

# LEED-Aligned Embodied Carbon Decision Support for Hospital Expansion: An LLM-Assisted Comparison of Mass Timber, Structural Steel, and Reinforced Concrete Structural Strategies

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## Keywords

embodied carbon; LEED v4.1; whole-building life-cycle assessment; hospital expansion; mass timber; structural steel; reinforced concrete; bill of materials; global warming potential; EnergyPlus; CBECS; LLM-assisted decision support

## Abstract

Hospital expansion projects require early carbon decisions that do not confuse material embodied carbon with hospital operational energy. This paper presents a LEED-aligned embodied-carbon decision-support workflow for comparing mass timber (MT), structural steel (SS), and reinforced concrete (RC) structural strategies during early expansion planning. The WBLCA experiment uses the public 2024 bill-of-materials and whole-building life-cycle-assessment dataset for nine functionally matched U.S. building alternatives: MT, SS, and RC at 8, 12, and 18 stories. Because the source WBLCA dataset is a structure-and-enclosure benchmark rather than a hospital energy model, a separate hospital operational-energy boundary check is added using the 2018 CBECS public-use microdata and DOE/PNNL ASHRAE 90.1-2022 hospital prototype output files. The embodied-carbon analysis evaluates material GWP for modules A-C and A-D; B6 operational energy and B7 water use are not inferred from structural material choice. MT reduced A-C embodied GWP by 39.15-50.87% relative to RC and by 28.08-34.48% relative to SS. Seven of nine pairwise comparisons exceeded a 20% GWP-only LEED screen, and the remaining two SS-versus-RC comparisons exceeded the 10% screen. The hospital-energy check found a CBECS inpatient-health-care floor-area-weighted site EUI of 190.30 kBtu/ft<sup>2</sup>-yr and DOE Appendix G proposed-hospital site EUIs of 81.29-120.00 kBtu/ft<sup>2</sup>-yr across 19 climate locations. These operational-energy results are used only to define the separate B6 workflow. The results support a table-grounded LLM-assisted explanation layer for hospital owners and architects while preserving a strict boundary between embodied-carbon screening and operational-energy simulation.

## Introduction

Hospitals are carbon-intensive facilities because they combine large floor areas, strict resilience requirements, continuous operation, and material-heavy structural systems. Early design teams therefore face two related but distinct carbon questions. Operational energy is driven by

equipment, envelope performance, loads, ventilation requirements, schedules, and controls, whereas embodied carbon is driven by products, assemblies, transport, replacement, end-of-life scenarios, and potential benefits beyond the system boundary. Life-cycle assessment standards separate these questions through goal and scope definition, system

boundaries, functional equivalence, and documented impact categories [1]-[4].

The design question addressed here is deliberately limited: given a hospital owner considering a future expansion, how can a LEED-aligned decision-support workflow compare the embodied-carbon implications of MT, SS, and RC structural strategies without claiming operational-energy savings? LEED v4.1 Building Life-Cycle Impact Reduction relies on baseline equivalence, structure-and-enclosure assessment, impact-category reduction, and a narrative explaining how reductions were achieved [5]. That logic is compatible with early embodied-carbon screening, but it is not a substitute for EnergyPlus or HVAC simulation.

Mass timber is a relevant candidate because high-rise and mid-rise timber systems have been investigated as lower-carbon alternatives to conventional concrete and steel structures [12]-[14], [20]-[28]. The conclusion must still be empirical rather than generic. Timber is not automatically preferable under every boundary, climate, fire-encapsulation strategy, procurement route, or treatment of biogenic carbon and Module D benefits [1]-[8], [25], [26]. A hospital owner also needs assembly-level explanations, because the appropriate design action depends on whether the hotspot is a floor system, wall assembly, foundation, roof, or fire-protection layer.

The primary WBLCA dataset used here contains MT, SS, and RC alternatives designed under the 2021 International Building Code provisions. It provides 8-story Type IV-C, 12-story Type IV-B, and 18-story Type IV-A alternatives, with Athena Impact Estimator outputs generated for a 75-year reference

study period and sensitivity values for a 60-year period [33]. The source models are used as structure-and-enclosure massing benchmarks for hospital expansion planning rather than as complete clinical facilities. The analysis therefore does not treat the dataset as if it contained operating rooms, imaging departments, medical equipment loads, air-change requirements, or hospital HVAC sequences.

To strengthen the hospital boundary, the study includes a separate operational-energy context check using CBECS inpatient-health-care records and DOE hospital prototype simulations [34], [35]. This check does not change the embodied-carbon comparison. Instead, it makes clear that B6 operational energy is an independent model and that material-selection results should not be used to claim hospital energy savings.

## Method

The method consisted of six steps: WBLCA table extraction, arithmetic validation, embodied-carbon computation, baseline comparison, LEED-aligned GWP screening, and hospital operational-energy boundary checking. The embodied-carbon boundary used modules A1-A3, A4-A5, B2-B4, C1-C4, and D as available in the source WBLCA tables. Modules B6 and B7 were excluded from the embodied-carbon claims.

Table 1 defines the data sources and boundaries used in the analysis. The WBLCA dataset supplies the structural alternatives, floor areas, life-cycle modules, and GWP values. CBECS and DOE hospital prototype data are used only to characterize the operational-energy workflow that would be required for a future hospital-specific B6 model.

**Table 1.** Data sources and carbon-accounting boundary.

Component	Implementation
Primary embodied-carbon dataset	2024 BOM/WBLCA dataset, DOI 10.17632/pgjvbwznk5.1 [33]
Structural systems	Mass timber (MT), structural steel (SS), reinforced concrete (RC)
Height cases	IVC-8, IVB-12, IVA-18
Life-cycle modules used for embodied carbon	A1-A3, A4-A5, B2-B4, C1-C4, and D

Component	Implementation
Excluded from embodied-carbon claims	B6 operational energy and B7 water use
Hospital operational-energy context	2018 CBECS inpatient/outpatient health-care records and DOE ASHRAE 90.1-2022 Hospital prototype output files [34], [35]
Impact metric	GWP in kg CO <sub>2</sub> e/m <sup>2</sup> , whole-building tCO <sub>2</sub> e, and separate site EUI in kBtu/ft <sup>2</sup> -yr for B6 context
Decision setting	Hospital expansion structure/enclosure embodied-carbon screening with separate operational-energy modeling

are not treated as fully specified hospital departments.

Table 2 lists the three massing cases. The floor areas are used as generic expansion-scale alternatives and

**Table 2.** Building alternatives used as hospital expansion massing cases.

Class	Stories	Height m	Area m <sup>2</sup>	Plan dimensions
IVC-8	8	25.60	7,717.10	34.75 x 25.6
IVB-12	12	38.40	11,424.80	37.19 x 25.6
IVA-18	18	57.60	17,137.30	37.19 x 25.6

A-C GWP was computed as A1-A3 plus A4-A5 plus B2-B4 plus C1-C4. A-D GWP was computed as A-C plus Module D. Whole-building totals were computed by multiplying kg CO<sub>2</sub>e/m<sup>2</sup> by the reported floor area and dividing by 1,000 to obtain tCO<sub>2</sub>e. Pairwise reductions were computed as 100 times the baseline value minus the proposed value, divided by the baseline value.

Material-level extraction was checked on the IVC-8 MT bill-of-materials sample. Table 3 shows that material name, unit, quantity, assembly allocation, and mass can be parsed for major entries. The full comparative experiment uses the nine WBLCA cases, while this sample confirms the material-level traceability expected in an owner-facing decision workflow.

**Table 3.** Top material-mass entries parsed from the IVC-8 mass-timber BOM sample.

Material	Unit	Quantity	Mass t	Mass share %
cross laminated timber	m <sup>3</sup>	2,676.40	1,272.49	31.31
concrete benchmark 2500 psi	USA m <sup>3</sup>	373.63	855.59	21.05
concrete benchmark 3000 psi	USA m <sup>3</sup>	271.55	622.77	15.32

Material	Unit	Quantity	Mass t	Mass share %
5/8 in fire-rated type X gypsum board	m2	48,546.52	510.22	12.56
glulam sections	m3	498.01	232.72	5.73
ballast aggregate stone	kg	182,755.03	182.75	4.50
2 in insulated metal panel	m2	5,109.31	75.34	1.85
triple glazed hard coated argon	m2	2,953.69	73.62	1.81
glazing panel	tonnes	72.13	72.13	1.77
joint compound	tonnes	37.06	37.06	0.91

Validation was performed before comparison. The computed stage totals and assembly totals in Table 4

agree within the rounding tolerance used for the published tables.

**Table 4.** Arithmetic validation of stage totals and assembly totals.

Class	Sys	A-C calc	A-C asm	A-D rep	A-D calc	A-D pass	A-C pass
IVC-8	MT	249.55	249.56	27.47	27.46	Yes	Yes
IVC-8	SS	380.88	380.88	319.97	319.97	Yes	Yes
IVC-8	RC	507.92	507.92	477.40	477.39	Yes	Yes
IVB-12	MT	280.78	280.77	59.32	59.33	Yes	Yes
IVB-12	SS	398.32	398.33	341.73	341.72	Yes	Yes
IVB-12	RC	487.38	487.39	459.15	459.14	Yes	Yes
IVA-18	MT	280.03	280.03	86.13	86.13	Yes	Yes
IVA-18	SS	389.38	389.38	358.98	358.97	Yes	Yes
IVA-18	RC	460.22	460.21	457.56	457.56	Yes	Yes

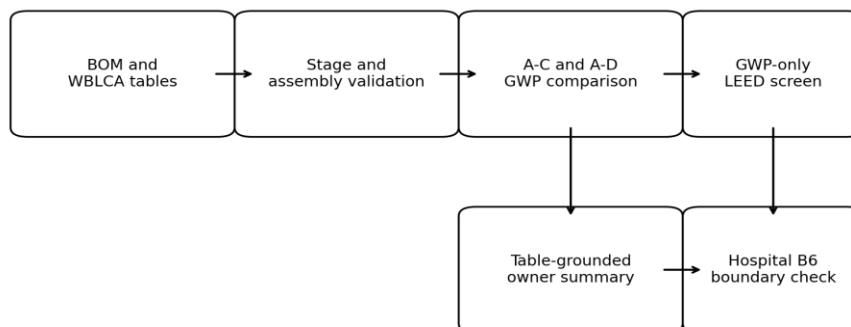
The LEED mapping was implemented as a conservative GWP-only screen. A comparison was marked as passing the 5%, 10%, or 20% screen only when the A-C reduction exceeded the threshold. The screen does not assign LEED points by itself because full LEED documentation requires additional impact categories, baseline-equivalence documentation, and a narrative explaining the reductions [5].

The hospital operational-energy boundary check used two independent sources. First, CBECS public-use microdata were filtered for PBA=16 inpatient health care and PBA=8 outpatient health care. Site EUI was calculated as annual major-fuels consumption divided by floor area, with final weights applied. Second, DOE ASHRAE 90.1-2022 Hospital prototype .htm output files were parsed for Total Site Energy and site EUI across 19 climate locations for standard, Appendix G baseline, and Appendix G proposed cases. Table 5 reports the

resulting context values; these values are not combined with the embodied-carbon totals.

**Table 5.** Hospital operational-energy boundary check from CBECS and DOE prototype outputs.

Source	Records or files	Weighted buildings	Weighted floor area, million ft <sup>2</sup>	Mean site EUI	Median or central value	Range or 24h share	Use in this paper
CBECS inpatient health care	276	8,529	2,293.2	190.30	204.75	100.0%	External stock benchmark
CBECS outpatient health care	217	128,540	1,760.5	81.96	58.97	2.9%	Contrast with inpatient operation
DOE Hospital STD2022	19	--	--	96.10	94.22	range 82.33-120.93	EnergyPlus prototype context
DOE Appendix G baseline	19	--	--	133.42	131.63	range 116.83-163.35	Baseline B6 model context
DOE Appendix G proposed	19	--	--	95.29	92.77	range 81.29-120.00	Proposed B6 model context
Appendix G proposed vs baseline	19	--	--	28.54%	29.52%	range 16.51-33.30%	Operational-energy comparison only



Boundary rule: embodied-carbon results are reported from structure/enclosure WBLCA; B6 operational energy is checked separately using hospital data.

**Figure 1.** Embodied-carbon decision-support workflow and boundary rule.

## Results and Discussion

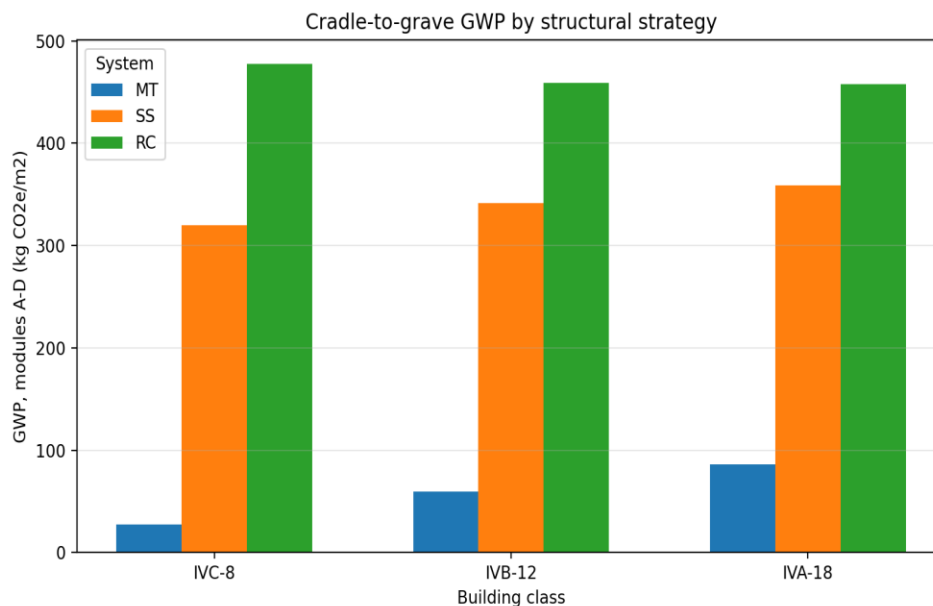
Table 6 reports the full life-cycle stage results for all nine structural alternatives. MT had the lowest A-C and A-D GWP values in all three height classes.

**Table 6.** Life-cycle GWP stage results for all nine structural alternatives.

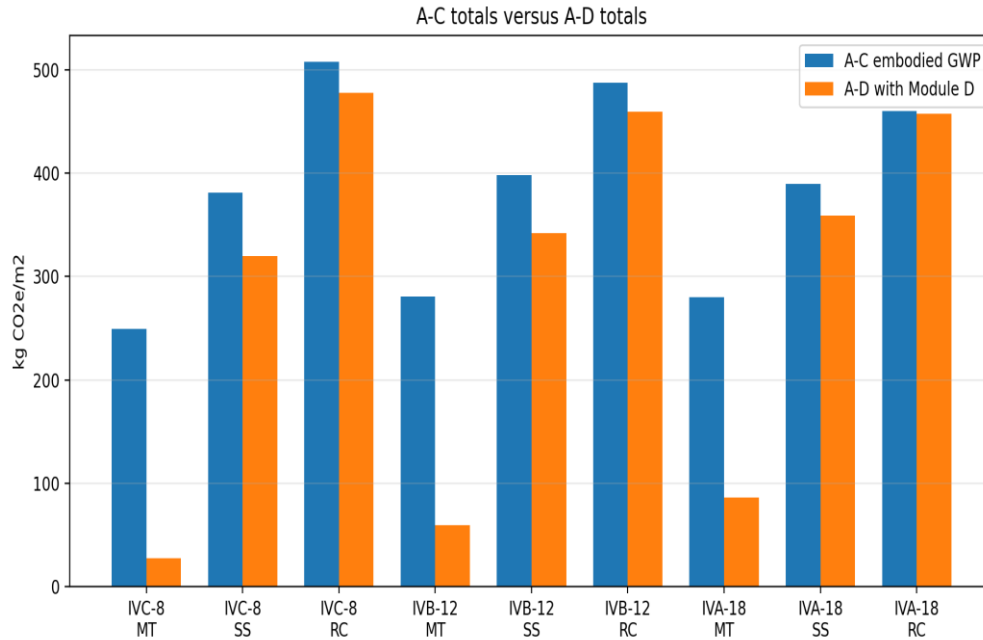
Class	Sys	A1-A3	A4-A5	B2-B4	C1-C4	D	A-C	A-D
IVC-8	MT	142.86	42.90	49.55	14.24	-222.09	249.55	27.47
IVC-8	SS	274.37	29.40	64.36	12.75	-60.91	380.88	319.97
IVC-8	RC	382.71	36.16	69.50	19.55	-30.53	507.92	477.40
IVB-12	MT	164.14	44.83	57.33	14.48	-221.45	280.78	59.32
IVB-12	SS	290.18	32.51	62.26	13.37	-56.60	398.32	341.73
IVB-12	RC	367.19	34.40	67.13	18.66	-28.24	487.38	459.15
IVA-18	MT	165.07	44.20	56.92	13.84	-193.90	280.03	86.13
IVA-18	SS	282.69	32.02	62.31	12.36	-30.41	389.38	358.98
IVA-18	RC	352.55	33.79	55.89	17.99	-2.66	460.22	457.56

The product stage dominated A-C totals in all systems. A1-A3 accounted for about 57.24-58.95% of MT A-C GWP, 72.04-72.85% of SS, and 75.34-

76.61% of RC. Figure 2 shows the A-D totals by height class, while Figure 3 compares A-C values with A-D values including Module D.



**Figure 2.** Cradle-to-grave A-D GWP by height class and structural system.



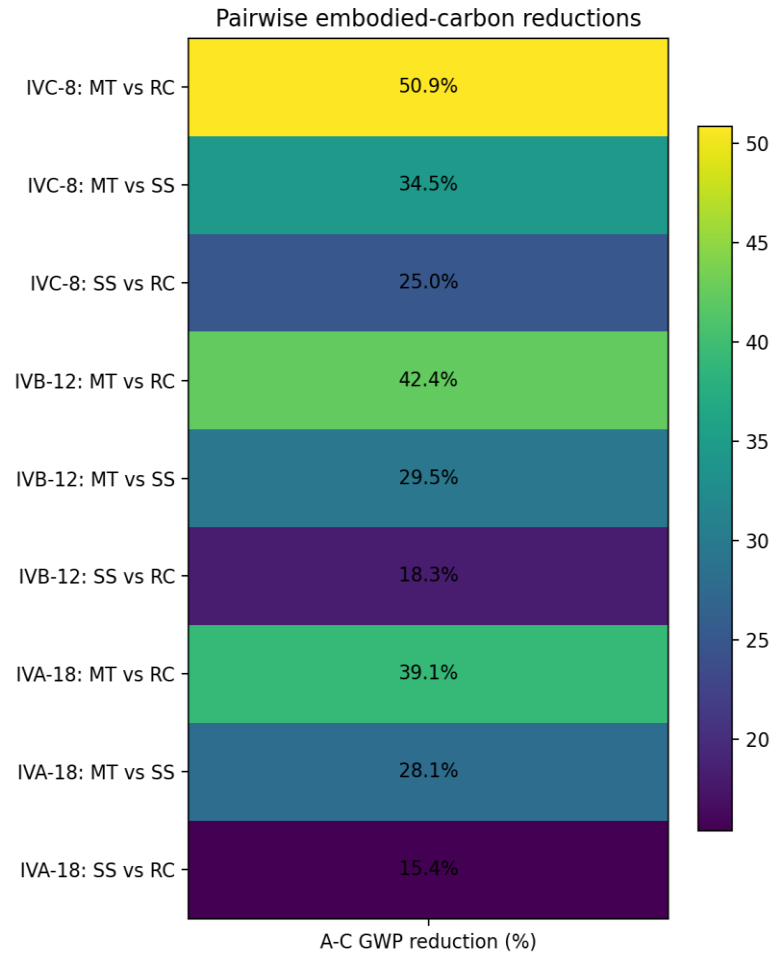
**Figure 3.** A-C embodied GWP compared with A-D GWP including Module D.

The A-C reduction results in Table 7 are the core embodied-carbon comparison. MT reduced A-C GWP by 39.15-50.87% compared with RC and by 28.08-

34.48% compared with SS. SS also reduced A-C GWP relative to RC, but by smaller margins.

**Table 7.** Pairwise A-C and A-D GWP reductions by proposed system and baseline.

Class	Prop	Base	Prop A-C	Base A-C	A-C red %	Prop A-D	Base A-D	A-D red %
IVC-8	MT	RC	249.55	507.92	50.87	27.47	477.40	94.25
IVC-8	MT	SS	249.55	380.88	34.48	27.47	319.97	91.41
IVC-8	SS	RC	380.88	507.92	25.01	319.97	477.40	32.98
IVB-12	MT	RC	280.78	487.38	42.39	59.32	459.15	87.08
IVB-12	MT	SS	280.78	398.32	29.51	59.32	341.73	82.64
IVB-12	SS	RC	398.32	487.38	18.27	341.73	459.15	25.57
IVA-18	MT	RC	280.03	460.22	39.15	86.13	457.56	81.18
IVA-18	MT	SS	280.03	389.38	28.08	86.13	358.98	76.01
IVA-18	SS	RC	389.38	460.22	15.39	358.98	457.56	21.54



**Figure 4.** Heatmap of pairwise A-C embodied-carbon reductions.

A-D reductions were larger than A-C reductions because the MT alternatives carry larger reported Module D credits than the RC and SS alternatives. The LEED-oriented screen therefore uses A-C values as the primary comparison boundary and treats A-D values as supplementary information about end-of-life and beyond-boundary assumptions.

Table 8 maps the A-C reductions to LEED v4.1 GWP-only screening thresholds. All nine comparisons exceeded the 5% and 10% screens, and seven exceeded the 20% screen. Figure 5 shows the same reductions against the 5%, 10%, and 20% reference lines.

**Table 8.** LEED v4.1 GWP-only screening results based on A-C reductions.

Class	Prop	Base	A-C red %	>=5%	>=10%	>=20%	Screen label
IVC-8	MT	RC	50.87	Yes	Yes	Yes	GWP exceeds 20% screen
IVC-8	MT	SS	34.48	Yes	Yes	Yes	GWP exceeds 20% screen

Class	Prop	Base	A-C red %	>=5%	>=10%	>=20%	Screen label
IVC-8	SS	RC	25.01	Yes	Yes	Yes	GWP exceeds 20% screen
IVB-12	MT	RC	42.39	Yes	Yes	Yes	GWP exceeds 20% screen
IVB-12	MT	SS	29.51	Yes	Yes	Yes	GWP exceeds 20% screen
IVB-12	SS	RC	18.27	Yes	Yes	No	GWP exceeds 10% screen
IVA-18	MT	RC	39.15	Yes	Yes	Yes	GWP exceeds 20% screen
IVA-18	MT	SS	28.08	Yes	Yes	Yes	GWP exceeds 20% screen
IVA-18	SS	RC	15.39	Yes	Yes	No	GWP exceeds 10% screen

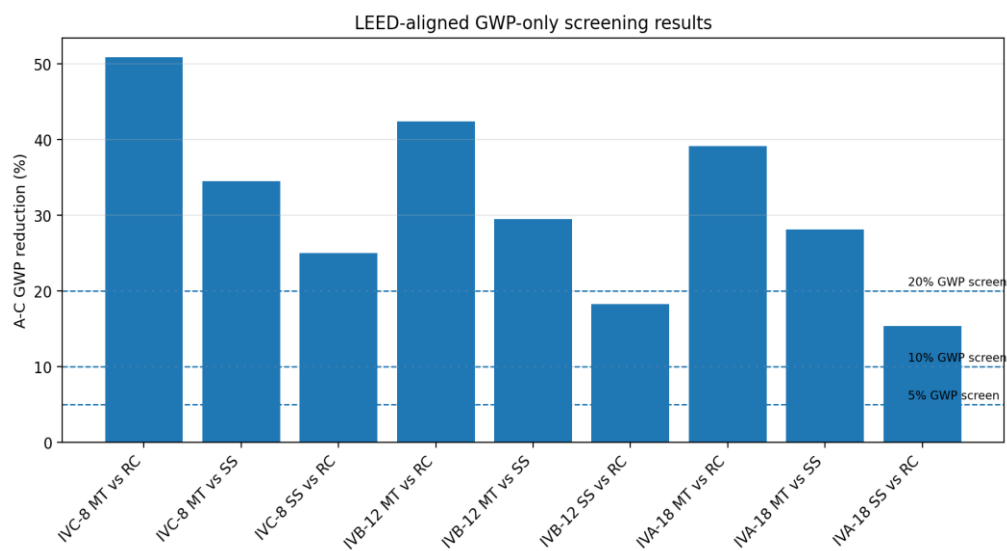


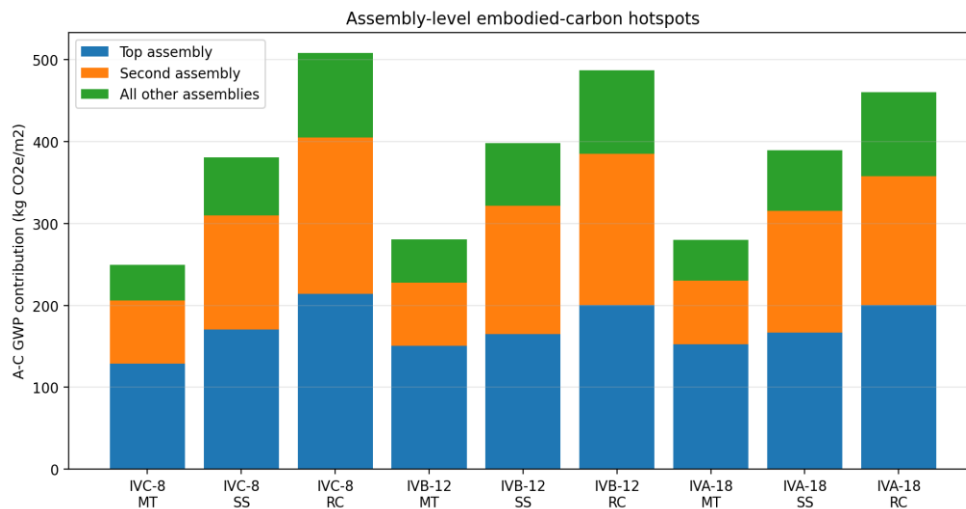
Figure 5. LEED-aligned GWP-only screening bars with 5%, 10%, and 20% threshold

Assembly-level results explain why the whole-building totals differ. Table 9 shows that the top MT hotspot was the wall assembly in all height classes, with floors consistently second. In the RC alternatives, floors were the top hotspot and walls were second. In the SS alternatives, walls were first and floors were second. Figure 6 groups each case into the top assembly, second assembly, and all other assemblies.

This result matters for hospital expansion because carbon-reduction actions depend on the dominant assembly. For MT, optimizing wall assemblies, gypsum fire protection, glazing, and floor build-ups may be more important than simply selecting timber as the frame. For RC, the floor system and concrete mix assumptions dominate. For SS, wall and floor assemblies jointly control most of the A-C burden.

**Table 9.** Assembly hotspot summary for each structural alternative.

Class	Sys	Top	Top kg	Top %	Second	Second kg	Second %	Top2 %
IVC-8	MT	walls	128.66	51.55	floors	77.27	30.96	82.52
IVC-8	SS	walls	170.54	44.78	floors	139.55	36.64	81.41
IVC-8	RC	floors	214.05	42.14	walls	190.85	37.57	79.72
IVB-12	MT	walls	150.43	53.58	floors	77.49	27.60	81.18
IVB-12	SS	walls	165.06	41.44	floors	156.88	39.38	80.82
IVB-12	RC	floors	200.43	41.12	walls	184.70	37.90	79.02
IVA-18	MT	walls	152.44	54.44	floors	77.78	27.78	82.21
IVA-18	SS	walls	166.79	42.83	floors	148.58	38.16	80.99
IVA-18	RC	floors	200.54	43.58	walls	156.94	34.10	77.68



**Figure 6.** Assembly-level A-C GWP hotspots for the nine alternatives.

Whole-building totals translate the normalized results into a project-scale signal. Table 10 shows, for

example, that the 12-story MT case had 3,207.86 tCO2e A-C, compared with 5,568.22 tCO2e A-C for the 12-story RC case. Normalized values are best for

baseline comparison, while tCO<sub>2</sub>e totals are useful for communicating project carbon budgets and procurement implications.

**Table 10.** Whole-building embodied-carbon totals by floor area.

Class	Sys	A-C tCO <sub>2</sub> e	A-D tCO <sub>2</sub> e
IVC-8	MT	1,925.80	211.99
IVC-8	SS	2,939.29	2,469.24
IVC-8	RC	3,919.67	3,684.14
IVB-12	MT	3,207.86	677.72
IVB-12	SS	4,550.73	3,904.20
IVB-12	RC	5,568.22	5,245.70
IVA-18	MT	4,798.96	1,476.04
IVA-18	SS	6,672.92	6,151.95
IVA-18	RC	7,886.93	7,841.34

Sensitivity results in Table 11 show how reference study period and code assumptions affect MT A-D values. Moving from the 75-year to the 60-year

reference study period reduced reported MT A-D GWP by 10.74%, 13.28%, and 21.17% for the 8-, 12-, and 18-story cases. The 2024 IBC sensitivity for the 12-story MT case reduced A-D GWP by 1.05%.

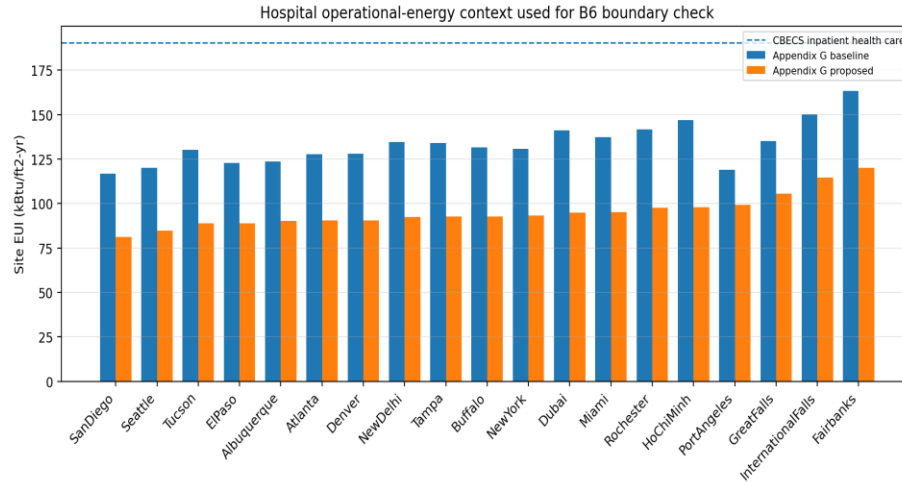
**Table 11.** Sensitivity summary for MT reference-study-period and code scenarios.

Case	Class	Sys	Base	Scenario	Change %	Change tCO <sub>2</sub> e
RSP 75 to 60	IVC-8	MT	27.47	24.52	-10.74	-22.77
RSP 75 to 60	IVB-12	MT	59.32	51.44	-13.28	-90.03
RSP 75 to 60	IVA-18	MT	86.13	67.90	-21.17	-312.41
IBC 2021 to 2024	IVB-12	MT	59.32	58.70	-1.05	-7.08

The hospital operational-energy data in Table 5 and Figure 7 confirm why B6 should remain separate. CBECs inpatient-health-care records produced a floor-area-weighted site EUI of 190.30 kBtu/ft<sup>2</sup>-yr, and all weighted inpatient records were reported as 24-hour operation. DOE Appendix G proposed hospital models ranged from 81.29 to 120.00 kBtu/ft<sup>2</sup>-yr across the 19 climate locations. Appendix G proposed models reduced site EUI by 28.54% on average relative to the Appendix G baseline, but that comparison reflects operational

modeling assumptions rather than structural material selection.

These values strengthen the hospital interpretation without weakening the embodied-carbon boundary. The paper can support early structure-and-enclosure carbon screening for a hospital expansion, while a certification-grade operational-energy claim would still require a separate hospital EnergyPlus model with project-specific schedules, ventilation, equipment, envelope, HVAC, and utility-emissions assumptions.



**Figure 7.** Hospital operational-energy context used only for the B6 boundary check.

The owner-facing explanation layer uses only computed table values. Table 12 shows three representative summaries: each includes the

comparison, the assembly hotspot, and the boundary statement needed to prevent operational-energy overreach.

**Table 12.** Owner-facing explanation checks used by the LLM-assisted narrative layer.

Design comparison	Computed reduction used in summary	Hotspot statement used in summary	Boundary statement
IVC-8 MT versus RC	50.87% A-C reduction; 94.25% A-D reduction	walls; top two assemblies = 82.52%	Does not claim operational-energy reduction
IVB-12 MT versus SS	29.51% A-C reduction; 82.64% A-D reduction	walls; top two assemblies = 81.18%	Points user to separate B6 model
IVA-18 SS versus RC	15.39% A-C reduction; 21.54% A-D reduction	walls; top two assemblies = 80.99%	Labels result as GWP-only screen

Overall, the results support the paper's title with a precise interpretation. The workflow is LEED-aligned because it uses structure-and-enclosure WBLCA logic, functional baseline comparison, GWP reduction thresholds, and a documented narrative. It is hospital-relevant because it frames the decision as an expansion planning screen and now includes hospital-specific operational-energy context. It is LLM-assisted because the final design explanation can be generated as controlled narrative text, but the environmental evidence remains in the computed tables and figures.

### Limitations

The first limitation is project specificity. The WBLCA dataset contains functionally matched structural alternatives under IBC 2021 provisions, but the source building layout is not a complete hospital. It does not include clinical departments, medical equipment loads, air-change requirements, emergency power systems, medical-gas systems, infection-control constraints, or hospital-specific enclosure detailing. The study therefore supports early structure-and-enclosure embodied-carbon screening, not final hospital certification or construction documentation.

The second limitation is impact-category scope. The LEED screen reported here uses GWP because the available WBLCA result tables consistently report GWP for all nine alternatives. LEED v4.1 whole-building LCA documentation requires multiple impact categories and limits on increases in other categories [5]. The labels in this paper therefore remain GWP-only screens rather than awarded LEED points.

The third limitation is treatment of Module D. A-D values are reported because they are present in the WBLCA results and help interpret end-of-life and beyond-boundary assumptions. However, A-D reductions can be much larger than A-C reductions. The main LEED-oriented comparison therefore uses A-C values.

The fourth limitation is the LLM component. The explanation layer is evaluated as a constrained, table-grounded communication module rather than as a general benchmark of a commercial LLM. Future work can compare models and prompting approaches under the same verification rules, but the environmental results do not depend on any proprietary LLM output.

The fifth limitation is operational energy. CBECS and DOE prototype files are used to define and quantify the separate B6 context, not to claim that MT, SS, or RC reduces hospital energy consumption. Future work should integrate a project-specific hospital EnergyPlus model with climate-zone, envelope, HVAC, schedule, equipment, ventilation, and utility-emissions assumptions.

## Conclusion

This paper conducted a data-grounded embodied-carbon evaluation for a LEED-aligned hospital expansion decision-support workflow. MT had the lowest embodied GWP in each height class. Across A-C boundaries, MT reduced GWP by 39.15-50.87% compared with RC and by 28.08-34.48% compared with SS. SS also reduced A-C GWP relative to RC, but by smaller margins. Seven of nine pairwise comparisons exceeded the 20% GWP-only LEED screen, while all nine exceeded the 10% screen.

The added hospital-energy boundary check addresses the main data gap in the hospital framing. CBECS and DOE hospital prototype results show that operational energy is a large and separate hospital-performance question; it should be modeled directly rather than inferred from structural material choice. This strengthens the paper by keeping the embodied-carbon contribution usable for early expansion planning while clearly reserving B6 operational-energy claims for a later EnergyPlus workflow.

Assembly hotspots further show that design action should focus on walls and floors for MT, floors and walls for RC, and walls and floors for SS. The LLM-assisted explanation layer can translate these computed results into owner-facing guidance, provided every numeric statement remains tied to the tables and figures.

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