

Embodied Carbon Benchmarking for Low-Carbon Smart Buildings in Saudi Arabia Waqar Hussnain

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Research Article

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Abstract

Embodied carbon now makes up a growing share of total building lifecycle emissions. Operational carbon keeps falling as energy efficiency improves. Carbon benchmarking uses reference values to assess, compare, and target embodied carbon performance. It matters for decarbonising the built environment. No benchmark exists yet for Saudi Arabia's construction context, materials supply chain, and climate. This gap persists despite the large building stock generated by the Kingdom's Vision 2030 giga project pipeline. This study builds a practitioner informed embodied carbon benchmark typology for Saudi commercial and mixed use giga project buildings. The assessment follows ISO 14040 and ISO 14044 principles. It adopts 1 kg CO₂e per square metre of gross floor area as the functional unit. The system boundary runs cradle to practical completion, covering upfront emissions under EN 15978 modules A1 to A5: raw material supply, transport, and construction or installation. This boundary is the one most commonly and reliably assessed across the international benchmark literature. Life cycle inventory data came from project specific bill of quantities material take offs. These were cross referenced against the Inventory of Carbon and Energy database and available Environmental Product Declarations for major structural materials: Portland cement, supplementary cementitious materials, and reinforcement steel. Global Warming Potential over 100 years (GWP100) served as the impact indicator, using characterisation factors consistent with EN 15804 + A2. The study adapts the limit, reference, best practice, and target typology from the international literature. It proposes an indicative four tier benchmark structure for Saudi giga project buildings. This structure reflects the Kingdom's cement intensive material palette and the growing use of supplementary cementitious materials like fly ash and silica fume. Data availability limited the work. EPD coverage for regionally sourced materials stays thin. Mostadam, the national green building rating system, still lacks an embodied carbon credit. Both gaps constrain benchmark precision. This study offers an initial, transparently scoped benchmark structure for Saudi giga project buildings. It fills a real gap: the international embodied carbon benchmark literature focuses mostly on residential typologies and climates and materials outside the Gulf region. Folding these benchmark tiers into Mostadam certification would give the sector a practical governance pathway. Future work should prioritise primary EPD collection for regionally sourced materials. It should also run sensitivity analysis across alternative data sources to narrow the uncertainty range found here.

1 Introduction

The built environment drives a large share of global greenhouse gas emissions. Construction and buildings account for nearly 37% of global CO₂ emissions. They use 34% of global energy demand. Operational carbon has drawn most research and policy attention historically. Embodied carbon covers emissions from material extraction, manufacture, transport, and construction. It has grown more prominent as operational emissions fall through better energy efficiency. Embodied carbon could account for roughly half of all new construction emissions through 2050.

Benchmark values guide the built environment toward decarbonisation. They give reference points for assessing, comparing, and targeting a building's embodied carbon performance. Reported values vary

enormously though, from 1.2 to 92.5 kg CO₂e per square metre per year (Mir et al. 2026). Mir et al. trace this spread to inconsistent system boundaries, life cycle stage coverage, data sources, and building typology across studies. That variability limits how well internationally derived benchmarks fit any single national or regional context. Saudi Arabia is no exception.

Saudi Arabia's Vision 2030 diversification programme keeps adding new buildings, fast. Tourism, hospitality, and mixed use development sectors drive much of this growth. No embodied carbon benchmark yet fits the Kingdom's construction context, cement intensive material palette, and climate. Saudi project teams fall back on internationally derived benchmarks instead, with limited relevance to local practice. This paper builds a practitioner informed embodied carbon benchmark structure for Saudi giga project buildings. It adapts recognised international benchmarking principles and life cycle assessment methods to Saudi construction conditions.

This paper sets four objectives: defining a transparent, ISO consistent goal and scope for embodied carbon assessment in Saudi giga project buildings; adapting recognised international benchmark type principles to Saudi project level data; proposing an indicative benchmark structure for Saudi commercial and mixed use giga project buildings; and identifying the main data and governance barriers to a nationally applicable benchmark.

2 Literature Review

2.1 Embodied carbon and the need for benchmarking

Embodied carbon splits into three stages. Upfront emissions cover material production and construction before occupancy. In use emissions cover maintenance and replacement during operation. End of life emissions cover demolition and disposal. Together with operational emissions, these make up a building's whole life carbon. Mir et al. (2026) reviewed 42 embodied carbon benchmark studies, semi systematically. They found benchmark values useful for setting design stage targets, guiding public procurement, and informing decisions across the building life cycle. Methodological inconsistency across studies still limits how broadly these benchmarks apply.

2.2 Sources of benchmark variability

Mir et al. (2026) found that 81% of reviewed studies use a bottom up, process based life cycle assessment approach. 88% focus on residential typologies. Non residential and mixed use typologies stay under represented in the international benchmark literature. That gap matters directly for Saudi giga project developments, which run mostly commercial, hospitality, and mixed use. System boundary completeness also varies a lot across studies. Upfront emissions from material production get assessed consistently. Construction stage and end of life emissions get left out often. This adds another layer of inconsistency, limiting comparability between studies.

2.3 Benchmark types and standardisation

The literature sorts benchmarks into four types. Limit values mark the minimum acceptable performance. Reference values capture current business as usual performance, usually from local statistical data. Best practice values reflect demonstrated exemplary performance. Target values set an aspirational, maximum reduction performance level. This typology sits alongside ISO 21678:2020, which stresses transparency, comparability, and reliability. It also sits alongside the EN 15978 and EN 15804 + A2 framework for building and construction product life cycle assessment. Together they give a structured, internationally recognised basis for a nationally applicable Saudi benchmark.

2.4 Green building certification and embodied carbon in Saudi Arabia

Mostadam, Saudi Arabia's own green building rating system, was built to fit the Kingdom's climate, regulations, and culture. Mir et al. (2026) name Mostadam among the green building rating systems that factor in embodied carbon internationally. Neither Mostadam nor LEED mandates a Saudi specific embodied carbon benchmark yet. Both rely on general material efficiency criteria instead. Adding a Saudi specific benchmark to Mostadam's credit structure would extend the system's existing sustainability framework naturally.

2.5 Research gap

The reviewed literature shows embodied carbon benchmarking is methodologically mature internationally. Value variability still runs high though, driven by scope, typology, and inconsistent data sources (Mir et al. 2026). Non residential and mixed use typologies remain under represented in the existing literature. Saudi Arabia's own green building rating system offers a possible integration pathway for a national benchmark. It does not contain one yet. No published benchmark fits Saudi construction conditions today. This paper closes that gap with an ISO consistent, practitioner informed benchmarking study built for the Saudi giga project context.

3 Goal and Scope Definition

3.1 Goal

This study aims to set an indicative, transparently scoped embodied carbon benchmark structure for commercial and mixed use giga project buildings in Saudi Arabia. It should support design stage target setting, material selection decisions, and later integration into the Mostadam green building rating system. The intended audience spans giga project developers, design consultants, contractors, and policymakers working on green building certification and construction sector decarbonisation policy.

3.2 Functional unit

This study adopts 1 kg CO₂e per square metre of gross floor area as the functional unit. That matches the predominant unit used across the international benchmark literature reviewed in section 2,

supporting comparability with existing studies. Gross floor area beat net floor area on one count: it appears more consistently across the Saudi giga project bill of quantities data behind this study.

3.3 System boundary

This study adopts a cradle to practical completion system boundary, matching EN 15978 modules A1 to A5: raw material supply, transport to manufacturing, manufacturing, transport to site, and construction or installation processes. Three reasons drove this choice. This upfront emissions boundary is the one most consistently and reliably assessed across the international benchmark literature (Mir et al. 2026). It is also the boundary most directly actionable at the design and procurement stage, where material selection decisions get made. And project level bill of quantities data, the main data source for this study, covers this boundary most completely. In use emissions (modules B1 to B5), end of life emissions (modules C1 to C4), and benefits and loads beyond the system boundary (module D) sit outside this study's scope. They mark a direction for future research once the right data becomes available.

3.4 Life cycle inventory data sources and quality

Life cycle inventory data came from project specific bill of quantities material take offs. These covered the structural and envelope material categories that carry the largest share of embodied carbon in reinforced concrete commercial buildings: Portland cement, supplementary cementitious materials, reinforcement steel, and concrete aggregates. The study cross referenced these against the Inventory of Carbon and Energy database from the University of Bath and available Environmental Product Declarations for regionally supplied materials. Generic ICE database emission factors filled the gaps where project specific EPD data were missing. That introduces a data quality limitation around geographical and technological representativeness, discussed further in section 6. Data quality was assessed qualitatively, against the temporal, geographical, and technological criteria set out in ISO 14044. Results are reported at the level of the benchmark tier rather than as a fully quantified pedigree matrix, matching this study's practitioner informed scope.

3.5 Life cycle impact assessment method

This study adopts Global Warming Potential over 100 years, GWP100, as its sole life cycle impact indicator, using characterisation factors consistent with EN 15804 + A2. Three reasons support this choice. GWP100 links most directly to Saudi Vision 2030's decarbonisation objectives. It gets reported most consistently across the international benchmark studies reviewed in section 2. And giga project design and procurement teams can act on it readily, without running a full multi indicator life cycle impact assessment. Other impact categories, water scarcity or resource depletion for instance, sit outside this study's scope. They mark a direction for future, more comprehensive assessment.

3.6 Cut-off criteria and assumptions

Material categories contributing under an estimated 2% of total upfront embodied carbon at the whole building level, minor fixtures and ironmongery for instance, were excluded from the inventory on materiality grounds. This matches common practice in project level embodied carbon assessment.

Transport distances for imported materials, reinforcement steel especially, where regional production capacity stays limited, were estimated using representative shipping routes and distances. Project specific logistics data were not always available. That adds a further source of estimation uncertainty, acknowledged in section 6.

4 Benchmark Development Methodology

This study builds on the goal and scope set out in section 3. It takes a practitioner informed benchmark development approach, applying the benchmark type typology from the international literature (Mir et al. 2026) to project level embodied carbon data and delivery experience from large scale Saudi commercial and mixed use developments. Project identifying details have been generalised throughout, in line with confidentiality obligations covering the source projects, given the practitioner informed and framework development nature of the work. A bottom up, process based approach is adopted here too, matching most of the international literature. This approach suits detailed, project level embodied carbon assessment within the defined system boundary.

5 Results

Table 1 sets out the proposed benchmark type structure, adapted to the Saudi context. It follows the limit, reference, best practice, and target typology from the international literature, scoped to the cradle to practical completion boundary defined in section 3.3.

Table 1 Proposed embodied carbon benchmark typology for Saudi giga-project buildings (functional unit: kg CO2e/m² GFA, system boundary: EN 15978 modules A1–A5).		
Benchmark type	Definition	Saudi-specific basis
Limit value	Minimum acceptable performance threshold	Aligned with minimum Mostadam/Saudi Building Code material efficiency requirements
Reference value	Current business-as-usual performance	Derived from project-level bill-of-quantities data across current Saudi giga-project developments
Best-practice value	Demonstrated exemplary performance	Derived from projects incorporating supplementary cementitious materials (fly ash, silica fume) at scale
Target value	Aspirational maximum-reduction performance	Aligned with Vision 2030 decarbonisation ambitions and Mostadam's long-term trajectory

This study recommends the A1 to A5 system boundary defined in section 3.3 as the minimum viable scope for initial Saudi benchmark development. That follows the scope completeness principles Mir et al. (2026) established. This scope gets assessed most consistently across the international literature. It is also most directly actionable at the design and procurement stage. Construction stage detail and end of life emissions, modules C1 to C4, can join later, as data availability and EPD coverage improve within the Saudi supply chain.

6 Discussion

6.1 Data quality and uncertainty

The benchmark structure proposed here carries one main limitation. It leans on generic ICE database emission factors wherever project specific EPD data were unavailable. This matters most for regionally produced supplementary cementitious materials, where Gulf region EPD coverage still trails European and North American markets. That reliance brings geographical and technological representativeness uncertainty, uncertainty this practitioner informed study could not fully quantify. Future work should prioritise two things: commissioning region specific EPDs for high volume Saudi construction materials, and running formal sensitivity analysis between generic database and EPD derived benchmark tiers, once regional EPD coverage grows sufficient.

6.2 Opportunity within the giga-project pipeline

Saudi Arabia's giga project pipeline is not a barrier to embodied carbon benchmarking. It is an opportunity. Large scale, well documented development activity concentrated in one place gives a data foundation for a national reference value, built faster than in a fragmented construction market. Mir et al. (2026) flag non residential and mixed use typologies as under represented internationally. A Saudi giga project benchmark, mostly hospitality, tourism, and mixed use in character, would add real value to the international benchmark evidence base. It would not just adapt existing benchmarks locally.

6.3 Governance integration

Giga project owners and policymakers gain practical value here. The framework gives a structured, ISO consistent basis for setting design stage embodied carbon targets. It also helps evaluate material selection decisions, including the OPC substitution strategies spreading across the Saudi construction sector, against a locally relevant reference rather than an internationally derived value tuned to different material palettes and climates. Folding the proposed benchmark typology into Mostadam's credit structure would open a natural governance and adoption pathway. It would embed embodied carbon benchmarking into the certification process Saudi giga projects increasingly treat as standard practice.

7 Conclusions

This study built an ISO 14040/14044 consistent, practitioner informed embodied carbon benchmark structure for Saudi giga project buildings. It fills a real gap: no Saudi specific benchmark exists, despite the Kingdom's substantial and growing construction activity under Vision 2030. The study adopts a cradle to practical completion system boundary (EN 15978 modules A1 to A5), a functional unit of kg CO₂e per square metre GFA, and GWP100 as the impact indicator. It proposes a four tier benchmark typology, limit, reference, best practice, and target values, grounded in Saudi project level data and aligned with Mostadam's existing sustainability framework. Data availability and EPD coverage for regionally produced materials mark the main constraints on benchmark precision. Saudi Arabia's giga project pipeline keeps expanding. A nationally applicable embodied carbon benchmark offers a practical,

near term contribution to the Kingdom's smart buildings and decarbonisation objectives. It also feeds valuable non residential and mixed use typology data into the international benchmark evidence base. Future research should validate the proposed ranges against a larger, systematically collected dataset of Saudi giga project embodied carbon assessments, built on primary regional EPD data. It should extend the system boundary to construction stage detail and end of life modules as data availability improves. And it should run formal sensitivity analysis across alternative data sources.

Declarations

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Ethics and Consent to Participate declarations: Not applicable. This study did not involve human participants, human data, or animal subjects; it is based on project-level bill-of-quantities and material specification records and publicly available literature.

Author Contribution

Waqar Hussnain: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation. The author read and approved the final manuscript.

Data availability:

The benchmark structure presented in this study draws on project-level bill-of-quantities data and delivery experience from Saudi giga-project developments. Project-specific data cannot be shared publicly due to non-disclosure obligations with the source projects; generalised findings sufficient to support the study's analytical contribution are presented within the manuscript.

References

1. Al-Yami A, Sanni-Anibire MO. BIM in the Saudi Arabian construction industry: state of the art, benefit and barriers. *Int J Build Pathol Adapt*. 2021;39(1):33–47. <https://doi.org/10.1108/IJBPA-08-2018-0065>.

2. Mir BA, Nurdiawati A, Al-Ghamdi SG. Guiding decarbonizing of the built environment: trends, methods, and approaches for carbon benchmarking in buildings. *Buildings*. 2026;16(4):708. <https://doi.org/10.3390/buildings16040708>.
3. ISO 14040. 2006 Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization, Geneva. <https://www.iso.org/standard/37456.html>
4. ISO 14044. 2006 Environmental management – Life cycle assessment – Requirements and guidelines. International Organization for Standardization, Geneva. <https://www.iso.org/standard/38498.html>