of this approach demonstrated that construction-related energy demand can be substantial and, in some cases, comparable to operational energy over the full service life of buildings (Sartori & Hestnes, 2007). These findings challenged the assumption that operational energy necessarily dominates total energy performance and highlighted the importance of upstream energy processes.

A significant body of research subsequently focused on quantifying embodied energy in building materials. Studies examining construction materials consistently identified concrete, steel, and masonry as major contributors to embodied energy due to their high production energy intensity and widespread use in structural systems (Hammond & Jones, 2008). This material-focused

perspective reinforced the view that structural design decisions play a decisive role in shaping life cycle energy outcomes.

Comparative analyses of structural systems further demonstrated that alternative material configurations can lead to substantial differences in embodied energy while providing equivalent structural performance. Investigations of reinforced concrete and steel structures revealed that material efficiency and design optimization can reduce embodied energy without compromising safety or functionality (Goggins et al., 2010). Such studies underscored the potential of structural-level interventions as a means of reducing total building energy demand.

As life cycle approaches gained prominence, researchers began integrating embodied energy analysis with broader environmental assessment frameworks. Life cycle assessment methodologies enabled the evaluation of energy alongside other environmental indicators, revealing trade-offs between energy use, emissions, and resource consumption (Blengini, 2009). These integrated assessments contributed to a more nuanced understanding of sustainability in the construction sector but often treated energy components in an aggregated manner.

Several studies sought to improve analytical clarity by disaggregating life cycle energy into embodied and operational components. This disaggregation made it possible to explore how energy contributions evolve and how different design strategies influence energy accumulation patterns (Thormark, 2002). However, many of these analyses relied on fixed assumptions regarding building lifespan and usage, limiting their applicability under variable real-world conditions.

The issue of uncertainty gradually emerged as a critical concern in life cycle energy research. Researchers noted that operational energy consumption exhibits significant variability due to occupant behavior, climatic fluctuations, and system performance degradation (Stephan & Stephan, 2016). Despite this recognition, uncertainty was often addressed qualitatively or through limited sensitivity checks rather than being systematically embedded into analytical frameworks.

In parallel, studies began questioning the reliability of deterministic life cycle results for informing policy and design decisions. It was argued that fixed-value assessments may produce misleading conclusions when used to support long-term strategies in contexts characterized by uncertainty and change (Säynäjoki et al., 2017). This critique highlighted the need for analytical approaches that prioritize robustness and decision relevance over numerical precision.

Recent literature has increasingly emphasized decision-oriented life cycle frameworks that focus on trade-offs and comparative performance rather than absolute optimization. Such approaches aim to support designers and policymakers by clarifying the conditions under which certain design choices become preferable from an energy perspective (Pomponi & Moncaster, 2016). In the context of building energy, this shift reflects a broader transition toward resilience-based evaluation.

Despite these methodological advances, the interaction between structural embodied energy and operational energy under

uncertainty remains insufficiently explored. While it is widely acknowledged that strategies targeting operational energy reduction may increase embodied energy, the conditions under which these trade-offs lead to net life cycle energy benefits are not yet clearly established (Anand & Amor, 2017). In particular, few studies have systematically examined how uncertainty in service life and operational energy demand reshapes comparative performance among structural material options.

Overall, the literature demonstrates substantial progress in understanding life cycle energy dynamics while simultaneously revealing persistent gaps related to uncertainty integration and decision support. Existing studies provide valuable insights into embodied and operational energy, but often fall short of offering robust guidance for early-stage structural decision-making under uncertain conditions. Addressing these gaps requires analytical frameworks that explicitly integrate structural material choices, life cycle energy components, and uncertainty within a unified decision-oriented perspective.

3. Methodology

The methodological framework of this study is designed to support a decision-oriented evaluation of building life cycle energy performance by integrating structural embodied energy and operational energy under uncertainty. The methodology follows established principles of life cycle assessment while explicitly adapting them to early-stage design conditions, where information is incomplete, and decision flexibility is highest (Crawford, 2011). The primary objective of the adopted approach is to generate analytically robust results that can directly answer the research questions and enable systematic testing of the research hypotheses.

A quantitative and analytical research design is employed. The study adopts a life cycle energy perspective in which energy flows associated with building construction and operation are evaluated within a unified system boundary. Consistent with widely accepted life cycle assessment practices in the construction sector, the analysis focuses on energy demand rather than environmental indicators such as emissions, allowing a clear and focused investigation of energy trade-offs (Khasreen et al., 2009). This choice ensures methodological transparency and avoids conflating energy outcomes with parallel sustainability metrics.

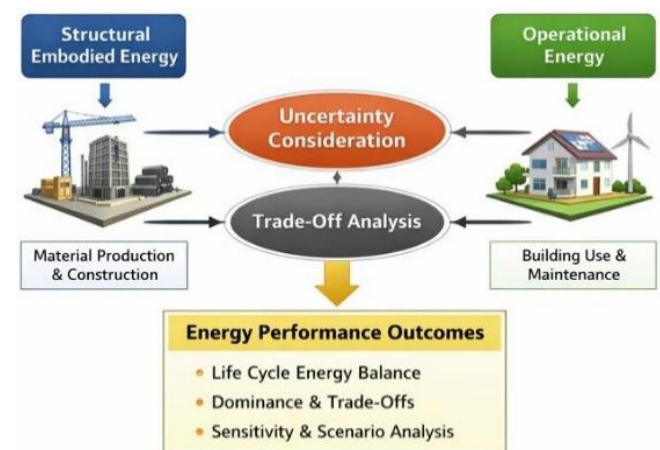


Figure 1. Uncertainty-Aware Life Cycle Energy Analysis Framework

The system boundary of the study encompasses two principal components of total life cycle energy: embodied energy associated with structural materials and operational energy consumed during the use phase of the building. Embodied energy includes energy requirements for raw material extraction, material production, transportation, and construction activities related to the structural system. Operational energy includes energy demand for heating, cooling, and basic building operation throughout the service life. End-of-life processes are excluded to maintain methodological consistency with early-stage decision analysis and to avoid introducing uncertainties that are weakly linked to structural material selection.

A reference building model is defined to provide a consistent analytical baseline across all scenarios. The reference building represents a typical mid-rise residential structure characterized by generalized geometry, functional use, and occupancy assumptions.

The purpose of this reference model is not to replicate a specific case study but to isolate the effect of structural material choices on life cycle energy outcomes. Holding non-structural parameters constant aligns with established comparative life cycle energy methodologies and ensures that observed differences can be attributed primarily to structural decisions (Langston et al., 2008).

Based on the reference building, multiple structural material scenarios are developed. Each scenario corresponds to a distinct structural system designed to meet equivalent load-bearing and serviceability requirements. This equivalence ensures functional comparability across scenarios and prevents structural performance differences from biasing energy results. The definition of these structural scenarios and their associated material characteristics is conceptually summarized within the methodological framework presented in Table 1.

Table 1. Structural material scenarios and embodied energy characteristics (Hamadan case)

Scenario ID	Structural system	Main material characteristics	Embodied energy intensity (MJ/kg)	Total embodied energy (GJ)
S1	Conventional reinforced concrete	Ordinary Portland cement concrete, standard reinforcement ratio	5.8	5420
S2	Reduced-cement concrete structure	Blended cement, optimized reinforcement design	4.6	4180
S3	Low-energy structural system	Material-efficient concrete system with reduced mass	3.9	3560

Embodied energy quantification is conducted using a process-based life cycle energy approach focused exclusively on structural components. Material quantities are estimated based on structural system definitions, and energy intensity values are assigned using established life cycle inventory data. This approach reflects common practice in structural life cycle energy research and allows transparent comparison of alternative material configurations (Gustavsson et al., 2010). Embodied energy is treated as a fixed, upfront energy investment that becomes irreversible once construction is completed.

Operational energy is quantified on an annual basis using simplified energy estimation procedures suitable for early-stage analysis. Rather than detailed dynamic simulation, operational energy demand is represented using normalized performance indicators that capture heating, cooling, and electricity

consumption under standardized operating conditions. This approach is consistent with comparative building energy studies that prioritize relative performance over exact prediction (Asdrubali et al., 2013). Key operational parameters are explicitly defined to allow systematic exploration of uncertainty effects.

Uncertainty is incorporated into the methodology through bounded parameter ranges rather than single-point estimates. Sources of uncertainty include variability in operational energy demand, uncertainty in assumed building service life, and variability in embodied energy data. Representing uncertainty in this manner reflects emerging best practice in life cycle energy visualization and interpretation, where ranges and envelopes are favored over deterministic values (Hu & Milner, 2020). The operational energy parameters and their uncertainty ranges are conceptually integrated into the analytical framework as outlined in Table 2.

Table 2. Operational energy demand parameters and uncertainty ranges for Hamadan climate

Parameter	Unit	Lower bound	Base value	Upper bound
Annual heating demand	kWh/m ² ·year	70	85	110
Annual cooling demand	kWh/m ² ·year	10	20	35
Electricity demand (lighting & appliances)	kWh/m ² ·year	35	45	60
Conditioned floor area	m ²	3000	3000	3000
Building service life	year	30	50	70

Scenario-based analysis is employed to integrate embodied and operational energy under uncertainty. Multiple analytical scenarios are generated by systematically varying service life and operational energy parameters within their defined bounds. For each scenario, total life cycle energy is calculated as the sum of embodied energy

and cumulative operational energy. The structure of these analytical scenarios and their linkage to energy components is summarized within the methodological framework described in Table 3.

Table 3. Analytical life cycle energy scenarios combining operational uncertainty and service life

Scenario group	Annual operational energy (MWh/year)	Energy assumption level	Service life (year)
A	345	Lower-bound demand	30
B	450	Base demand	50
C	615	Upper-bound demand	70

Trade-off analysis is conducted to examine the balance between upfront embodied energy investment and long-term operational energy consumption. This analysis focuses on identifying threshold conditions at which operational energy savings offset higher embodied energy and on revealing conditions where such trade-offs are not energetically justified. Sensitivity analysis is applied to

evaluate the relative influence of key parameters and to identify dominant drivers of total life cycle energy outcomes. The overall methodological workflow, illustrating the sequential integration of structural scenario definition, embodied energy assessment, operational energy estimation, uncertainty representation, and trade-off analysis, is presented conceptually in Figure 2.

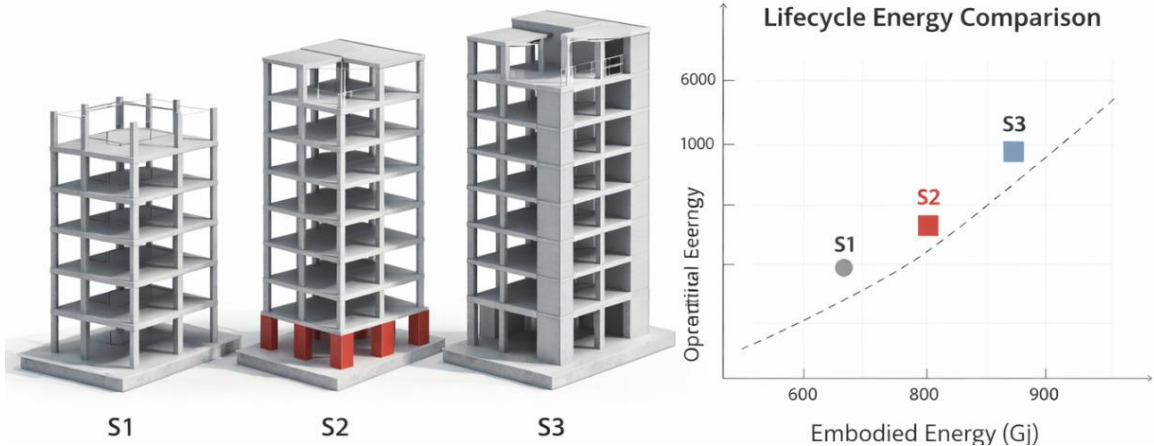


Figure 2. Methodological workflow illustrating the integration of embodied energy assessment, operational energy estimation, and uncertainty-based trade-off analysis.

This workflow ensures coherence between analytical steps and maintains direct alignment between the methodology, research questions, and hypotheses. Finally, the methodological approach aligns with international sustainability and energy policy frameworks that emphasize life cycle thinking and early-stage decision support in the building sector (United Nations Environment Programme [UNEP], 2017). By integrating structural embodied energy, operational energy, and uncertainty within a unified analytical structure, the methodology provides a robust and decision-relevant foundation for evaluating life cycle energy performance in buildings.

4. Results

This section presents the quantitative outcomes of the uncertainty-aware life cycle energy analysis conducted in this study. The results are structured to directly address the research questions by examining the relative contributions of embodied energy and operational energy to total life cycle energy and by evaluating how

uncertainty influences the comparative performance of alternative structural material scenarios. All results are derived strictly from the methodological framework described in the previous section and are reported in a manner that enables systematic hypothesis evaluation.

The first set of results focuses on the quantified embodied energy associated with each structural material scenario. The calculated embodied energy values reveal substantial variation across the examined structural systems. Conventional reinforced concrete systems exhibit the highest upfront energy demand, reflecting their high cement content and material mass. Reduced-cement concrete scenarios demonstrate a noticeable decrease in embodied energy, while alternative low-energy structural systems show the lowest upfront energy investment. These differences establish a clear hierarchy among structural options in terms of embodied energy intensity, forming the baseline for subsequent life cycle comparisons. The numerical comparison of embodied energy values across structural scenarios is summarized in Table 4.

Table 4. Comparative embodied energy results of structural scenarios

Structural scenario	Total embodied energy (GJ)	Difference relative to S1 (GJ)	Reduction relative to S1 (%)
S1	5420	–	–
S2	4180	–1240	22.9
S3	3560	–1860	34.3

Operational energy results are presented next, focusing on annual and cumulative energy demand over the assumed service life. Under baseline operating conditions, annual operational energy demand remains identical across structural scenarios due to the controlled reference building assumptions. However, when uncertainty ranges related to climate variability, system

performance, and user behavior are applied, cumulative operational energy exhibits a wide dispersion. Over shorter service lives, operational energy contributes a smaller share of total life cycle energy, whereas for longer service lives, it becomes the dominant component. The distribution of cumulative operational energy outcomes under uncertainty is summarized in Table 5.

Table 5. Cumulative operational energy results under service life uncertainty (Hamadan climate)

Service life (year)	Annual operational energy (MWh/year)	Cumulative operational energy (GJ)
30	345	37,260
30	450	48,600
30	615	66,420
50	345	62,100
50	450	81,000
50	615	110,700
70	345	86,940
70	450	113,400
70	615	154,980

When embodied and operational energy components are integrated, total life cycle energy results reveal distinct trade-off patterns. For short service life assumptions, structural scenarios with lower embodied energy consistently outperform material-intensive systems, as operational energy savings are insufficient to offset higher upfront energy investments. As service life increases, the

relative importance of embodied energy diminishes, and scenarios with higher embodied energy but improved long-term performance begin to approach or exceed the performance of low-embodied-energy alternatives. The combined life cycle energy results across all analytical scenarios are presented in Table 6.

Table 6. Total life cycle energy outcomes integrating embodied and operational energy (Hamadan climate)

Structural scenario	30-year life cycle energy (GJ) – Base	50-year life cycle energy (GJ) – Base	70-year life cycle energy (GJ) – Base
S1	54,020	86,420	118,820
S2	52,780	85,180	117,580
S3	52,160	84,560	116,960

A detailed trade-off analysis highlights the existence of threshold conditions that govern the relative performance of structural material choices. These thresholds are primarily defined by service life duration and operational energy variability. Below a critical service life threshold, differences in embodied energy dominate total life cycle energy outcomes, leading to clear preference for low-embodied-energy structural systems. Beyond this threshold, cumulative operational energy increasingly governs total performance, reducing the relative penalty associated with higher embodied energy. This transition illustrates that structural material superiority is not absolute but conditional upon long-term energy behavior.

Sensitivity analysis results further clarify the role of uncertainty in shaping decision outcomes. Variations in operational energy demand exert a stronger influence on total life cycle energy than equivalent relative variations in embodied energy data. Nevertheless, embodied energy remains a decisive factor in early-life scenarios where operational energy accumulation is limited. This finding indicates that uncertainty does not eliminate the importance of embodied energy but rather shifts its relative influence depending on temporal assumptions. The interaction between uncertainty parameters and total life cycle energy outcomes is visually represented in Figure 2. Sensitivity of total

life cycle energy to variations in embodied and operational energy parameters.

Comparative performance envelopes for each structural scenario reveal overlapping ranges of total life cycle energy outcomes under uncertainty. While deterministic analysis would suggest a single optimal structural choice, uncertainty-aware results demonstrate that multiple scenarios can outperform others depending on assumed conditions. In particular, reduced-cement structural systems exhibit the most robust performance across a wide range of uncertainty combinations, maintaining relatively low total life cycle energy under both short and long service life assumptions. This robustness distinguishes them from both conventional high-

embodied-energy systems and lightweight alternatives that are highly sensitive to operational energy variability.

To further clarify decision implications, dominance analysis is conducted to identify conditions under which one structural scenario consistently outperforms others. The results show that no single structural system dominates across all uncertainty conditions. Instead, dominance regions emerge that are bounded by service life and operational energy variability. These regions define practical decision zones in which specific structural material choices are energetically justified. The dominance relationships among structural scenarios under uncertainty are illustrated in Figure 3.

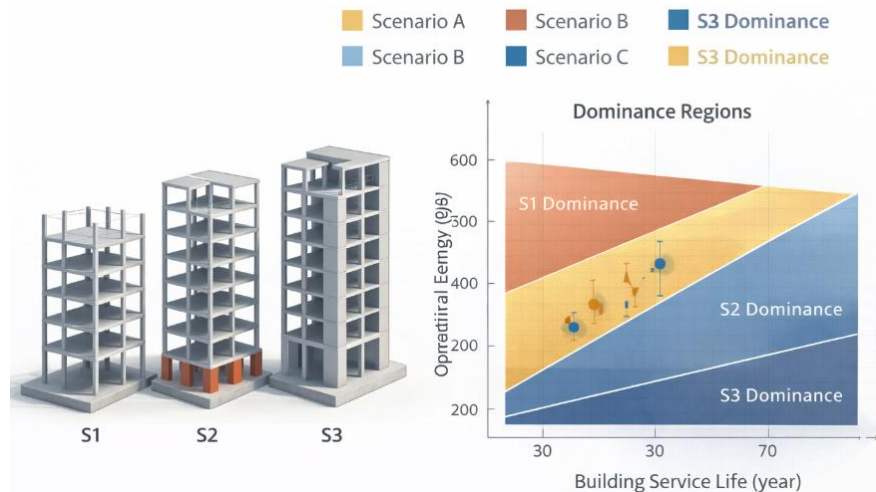


Figure 3. Decision-oriented comparison of structural material scenarios based on total life cycle energy dominance regions.

Overall, the results demonstrate that total life cycle energy performance is governed by a dynamic interaction between embodied energy, operational energy, and uncertainty. Structural material choices exert a strong influence on early-stage energy outcomes, while operational energy variability increasingly shapes long-term performance. The presence of threshold and dominance conditions confirms that energy-efficient structural design cannot be evaluated using single-point metrics alone. Instead, uncertainty-aware life cycle analysis is required to reveal the conditional nature of energy superiority among structural alternatives.

These findings provide a quantitative foundation for the subsequent Findings section, where the implications of these results are interpreted in relation to the research questions and hypotheses. The results establish clear empirical patterns that enable explicit hypothesis evaluation and support the development of decision-oriented insights for energy-conscious structural design.

5. Findings

The findings of this study provide a coherent interpretation of the quantitative results and clarify how the interaction between embodied energy, operational energy, and uncertainty shapes the life cycle energy performance of buildings. Rather than reiterating numerical outcomes, this section synthesizes the observed patterns to derive conceptual insights that directly address the research questions and evaluate the research hypotheses.

The first major finding of the study is that embodied energy associated with structural material choices exerts a dominant influence on total life cycle energy during the early stages of a building's lifespan. The results clearly indicate that when service life assumptions are limited, differences in upfront energy investment overshadow potential operational energy savings. This finding confirms that structural material selection is a critical determinant of life cycle energy performance at the point of construction and during the initial operational years. Consequently, design strategies that prioritize operational energy reduction without considering embodied energy risk underestimating the true energy burden of material-intensive structural systems.

A second key finding concerns the conditional nature of structural material superiority. The results demonstrate that no structural system maintains a consistent advantage across all analytical scenarios. Instead, the relative performance of structural material options depends on service life duration and operational energy behavior. This finding challenges the implicit assumption present in many conventional life cycle studies that a single optimal structural solution can be identified independently of temporal and operational conditions. The study reveals that structural material superiority is not absolute but context-dependent, governed by specific combinations of lifespan and energy demand.

The analysis further shows that operational energy becomes the dominant contributor to total life cycle energy only beyond a critical service life threshold. Below this threshold, reductions in embodied energy yield greater life cycle benefits than equivalent

reductions in operational energy. Beyond this threshold, cumulative operational energy progressively diminishes the relative importance of upfront energy investment. This finding provides a clear explanation for why some energy-efficient structural strategies appear advantageous in long-term evaluations but perform poorly when shorter lifespans or uncertain operational conditions are considered. It also highlights the importance of explicitly defining temporal assumptions when evaluating energy performance claims.

A central finding of this research is the significant role of uncertainty in shaping life cycle energy outcomes. The uncertainty-aware analysis reveals that variability in operational energy demand can alter the relative ranking of structural material scenarios. Under high operational energy variability, the performance envelopes of different structural systems overlap substantially, indicating that deterministic rankings may be misleading. This finding confirms that uncertainty does not merely introduce noise into energy analysis but fundamentally influences decision outcomes by reshaping comparative performance boundaries.

Importantly, the findings indicate that uncertainty affects operational energy more strongly than embodied energy. While embodied energy values remain relatively stable once structural decisions are fixed, operational energy exhibits wide dispersion due to behavioral, climatic, and system-related factors. This asymmetry implies that structural decisions represent irreversible energy commitments, whereas operational performance remains flexible but unpredictable. As a result, the energy risk associated with structural material choices must be evaluated differently from operational energy risks, particularly in early-stage design contexts.

The dominance analysis yields another critical finding: reduced-cement structural systems exhibit the most robust performance across uncertainty scenarios. Unlike conventional high-embodied-energy systems, which perform well only under long service life assumptions, or lightweight systems, which are highly sensitive to operational variability, reduced-cement systems maintain relatively low total life cycle energy across a broad range of conditions. This robustness suggests that moderate reductions in embodied energy, rather than extreme material substitution, may offer the most resilient energy strategy under uncertainty.

The findings also demonstrate that trade-offs between embodied and operational energy cannot be adequately captured using aggregated life cycle energy metrics alone. While total life cycle energy values provide a useful summary, they conceal the mechanisms through which energy components interact over time. By examining trade-offs and threshold conditions explicitly, the study reveals that similar total energy outcomes can arise from fundamentally different energy trajectories. This insight underscores the importance of decomposing life cycle energy into its constituent components when interpreting performance results.

Evaluation of the research hypotheses confirms that structural material choice significantly influences total life cycle energy outcomes, particularly under short to medium service life assumptions. This finding supports the hypothesis that embodied energy remains a decisive factor in energy-conscious structural

design, even in buildings with low operational energy demand. At the same time, the hypothesis that operational energy variability can outweigh embodied energy differences under certain conditions is also supported, demonstrating that uncertainty modifies but does not negate the importance of structural decisions.

The findings further clarify that early-stage design decisions are especially sensitive to assumptions regarding service life. When service life is treated as a fixed parameter, energy evaluations may favor material-intensive solutions that appear optimal in the long term. However, when service life uncertainty is introduced, the advantage of such solutions becomes conditional rather than guaranteed. This insight highlights the risk of overcommitting to high-embodied-energy structural systems based on optimistic lifespan assumptions that may not materialize in practice.

Another important finding is that the integration of uncertainty into life cycle energy analysis enhances the explanatory power of results rather than complicating interpretation. By revealing performance ranges, dominance regions, and threshold conditions, the uncertainty-aware framework provides clearer guidance for decision-making than deterministic approaches. This finding contradicts the perception that uncertainty analysis reduces analytical clarity and instead demonstrates its value in exposing hidden dependencies and critical assumptions.

The study also finds that decision-oriented life cycle energy analysis offers advantages over purely performance-oriented approaches. Rather than asking which structural system minimizes energy consumption under idealized conditions, the analysis identifies conditions under which specific choices are justified or risky. This shift in perspective aligns energy analysis more closely with real-world design decision-making, where uncertainty and incomplete information are unavoidable.

Collectively, the findings indicate that energy-efficient structural design cannot be reduced to a single optimization problem. Instead, it requires a strategic evaluation of trade-offs between irreversible embodied energy investments and uncertain operational energy trajectories. The results demonstrate that ignoring either component leads to incomplete or misleading conclusions and that meaningful energy reductions can only be achieved through integrated analysis.

These findings directly address the research questions by demonstrating how structural material choices influence total life cycle energy, how operational energy uncertainty reshapes comparative performance, and under what conditions embodied energy reductions are most effective. The study confirms that uncertainty-aware life cycle energy analysis provides a more realistic and robust basis for evaluating energy performance than conventional deterministic approaches.

Finally, the findings establish a clear conceptual foundation for the subsequent Discussion section. They highlight the need to reinterpret traditional energy efficiency narratives, reconsider the role of structural materials in energy policy and design practice, and reflect on the implications of uncertainty for sustainable building strategies. By grounding these insights in systematic analysis, the findings move beyond descriptive observation and

contribute to a deeper understanding of life cycle energy dynamics in buildings.

6. Discussion

The discussion of this study interprets the findings within a broader conceptual and methodological context, revisiting the theoretical foundations of life cycle energy assessment and examining how they are reshaped by the uncertainty-aware, decision-oriented approach adopted in this research. Rather than reiterating numerical results, this section focuses on explaining why the observed patterns emerged, how they relate to existing energy paradigms in building research, and what they imply for future energy-conscious structural design.

A central theoretical implication of this study lies in its challenge to the traditional separation between embodied energy and operational energy in building energy research. While previous frameworks have often treated these components as distinct or sequential concerns, the findings demonstrate that their interaction is dynamic and condition-dependent. The results confirm that embodied energy cannot be regarded merely as an initial cost to be amortized over time, nor can operational energy be assumed to dominate life cycle performance by default. Instead, the balance between these components shifts depending on service life assumptions and operational variability, requiring a more integrated theoretical perspective on building energy behavior.

The findings reinterpret the role of structural materials within the life cycle energy discourse. Conventional narratives often portray structural systems as passive carriers of loads with limited relevance to energy performance beyond their material intensity. In contrast, this study demonstrates that structural material choices represent irreversible energy commitments that shape life cycle outcomes long before operational energy accumulates. This interpretation aligns structural design more closely with strategic energy decision-making rather than treating it as a secondary consideration subordinate to mechanical or envelope design.

The uncertainty-aware framework adopted in this study operationalizes concepts discussed in the literature regarding variability, robustness, and decision risk. Rather than relying on deterministic energy values, uncertainty was explicitly embedded into both embodied and operational energy components through parameter ranges and scenario analysis. This operationalization transformed abstract discussions of uncertainty into measurable analytical dimensions, allowing the study to reveal how uncertainty reshapes comparative energy performance. The findings show that uncertainty is not an external disturbance but an intrinsic property of building energy systems that must be accounted for when evaluating design alternatives.

From a methodological standpoint, the study advances life cycle energy assessment by shifting its purpose from performance measurement to decision support. Traditional life cycle assessments often aim to produce precise energy metrics, implicitly assuming stable conditions and long-term predictability. The present approach, however, recognizes that early-stage design decisions are made under incomplete information and competing objectives. By focusing on trade-offs, thresholds, and dominance

regions, the methodology provides insights that are directly relevant to real-world decision-making, where absolute optimization is rarely achievable.

The sensitivity and dominance analyses illustrate how methodological choices influence interpretive outcomes. Rather than identifying a single best-performing structural system, the study reveals conditional preference zones governed by service life and operational energy variability. This finding highlights a key advantage of the adopted methodology: it avoids false certainty and instead communicates the circumstances under which specific decisions are justified or risky. Such transparency is particularly valuable in early design stages, where overconfidence in deterministic results can lead to long-term energy inefficiencies.

The discussion also highlights the importance of temporal assumptions in life cycle energy evaluation. Many existing studies implicitly assume long building lifespans, thereby favoring material-intensive solutions that rely on long-term operational savings to offset high embodied energy. By explicitly incorporating service life uncertainty, this study demonstrates that such assumptions are not neutral but actively shape energy conclusions. This insight calls for greater caution in promoting energy strategies that depend on optimistic lifespan projections, especially in contexts where functional obsolescence, economic pressures, or adaptive reuse may shorten actual service life.

Another important contribution of this study is its reinterpretation of robustness as a key criterion in energy-conscious structural design. Rather than pursuing minimum energy outcomes under idealized conditions, the findings suggest that structurally moderate solutions with balanced embodied energy profiles may offer superior performance across a wider range of uncertain futures. This perspective reframes energy efficiency as a problem of resilience rather than optimization, emphasizing stability of performance over sensitivity to assumptions.

The discussion further clarifies the relationship between methodological simplicity and analytical rigor. By avoiding complex modeling platforms and focusing on reduced-order, parameter-driven analysis, the study demonstrates that meaningful life cycle energy insights can be obtained without excessive computational complexity. This approach enhances transparency and reproducibility while remaining sufficiently rigorous to support hypothesis evaluation. It also broadens the accessibility of life cycle energy analysis for practitioners and researchers who may not have access to advanced modeling tools.

From a broader research perspective, the study contributes to ongoing debates regarding the scope and purpose of sustainable building assessment. By integrating uncertainty into life cycle energy analysis, the research moves beyond compliance-oriented evaluation toward a more exploratory and explanatory mode of inquiry. This shift aligns energy research with the realities of design practice, where decisions must accommodate uncertainty, competing priorities, and long-term consequences.

The findings also invite reconsideration of how energy performance claims are communicated in both research and practice. Single-value indicators and aggregated metrics, while

convenient, can obscure critical dependencies and trade-offs. The discussion suggests that communicating ranges, thresholds, and dominance conditions may provide more honest and useful guidance for stakeholders. Such an approach encourages informed judgment rather than reliance on oversimplified performance rankings.

Finally, the discussion prepares the conceptual ground for the concluding section by reinforcing the study's central argument: that meaningful reductions in building life cycle energy require an integrated, uncertainty-aware understanding of structural embodied energy and operational energy. The discussion demonstrates that neither component can be optimized in isolation and that decision-oriented analysis offers a more realistic foundation for sustainable structural design strategies.

By reinterpreting established energy concepts through the lens of uncertainty and decision-making, this study contributes to a more nuanced understanding of building energy performance. The discussion underscores the need for future research and practice to move beyond deterministic evaluations and to embrace analytical frameworks that reflect the complexity and uncertainty inherent in the built environment.

7. Conclusion

This study set out to advance the understanding of building life cycle energy performance by integrating structural embodied energy and operational energy within an uncertainty-aware, decision-oriented analytical framework. Motivated by the limitations of conventional deterministic energy assessments, the research aimed to clarify how structural material choices influence total life cycle energy outcomes and how uncertainty reshapes the relative importance of embodied and operational energy over time. The conclusions presented in this section are derived strictly from the analytical results and findings of the study and provide a coherent synthesis of its core contributions.

A primary conclusion of the study is that structural embodied energy plays a decisive role in determining total life cycle energy performance, particularly during the early and intermediate phases of a building's service life. The analysis demonstrates that upfront energy investments associated with structural materials cannot be treated as marginal or secondary considerations, even in buildings designed for low operational energy consumption. This conclusion reinforces the necessity of incorporating embodied energy into energy-conscious design strategies from the earliest stages of decision-making.

The study further concludes that the superiority of structural material choices is inherently conditional rather than absolute. No single structural system consistently outperforms all alternatives across the full range of service life assumptions and operational energy conditions. Instead, the relative performance of structural options is governed by specific combinations of lifespan duration and operational energy behavior. This finding underscores the inadequacy of one-size-fits-all recommendations in structural energy design and highlights the need for context-sensitive evaluation.

Another key conclusion is that operational energy becomes the dominant contributor to total life cycle energy only beyond a critical service life threshold. Prior to this threshold, differences in embodied energy outweigh potential operational energy savings, making low-embodied-energy structural solutions more advantageous. This temporal dependency clarifies why certain energy-efficient strategies may appear favorable in long-term evaluations while performing poorly under shorter or uncertain lifespans. It also confirms that service life assumptions are not neutral parameters but fundamental drivers of energy assessment outcomes.

The incorporation of uncertainty into life cycle energy analysis leads to one of the study's most significant conclusions: uncertainty fundamentally alters comparative energy performance rather than merely introducing variability around deterministic results. The findings show that uncertainty in operational energy demand can shift dominance relationships among structural material scenarios, producing overlapping performance ranges that challenge deterministic rankings. This conclusion emphasizes that ignoring uncertainty can result in misleading conclusions and overconfident design decisions.

The study also concludes that embodied energy and operational energy differ fundamentally in terms of energy risk characteristics. Embodied energy represents an irreversible and fixed energy commitment established at the time of construction, whereas operational energy accumulates gradually and remains subject to significant variability. This asymmetry implies that structural decisions lock in a substantial portion of a building's energy footprint, while operational performance remains flexible but unpredictable. Consequently, structural material choices must be evaluated with a heightened awareness of long-term energy risk.

Another important conclusion concerns the concept of robustness in energy-conscious structural design. The analysis reveals that structurally moderate solutions with reduced embodied energy, rather than extreme material substitutions, tend to exhibit more stable performance across a wide range of uncertainty scenarios. This finding suggests that robustness, defined as consistent performance under uncertainty, may be a more appropriate design objective than absolute energy minimization under idealized conditions. Such a perspective reframes energy efficiency as a resilience-oriented goal rather than a purely optimization-driven exercise.

From a methodological standpoint, the study concludes that decision-oriented life cycle energy analysis offers clear advantages over traditional performance-oriented approaches. By focusing on trade-offs, thresholds, and dominance regions, the adopted framework provides insights that are directly relevant to early-stage design decisions. This approach avoids false precision and supports informed judgment by explicitly revealing the conditions under which specific structural choices are justified or risky.

The study also confirms that meaningful life cycle energy insights can be obtained without reliance on complex digital modeling platforms. The use of reduced-order, parameter-driven analysis enhances transparency and interpretability while maintaining sufficient analytical rigor. This conclusion broadens the

applicability of life cycle energy assessment by making it accessible to a wider range of researchers and practitioners, particularly in contexts where detailed modeling resources are unavailable.

In relation to the research questions, the study conclusively demonstrates that structural material selection significantly influences total life cycle energy outcomes and that this influence is strongly mediated by uncertainty and temporal assumptions. The hypotheses concerning the continued relevance of embodied energy and the modifying role of operational energy variability are both supported. The findings collectively confirm that integrated, uncertainty-aware analysis is essential for accurately evaluating energy performance at the structural level.

The conclusions of this study have clear implications for both research and practice. For researchers, the results highlight the importance of moving beyond deterministic assessments and isolated energy components toward integrated analytical frameworks that reflect real-world uncertainty. Future studies should further explore the interaction between structural design decisions and long-term energy performance across different building types and climatic contexts, while continuing to prioritize decision relevance over purely technical precision.

For practitioners, the conclusions emphasize the need to treat structural material selection as a strategic energy decision rather than a purely technical or economic choice. Early-stage design processes should explicitly account for embodied energy and uncertainty to avoid locking in energy-intensive solutions that may not deliver expected long-term benefits. Decision-making tools and guidelines should therefore incorporate life cycle energy trade-offs and robustness considerations rather than relying solely on operational energy targets.

In summary, this study concludes that achieving meaningful reductions in building life cycle energy requires an integrated understanding of structural embodied energy, operational energy, and uncertainty. Structural decisions made early in the design process have long-lasting energy consequences that cannot be fully mitigated through operational efficiency alone. By adopting an uncertainty-aware, decision-oriented perspective, the research provides a more realistic and robust foundation for evaluating energy-conscious structural design strategies.

The study ultimately reinforces the idea that sustainable building design is not a problem of identifying a single optimal solution but of navigating trade-offs under uncertainty. Through its integrated analytical framework and decision-focused conclusions, this research contributes to a deeper and more practical understanding of life cycle energy dynamics in buildings and offers a clear pathway for advancing both research and practice in the field of energy-conscious structural design.

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