TELLING THE STORY: Knife River's Whole Building Life Cycle Assessment for Two-Story Data Centers

Comparative WBLCA of a typical two-story data center building in the Pacific Northwest using Precast, Concrete Tilt-wall, CMU, and Mass Timber designs.

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Introduction

DCI Engineers partnered with Knife River Prestress and Ware Malcomb Architects to measure and compare the potential environmental impacts of a real-world, two-story data center in the Pacific Northwest using whole building life cycle assessment (WBLCA). With a rise in data center construction worldwide and their impact on energy demand, the necessity to reduce their environmental impacts wherever possible is of utmost importance. The study leveraged an actual completed project design and analyzed five different combinations of exterior wall assemblies and structure to better understand and compare their associated embodied carbon impacts. The five comparative designs studied and the carbon intensities utilized include:

1. Structural Precast Concrete (Industry Average Precast Concrete*)
    a. Structural Precast Concrete (Knife River's CarbonCutter™ Mix)
2. Non-Structural Precast Concrete (Industry Average Precast Concrete*)
    a. Non-Structural Precast Concrete (Knife River's CarbonCutter™ Mix)
3. Structural Cast-In-Place Concrete Tilt-Wall (Industry Average Concrete Mix*)
4. Non-Structural Concrete Masonry Unit (Industry Average CMU*)
5. Non-Structural Cross-Laminated Timber (Industry Average CLT*)

*Refer to Appendix A for environmental product declaration data used for all industry averages.

In this study, we assess the differences between these exterior wall assemblies—with regards to sustainability, performance, and constructability— and how this information can be used to further optimize designs and achieve even greater embodied carbon reductions on large-scale, high-mass buildings such as data centers. While these results only represent a snapshot of present practices and pull from currently available environmental product data, the hope is lessons learned can be used to contribute to the industry moving forward towards net-zero construction in the future.

Project Description

The baseline project is a recently completed two-story data center project which is approximately 297,000-sf and located in Hillsboro, Oregon. The building has an average height of 58'-0" with typical floor-to-floor heights of 23'-0" and a 12'-0" parapet to conceal rooftop mechanical equipment. Steel framing was utilized at the primary structure supported by shallow concrete foundations. Lateral framing consisted of buckling restrained braced frames (BRBFs).

Each of the five comparative designs meet the following criteria:

- 2019 Oregon Structural Specialty Code (Based on the 2018 IBC)
- Risk Category II
- Soil Site Class D
- Seismic Design Category D
- Exposure Category C
- Climate Zone 4c
- Occupancy Types B, S-1, S-2

A non-structural precast concrete wall assembly was the original design option in the baseline building. The structural precast, structural cast-in-place (CIP) tilt, non-structural CMU, and non-structural CLT walls were all designed by DCI engineers to a level of completion that ensures they are all considered technically viable.

For the WBLCA, material quantities were gathered from drawings and associated Revit models (when available), both structural and architectural. The five comparative designs are considered functionally equivalent and account for appropriate construction type, fire protection measures, acoustic performance, thermal performance, and programming. Two building lifespans were considered in the analysis to study the effects of each material's durability and maintenance requirements: a standard 60-year lifespan per LEED requirements and a longer 100-year lifespan. The structural design for each material system was also optimized and adjustments to building height, weight, and the lateral system were accounted for as necessary. Although the basis of design referenced a completed data center, we believe similar large-scale, high-mass buildings such as distribution centers, gymnasiums, and warehouses could expect similar results to the ones outlined in this case study.

Exterior Wall Assembly Descriptions:

The following are in-depth descriptions of each of the five exterior wall assemblies analyzed in the comparative WBLCA. "Structural" assemblies are considered to be capable of supporting gravity and lateral loads from the floor and roof framing without additional steel framing at the perimeter, whereas "non-structural" assemblies only support the self-weight of enclosure materials and therefore require additional steel framing at the perimeter. All wall heights range between 56'-9" and 59'-9" per the original design, with the CMU and CLT designs requiring additional out-of-plane bracing steel (as described below) to meet deflection and strength requirements while maintaining the tall parapets and floor-to-floor heights. Insulation, backing studs, cladding materials, and interior finishes were all selected to normalize R-values to the original non-structural precast assembly as well as meeting typical occupant requirements based on past real-world project experiences. Concrete and reinforcement strengths match industry standards and DCI's real-world project experiences.

Non-Structural Precast Concrete:

In the baseline project design, the non-structural precast concrete wall assembly consisted of an exterior 3" precast layer and interior 5" precast layer sandwiching 4" of EPS insulation for a total thickness of 12". The assembly wythes are cast to behave compositely with Carbon Cast (C-Grid) longitudinal reinforcing panels at 24" o.c., or less. This assembly was not designed to support gravity or lateral loading, so there are additional perimeter steel columns, beams and BRBFs to meet structural demands. Refer to Figure 2 below for further information on the non-structural precast wall assembly:

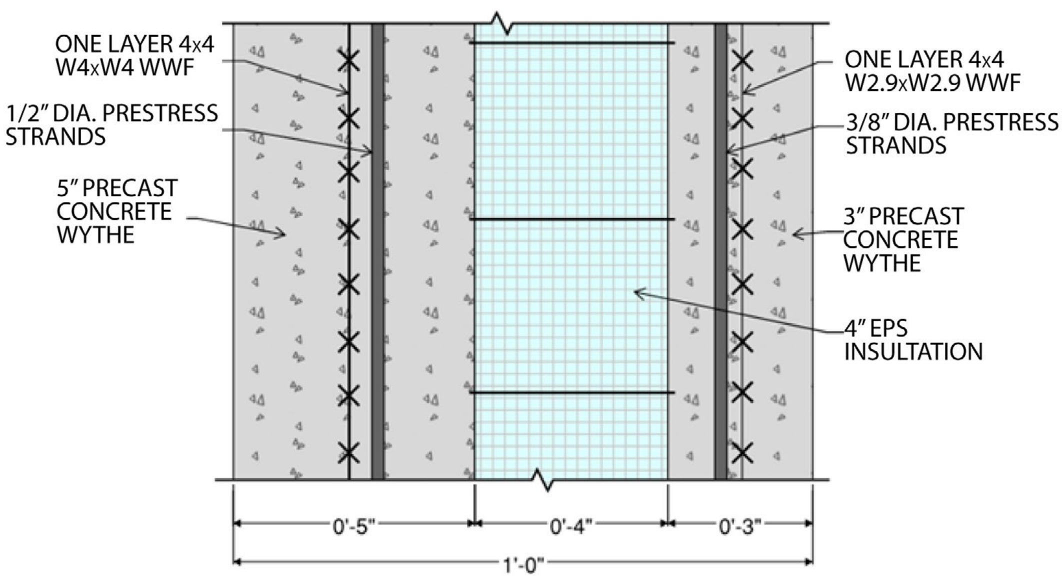

FIGURE 1: Non-structural precast wall assembly section detail

Wall Assembly Type	Concrete Strength	Typical Wall Reinforcement	Reinforcement Strength	R-Value
Non-structural Precast Concrete (Baseline)	F'c = 7ksi F'ci = 3.5ksi	(8) 1/2" DIA PRESTRESS Strand & 4x4 W4x WWF (5" WYTHE) (8) 3/8" DIA PRESTRESS Strand & 4x4W2.9xW2.9 WWF (3" WYTHE) #4 CONT AT ALL EDGES	Fu = 270ksi (strand) Fy = 80ksi (WWF) Fy = 60ksi (mild rebar)	18.8

TABLE 1: Non-structural precast wall assembly properties

Structural Precast Concrete:

The structural precast concrete wall assembly consists of an exterior 4” precast layer and interior 4” precast layer sandwiching 4” of EPS insulation for a total thickness of 12”. The assembly wythes are cast to behave compositely with Carbon Cast (C-Grid) longitudinal reinforcing panels at 24” o.c., or less. This assembly was designed to support gravity and lateral loading, so no additional perimeter steel columns or beams are required at the perimeter and BRBF’s at the perimeter in the baseline design are no longer required.
To achieve a similar thickness to the non-structural precast baseline, this assembly increased reinforcement in the interior wythe, balanced the wythe thicknesses, and relies on composite action. Refer to Figure 2 below for further information on the structural precast wall assembly:

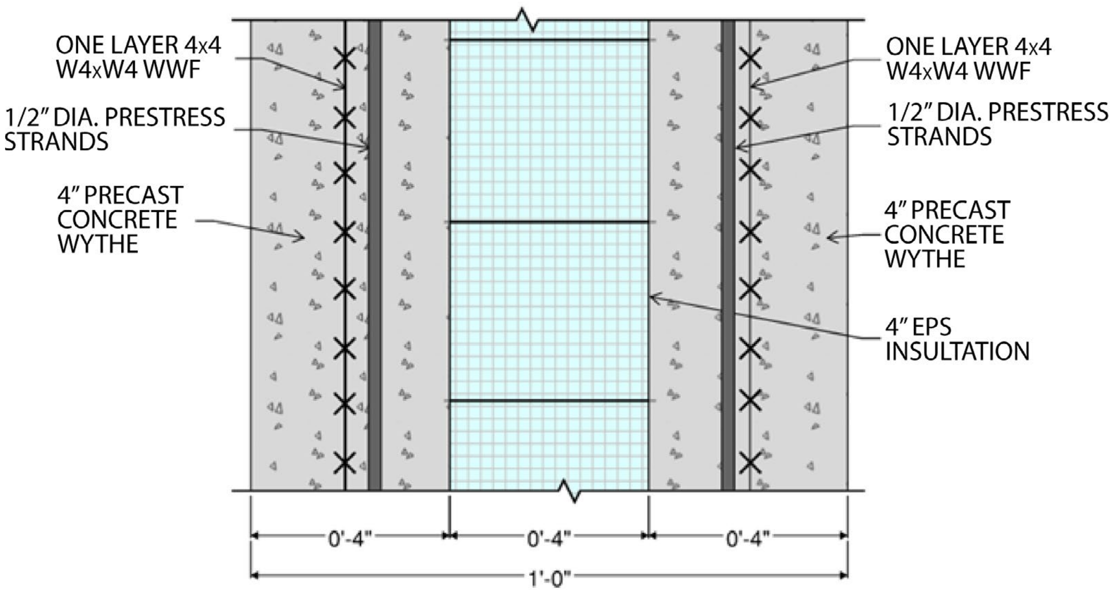

FIGURE 2: Structural precast wall assembly section detail

Wall Assembly Type	Concrete Strength	Typical Wall Reinforcement	Reinforcement Strength	R-Value
Structural Precast Concrete	F’c = 7ksi F’ci = 3.5ksi	4x4 W4x WWF (5” WYTHE) (8) 1/2” DIA PRESTRESS Strand EA WYTHE #4 CONT AT ALL EDGES	Fu = 270ksi (strand) Fy = 80ksi (WWF) Fy = 60ksi (mild rebar)	18.8

TABLE 2: Structural precast wall assembly properties

Structural Cast-in-Place Tilt-up Concrete:

The structural cast-in-place tilt-up concrete wall assembly consists of an exterior 4” concrete layer and interior 8” concrete layer sandwiching 4” of EPS insulation for a total thickness of 16”. The wythes are anchored with Thermomass pins in both directions. This is a common system for connecting Tilt-up wythes, but does not achieve similar composite characteristics to the C-Grid system for plant-cast precast wall panels. This assembly was designed to support gravity and lateral loading, so no additional perimeter steel columns, beams or BRBFs are required at the perimeter. To limit overall thickness of the assembly, the design of the interior wythe relies on composite action. Refer to Figure 3 below for further information on the structural CIP tilt-up wall assembly:

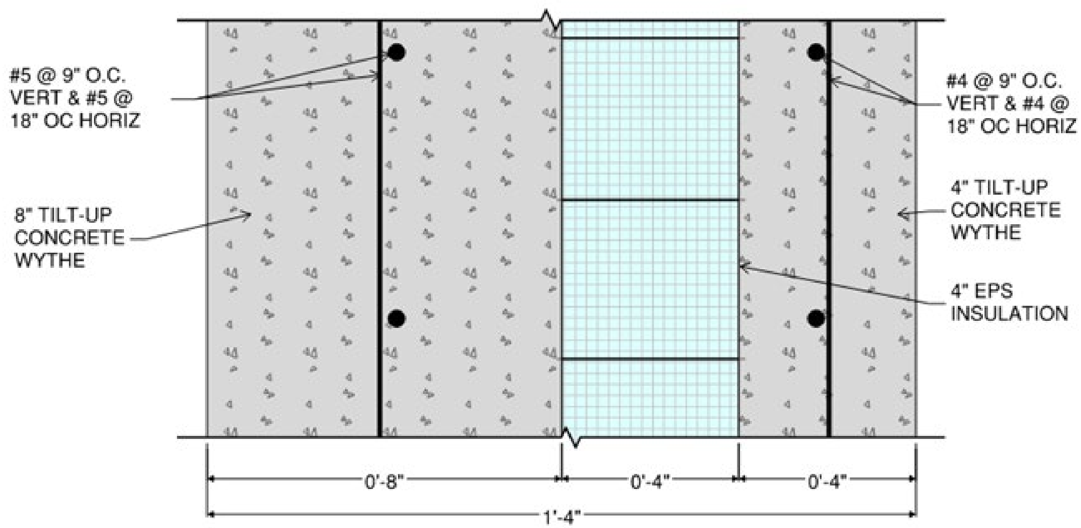

FIGURE 3: Structural cast-in-place tilt-up concrete wall assembly section detail

Wall Assembly Type	Concrete Strength	Typical Wall Reinforcement	Reinforcement Strength	R-Value
Tilt-up Concrete	F’c = 5ksi F’ci = 3.5ksi	#5 @ 9” OC VERT & #5 @ 18” OC HORIZ (8”WYTHE #4 @ 9” OC VERT & #4 @18” OC HORIZ (4” WYTHE)	Fy = 60ksi	19.4

TABLE 3: Structural cast-in-place tilt-up concrete wall assembly properties

Non-Structural Concrete Masonry Units (CMU):

The non-structural CMU wall assembly consists of 10” fully grouted CMU blocks (9 5/8” Nominal), inside and outside air film membrane, 3” rigid insulation, 2 ½” CFS backing studs, and 5/8” interior gypsum board for a total thickness of 15 3/4”. This assembly was not designed to support gravity or lateral loading, so there are additional perimeter steel columns, beams and BRBFs at the perimeter to meet structural demands. Steel kickers are also required at the parapets. Refer to Figure 4 below for further information on the non-structural CMU wall assembly:

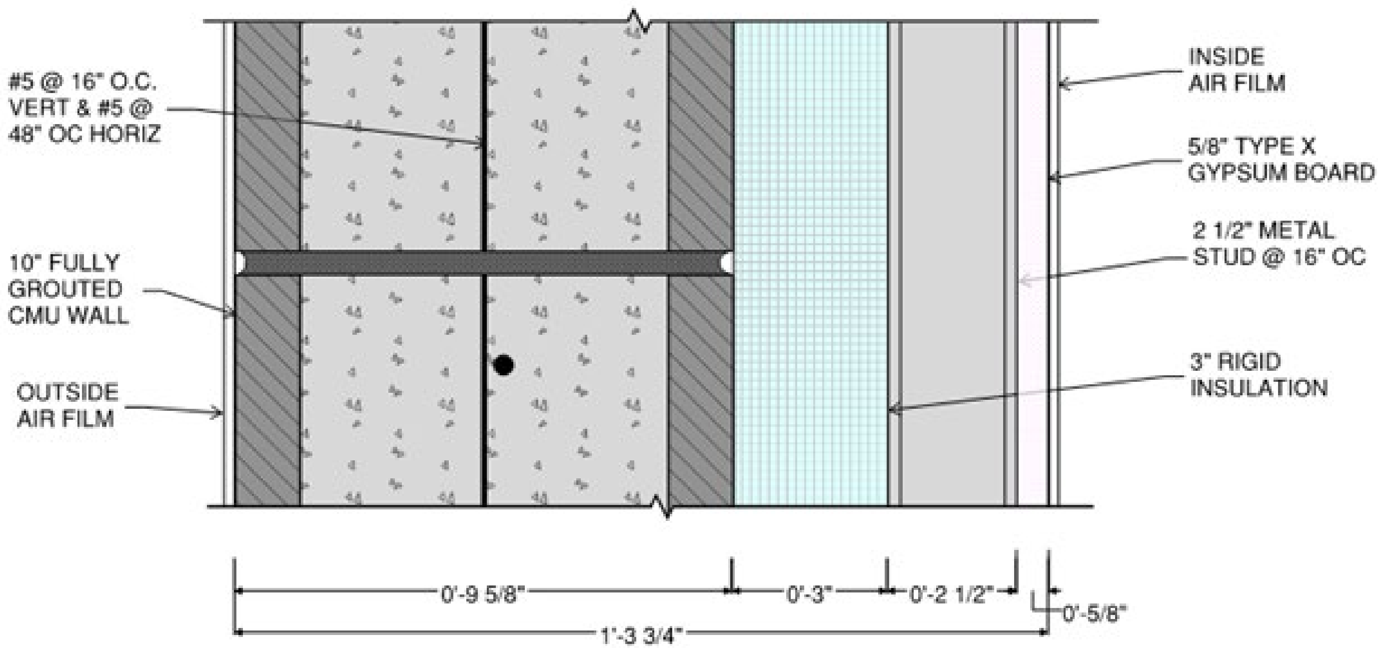

FIGURE 4: Non-structural concrete masonry unit wall assembly section detail

Wall Assembly Type	Concrete Strength	Typical Wall Reinforcement	Reinforcement Strength	R-Value
CMU Non-Load Bearing	F’c = 2.5ksi F’ci = 61psi	#5 @ 16” OC VERT & #5 @ BOND BEAMS @48” OC	Fy = 60ksi	18.4

TABLE 4: Non-structural concrete masonry unit wall assembly properties

Non-Structural Cross-Laminated Timber (CLT):

The non-structural CLT wall assembly consists of 3-ply CLT (4 1/8”) at the interior, inside and outside air film membrane, 3” rigid insulation, and 1/2” exterior fiber cement panels for a total thickness of 7 5/8”. This assembly was not designed to support gravity or lateral loading, so there are additional perimeter steel columns, beams and BRBFs at the perimeter to meet structural demands. Unlike the other wall panel designs, the most feasible design for CLT was to add more intermediate perimeter columns and span the assembly horizontally due to the floor-to-floor height exceeding the 3-ply CLT’s span capabilities. Rather than using kickers at the parapet like the CMU design, the perimeter columns were extended to the top of the parapet height with an added top beam to support the CLT. Refer to Figure 5 below for further information on the non-structural CLT assembly:

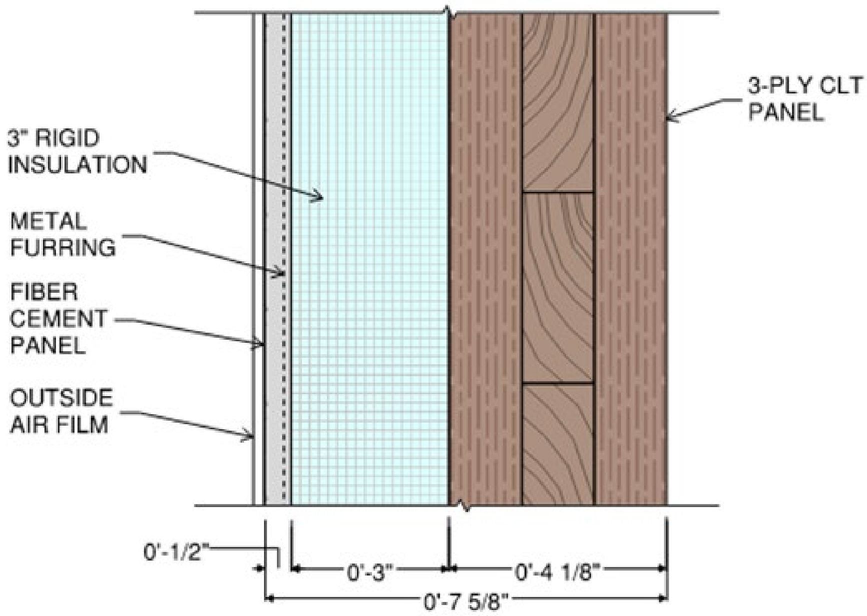

FIGURE 5: Non-structural cross-laminated timber wall assembly section detail

Wall Assembly Type	R-Value
Non-structural CLT	18.2

TABLE 5: Non-structural cross-laminated timber wall assembly properties

Roof Enclosure Description:

The horizontal enclosure at the roof is mostly constant between comparative designs, with metal decking and gypsum substrate board above the deck, vapor retarder, rigid roof insulation, cover board, and PVC sheeting. A minimum thickness of 6.5” of rigid insulation was used to meet an R-value of 32.5 for the roof assembly. To ensure functional equivalency, a standard COMcheck analysis was run to ensure that the comparative design options all met the regional energy code compliance. It was found that although the wall assemblies were designed to have similar r-values, the roof assembly was the biggest driver in meeting energy code requirements. The minimum R-value of 32.5 roof assembly worked for the precast and cast-in-place tilt-up concrete wall designs due to their overall thickness with sandwiched insulation. The CLT and CMU wall designs, however, required an extra ½ inch of roof insulation to reach an R-value of 35 for the roof assembly and meet the energy code compliance. The different thickness of rigid insulation is reflected in the embodied carbon analysis in the results section. Refer to Figure 6 below for further information on the roof enclosure assembly:

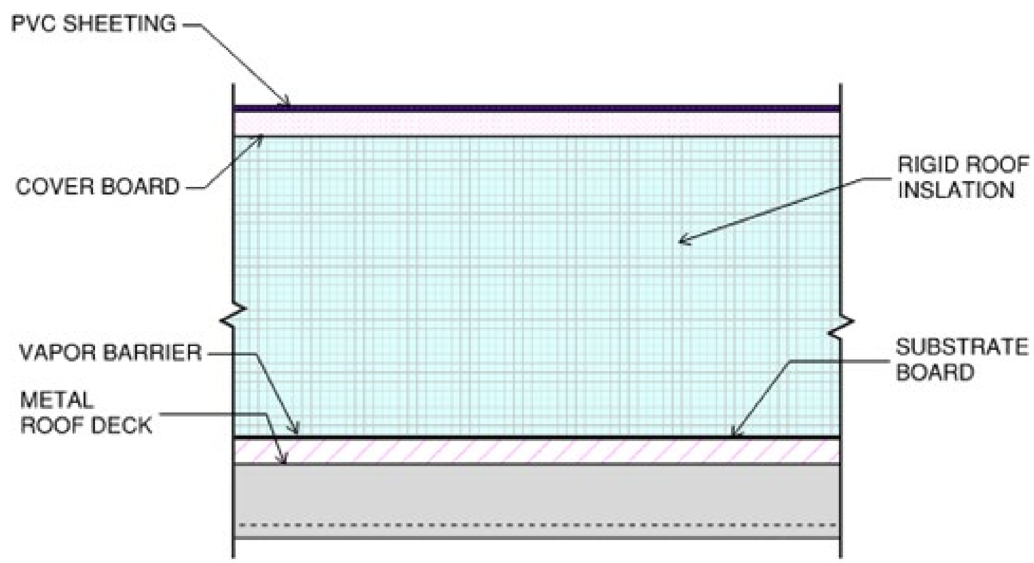

FIGURE 6: Roof enclosure section detail

Structural Description: Composite Steel Framing over Shallow Concrete Foundations

The structural system for level 2 and the roof level is steel framing consisting of wide-flange beams and columns. The level 2 floor assembly consists of 3 ½” concrete topping over 3” 18 gage metal deck with ¾” diameter studs welded onto the wide-flange beams for composite action. As described previously, the roof assembly has no concrete topping and utilizes a 1 ½” 18 gage metal deck due to lighter loading.

The lateral system consists of steel buckling restrained brace frames (BRBFs) spanning from foundation to the roof in both directions at the interior of the building, as well as the perimeter where required in the non-structural wall designs.

The steel columns and BRBFs are supported by concrete pedestals bearing on spread and mat footings. Around the perimeter, the exterior walls bear on a concrete stem wall on top of a continuous strip footing . The concrete thickness and rebar quantities vary from column to column, frame to frame, and wall to wall, based on loading criteria. At grade is a 6” non-structural slab on grade, which is locally thickened where required for higher loading areas such as loading docks and mechanical units.

Structural Modifications: Additional Exterior Framing at Non-Structural Assemblies

For the non-structural precast, CMU, and CLT exterior wall designs, an additional line of steel columns is required along the perimeter to support the level 2 and roof framing, rather than the floor framing being supported directly by the walls themselves. This also results in extra perimeter steel beams at Level 2 and the roof. As described previously, the CLT panels are more efficient spanning horizontally rather than vertically which required almost twice as many perimeter columns compared to the other nonstructural designs, shortening the typical bay spacing from 32’-0” to 16’-0”. The increased number of perimeter columns does decrease the column and beam sizing because shorter spans decrease the amount of load on each member. Additional steel columns for these non-structural designs require modifications to the foundations as well. The strip footings at the perimeter decrease slightly with less load on the wall assemblies, while there are more concrete pedestals and spread footings required at each added perimeter column and BRBF location. Based on DCI’s past-project experience, the additional framing described is the optimal strategy for reducing cost and easier constructability than increasing CMU block or CLT panel thickness to achieve the same spans as the other exterior wall designs, however this can vary depending on each project’s unique circumstances.

Life Cycle Assessment Scope & Methodology

DCI Engineers undertook WBLCAs for all design alternatives. They were conducted using One Click LCA, a global tool consisting of multiple calculation tools aimed at helping designers and owners achieve carbon reduction and building certification goals. One Click LCA calculations conform to ISO 14040 (ISO, 2006) and ISO 14044 (ISO, 2006) North American standards and Europe’s EN 15978 (EN, 2011). Background data sets within the tool are based on environmental product declarations (EPDs), LCA databases, and One Click LCA-generated data. Additional data for all life cycle stages is calculated within One Click LCA based on parameters that include building location, energy grid, and end-of-life options.

The primary calculation tool was One Click’s LCA for LEED, U.S. Material quantities were primarily based on the project’s Revit models (where available) and drawings, with hand-calculations used to estimate materials not accurately modeled in Revit (such as reinforcement). One Click LCA’s Life Cycle Carbon – North America tool was also used to provide A5 module impacts.

System Scope and Exclusions

The comparative WBLCA study assessed the potential environmental impacts of the as-built, non-structural precast assembly and functionally equivalent structural precast, structural CIP tilt-up, non-structural CMU, and non-structural CLT wall alternatives. The primary scope is structure and enclosure.

The structural system includes the components of the floors, roofs, and load-bearing walls as discussed in the project descriptions. For the lateral system, the analysis includes BRBF members. MEP systems, fenestration, connections, and hardware are not included.

The assessment includes the following ancillary items: elevator overrun framing and architectural concrete curbs. The elevator overrun roof framing is included in the structural system, and the architectural curbs, cladding, membranes, rigid insulation, and interior gypsum wall board are included in the enclosure (where applicable).

Life Cycle Stages

The life cycle modules included in this assessment are:

- A1: Raw Material Extraction
- A2: Transport to Manufacturing Site
- A3: Manufacturing
- A4: Transportation to Construction Site
- A5: Construction Site – Material Wastage
- B1: Use
    - B1-d: Carbonization
- B4: Replacement
- B5: Refurbishment
- C2: Transportation to Waste Processing
- C3: Waste Processing
- C4: Disposal

LIFE CYCLE STAGES: CRADLE-TO-GRAVE + MODULE D																		
Production			Construction		Use							End-of-Life				Module D		
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3
Raw Material Extraction	Transport to Manufacturing Site	Manufacturing	Transportation to Construction Site	Construction Site - Material Wastage	Use B1-d: Carbonization	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction/Demolition	Transportation to Waster Processing	Waste Processing	Disposal	Reuse	Recycling	Energy Recovery

Note that the stages and information modules shown here deviate slightly from the naming convention used in ISO 21930 (ISO, 2017). However, this series generally uses terminology consistent with ISO 21930.

FIGURE 7: LCA life-cycle stages; scope inclusions in light green

Transportation distances and modes in Module A4 were approximated by One Click LCA using industry averages for each material type but adjusted for materials with known values from the referenced job such as concrete.

Two different building service lives were analyzed: 60 years, which is consistent with the LEED v4.1 Materials and Resources Building Life-Cycle Impact Reduction credit (USGBC, 2023), and 100 years, which aligns more with expected performance and durability of concrete structures. Most structural elements are assumed to have a service life equal to the expected building life. However, based on their EPDs, waterproofing membranes, insulation, and gypsum board are assumed to be replaced during the building's use, with additional impacts due to maintenance and replacement reported in Stage B. The impacts from those product replacements are considered major replacements/refurbishments which fall into the B4-B5 modules, minor maintenances repairs in the B2-B3 modules are not included in the scope of this study. B1 module impacts would typically be ignored since operational scope is not included, but this module is used to incorporate benefits from carbonization that occurs during the building's use. Additionally, stage D module impacts have been excluded to match standard LEEDv4.1 reporting practices.

Environmental Impact Categories

The primary impact category assessed in this study is global warming potential (GWP) as it represents the amount of carbon in the atmosphere, which is the focus of many policies aimed at the reduction of greenhouse gas (GHG) emissions. The results will provide the embodied carbon (in terms of GWP) associated with each comparative design; embodied carbon represents the carbon impact of the building materials and construction processes over the lifetime of the materials, from extraction through end of life (Modules A1-C4).

In addition to GWP, One Click's LCA for LEED tool, U.S. reports impacts in the following categories: acidification potential, eutrophication potential, ozone depletion potential, smog formation potential, and depletion of nonrenewable energy. These impacts are also reported in this study.

Data Sources

It is DCI's practice to use product-specific EPDs for the materials included in an LCA as often as possible. Where product-specific information was unknown or EPDs were unavailable in One Click LCA, industry-wide EPDs were used per guidelines set in the Carbon Leadership Forum's 2025 CLF North American Material Baselines Report. All data sources used are provided in Appendix A.

For concrete data, regional industry-wide EPDs were used for all buildings, except where Knife River Prestress' CarbonCutter™ mix was substituted. The industry-wide concrete EPDs are based on northwest regional averages determined by the National Ready Mixed Concrete Association (NRMCA). This project specified standard 28-day concrete test ages to match assumptions of the NRMCA average mix EPDs, however actual test age requirements may vary in practice to meet project requirements.

End-of-Life Assumptions

One Click LCA allows the user to choose end-of-life scenarios for each material from a list of options, which affects environmental impacts reported in Modules A5, and C2-C4. DCI utilized the default end-of-life scenarios assumed by One Click LCA, with the following exceptions: gypsum board/cover board, insulation, weatherproofing membranes, CLT, and precast concrete panels (including sandwiched EPS insulation) were all adjusted. The gypsum, insulation, and membrane product assumptions were adjusted to landfilling to align with standard practice in the United States, while the precast, tilt-up concrete and CLT panels were changed to be reused to benefit from their modular nature which makes disassembly possible at the end of building life.

Although the assumption that 100% of each material will meet the chosen end-of-life scenario is highly unlikely, One Click LCA does not allow users to specify a mix of scenarios unless the material quantities associated with each end-of-life scenario are inputted separately. The decision was therefore made to select the scenario most closely aligned with standard industry assumptions at the time of this analysis.

Material	EOL Process
Rebar, Hot-Rolled and cold-formed steel, metal deck, hollow tube steel, and steel studs	Steel recycling
Ready-mix concrete, CMU, BRBF Grout, Fiber Cement Panels	Concrete crushed to aggregate
Rigid wool insulation board, gypsum board, weather barrier, vapor retarder, substrate/cover board	Landfilling (for inert materials)
CMU Grout	Cement/mortar use in backfill
Precast wall panel, CarbonCutter™ precast wall panel, Pre-stressed tendons and rebar in precast wall panels, EPS Insulation in precast wall panels, CLT, Tilt-up concrete wall panels, Rebar and EPS insulation in tilt-up panels	Reuse as material

TABLE 6: Assumed end-of-life scenarios by material type

Carbonization Benefits

Concrete carbonization is a natural process that occurs on the surface of concrete elements over time in which CO2 reacts with cement to form calcium carbonate, helping to sequester the CO2 from the atmosphere. The amount of sequestered CO2 on the concrete surface is dependent on several factors: interior/exterior exposure, moisture exposure, porosity of the concrete, cement ratio, and time.

In One Click LCA, carbonization benefits are accounted for in the B1 life cycle stage through the Life Cycle Carbon – North America tool. The quantification method used by One Click LCA to calculate carbonization is based on the EN 16757 European standard. Carbonization progresses at the highest rate in a sheltered outdoor environment and concrete mixes containing supplement cementitious materials, such as the CarbonCutter™ mix, see the highest uptake in the slab-on-grade interior face and CarbonCutter™ precast wall panels. Carbonization benefits were not accounted for on faces of concrete elements that are covered by impermeable membranes.

With concrete being expected to be crushed into aggregate as the assumed end-of-life scenario for foundation members, it is possible that the increased surface area of all of those aggregate pieces could result in further carbonization, but that calculation goes beyond the scope of this study. For additional information on concrete carbonization and the EN 16757 standard used in One Click LCA, see the IVL Swedish Environmental Research Institute article, CO2 Uptake in Cement-Containing Products.

CarbonCutter™ Mix

CarbonCutter™ represents Knife River Prestress, Inc.'s commitment to advancing low-carbon solutions in their concrete production. The mix can be used in a variety of structural and architectural concrete components such as beams, girders, wall panels, and cladding within many building types. CarbonCutter™ achieves reduction in global warming potential where utilized, by reducing/replacing cement content with supplemental cementitious materials such as slag. For this case study, this proprietary mix offered a low-carbon alternative to industry average mixes in all precast elements. In future projects, the reductions in embodied carbon could be extended further into ready-mix concrete applications with further opportunities through design coordination. When used in conjunction with prestressing technology, CarbonCutter™ mixes may further reduce embodied carbon when compared to similar conventionally reinforced concrete construction methodologies.

Results and Discussion

This section provides the results of the five LCAs along with additional discussion. As noted, the focus of the study is global warming potential; therefore, most of the results are centered around this parameter, reported in kilograms of carbon dioxide equivalent (kgCO2eq), or GWP per gross floor area (kgCO2eq/m2).

Global Warming Potential Results

When considering Stages A-C, the structural precast building presents the lowest embodied carbon option, which is 19% lower in global warming potential (GWP) than the highest embodied carbon option, the non-structural CMU option, with an overall GWP per square meter of 338.5 kgCO2eq/m2. Adding in the benefits of the CarbonCutter™ mix, the structural precast design becomes 26% lower than non-structural CMU, with an overall GWP per square meter of 309.7 kgCO2eq/m2.F

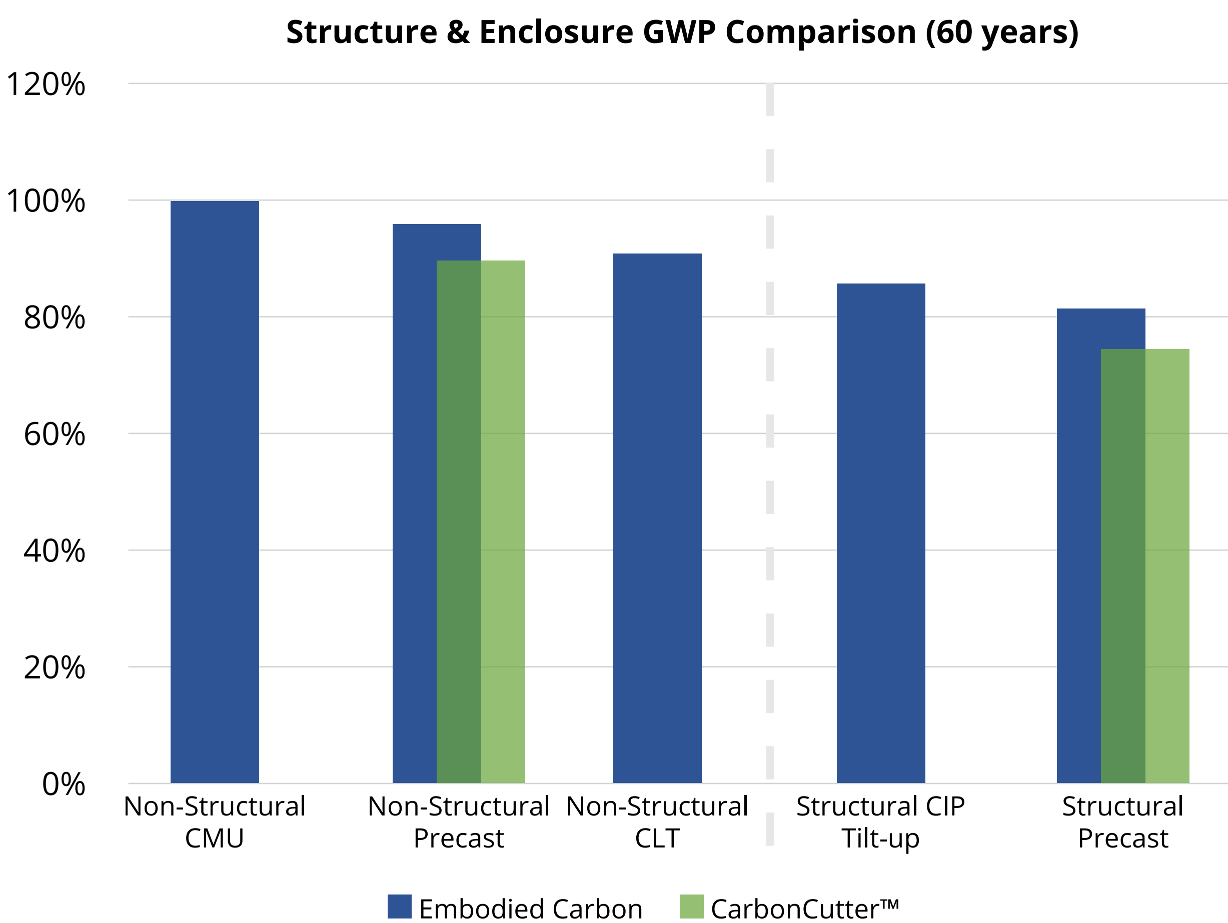

FIGURE 8: Total building GWP (structure and enclosure) comparison of the five designs

STRUCTURE & ENCLOSURE GWP COMPARISON		
Category	**Global Warming (kg CO_2e/m2)**	
Non-Structural CMU	418	100%
Non-Structural Precast	402	96%
	incl. CarbonCutter™ Replacement	
	375	90%
Non-Structural CLT	379	91%
Structural CIP Tilt-up	358	85%
Structural Precast	339	81%
	incl. CarbonCutter™ Replacement	
	310	74%

TABLE 7: Total building GWP (structure and enclosure) comparison of the five designs

When considering the emissions per life-cycle stage , the structural precast design is 19% lower in A1-A3 global warming potential (GWP) than the highest embodied carbon option, the non-structural CMU option for Stages A-C, 26% if the CarbonCutter™ mix is utilized (Figure 8). Reductions are similar across all stages, with the most prominent (by percentage) being in the A5 and B4-B5 stages, because the insulation and finishes in the wall assemblies require replacement/maintenance more frequently in the CMU and CLT designs. Negative emissions or carbon uptake shown in the B1 phase is due to the previously noted benefits of concrete carbonization. All five comparative designs have carbonization benefits due to concrete foundations and floor topping, but the precast and concrete tilt wall assemblies provide additional uptake. Carbonization benefits of CMU are accounted for in the A3 phase due to occurrence in the production phase of dry-casting units, which is further explained in the EPD used, which was published by CMHA (Concrete Masonry and Hardscape Association) in 2024. There is often further B1 use stage benefits in CMU provided through surface area absorbing carbon over time, but to meet the energy requirements of a data center, all surfaces of the CMU walls were covered by insulation and finishes. Reductions are also evident in the C2 waste transport stage, due to the assumption that precast and CIP tilt-wall assemblies can be reused in future buildings. CLT panels can also be reused, but the non-structural design still requires perimeter steel; and since the insulation is permanently attached to the CLT, it would likely be separated and landfilled along with the other enclosure assembly layers.

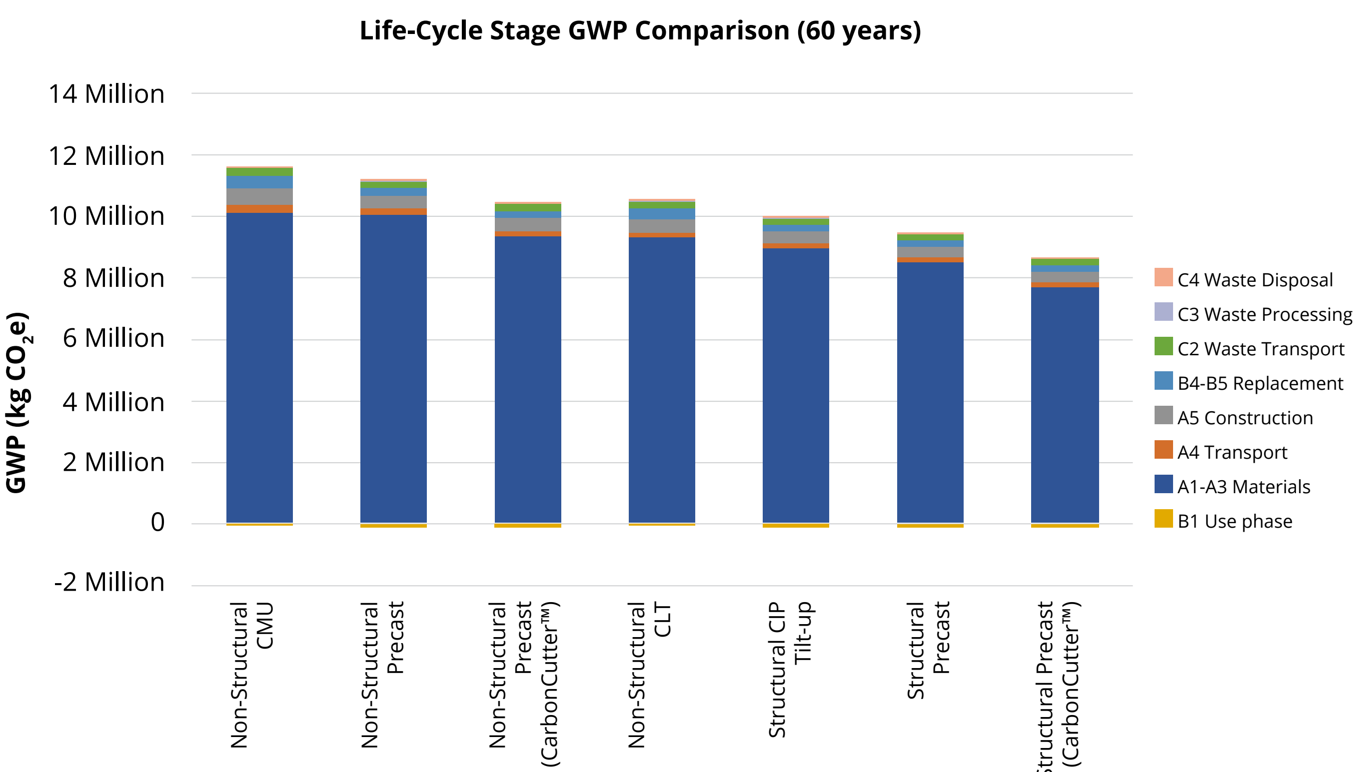

FIGURE 9: Life-cycle stage GWP (structure and enclosure) comparison

LIFE-CYCLE STAGE GWP COMPARISON (kg CO_2e) (60 YEARS)								
Category	**A1-A3 Materials**	**A4 Transport**	**A5 Construction**	**B1 Use Phase**	**B4-B5 Replacement**	**C2 Waste**	**C3 Waste Processing**	**C4 Waste Disposal**
Non-Structural CMU	10,227,640	186,570	549,348	(72,040)	385,621	255,014	20,757	1,556
Non-Structural Precast	10,104,564	190,709	413,447	(94,465)	221,796	235,667	18,909	1,105
Non-Structural Precast (CarbonCutter™)	9,383,834	178,440	413,507	(94,465)	221,796	235,674	18,910	1,105
Non-Structural CLT	9,342,161	163,113	441,992	(72,040)	342,038	236,751	19,034	1,319
Structural CIP Tilt-up	8,970,007	154,055	425,342	(95,719)	221,796	187,003	15,155	1,105
Structural Precast	8,521,318	161,666	349,681	(93,997)	221,796	187,003	15,155	1,105
Structural Precast (CarbonCutter™)	7,737,564	149,500	349,681	(93,997)	221,796	187,003	15,155	1,105

TABLE 8: Life-cycle stage GWP (structure and enclosure) comparison

If the building lifespan is increased to 100 years, the emissions by life-cycle generally stay the same except for the B4-B5 replacement emissions shown in Table 9. The biggest increase in GWP for that stage is again in the CMU and CLT designs where insulation and finishes require more replacement/maintenance. All five comparative designs see an increase because the roof assemblies account for a large portion of the envelope and typically requires replacement of the rigid insulation and weatherproofing layers over time.

STAGE B4-B5 REPLACEMENT GWP COMPARISON (kg CO_2e)		
Category	**60-year value**	**100-year value**
Non-Structural CMU	385,621	1,196,701
Non-Structural Precast	221,796	733,993
Non-Structural Precast (CarbonCutter™)	221,796	733,993
Non-Structural CLT	342,038	1,109,535
Structural CIP Tilt-up	221,796	733,993
Structural Precast	221,796	733,993
Structural Precast (CarbonCutter™)	221,796	733,993

TABLE 9: Life-cycle stage B4-B5 GWP (structure and enclosure) comparison

Considering the GWP attributed to various building systems, the embodied carbon of all five comparative designs is most concentrated in the foundations, contributing about a quarter of total GWP (Figure 10). However, each system has a notable impact, with the choice between external wall designs carrying through all parts of the building design. Focusing solely on the external walls themselves, the non-structural CLT is shown as the best performing option with a reduction of 65% over the structural CIP tilt-up assembly, now the worst performing option. This conclusion proves short-sighted when zooming out to look at the whole building but could be valuable information for other design scenarios. The two structural assembly designs (Structural Precast and Structural CIP Tilt-up) have the biggest impact reductions compared to the nonstructural CMU assembly due to the elimination of the perimeter steel structure and double functionality as lateral structure and enclosure elements. This results in foundation reductions of 22%, BRBF reductions of 57%, and column reductions of 41%. On top of those reductions, the structural precast assembly has further reductions over the structural CIP tilt-up assembly when only considering the vertical enclosure itself, because it has a much thinner concrete profile. And when considering the use of CarbonCutter™ mix, the precast structural wall assembly is 22.86 kgCO2eq/m2 which is similar to the impacts of the CLT option and 56% below industry average nonstructural assembly.

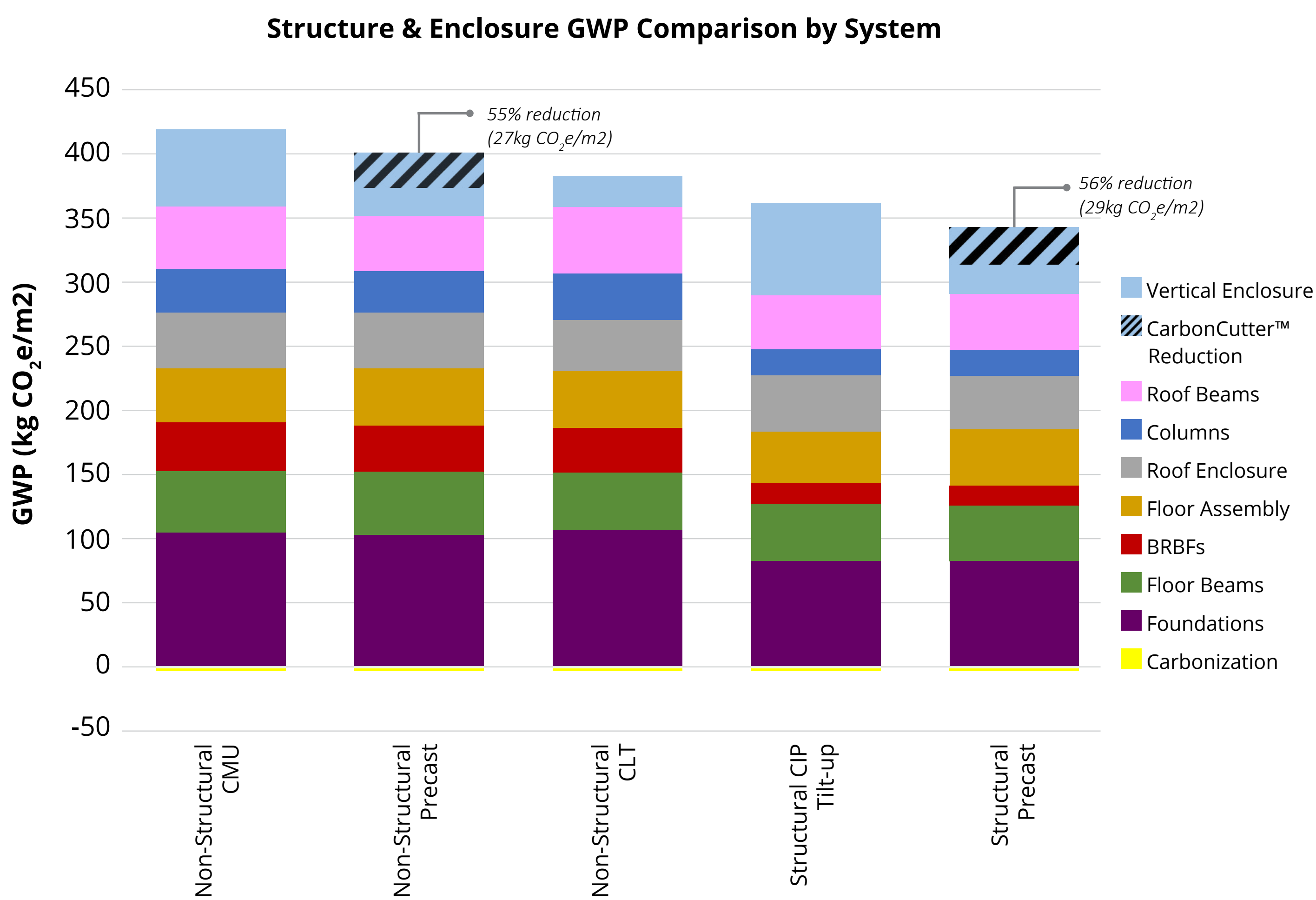

FIGURE 10: Structure and enclosure GWP comparison by system

STRUCTURE & ENCLOSURE GWP COMPARISON BY SYSTEM (kg CO_2e/m2)					
Category	**Non-Structural CMU**	**Non-Structural Precast**	**Non-Structural CLT**	**Structural CIP Tilt-up**	**Structural Precast**
Roof Beams	51	47	52	43	43
Columns	34	34	34	20	20
Roof Enclosure	43	42	43	42	42
Floor Assembly	43	43	43	43	43
BRBFs	37	37	34	16	16
Vertical Enclosure	60	49	25	71	52
Floor Beams	49	49	46	44	44
Foundations	104	104	105	82	82
Carbonization	(3)	(3)	(3)	(3)	(3)
Total	**418**	**402**	**379**	**358**	**339**

TABLE 10: Structure and enclosure GWP comparison by system

Other Impact Categories

Although GWP results are the primary focus of this study, results for the other impact categories are shown in Table 11. The structural precast design has significantly lower impacts in five of the six major categories—including global warming potential, acidification potential, tropospheric ozone formation, ozone depletion, and depletion of nonrenewable energy. Structural precast also achieves the lowest eutrophication impacts with the use of the CarbonCutter™ mix.

ALL IMPACT CATEGORIES						
Category	**Global Warming (kg CO2e)**	**Ozone Depletion (kg CFC11e)**	**Acidification (kg CO2e)**	**Eutrophication (kg Ne)**	**Tropospheric Ozone (kg O3e)**	**Nonrenewable Energy (MJ)**
Non-Structural CMU	11,047,533	3.18	48,783	6,910	574,675	111,607,814
Non-Structural Precast	10,757,936	2.85	46,265	7,337	559,709	109,463,847
Non-Structural Precast (CarbonCutter™)	10,024,945	2.72	43,905	6,198	533,526	103,575,349
Non-Structural CLT	10,074,790	2.75	50,734	6,452	621,245	108,493,125
Structural CIP Tilt-up	9,534,308	2.72	39,540	6,665	529,769	94,566,204
Structural Precast	9,093,229	2.71	39,253	6,606	492,871	94,699,147
Structural Precast (CarbonCutter™)	8,297,309	2.70	36,279	5,467	450,561	87,817,738

TABLE 11: Environmental impact category results for structure and enclosure

Supplemental Results

Next Step: Carbon Optimization by Design

As stated previously, each of these comparative designs were based off a real-world data center, but future designs can use lessons learned from this study to further optimize designs and achieve even greater embodied carbon reductions. Examples of design strategies are:

- Lowering parapet heights
  - Lowering parapet heights would inherently reduce material, but also could reduce panel thickness as deflection at the top of the precast assembly was a main driver in why the non-structural precast assemblies were designed with a 3-4-5 configuration rather than a thinner 3-4-4 or 3-4-3
- Reconfiguring wall tieback locations for erection (Precast/CIP Tilt-up Assemblies)
  - Depending on panel size, penetrations, and loading requirements, the erection tieback locations can be reconfigured to achieve thinner assemblies
- Use of CarbonCutter™ or similar low-carbon concrete mixes in all concrete applications
  - CarbonCutter™ mixes were limited to exterior wall applications in this study, but could be used in all concrete elements in future projects with additional coordination
- Grid/Floor-to-Floor optimization
  - Each system has span limits which affect its optimal design, which is why CLT needed additional framing and a horizontal configuration
  - Shorter spans are not conducive to open layouts required for data centers, so that should be considered during design discussions

Early-stage collaboration with design and material suppliers is important for design optimization and meaningful carbon reductions. Those early meetings should also include constructability and performance related conversations to reduce waste, project schedule, and cost.

Looking Ahead: Operational Carbon

This initial study focuses solely on embodied carbon reductions with efforts to maintain equivalent energy performance by designing exterior wall panels with similar R-values and roof assemblies meeting energy code minimum requirements. In future studies, that focus could shift to operational carbon in the building over time. Topics of interest in that study could be:

- Effects of high thermal mass to moderate temperature swings
- Long-term operational emissions and costs

Conclusion

The results of this study demonstrate that for a typical two-story data center in the Pacific Northwest or similar large-scale, high-mass buildings, the carbon impacts of a structural precast design are lower than those for functionally equivalent structural CIP tilt-up, non-structural CMU, CLT, or precast designs. Structural vs. non-structural wall assembly designs had the largest effects on the rest of the building, with structural assemblies saving material volume and carbon throughout by reducing foundations, perimeter framing, and lateral frames. The potential to disassemble and reuse the precast, tilt-wall, and CLT panels offers additional reductions in material waste and embodied carbon. While not a significant driver in overall reductions, carbonization of concrete does provide additional embodied carbon benefits to the concrete designs beyond material optimization. With further coordination design optimization strategies like the CarbonCutter™ mix and grid/floor-to-floor optimization can further reduce embodied carbon impacts and cost.

There are many drivers when making design decisions including occupant satisfaction, cost, performance, constructability, schedule, and sustainability. Early design coordination is a crucial factor to achieve the best outcomes for your building by all these metrics. Each material and product have unique benefits and challenges, so conducting comparative designs and incorporating life-cycle assessments provides more information on embodied carbon impacts, and those lessons learned can carry through to all other project drivers.

Appendix A: documentation of LCA data used in the study

The following data sets have been used as sources for this assessment. All data used complies with ISO 14040 and 14044 and is drawn from One Click LCA database and has been verified following the BRE-verified data qualification methodology by LCA data specialists.

Resource name	Country	Product	Density	Year	Environment Data Source	Standard	EPD number	EPD program	Manufacturer	Product Category Rules (PCR)	Notes about PCR	Technical specification	Upstream database	Verification
Acrylic-based membrane, fluid applied	[tennessee, illinois, USA]	Perm-A-Barrier® (PAB) VPL		2022	EPD PERM-A-BARRIER® (PAB) Air Barrier System	ISO 14040	EPD10786	NSF	GCP Applied Technologies	PCR ASTM International Water-Resistive and Air Barriers	Only with EN15804 (TRACI 2.1 units only)	0.64 mm, 1.54 kg/m2, 1400 kg/m3	GaBi	verified
Concrete masonry unit (CMU)	[texas, oregon, newYork, california, massachusetts, northCarolina, florida, illinois, georgiaUS, virginia, pennsylvania, nebraska, kentucky, indiana, tennessee, iowa, delaware, maryland, wisconsin, michigan, arizona, missouri, colorado, USA]	NW1	2002.31	2024	EPD for Concrete Masonry Units as Manufactured by Members of Concrete Masonry & Hardscapes Association (CMHA)	ISO 14040	EPD-766	ASTM	CMHA	Part B: Concrete Masonry and Segmental Concrete Paving Product EPD Requirements, March 2022. V1.1	Only with ISO21930	2000 psi, 2002.31 kg/m3	ecoinvent	verified
Fabricated hollow structural steel sections, North American industry average	[northAmerica]		7800	2022	EPD FABRICATED HOLLOW STRUCTURAL SECTIONS AMERICAN INSTITUTE OF STEEL CONSTRUCTION	ISO 14040	4789556099 .103.1	UL Environment	American Institute of Steel Construction (AISC) & Steel Tube Institute	PCR Part A: Calculation rules for the LCA and requirements project report (IBU/UL Environment, V3.2, 12.12.2018) and Part B: Designated Steel Construction Product EPD Requirements (UL Environment, V2.0, 08.26.2020)	Only with EN15804	7800 kg/m3	GaBi	verified
Glass-mat gypsum boards, fire and moisture resistant	[USA, canada]		854.71698	2021	EPD glass-mat gypsum boards	ISO 14040	EPD-206	ASTM	Gypsum Association (GA)	NSF International, PCR for Environmental Product Declarations, PCR for Gypsum Panel Products, April 2020	Only with EN15804 (TRACI 2.1 units only)	15.9 mm, 13.59 kg/m2, 855 kg/m3, Type X	ecoinvent	verified
Grouts for masonry applications	[ontario, quebec, canada]	King® CellFiller C-20		2023	EPD SIKA MASONRY MORTARS AND GROUTS	ISO 14040	0452-1789	CSA Group	Sika Canada	PCR 2019:14 Construction products (version 1.11)	Only with EN15804 (TRACI 2.1 units only)		ecoinvent	verified
Gypsum board with glass mat sheathing	[USA, canada]	DensDeck® Roof Board	780.3	2016	EPD Georgia-Pacific Gypsum EPD for 1/2 DensDeck® Roof Board	ISO 14040	EPD-044	ASTM	Georgia-Pacific Gypsum	ASTM PCR for Preparing an EPD for Glass Mat Gypsum Panels, August 2016	Only with EN15804 (TRACI 2.1 units only)	1/2in, 2.03 lb/ft2	ecoinvent, USLCI	verified
Hot-rolled structural steel sections, North American industry average, per m3	[USA]		7800	2021	EPD FABRICATED HOT-ROLLED STRUCTURAL SECTIONS AMERICAN INSTITUTE OF STEEL CONSTRUCTION	ISO 14040	4789556099 .102.1	UL Environment	American Institute of Steel Construction (AISC)	PCR Part B: Designated Steel Construction Product EPD Requirements (UL Environment, V2.0, 08.26.2020)	Only with EN15804	7800 kg/m3	GaBi	verified

Resource name	Country	Product	Density	Year	Environment Data Source	Standard	EPD number	EPD program	Manufacturer	Product Category Rules (PCR)	Notes about PCR	Technical specification	Upstream database	Verification
Liquid applied vapour permeable air barrier membrane	[quebec, canada]	SOPRASEAL LM 204 VP	1078	2023	EPD SOPRASEAL LM 204 VP Liquid Applied Air Barrier Membrane	ISO 14040	EPD-552	ASTM	SOPREMA	PCR for Water-Resistive and Air Barriers	Only with EN15804 (TRACI 2.1 units only)	40 mils, 1.08 kg/L (9.01 lb/gal)	ecoinvent	verified
Plate steel - fabricated, Carbon Leadership Forum benchmark	[northAmerica]			2021	2023 Carbon Leadership Forum North American Material Baselines	ISO 14040	4789556099.101.1	CLF	American Institute of Steel Construction (AISC)	PCR Part B: Designated Steel Construction Product EPD Requirements (UL Environment, V2.0, 08.26.2020).	Only with EN15804		GaBi	verified
Polyisocyanurate (PIR) roof insulation boards, glass fiber reinforced cellulosic faced (GRF)	[USA, canada]			2020	EPD Polyiso Roof Insulation Boards	ISO 14040	EPD10465	NSF	Atlas Roofing Corporation, Carlisle Construction Materials, Firestone Building Products, GAF, IKO, Johns Manville, Rmax - A Sika Brand, Soprema, Inc. (USA)	PCR Guidance for Building-Related Products and Services Part B: Building Thermal Insulation EPD Requirements (UL10010-1, Version 2.0).	Only with EN15804 (TRACI 2.1 units only)	0.846 kg/m2 (1.87 lb/m2), 25 mm (0.984 in)	ecoinvent	verified
Ready-mix concrete	[montana, idaho, washington, oregon, USA]		2400	2022	NRMCA Member National and Regional LCA Benchmark (Industry Average) Report – V 3.2, updated 2022	ISO 14040	-	NRMCA	Industry average ready-mix concrete for Pacific Northwest region USA NRMCA (2022)	-	Only with EN15804 (TRACI 2.1 units only)	4000 psi, 27.6 Mpa	ecoinvent	verified
Ready-mix concrete	[montana, idaho, washington, oregon, USA]		2400	2022	NRMCA Member National and Regional LCA Benchmark (Industry Average) Report – V 3.2, updated 2022	ISO 14040	-	NRMCA	Industry average ready-mix concrete for Pacific Northwest region USA NRMCA (2022)	-	Only with EN15804 (TRACI 2.1 units only)	5000 psi, 34.5 Mpa	ecoinvent	verified
Reinforcement steel (rebar)	[northAmerica]		7850	2022	EPD STEEL REINFORCEMENT BAR	ISO 14040	EPD-362	ASTM	CRSI	PCR Guidance for Building-Related Products and Services Part B: Designated Steel Construction Product EPD Requirements.	Only with EN15804 (TRACI 2.1 units only)	ASTM A615, ASTM A706, 7850 kg/m3	GaBi	verified
Steel roof and floor deck, North America average	[northAmerica]		7800	2022	Steel roof and floor deck, Steel Deck Institute 2022	ISO 14040	4789985146.101.1	UL Environment	Steel Deck Institute	PCR Designated Steel Construction Product EPD Requirements (UL Environment, V2.0, 08.26.2020)	Only with EN15804 (TRACI 2.1 units only)	38-76 mm	GaBi	verified
Steel stud reinforcing product	[virginia, USA]	Suncoast SRS®		2021	EPD Suncoast Post-Tension Suncoast Stud Reinforcing System®	ISO 14040	SCS-EPD-06742	SCS Global	Suncoast Post-Tension	PCR Guidance for Building-Related Products and Services, Part B: Designated Steel Construction Product EPD Requirements. v.2.0. 2020.	Only with EN15804		ecoinvent	verified
Structural and nonstructural framing components composed from hot-dipped galvanized cold-formed steel, USA industry average	[USA]		7769	2021	EPD Cold-Formed Steel Framing	ISO 14040	SCS-EPD-07103	SCS Global	SFIA	PCR Designated Steel Construction Product EPD Requirements. UL Environment. August 2020	Only with EN15804	7769 - 7849 kg/m3	ecoinvent	verified

Resource name	Country	Product	Density	Year	Environment Data Source	Standard	EPD number	EPD program	Manufacturer	Product Category Rules (PCR)	Notes about PCR	Technical specification	Upstream database	Verification
Insulated precast concrete products, PCI West Region	[USA]			2025	EPD for Insulated Precast Concrete	ISO 14040	EPD-963	ASTM	Precast/Prestressed Concrete Institute (PCI)	NSF/ASTM International, PCR for Precast Concrete, Version 3.0, May 2021	Only with ISO 21930		ecoinvent	verified
Thermoplastic polyolefin (TPO) single-ply roofing membrane	[USA]			2023	EPD TPO SINGLE PLY ROOFING MEMBRANE SINGLE PLY ROOFING INDUSTRY (SPRI)	ISO 14040	EPD-446	ASTM	Single Ply Roofing Industry	PCR for Single Ply Roofing Membrane	Only with EN15804 (TRACI 2.1 units only)	60 mil, 1.48 kg/m2	GaBi	verified
Concrete masonry unit (CMU), normal weight	[canada]		2186.12	2022	EPD NORMAL WEIGHT AND LIGHTWEIGHT CONCRETE BLOCK MASONRY UNITS AS MANUFACTURED BY MEMBERS OF THE CANADIAN CONCRETE MASONRY PRODUCERS ASSOCIATION (CCMPA)	ISO 14040	EPD-338	ASTM	CCMPA, West Region	UL PCR Part B: Concrete Masonry and Segmental Concrete Paving Product EPD Requirements ULE 10010-29 v.1.0	Only with EN15804 (TRACI 2.1 units only)	15 Mpa, GU cement, 2186.12 kg/m3	ecoinvent	verified
EPS insulation, North American average	[USA, canada]			2023	EPD Expanded Polystyrene Insulation MOLDED, CLOSED-CELL FOAM PLASTIC INSULATION	ISO 14040, EN15804+A1	4790678084.101.1	UL Environment	EPS Industry Alliance	UL PCR: Building Envelope Thermal Insulation EPD Requirements (UL, v2.0, 2018)	Only with EN15804 (TRACI 2.1 units only)	L=0.0401 W/mK, Rsi=1 m2K/W, 40.1 mm (1.58 in), 0.578 kg/m2	ecoinvent	verified
Pre-stressed steel tendons, coated and extruded with HDPE plastic	[virginia, USA]			2021	EPD Post-Tensioning System	ISO 14040	SCS-EPD-06741	SCS Global	Suncoast Post-Tension	PCR Guidance for Building-Related Products and Services, Part B: Designated Steel Construction Product EPD Requirements. v.2.0. 2020.	Only with EN15804		ecoinvent	verified
Ready-mix concrete	[washington, USA]	Mix 506-S45	2400	2024	EPD for Mix 506-S45	ISO 14040	d40dd301-0b67-4ebb-aa9e-e42a521acd02,1	NRMCA	Knife River Corporation, Prestress – Spokane Valley (Washington) Plant	ISO 21930:2017. Sustainability in buildings and civil engineering works	Only with ISO 21930	5500 psi; Curing time 28d; Cement type: Manufacturer/Plant specific	ecoinvent	verified
Fibre reinforced concrete panels, white cement base with pozzolanic micro-aggregate	[pennsylvania, USA]	W15	2195	2021	EPD Architectural Ultra High Performance Concrete	ISO 14040	EPD248	ASTM	TAKTL® LLC	ISO 21930 (2017)	Only with EN15804 (TRACI 2.1 units only)	15.9 mm (5/8 in), 2195 kg/m3 (137 lb/ft3)	ecoinvent	verified
Glued laminated timber (GLT)	[USA, canada]		548	2020	EPD North American Glued Laminated Timber	ISO 14040	4788424634.104.1	UL Environment	American Wood Council, Canadian Wood Council	UL Environment: Product Category Rules for Building-Related Products and Services Part A: Calculation Rules for the Life Cycle Assessment and Requirements on the Project Report, v3.2 Part B: Structural and Architectural Wood Products EPD Requirements, v1.0	Only with EN15804 (TRACI 2.1 units only)	50 mm, 548 kg/m3, 14% moisture content	ecoinvent	verified
Stone wool insulation board and batt	[mississippi, westVirginia, USA, ontario, britishColumbia, canada]	Comfortbatt R13		2025	EPD ROCKWOOL STONE WOOL INSULATION, ver 2025	ISO 14040	4790711618.101.2	UL Environment	Rockwool North America	PCR Part B: Mineral insulating materials, 12.2018	Only with EN15804	RSI= 1 m2K/W, 89 mm, 1.2 kg/m2	GaBi	verified