

Life Cycle Assessment Report – Lodestar Structures- Precast Modules & Wall Panels

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Executive Summary

Lodestar Structures Inc. is committed to understanding the environmental impacts of its operations and products and has committed to emissions reductions that align with long-term Science-Based Targets (SBTs) aimed at reducing climate change. Lodestar Structures are modular precast concrete building frames that incorporate new low-carbon designs. Recently, Lodestar Structures changed the mix design for the modules to a lower impact concrete mix (Mix#132), and also replaced traditional steel rebar with lower-carbon glass fibre rebar in the Lodestar wall panels.

This report evaluates the environmental impacts, specifically the Global Warming Potential (GWP), associated with the production of the Lodestar modules and wall panels. It provides a detailed life cycle impact assessment (LCIA) of Lodestar Structures using a cradle-to-gate approach. The functional unit used to assess the GWP of operations was one cubic meter (m³) of concrete mix per year. Based on the results of this report, the following summaries can be made:

Summary of Results

1. The GWP of the new concrete mix (Mix#132), results in approximately 9.5% fewer emissions than the baseline concrete mix. The GWP impact for the baseline mixes was 361 kg CO₂eq/m³, while Mix 132 reduced it to 339 kg CO₂eq/m³. This reduction signifies a significant step towards achieving Lodestar Structures' emissions reduction targets aligned with SBTs.
2. Integrating glass fiber rebar in Lodestar wall panels showed notable GWP reductions. Steel rebar's GWP contribution for above- and below-ground panels was 28-44%. In contrast, glass fibre rebar, while using less mass than steel, had comparable GWP impacts on a per unit mass basis. This underscores the complexity of substituting steel and highlights potential post-construction benefits of materials like GFRP.
3. The shift to Mix#132 has shown GWP reductions. On average, replacing the Baseline Mix with Mix#132 resulted in a GWP reduction of 3.5-4.5% for the Lodestar modules and approximately 5-6% for the above- and below-ground wall panels. These reductions exceed the required annual reduction rate for 2023 and place Anchor approximately a year and a half ahead in their trajectory to meet Science-Based Targets (SBTs). Current indications show that the reductions are on pace for the desired trajectory, but continuous efforts and innovations will be pivotal for Lodestar to maintain and surpass their sustainability benchmarks.

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1. Introduction

Concrete is a widely used construction material known for its strength, durability, and versatility. However, it is essential to recognize that its production has significant environmental consequences, particularly in terms of greenhouse gas emissions, water use, and waste generation. The cement and concrete industry, as the third-largest industrial energy consumer and the second-largest industrial CO₂ emitter, has a significant role to play in climate action. The sector represents about 7% of current global CO₂ emissions [IEA 2018, IEA 2020], but cement demand is projected to increase significantly, meaning decarbonization efforts are essential to curbing emissions growth.

As a response to this environmental concern, research has been increasing to understand how the impacts of concrete products can be reduced. There are two areas of information needed to understand this. The pathway involves quantifying what the baseline or existing impacts of concrete products are, and then determining how those impacts can be reduced to meet short- and long-term reduction targets. To address this complexity, many companies have begun utilizing life cycle assessment (LCA) as a means of understanding what the baseline impacts of products or processes are. LCA can offer a tailored approach to measuring environmental impacts across a range of different products, processes, and impact categories. This comprehensive approach also allows for a better understanding of potential hot spots where environmental improvements can be made over time.

In order to determine the rate at which the baseline LCA impacts need to be reduced to reach short- and long-term targets, target goals need to be set. One of the most reliable ways is to adopt a science-based target (SBT) approach. Science-based targets (SBTs) play a pivotal role in guiding businesses and companies towards urgent climate action, aligning their GHG emissions reduction goals with the objectives of the Paris Agreement. The Paris Agreement aims to limit global warming to well-below 2°C above pre-industrial levels and pursue efforts to further limit warming to 1.5°C. This necessitates halving baseline GHG emissions by 2030 and achieving net-zero emissions by 2050. Setting SBTs empowers companies to take a clear path towards decarbonization and contributes to building a resilient, zero-emissions economy. SBTs provide resources for companies in the cement sector to set near- and long-term climate targets aligned with a 1.5°C scenario. These targets are instrumental in addressing the tension between rapid decarbonization and industry growth, allowing for the adoption of science-based emissions reduction strategies. By adopting SBTs, businesses across the cement and concrete industry can demonstrate that their plans align with the latest climate science. It guides companies in modeling GHG reduction targets that align with the sector-specific pathway of an underlying climate scenario and sets the pace for the rate of decarbonization needed to achieve Paris-aligned goals.

1.1. Precast Concrete Supply Chain Impacts

It is important to note that not all concrete products are manufactured the same way, leading to variations in the environmental footprint of concrete structures based on the materials and production processes used. One notable alternative is precast concrete, which offers advantages such as precision, quality control, and sustainability through reduced waste and recyclability potential [Hooten et al., 2002]. Studies comparing precast concrete with cast-in-place concrete have demonstrated superior environmental performance in precast options [Ramsey et al., 2014]. However, it is important to recognize that environmental impacts can differ due to various factors and regional variations.

Industry-wide surveys and impact analyses provide an average benchmark but may not capture the nuances of companies actively working to minimize their environmental impact through innovation. Additionally, they are limited in their ability to demonstrate which companies have plans for the GHG emissions of their products to be reduced over time, and how they might align with SBTs. In the following sections, a review of the specific stages of precast concrete supply chains where significant environmental impacts may occur is summarized and are important to quantify. A review of the largest and most common areas where impacts may originate provides the basis for which system processes can be identified that need to be accounted for in precast concrete supply chains.

1.1.1. Raw material Extraction and Processing

The impacts of raw material extraction and processing can be measured by quantifying the energy consumption, carbon emissions, and other environmental burdens associated with these activities. For cement production, the carbon footprint can be assessed by calculating the CO₂ emissions resulting from the chemical conversion of limestone into clinker, which requires high-temperature processes often fueled by fossil fuels. Similarly, the environmental impacts of aggregate and sand extraction can be measured by assessing the energy consumption and emissions associated with these activities, as well as the potential ecological consequences such as habitat destruction and water contamination. These impacts need to be included in the LCA because both cement production and raw material extraction require substantial energy inputs and can result in significant greenhouse gas emissions.

1.1.2. Manufacturing Process

In an LCA, the environmental impacts of the precast concrete manufacturing process can be measured by assessing the energy consumption and emissions associated with operating machinery, curing, and other production activities. The water usage during the manufacturing process can also be quantified to understand its environmental implications. The impacts of the manufacturing process are likely to have measurable impacts since energy-intensive operations contribute to GHG emissions. Water usage generally has a significant effect on GHG emissions where pumping or purification processes require energy from fossil fuels, and can be exacerbated in areas with water issues due to larger pumping distances or retrieval processes.

1.1.3. Waste Generation and Management

When considering the impacts of waste generation and management, they can be measured by quantifying the amount of waste generated and its environmental consequences. For wastes that degrade into CO₂ or CH₄, these can contribute to GHG emissions. The energy and resources required for waste disposal and recycling processes can also be assessed. The impacts of waste generation and management can vary depending on the efficiency of waste reduction and recycling practices implemented by the precast concrete manufacturer. For mining and concrete operations, there are not often many wastes associated with decomposition downstream resulting in additional GHG emissions. However, use of substances that have toxicity or hazardous materials concerns, can result in increased environmental impacts in areas such as ecotoxicity, human carcinogens, or other non-GHG impact categories.

1.1.4. Chemical Changes in Concrete

In the context of concrete product life cycles, the impacts of chemical changes in hardened concrete can be measured by assessing the potential degradation of the material and its consequences over time. For example, evaluating the carbonation process helps understand its influence on the durability of concrete and potential impacts on embedded steel. Similarly, quantifying the potential for sulfate attack and alkali-aggregate reactions allows for an assessment of their implications on the structural integrity and longevity of precast concrete elements. Generally, these types of changes occur after the installation or curing process of concrete, spanning longer periods than those associated with the upstream production of the concrete products. As a result, most LCAs that consider concrete products at cradle-to-gate scopes exclude these impacts. However, when the scope is expanded, such as in a cradle-to-grave LCA, it becomes essential to understand the long-term impacts that material choices have in the cradle-to-gate scope as part of the design process.

1.2. Objectives

Lodestar Structures is dedicated to aligning its environmental initiatives with Science-Based Targets (SBTs). As part of its ongoing effort to reduce the environmental footprint of its operations and products, the company has enhanced its Lodestar module by introducing a more sustainable concrete mix. Lodestar Structures has also transitioned to glass fibre rebar in lieu of traditional steel rebar in the Lodestar wall panels.

The primary objective of this report is to conduct a comprehensive Life Cycle Analysis (LCA) of four Lodestar modules and two versions of above-grade and below-grade wall panels. The LCA will be a comparative LCA looking at the baseline impacts of each module and wall panel and how those impacts change when the modules use the lower-carbon Mix#132, and when the wall panels replace steel rebar with glass fiber rebar. In the context of SBTs, this LCA also aims to quantify a GHG emissions baseline and the extent to which these new improvements in the concrete mix and rebar align with the emissions reductions required to meet SBTs.

The LCA will analyze the embodied impacts at each stage of the life cycle to identify hotspots and opportunities for greater sustainability in Lodestar products. The report aims to provide Lodestar Structures with actionable insights to continue driving down its environmental footprint and contribute positively to global climate goals. By conducting this assessment, Lodestar Structures can better understand the extent to which its efforts to improve the concrete mix and rebar align with science-based targets for emissions reduction. The findings of this LCA will serve as a foundation for informed decision-making, policy development, and the pursuit of innovative changes to the way Lodestar products are manufactured.

2. Methods

Following the framework established by the ISO 14040 and ISO 14044, the methodology of this LCA study for Lodestar modules and Lodestar wall panels manufactured by Anchor Concrete can be broken down into four main phases: Goal and Scope definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. Each of these phases is explained in detail below.

2.1. Goal & Scope

This LCA aims to conduct an in-depth, accurate, and comprehensive evaluation of the environmental impacts throughout the entire life cycle of Lodestar modules and accompanying precast concrete wall panels. The primary objective is to assist Lodestar Structures and its stakeholders in gaining insights into the environmental footprint of their products, based on different material inputs. This knowledge will inform decision-making on potential enhancements in environmental performance and aid in the understanding of the product's life cycle impacts.

The scope of this LCA follows a cradle-to-gate approach, which includes stages from raw material extraction up until when the product departs from the factory. The system boundaries capture all significant aspects of Lodestar modules and precast concrete wall panel production and are depicted as a systems flow diagram in Figure 1. All key process data are included, in compliance with ISO 14044:2006 and all flows known to contribute a significant impact are included. The cut-off rules are not applied to hazardous and toxic materials – all are included in the life cycle inventory. Regarding allocation, this LCA recognizes fly ash, silica fume, and slag as recovered materials, and thus the environmental impacts allocated to these materials are limited to the treatment and transportation required to use them as concrete material inputs. The processes included within the system boundaries are:

- **Raw Material Extraction and Processing** – Includes extraction and processing of raw materials for the production of materials used in the concrete mix and the rebar used for structural reinforcement (both steel and glass fibre rebar). This stage encompasses the extraction and processing of all raw materials used in the production of the Lodestar modules, including cement, aggregate, reinforcement materials, and admixtures.
- **Transport** – Transportation of raw materials to the production site. This stage covers the transportation of raw materials to the manufacturing plant in Kingston, Ontario.

- Lodestar Manufacturing** – On-site production, including the consumption of electricity and natural gas. This stage involves all processes necessary for the production of the Lodestar products at the facility, including energy usage, emissions, and waste generation.

The assessment includes the evaluation of four different sized Lodestar modules (15'x15', 15'x30', 12'x12', 12'x24'), comparing the impact differences between an average baseline mix consisting of Anchor's Mix#170 and #171, and a newer Mix#132. Another comparison between above-grade wall panels and below-grade wall panels was made for each using the baseline mix and Mix#132, as well as comparing steel rebar with glass fiber rebar. Specific rebar and concrete ratios of each component are listed in the inventory section of the methods.

The functional unit for this study is defined as 1 m³ of precast Lodestar modules. This functional unit was chosen as it best represents the function of the product and facilitates comparisons with similar products or alternative designs. This study assumes that the quality and performance of the concrete, including mechanical properties, workability, and durability-related properties, remain constant across all mixtures and types of rebar. This uniformity ensures that environmental impacts can be compared accurately without performance-based discrepancies. To align with industry standards and facilitate comparison with other products, results are also provided as total impacts per Lodestar unit, and per tonne of precast concrete.

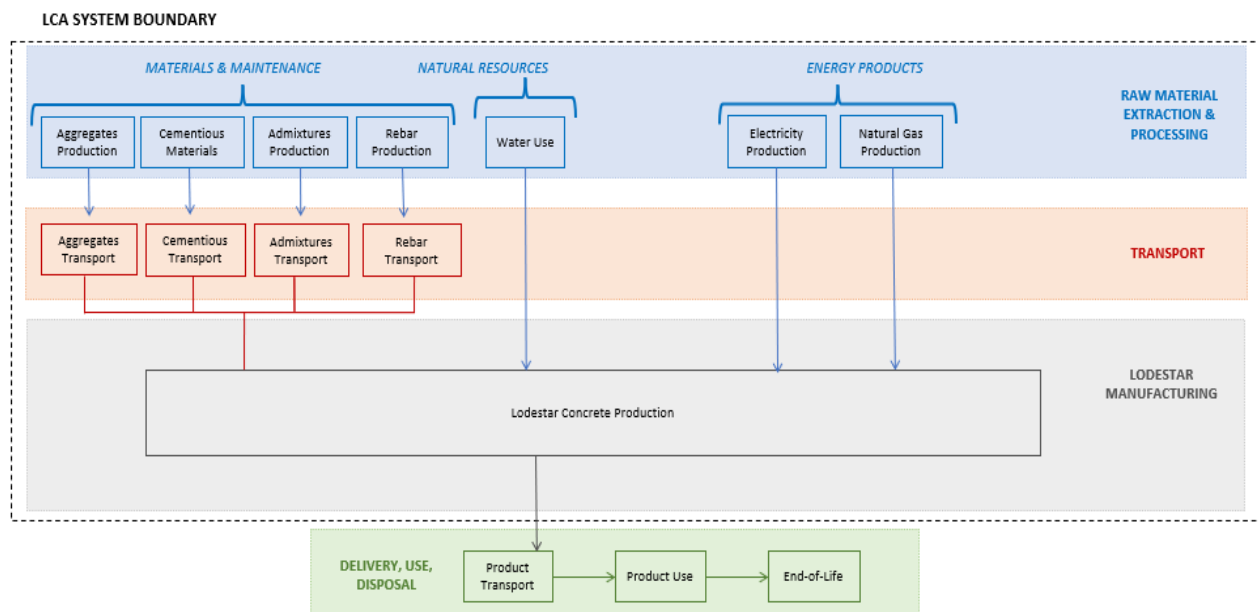


Figure 1. System boundary of processes, materials, and energy considered as part of the footprint assessment. Boundary includes all processes in the dashed line such as upstream production (aggregates, cementitious materials, rebar, etc.), product transport (where appropriate), and concrete operations. Downstream transport & use are outside the system boundary and not considered as part of this current assessment.

2.1.1. Data Quality & Variability

The calculated data in this report is linked to the actual compositions of precast concrete produced by Anchor Concrete, and the manufacturer-specific data is averaged over the past 12 months. The datasets utilized are comprehensive, as per the system boundary, in line with the criteria for the exclusion of inputs and outputs as set out in ISO 14040/44 methods. To estimate the life cycle of the declared precast concrete products, a mixture of primary data from Anchor Concrete and secondary data from databases were used. The quality of the data is considered high to medium, ensuring robustness in the analysis. A complete data quality assessment review is listed in Appendix 1.

2.2. Life Cycle Inventory Analysis (LCI)

In the LCI phase, data is gathered for every process within the system boundaries. This includes material and energy inputs and outputs, emissions to air, water, and soil, waste generation, and other related parameters. Primary data collection came directly from Anchor Concrete, including raw material consumption, energy use, production-related emissions, and waste production. For the transportation stage, distance traveled and mass of raw materials transported from various sources to the Anchor Concrete facility is documented as well. Given the upstream processes' complexity, the extraction and processing of raw materials will rely on secondary data from databases, EPDs, and relevant literature, including transportation emissions. These processes include cement production, sand and gravel extraction for aggregate, the production process for rebar, admixture production, energy consumption, and transportation pathways. The inventory data for each process and pathway is summarized below:

2.2.1. Aggregate Inventory Data

Impact data from aggregate production is available from two general sources: EPDs directly from suppliers for specific products, or large aggregated databases at regional, national, or international scales. The primary international source used in many international EPDs is EcoInvent which has a focus on European data. EPDs available in North America are predominantly from the West Coast, largely due to environmental regulations adopted by the state of California. Another source primarily for North American construction data, is the Athena Building materials database that has aggregated regional data for Canada. There are no specific EPDs for local quarries here in Ontario that were found; the average emission factors for coarse and fine aggregates were used from the Athena inventory database. The Athena Sustainable Materials Institute, based in Ontario, Canada, created the Athena Impact Estimator for Buildings that was developed to support decision-making for buildings at the conceptual

design stage. It provides cradle-to-grave LCA results for a building and its associated assemblies. It can generate a bill of materials based on inputs, and material can be adjusted to match known material quantities or other real-world datasets. For this study, Athena was used for aggregates and the calculated emissions for the use of 1 tonne of aggregates is shown in Table 1.

Table 1. Emissions associated with the production of 1 tonne of aggregates (Source: Athena).

Impact Category	Coarse Aggregate	Fine Aggregate (natural)
Global Warming Potential (kg CO ₂ eq)	1.66E+00	1.40E+00
Acidification Potential (kg SO ₂ eq)	4.00E-03	3.00E-03
HH Particulate (kg PM _{2.5} eq)	3.64E-04	2.07E-04
Eutrophication Potential (kg N eq)	7.14E-04	3.01E-04
Ozone Depletion Potential (kg CFC-11 eq)	7.78E-09	3.15E-09
Smog Potential (kg O ₃ eq)	5.20E-02	4.20E-02
Non-Renewable Energy (MJ)	2.07E+01	1.85+01

2.2.2. Cement Products Inventory Data

There are several different sources for the impacts of cementitious products, but they differ in the scale of their analysis and the products they report for. There are several national and regional groups that have produced EPDs that are industry averages of all their members within that region and generally are able to reflect the impacts of specific GUL and HE cement product used. Additionally, they also specify the ASTM or CSA standards to which the concretes adhere to make comparisons between products easier.

Due to the growing interest in finding more environmentally friendly buildings, cement facilities are increasingly creating their own EPD data in addition to the industry averaged EPDs. These create much more specific and reliable data for locally produced cement. For this LCA report, cement data from the Lafarge EPD (Lafarge, 2021) was used and for emissions from slag the impacts were acquired from the ASTM Industry Average Slag Cement EPD for the U.S. and Canada (Slag Cement Association, 2021). The cement emissions are listed on a per tonne basis and are listed in Table 2.

Table 2. Emissions associated with the production of 1 tonne of cement products. Cement products are from the Lafarge EPD (2021) and the Slag Cement Association EPD (2021).

Impact Category	General Use (GU- Type 1/II)		
	High Early (HE- TIII) - (CSA A3001, ASTM C150, AASHTO M85)	(CSA A3001, ASTM C150, AASHTO M85)	Slag Cement
Global Warming Potential (kg CO ₂ eq)	8.42E+02	8.43E+02	1.47E+02
Acidification Potential (kg SO ₂ eq)	4.00E-01	4.00E-01	2.10E+00
Eutrophication Potential (kg N eq)	1.40E-01	1.40E-01	2.70E-01
Ozone Depletion Potential (kg CFC-11 eq)	3.10E-05	3.10E-05	1.70E-05
Smog Potential (kg O ₃ eq)	4.60E+00	4.60E+00	2.63E+01
Non-Renewable Energy (MJ)	2.86+03	2.86+03	2.43E+03
Freshwater Consumption (m ³)	1.12E+00	1.12E+00	N/A

2.2.3. Admix Inventory Data

One of the earliest and most cited works on the LCA of Portland Limestone Cement by Marceau et al (2007) initially excluded admixes from their LCA. Their rationale was rooted in the small quantities of admixtures used and their limited influence on the total energy and emissions profile of the cement. Moreover, the lack of reliable and specific data on admixtures at that time led to their exclusion. However, with advancements in environmental impact assessments and their increasing importance, particularly in the concrete sector, there is now a more concerted effort to account for all concrete inputs. This approach enables a more transparent discussion about impacts and their relevance. Although admixtures may not significantly influence the carbon and energy balance due to their small quantities, they might affect other environmental impact categories disproportionately, and therefore, are now included in this LCA report.

Most current concrete LCAs use chemical admixture data from either the EcoInvent database, which aggregates regional data from admixture production, or the industry-average EPD published by the European Union on concrete additives, updated in 2021. Sika, which recently acquired parts of Master Builders Solutions, has also published data for their admixtures. Although not the exact brand used by Anchor, these admixtures comply with the same ASTM standards, providing a reasonable estimate given the low overall impact of admixtures on the environmental footprint of concrete. The GWP values from the Sika EPD are summarized in Table 3, and based on Sika's supply in Canada, they meet geographical criteria and are used as baseline emission factors for admixtures in this report.

Table 3. Emissions associated with the production of 1 kg of admixtures from Sika EPDs.

Product	GWP (kg CO ₂ eq)	Source
Air Entrainers (Sika Air-260)	0.54	Sika Concrete Admixtures and Cement Additives – Product Specific Type III EPD (2022)
High Range Water Reducers (Sika® ViscoCrete®-1000)	1.02	
High Range Water Reducers (Sika® ViscoCrete®-2100)	1.36	
High Range Water Reducers (Sika® ViscoCrete®-2110)	1.35	
Type S Specialty (Sika® Control-75)	1.76	
Type C and E Set Accelerators (SikaSet® NC)	2.47	
Type C and E Set Accelerators (SikaSet® RHE)	3.24	

2.2.4. Structural Inventory Data

Lodestar Structures directly reported the total rebar used per unit of concrete. The Athena inventory for steel rebar suggests an industry average of approximately 0.9 t of CO₂e per tonne of steel rebar. For the glass fiber rebar, the manufacturer provided emission factors, based on a functional unit of 1 kg of glass fiber rebar. The environmental impacts, based on the company reported values along with emissions from Athena are also included in Table 4.

Table 4. Total emissions associated with the production of 1 tonne of steel rebar, or 1 kg of glass fiber rebar.

Source	Global Warming Potential (kg CO ₂ eq)	Acidification Potential (kg SO ₂ eq)	Eutrophication Potential (kg N eq)	Smog Potential (kg O ₃ eq)
Athena (steel rebar) (per tonne)	9.00E+02	4.02E+00	1.00E-01	4.08E+01
Glass Fibre Rebar (per kg)	2.99E+00	2.25E-02	6.64E-03	3.64E-02

For the acetal plastic used in the structural plastic inserts, a production-focused LCA of plastic products by Mannheim (2021) was used, which evaluated impacts to produce 1 kg of plastic, and these impacts are displayed in Table 5.

Table 5. Emissions associated with the production of 1 kg of plastic.

Source	Global Warming Potential (kg CO ₂ eq)	Acidification Potential (kg SO ₂ eq)	Eutrophication Potential (kg N eq)	Smog Potential (kg O ₃ eq)
Mannheim (2021)	1.08E-10	3.08E-11	4.85E-12	5.47E-11

2.2.5. Transportation Inventory Data

The Canadian government has recently (2023) released a fuel LCA model based in the software OpenLCA, that can calculate emissions from a number of different transport fuel options and is linked exclusively to Canadian data. While it is limited to impacts associated with GWP, it includes emissions impacts for the increasingly important sulfur hexafluoride (SF₆) and CO₂ emissions from land-use change in addition to the more commonly reported contributions to GWP from CO₂, nitrous oxide (N₂O), methane (CH₄). This product system flow makes it a robust and up-to-date GWP emissions source for transportation. Based on generic truck transportation in Canada, the average GWP from the OpenLCA model is 90.8 g CO₂e/t*km.

2.2.6. Energy Inventory Data

GHG emissions (tCO₂e) for electricity and natural gas use were calculated using emission factors for the year 2022, taken from the National Inventory Reports (ECCC 2023). An electricity emission factor of 30 g CO₂e/kWh was used, along with a natural gas emission factor of 1921 g CO₂e/m³.

2.2.7. Site-Specific Inventory Data

Whenever possible, site-specific data from actual operations were used to ensure accuracy. Anchor provided all the on-site material inputs, energy use, and distance materials travelled to produce the concrete materials. The total amount of electricity and natural gas from Anchor Concrete operations were supplied and averaged across all concrete poured in the same year. The densities of concrete were applied to the mass of concrete poured in order to establish electricity and natural gas usage factors based on the functional unit (m³). Lodestar Structures provided the dimensions and specifications of each wall panel assessed, along with densities, and concrete and rebar ratios. Panels designated with "FRP" in all tables and figures used in this report refer to the glass fiber rebar.

3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase assesses potential environmental impacts linked to inputs and outputs identified during the Life Cycle Inventory (LCI) stage. This study evaluates several impact categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Smog Potential (SP), and Non-Renewable Energy (NRE) use.

3.1. Impacts of Concrete Mixes

Table 6 displays the environmental impacts associated with the upstream production and transportation of materials used in the concrete production stage. GWP emerges as the impact category with the most significant effects. Both Mix#170 and Mix#171 showed similar total emissions and the average of both concrete mixes was calculated in the table. This average was used as the Baseline Mix for the Lodestar Module LCA.

When Mix#132 is compared with the Baseline Mix, it produces 9.5% less emissions over the entire cradle-to-gate system boundary. A review of the upstream impacts of materials used in concrete production reveals cement production and natural gas as the major emissions sources followed closely by slag cement (Table 7). Transportation impacts were not included in the data compared in Table 6 due to the marginal difference (0.40 kg/m³) in transportation impacts observed between Mix#132 and the Baseline Mix.

Table 6. Environmental impacts of the upstream materials and transportation associated with each mix design material inputs.

Concrete Mix	Stage	GWP (kg CO ₂ eq/m ³)	AP (kg SO ₂ eq/m ³)	EP (kg N eq/m ³)	ODP (kg CFC-11 eq/m ³)	SP (kg O ₃ eq/m ³)
Mix 170	Materials	351.36	0.56	0.14	0.59	8.60
	Transportation	11.95	--	--	--	--
	TOTAL	363.31	0.56	0.14	0.59	8.60
Mix 171	Materials	348.08	0.53	0.12	0.15	8.70
	Transportation	11.83	--	--	--	--
	TOTAL	359.91	0.53	0.12	0.15	8.70
Average (Baseline Mix)	Materials	349.72	0.54	0.13	0.37	8.65
	Transportation	11.89	--	--	--	--
	TOTAL	358.65	0.54	0.13	0.37	8.65
Mix 132	Materials	328.57	0.40	0.11	0.43	5.98
	Transportation	10.44	--	--	--	--
	TOTAL	339.01	0.40	0.11	0.43	5.98

Table 7. The GWP of the upstream impacts of each material input for the three concrete mixes. The percent contribution that each material input has for each mix is listed next to each input. Transportation impacts are not included in these contributions.

Mix Material Input	GWP (kg CO ₂ eq/m ³)					
	Mix 132	% Contribution	Mix 171	% Contribution	Mix 170	% Contribution
Coarse Aggregate	1.39	0.420%	1.21	0.350%	1.21	0.340%
Fine Aggregate (natural)	1.24	0.380%	1.20	0.340%	1.21	0.350%
HE-TIII Cement	271	82.5%	143	41.1%	282	80.3%
Slag Cement	15.9	4.83%	26.5	7.60%	26.5	7.53%
GU Cement	0.00	0.00%	143	41.1%	0.00	0.00%
Air Entrainers	0.04	0.01%	0.06	0.02%	0.06	0.02%
High Range Water Reducers	5.47	1.67%	4.49	1.29%	3.76	1.07%
Type S Specialty	2.00	0.61%	2.01	0.58%	2.04	0.58%
Type C and E Set Accelerators	5.19	1.58%	0.00	0.00%	8.30	2.36%
Natural Gas	24.9	7.57%	24.9	7.15%	24.9	7.08%
Electricity	1.34	0.41%	1.34	0.39%	1.34	0.38%
TOTAL	328		348		351	

3.2. Impacts of Different Lodestar Modules

When each of the four Lodestar modules are compared using either the Baseline Mix or the Mix#132, the total impacts for each category were calculated and are displayed in Table 8. The results are presented based on the functional unit of 1 m³, but also as impacts per unit, and impacts per tonne. The percent reduction for each module when replacing concrete with Mix#132 is calculated. On average, replacing the Baseline Mix with Mix#132 alone reduced the overall GWP of each Lodestar Module by 3.5-4.5%.

Table 8. The GWP of each Lodestar module based on different concrete mixes. The GWP is listed based on the total per unit, per tonne, and per m³. The percent reduction for each module when replacing concrete with Mix#132 is calculated.

Lodestar Module	Concrete mix	GWP (kg CO ₂ eq/unit)	GWP (kg CO ₂ eq/tonne)	GWP (kg CO ₂ eq/m ³)	% Reduction
15x15	Baseline Mix	3834	233	537	
	Mix 132	3672	223	515	4.21%
15x30	Baseline Mix	5776	218	504	
	Mix 132	5516	209	481	4.49%
12x12	Baseline Mix	2566	274	632	
	Mix 132	2474	264	610	3.57%
12x24	Baseline Mix	3725	249	575	
	Mix 132	3579	240	552	3.93%

The relative contribution of concrete and steel rebar to the overall impacts per wall panel unit, depending on concrete mix used, are shown in Table 9. For each product composed of concrete and steel rebar, the contribution from concrete amounted to 56-72% of GWP impacts, while steel rebar contributed 28-44% of GWP impacts. A full breakdown of the total contribution of each major material or process input for each Lodestar module is displayed in Figure 2. In nearly every instance, the cement contribution exceeds the total impacts of rebar, except for the 12x12 module due to the additional ratios of rebar used.

Table 9. The GWP of the concrete and steel impacts for each four Lodestar modules and different concrete mix. The percent contribution that each material input has for each product is listed next to the GWP contribution for each component.

Unit Size	Unit size	Concrete (kg CO ₂ eq)	% Contribution	Steel (kg CO ₂ eq)	% Contribution
15x15	Baseline Mix	2581	68%	1218	32%
	Mix 132	2420	67%	1218	33%
15x30	Baseline Mix	4148	72%	1583	28%
	Mix 132	3888	71%	1583	29%
12x12	Baseline Mix	1468	58%	1068	42%
	Mix 132	1376	56%	1068	44%
12x24	Baseline Mix	2343	64%	1344	36%
	Mix 132	2196	62%	1344	38%

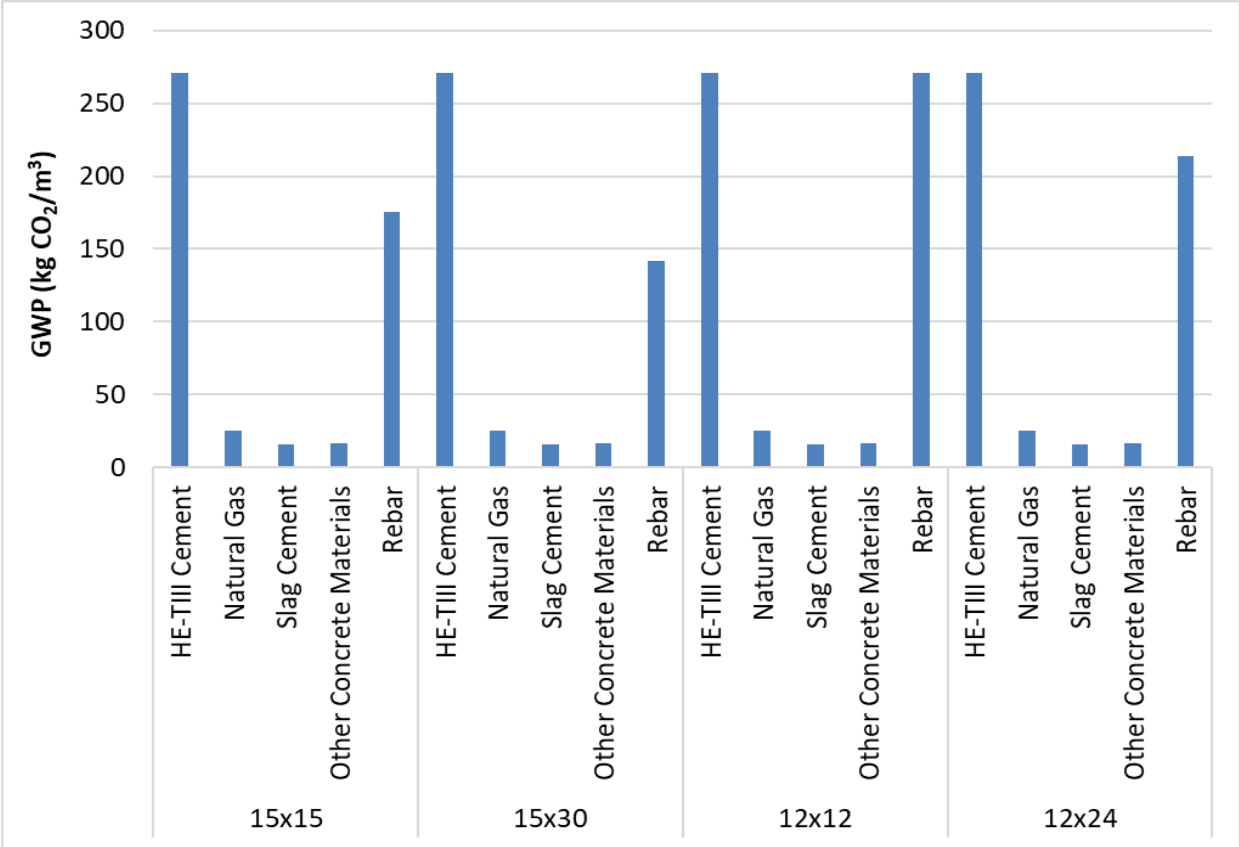


Figure 2. Contribution of materials and processes to GWP of each Lodestar Module size.

3.3. Impacts of Above- and Below-grade Panels

When comparing the below-grade (BG) panels and above-grade (AG) panels using the Baseline Mix or Mix#132, the total GWP impacts are lower for panels using Mix#132 (Table 10). The results are presented based on the functional unit of 1 m³, but also as impacts per panel unit, and impacts per tonne. The percent reduction for each panel when replacing concrete with Mix#132 is also calculated. On average, the GWP reduction is about 5-5.5% when replacing the Baseline Mix with Mix#132.

The relative contribution of concrete and steel rebar to the overall impacts per wall panel unit are displayed in Table 11. The type of rebar (steel or glass fibre) makes minimal difference to the GWP on a volume basis. Even though GFRP uses less mass than steel rebar, their GWP differences are marginal when based on equivalent mass units. Figure 3 provides a breakdown of each material or process input for the wall panels. The results emphasize the significant impacts of cement. The choice between steel rebar and glass fiber rebar shows negligible variation in the cradle-to-gate scope.

Table 10. The GWP of each below-grade (BG) and above-grade (AG) panel when using the Baseline Mix or Mix#132. The GWP is listed based on the total per unit, per tonne, and per m³. The percent reduction when replacing the Baseline Mix with Mix#132 is calculated.

Unit Size	Unit size	GWP (kg CO ₂ eq/unit)	GWP (kg CO ₂ eq/tonne)	GWP (kg CO ₂ eq/m ³)	% Reduction
BG Middle Panel FRP	Baseline Mix	670	192	443	
	Mix 132	636	182	420	5.10%
BG Middle Panel	Baseline Mix	672	192	444	
	Mix 132	637	183	421	5.09%
AG Wall Panel FRP	Baseline Mix	425	185	426	
	Mix 132	403	175	404	5.30%
AG Wall Panel	Baseline Mix	411	179	412	
	Mix 132	388	169	389	5.49%

Table 11. The GWP of each below-grade (BG) and above-grade (AG) panel based on different concrete mixes and rebar types is summarized. The percent contribution that each material input has for each product is listed next to the GWP contribution for each component.

Unit Size	Unit size	Concrete (kg CO ₂ eq)	% Contribution	Rebar (kg CO ₂ eq)	% Contribution
BG Middle Panel FRP	Baseline Mix	547	82%	121.7	18.2%
	Mix 132	513	81%	121.7	19.2%
BG Middle Panel	Baseline Mix	547	82%	121.0	18.1%
	Mix 132	513	81%	121.0	19.1%
AG Wall Panel FRP	Baseline Mix	361	85%	63.99	15.1%
	Mix 132	338	84%	63.99	15.9%
AG Wall Panel	Baseline Mix	361	88%	48.74	11.9%
	Mix 132	338	87%	48.74	12.6%

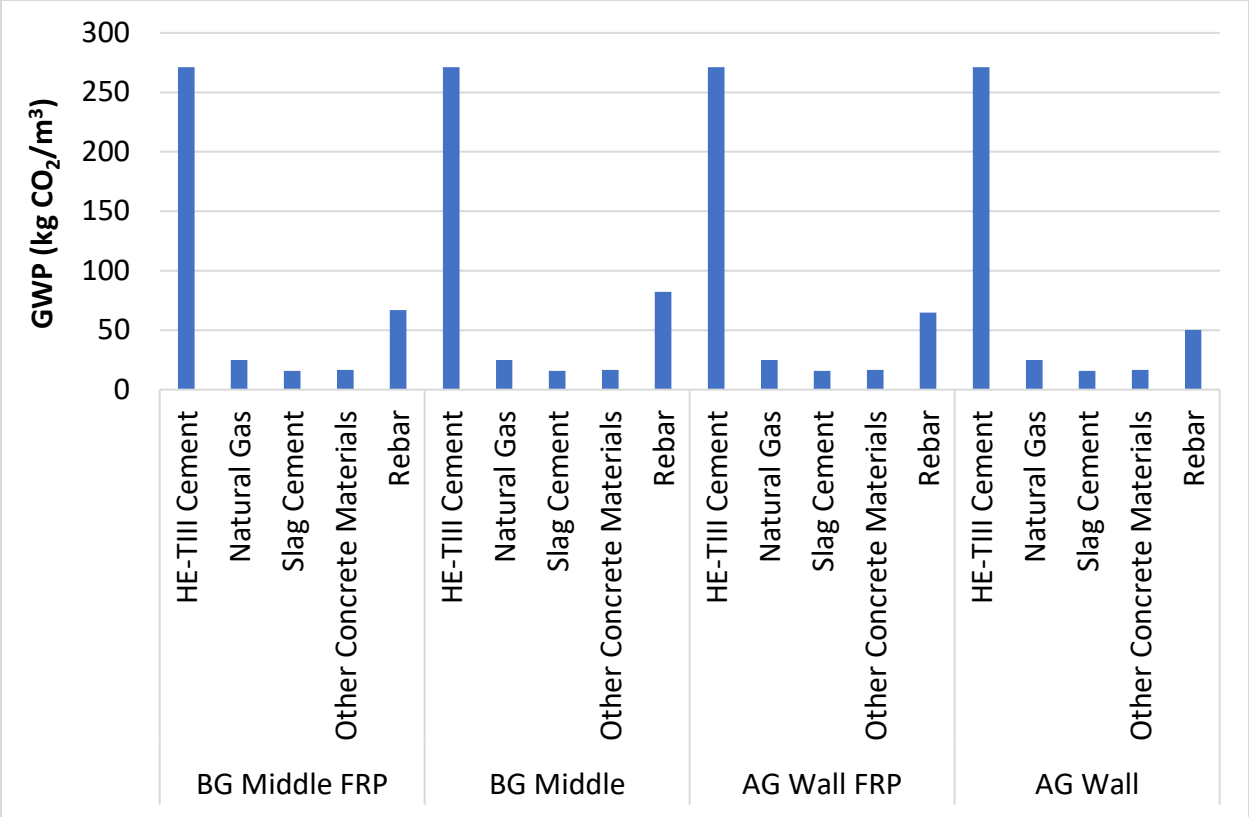


Figure 3. Contribution of materials and processes to GWP of each wall panel type.

4. Results Interpretation

The Life Cycle Impact Assessment (LCIA) exposes notable differences in environmental performances of concrete mixes and rebar combinations for various Lodestar sizes and wall panels. Table 8 illustrates the impacts for the Baseline Mix and Mix#132 across the four Lodestar modules, based on 1 m³, per unit, and per tonne. On average, replacing the Baseline Mix with Mix#132 alone reduced the overall Global Warming Potential (GWP) of each Lodestar module by 3.5-4.5%.

Table 9 highlights the contributions of concrete and steel rebar to overall impacts depending on the concrete mix. Concrete contributes 56-72% of the GWP impacts, with steel rebar accounting for 28-44%. Similarly, when comparing BG and AG panels with the Baseline Mix or Mix#132, Table 10 shows that using Mix#132 leads to an average GWP reduction of 5-6%.

For BG and AG panels, Table 11 illustrates that the GWP contribution of steel rebar is almost equal to that of glass fiber rebar. Despite GFRP needing less mass, its GWP on comparable units of mass exceeds steel's. It's crucial to note that GFRP's full life cycle benefits often emerge post-construction, which this report's scope doesn't cover.

While the data suggests that GFRP is similar to steel in terms of life cycle GWP, this interpretation is not entirely accurate. It's paramount to emphasize that many of GFRP's life cycle benefits come into play post-construction, a phase not covered within this report's life cycle assessment scope. To clarify, while assessing the GFRP product's impacts, it's observed that the majority of the GWP credits linked to GFRP life cycles are realized after Stages A1-A3. However, this report's cradle-to-gate scope primarily captures these initial stages. Furthermore, it's worth noting that the rebar ratio in the AG and BG wall panels isn't as prominent as in other Anchor products, like the Lodestar modules. Therefore, in structures with a higher rebar ratio, the slight GWP benefits of GFRP over steel rebar could be more pronounced

4.1. Sensitivity Analysis

Certain inputs and assumptions inherently bear higher degrees of uncertainty due to factors such as geographic coverage of data, temporal shifts in data, the diversity of sources, or discrepancies among different sources. The following sections detail sensitivity analyses performed on some selected data elements.

4.1.1. Transportation

For this study, a distance-weighted emission factor of 90.8 g CO₂e/t*km was utilized as the baseline, representing national average truck transportation emissions. A sensitivity analysis of the distance-weighted emission factor was explored to determine how reductions in transportation emissions would influence the overall GWP impacts. If the transportation of materials was improved by 30%, either through fuel efficiencies, use of biofuels, or other reduction impacts. The GWP of transporting materials for the Baseline mix is 8.32 kg and for Mix#132 it is 10.44 kg compared with the original transportation impacts of 11.89 and 11.40 kg. Overall, a 30% change in the emission factor used for transportation is likely only going to reduce the overall GWP of concrete mixes by approximately 3.5 kg. When this is taken into consideration for the entire GWP of a m³ of concrete mix, this only represents around a 1% change in the overall GWP. Similar trends were observed when the GWP of transporting rebar was compared across wall panels. When comparing the GWP of transportation of rebar for the BG and AG panels when using Mix#132 and reducing the emission factor by 30%, results in emissions reductions of 2kg when transporting steel rebar, and by 0.49 kg when transporting glass fiber rebar. In both instances the reductions are less than 1% of the overall GWP impact of each wall panel.

4.1.2. Glass Fiber Mass Ratios

Per communication with the GFRP supplier, GFRP should weigh about 25% of steel when replaced at a 1:1 ratio. However, the wall panel plans use GFRP weighing 30% and 40% of the steel mass for BG and AG panels, respectively. Table 12 presents a sensitivity analysis for GFRP substitution at the recommended 25% mass ratio. This leads to a 20% GWP improvement for BG panel rebar components and 17% for AG panels, yielding an overall 2-3% reduction for all wall panel components. A similar analysis for Lodestar modules (which don't use GFRP yet) indicates an 8.5% and 17% GWP reduction when substituting 50% and 0% of steel rebar mass, respectively (Table 13). Given the higher rebar proportion in Lodestar modules, the GFRP offers more significant GWP improvements at the cradle-to-gate scale.

Table 12. The total GWP impact contributed to each lodestar module from the rebar used when 100% of the rebar is steel, compared with when 25% and 50% of the steel is substituted for glass fibre rebar.

Unit Size	Unit size	Concrete (kg CO ₂ eq)	% Contribution	Rebar (kg CO ₂ eq)	% Contribution
BG Middle Panel FRP	Baseline Mix	547	83.1%	111	16.9%
	Mix 132	513	83.6%	100	16.4%
BG Middle Panel	Baseline Mix	547	82.0%	121	18.1%
	Mix 132	513	81.0%	121	19.1%
AG Wall Panel FRP	Baseline Mix	361	87.4%	52.2	12.6%
	Mix 132	338	89.3%	40.4	10.7%
AG Wall Panel	Baseline Mix	361	88.0%	48.7	11.9%
	Mix 132	338	87.0%	48.7	12.6%

A similar sensitivity analysis was performed for the Lodestar modules, which have yet to incorporate GFRP, but the GWP might benefit from some or full substitution. When the steel rebar in the Lodestar modules was substituted at 50% and 0% of mass used, there was an 8.5% and 17% reduction in the GWP of the rebar used respectively (Table 13). The larger proportion of the rebar used in the Lodestar modules compared with the wall panels is able to capture more of the marginal per unit improvement in GWP that the GFRP product provides at the cradle-to-gate scale.

5. Conclusion & Takeaways

This LCA conducted for Lodestar Structures' modules and wall panels provides valuable insights into the environmental impacts of their products. The results offer a blueprint for improving environmental sustainability and guiding future product strategies. The conclusions and key takeaways outlined below highlight the significant findings and potential opportunities for Lodestar Structures to progress on its sustainability journey:

i) Improved Concrete Mix Design Reduces Global Warming Potential (GWP)

To achieve net-zero emissions by 2050, the baseline year (e.g., 2022) would require an annual reduction of approximately $300 \text{ kg CO}_2\text{eq} / 28 \text{ years} = 10.71 \text{ kg CO}_2\text{eq per year}$. Upon transitioning from the Baseline Mix to Mix#132, the current reduction achieved in GWP is 3.5-4.5%. This reduction is equal to approximately $13.5 \text{ kg CO}_2\text{eq}$, which puts Lodestar Structures on track to meet their expected reduction rate for the year 2023.

The company that Anchor sources their cement products from, Lafarge, has already made commitments to reduce the impacts of their products over time, in accordance with SBT guidelines to reach net-zero targets by 2050. As Lafarge lowers the impacts of their products in line with SBT targets, it is expected that there should be a corresponding reduction in the impacts of Anchor's products accordingly.

ii) Optimize Rebar Selection for Targeted GWP Reductions

The inclusion of glass fiber rebar has predominantly been seen within the wall panels. Our updated life cycle assessment results illustrate that while there are GWP advantages to using glass fiber rebar in wall panels, its benefits could be more pronounced in structures like the Lodestar modules, which possess higher rebar proportions.

Upon conducting a sensitivity analysis on the Lodestar modules, we found that when substituting 50% of steel rebar with glass fiber rebar, there was an 8.5% reduction in GWP. If steel rebar were completely replaced by glass fiber rebar, which corresponds to a 0% steel rebar usage, there's a 17% reduction in GWP. This indicates potential avenues for notable GWP reductions with the strategic inclusion of glass fiber rebar.

Considering these GWP reductions, it becomes evident that integrating glass fiber rebar into the Lodestar modules could considerably aid in meeting the Science-Based Targets (SBTs) related to rebar materials by 2050. Lodestar Structures' trajectory in GWP reduction signifies a

promising start, but the full realization of their long-term sustainability ambitions concerning rebar will necessitate continuous exploration and adaptation of sustainable rebar solutions.

Given the noted GWP reductions and taking into account the entire life cycle of GFRP, there's a potential that utilizing glass fiber rebar in the Lodestar modules might surpass the linear trajectory needed to align with the Science-Based Targets (SBTs) for rebar materials by 2050. While the current progress in GWP reduction is commendable, Anchor's trajectory toward achieving their long-term sustainability objectives concerning rebar will rely on their continuous efforts in identifying methods to integrate more sustainable rebar options, such as glass fiber rebar.

iii) Potential for CarbonStar Certification and Simplified Application Process

In line with Lodestar Structures' commitment to environmental sustainability and industry-leading standards, the company may consider seeking certification through the CarbonStar program. The methods used in this comprehensive LCA report to quantify Global Warming Potential (GWP) align with the requirements of the CarbonStar program, as both draw on ISO LCA methods. This congruence means that the data and results obtained from this LCA can be easily converted into the CarbonStar application form, streamlining the certification process. Obtaining CarbonStar certification would further set Lodestar Structures apart in the market, providing a recognized and trustworthy verification of their product's environmental performance. The certification could potentially open up new business opportunities, attract environmentally conscious clients, and showcase the company as an industry leader in reducing carbon emissions. As the construction industry continues to prioritize sustainability and decarbonization efforts, CarbonStar certification can be a valuable asset in positioning Lodestar Structures as a responsible and forward-thinking supplier within the sector.

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7. Appendix

Appendix 1. Summary review data quality assessment, based on geographical and temporal coverage of system boundaries and data sources.

Data Quality and Variability Metric	Assessment
Technological Coverage	This LCA captures the prevailing technology in use at the Anchor Concrete's facility. The data embodies the actual production processes for the declared precast concrete products. The technology coverage is characterized as “high”.
Geographic Coverage	The geographic region considered for this LCA is Ontario, Canada. The electricity used was modeled based on the Ontario provincial grid mix. The geographical representativeness of the data is characterized as "high".
Time Coverage	Primary data are representative of the 12 months leading up to this LCA report, covering all processes related to the production of precast concrete products at the Anchor Concrete facility. Secondary data were sourced from relevant databases and EPDs. The temporal representativeness is characterized as “high”.
Completeness	The LCA took into consideration all pertinent processes specific to Anchor Concrete, including inputs (raw materials, energy, and ancillary materials) and outputs (emissions and production volume) to complete the production profile for Lodestar Structures.
Consistency	In a bid to maintain consistency, the modeling of the production input and output LCI data for Lodestar Structure products followed the same LCI modeling structure, involving input material, intermediate products, energy flows, water resource inputs, product outputs, emissions to air, water, and soil, and waste disposal. This calculated LCI was subsequently evaluated using the Athena Impact Estimator for Buildings. Mass and energy balances were conducted at the facility level and selected process levels to ensure a high level of consistency.
Reproducibility	The data and models, being preserved in the Athena Impact Estimator for Buildings, facilitate internal reproducibility. Key primary (manufacturer-specific) and secondary (generic) LCI data sources are also summarized in the Athena Impact Estimator for Buildings documentation.
Transparency	Activity and LCI datasets are disclosed in the project report, encompassing all data sources. The report provides the requisite transparency for the critical review process.